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# Feasibility of Reduced Gravity Experiments Involving Quiescent, Uniform Particle Cloud Combustion

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# FEASIBILITY OF REDUCED GRAVITY EXPERIMENTS INVOLVING QUIESCENT, UNIFORM PARTICLE CLOUD COMBUSTION

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## Summary

The study of combustible particle clouds is of fundamental scientific interest as well as a practical concern. Such clouds spread fires in underground mining operations and contribute to the fire and explosion hazards of grain storage and handling facilities. The principal scientific interests are the characteristic combustion properties, especially flame structure, propagation rates, stability limits, and the effects of stoichiometry, particle type, transport phenomena, and nonadiabatic processes on these properties.

The feasibility tests for the particle cloud combustion experiment (PCCE) were performed in reduced gravity in the following stages: (1) fuel particles were mixed into cloud form inside a flammability tube; (2) when the concentration of particles in the cloud was sufficiently uniform, the particle motion was allowed to decay toward quiescence; (3) an igniter was energized which both opened one end of the tube and ignited the suspended particle cloud; and (4) the flame proceeded down the tube length, with its position and characteristic features being photographed by high-speed cameras.

Gravitational settling and buoyancy effects were minimized because of the reduced gravity environment in the NASA Lewis drop towers and aircraft. Feasibility was shown as quasi-steady flame propagation which was observed for fuel-rich mixtures. The observed shape of the flame front and wake structures were as anticipated but had not been previously obtained. Of greatest scientific interest is the finding that for near-stoichiometric mixtures, a new mode of flame propagation was observed, now called a "chattering flame." These flames did not propagate steadily through the tube. Our current explanation is that the flame induced an (Kundt's tube) acoustic disturbance which could segregate the air-suspended particles into alternating fuel-rich and fuel-lean laminae. The flame then would propagate in a leaping, or chattering, fashion from one fuel-rich regime to the next.

Chattering modes of flame propagation are not expected to display extinction limits that are the same as those for acoustically undisturbed, uniform, quiescent clouds. A low concentration of fuel particles, uniformly distributed in a volume, may not be flammable but may be made flammable, as was observed, through induced segregation processes. A new theory was developed which showed that chattering flame propagation was controlled by radiation from combustion products which heated the successive discrete laminae sufficiently to cause autoignition.

## Introduction

### Justification for the Particle Cloud Combustion Experiment

The study of combustible particle clouds is of fundamental scientific interest as well as a practical concern. Such clouds spread fires in underground mining operations and contribute to the fire and explosion hazards of grain storage and handling facilities. The principal scientific interests are the characteristic combustion properties, especially flame structure, propagation rates, stability limits, and the effects of stoichiometry, particle type, transport phenomena, and nonadiabatic processes on these properties.

These same issues are the subjects of classical premixed gas combustion studies. Such studies involve normally a quiescent combustible mixture of fuel, oxygen, and nitrogen contained in a flame tube of standard dimensions (5 cm diameter by 100 cm length). The tube is simultaneously opened and the mixture ignited at one end. The flame then propagates through the tube, achieving a steady flame speed and shape. The observed speed is a function of the fuel and oxidizer concentrations; as the initial fuel concentration is reduced, a concentration will be reached which will no longer support flame propagation. This concentration is called a lean flammability limit. Such experiments have been conducted primarily in normal gravity (ref. 1), but they also have been conducted in reduced gravity (ref. 2).

A corresponding flame tube study of premixed solid particle clouds is difficult because of gravitational settling of particles which destroys the requirements of quiescence and of uniform fuel concentration. In order to achieve uniformity, stirring devices or particle feeders (ref. 3) have been employed at the sacrifice of quiescence. The problems that these introduce include a time-dependent turbulent field which is known to affect flame propagation and limit behavior, as well as a complex interaction between the turbulent field and buoyantly driven flows induced by the spreading flame. Both problems are such that detailed analysis of flame propagation mechanisms in normal gravity is beyond the current state of understanding.

As an alternative, a reduced gravity experiment was conceived which emulates the characteristics of the classical premixed gas studies (ref. 4). The reduction of gravity minimizes particle settling and buoyantly driven flows while maintaining the other features of the classical experiment.

The particle cloud combustion experiment (PCCE) is performed as shown on figure 1 in the following stages: (1) fuel particles are mixed into cloud form inside a flammability tube; (2) when the concentration of particles in the cloud is sufficiently uniform, the particle motion is allowed to decay toward quiescence; (3) an igniter is energized which both opens one end of the tube and ignites the particle cloud; and (4) the flame proceeds down the tube length, with its position and shape being photographed by high-speed cameras.

The duration of the experiment, that is, the required time for reduced gravity, is dependent on the time for mixing, and the time for quiescence, as well as on the observed flame speed

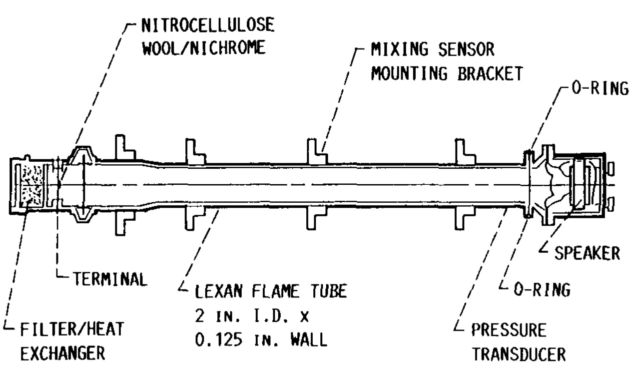



Figure 1.—Schematic of flame tube assembly.

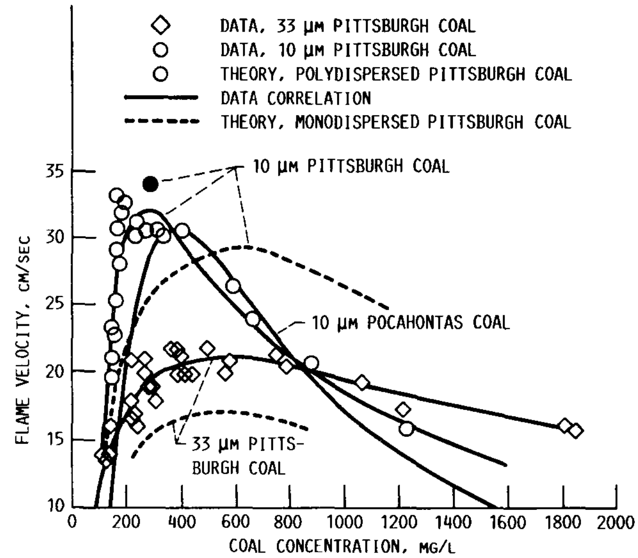



Figure 2.—Measured and predicted effects of coal particle size and coal concentration (ref. 2).

which is a function of the stoichiometry of the fuel-air system. Figure 2 displays approximate flame speeds predicted for different stoichiometries, based on Smoot's normal gravity stabilized flame experiments with coal (ref. 5). As the lean flammability limit is approached, flame speeds are expected to diminish, so that the times required for the flames to propagate the full tube length increase. Time is also required for a cloud to form and the airflow to decay to quiescence. Originally the total time to conduct an experiment was estimated to be 0.5 to 5 min, an amount of time which exceeds that available in ground-based reduced gravity facilities. As such, development began for the conduct of the experiment aboard the space shuttle. The desired experimental test conditions and requirements were specified and are displayed in table I (ref. 6).

TABLE I.—EXPERIMENTAL TEST MATRIX FOR PARTICLE CLOUD COMBUSTION EXPERIMENT (PCCE) STUDIES FOR LEAN AND NEAR-STOICHIOMETRIC MIXTURES

| Particle type | Equivalence ratio, $\Phi$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Lycopodium | 1.3 | 1.2 | 1.1 | 1.0 | 0.92 | 0.84 | 0.78 | 0.72 |
| Lycopodium and inert particles | (a) | (a) | (a) | (a) | (a) | (a) | (a) | (a) |
| Pocahontas coal | | | | | | | | |
| 25 μm | 2.0 | 1.8 | 1.6 | 1.4 | 1.2 | 1.0 | 0.85 | 0.75 |
| 40 μm | 2.4 | 2.0 | 1.6 | 1.4 | 1.2 | 1.0 | .85 | .75 |
| 55 μm | 2.8 | 2.4 | 2.0 | 1.6 | 1.4 | 1.2 | 1.0 | .90 |
| Pocahontas coal and inert particles, 25 μm | (a) | (a) | (a) | (a) | (a) | (a) | (a) | (a) |
| Cellulose, 25 μm | 2.0 | 1.8 | 1.6 | 1.2 | 1.0 | 1.0 | 0.85 | 0.75 |

[a]To be determined.

## Experimental Design Development

The conceptual design for the experimental hardware is displayed in figure 1. Fuel particles were contained inside the flammability tube whose ends were capped with flexible mylar diaphragms. Based on recommendations in (ref. 7), an inline acoustical speaker was selected as the technique which, when energized, excited airflows within the tube and distributed the particles into a uniform cloud. Fuel particle concentration was to be determined at four axial locations via optical detector assemblies operating on the classical light extinction principle (ref. 8). An igniter at the opposite tube end both burned through a mylar diaphragm and ignited the particles. In order to minimize the hazard and required expansion volume, a heat exchanger was employed to cool the combustion products as they escaped through the open tube end.

A 3-yr development program resulted in successful ignition and observed flame propagation in tubes of one-third the length of the PCCE tube, and in the successful development of the heat exchange system and a working detector system. However, substantial technical problems also occurred. The cloud formed by the acoustic system in PCCE tubes did not reach nor tend toward sufficient uniformity. In addition, the longer the acoustic system operated, the greater the number of particles which adhered to the tube walls rather than remained in air suspension as desired. These observations are documented in reference 9. Efforts to control particle adhesion via electrically conductive tube walls failed as well (ref. 10). Perhaps because of these problems, flame propagation in a full length PCCE tube was never attempted.

In the midst of research efforts to resolve these problems, the space shuttle Challenger disaster occurred, delaying the manifestation of all planned space-based experiments. Ross and Berlad conceived then of a ground-based experimental program examining fuel-rich mixtures using the PCCE conceptual design and hardware (ref. 6). As shown in figure 2, the anticipated flame speeds are only mildly dependent on stoichiometry for rich mixtures, permitting a greater allowable variation in the uniformity requirement. Initial particle position could also be specified and controlled, so that the desired mixing uniformity was more likely to be achieved. With this same specification, the required mixing time would be reduced, and the particle adhesion problem diminished, as described above. The reduced mixing time and the rapid flame speeds for rich mixtures, as shown in figure 2, suggested the total time to conduct the experiment could be reduced by an order of magnitude to a time which might be achieved in ground-based facilities. Finally, the use of ground-based facilities offered the advantages of lower cost, greater design flexibility, increased operator-experiment interaction, rapid turnaround time, and lesser reliability requirements. New specifications were developed for such an experiment and are displayed in table II (ref. 6). Note that a shorter, constant diameter tube was selected for study in that limit behavior was not of principal interest, and ignition phenomena were less critical therefore.

TABLE II.—EXPERIMENTAL TEST MATRIX FOR PARTICLE CLOUD COMBUSTION EXPERIMENT (PCCE) STUDIES OF FUEL-RICH MIXTURES

| Particle type | Equivalence ratio, $\Phi$ | | | | | |
|---|---|---|---|---|---|---|
| Lycopodium | 1.3 | 2 | 3 | 4 | 5 | 6 |
| Lycopodium and inert particles | (a) | (a) | (a) | (a) | (a) | (a) |
| Pocahontas coal | | | | | | |
| 25 $\mu$m | 2 | 3 | 4 | 5 | 6 | 7 |
| 40 $\mu$m | 2.4 | 3.2 | 4 | 5 | 6 | 7 |
| 55 $\mu$m | 2.8 | 3.4 | 4 | 5 | 6 | 7 |
| Pocahontas coal and inert particles, 25 $\mu$m | (a) | (a) | (a) | (a) | (a) | (a) |
| Cellulose, 25 $\mu$m | 2.0 | 3.0 | 4 | 5 | 6 | 7 |

[a]To be determined.

## Goals, Objectives, and Approach of Feasibility Study

It was the goal of this study to determine the feasibility of using the current PCCE hardware design to collect valid flame spread data for fuel-rich particle cloud mixtures in a ground-based reduced gravity facility. In support of this goal, the following objectives were established:

(1) Determine if acoustic mixing can create a sufficiently uniform cloud in low gravity, and for how long.

(2) Determine the reduced gravity time required to conduct the experiment.

(3) Determine if quasi-steady flame speeds and flame structures for rich mixtures can be achieved in reduced gravity.

(4) Determine which ground-based facility will be needed for ground-based scientific data collection.

(5) Determine the operational and scientific success rate for the collection of such data.

(6) Reestimate tasks, costs, and schedules for the ground-based science program data collection.

Part way through the test program to make these determinations, it was suggested that an additional objective be added:

(7) Determine the applicability of the ground-based program techniques to the shuttle flight program.

To achieve these objectives, the following approach was selected:

(1) The study was limited to consideration of the conceptual design: that is, one inline speaker on one end of the tube, and an inline igniter on the other end. As such, the variables to improve cloud formation were limited to diaphragm tension, electrical power, acoustic frequency selection, speaker runtime, and initial particle position.

(2) Mixing, ignition, and flame propagation tests involving various fuel-air ratios would be conducted in both the NASA Lewis Research Center 2.2-sec drop tower and in the NASA Lewis Learjet aircraft to bound the problem and estimate the minimum and maximum times required to conduct the experiment.

(3) Because of the lower cost and turnaround time, tests in the 2.2-sec drop tower would precede those in the aircraft.

(4) The initial fuel particle position would be spread as evenly as possible in the tube bottom. Facca had shown previously that this initial fuel position allowed a briefer mixing time and a more uniform cloud (Facca, personal communication). Unlike the tests described in reference 9, the speaker runtime would be minimized to a quick burst (less than 1 sec) to distribute the fuel radially and circumferentially into cloud form. Axial migration of fuel would no longer be required, and in fact would be undesirable.

(5) Though a technique was developed which actively reduced or prevented the particle adhesion problem (i.e., the use of radioactive material on the inner tube walls (ref. 10)), it would not be employed in these tests because of safety concerns and/or cost considerations. Instead, it was hoped that the mixing technique described previously would keep adhesion levels within bounds.

(6) The feasibility tests would be restricted to lycopodium. It was assumed that the change of fuel type to coal or cellulose would not require a major reconfiguration of the experimental methods.

These tests in total were conducted between October 1987 and August 1988.

### Scientific Goals and Requirements

Before discussing the experimental tests, the nature of and reasoning for the scientific requirements should be understood. Few, if any, of the requirements specified in reference 6 are intrinsic standards, but instead represent experimental goals which make the observations more easily interpretable.

Ideally, the particle cloud should be uniform and quiescent during the combustion event. In practice these requirements are virtually impossible to meet. In the presence of a gravitational field, even the weak fields in the Lewis reduced gravity facilities, particle settling will occur over time and destroy both uniformity and quiescence. The effects of weak, uncontrolled forces whose presence is masked in normal gravity will also degrade particle uniformity. Over long periods of time, thermodynamic equilibrium requirements suggest that all the particles will either agglomerate into a single mass or attach to the tube walls. The time scales involved in these processes are fortunately long, compared to the predicted time for the conduct of the experiment.

Defects in the particle cloud uniformity and quiescence are acceptable if the length and time scales of the defects are small and large, respectively, compared to the important scales of the combustion process. The normally conceived reaction zone thickness is believed to be on the order of 1 to 10 mm in reduced gravity. If the uniformity defects are sufficiently smaller, then the flame passage will be relatively unaffected. The flame propagation rate is estimated from figure 2. If it is long compared to estimated settling rates and the residual particle motion following secondary airflow mixing, then the observed flame propagation rate should be unaffected by the particle motion.

The character and magnitude of these gravitational effects have been examined previously (ref. 11). It is useful here to identify the three generally disruptive gravitational effects which must be dealt with.

Particles of initial interest in this investigation have maximum densities (specific weight of about 1.35) and maximum diameters (about 70 $\mu$m) 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

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

where $g$ is the acceleration due to gravity, $r$ the particle radius, $\rho_p$ the particle density, and $\mu_g$ the gas (air) viscosity. The first fuel particulate under study is the lycopodium spore, which has a mean diameter of about 27 $\mu$m and a specific weight close to unity.

At normal gravity, lycopodium has a settling speed of about 2 to 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) 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 the 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) and flame speeds of the order of 10 cm/sec, or less, may be characteristic. Any reasonable criterion of both quiescence and uniformity cannot be met. Post-mixing periods needed to achieve quiescence have been estimated to be of the order of 10 sec, 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 sec, or more. If the cloud of mixed particles is allowed to settle (or drift) by no more than 10 percent of the tube diameter during a total experimental time of 5 to 10 sec, utilization of equation (1) implies the need of a reduced gravity environment $g^*$ of about 0.01 to $0.005g_0$.

A second 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

$$c^* = c_0 \left[ 1 \pm \frac{V_t}{U_f} \right] \tag{2}$$

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 upward propagation, and the negative sign corresponds to downward propagation. The upward propagating front enjoys an enriched fuel concentration. The downward propagating front experiences a depleted fuel concentration. This effect is especially 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 downward 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 $(V_t/U_f)$ be less than 0.02, we find that the required range of reduced gravity conditions is of the order of $g^* = 0.01$ to $0.001g_0$.

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 and are also observed for particle cloud flames (ref. 4). As noted in reference 11, Lovachev has discussed the relation between a characteristic time and other parameters for hot combustion product buoyancy effects on premixed flame propagation rates. His studies lead to the relation

$$\frac{t_k^3 g^2}{\nu} = \text{constant} \tag{3}$$

where $t_k$ is the time (after ignition) necessary for the development of significant buoyancy effects on flame propagation, $g$ the gravitational constant, and $\nu$ 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 and an estimate of some 20 sec needed for a particle cloud combustion experiment at reduced gravity, it follows that a value of $g^*$ of about $0.01g_0$ is adequate to achieve the same buoyancy-suppression effects for particle cloud flames at reduced gravity.

Based on these considerations, it is concluded that low-gravity combustion experiments require values of $g^*$ no lower than $0.005g_0$ if the post-mixing combustion can be consummated during a period of about 10 sec. This includes virtually all expected flame propagation speeds, with the possible exception of those very slow flames which are very close to extinction limits.

The measurement of uniformity and quiescence is determined principally by the four optical detectors. Ideally, their signals would be identical and invariant in time. At a single instant in time, the detectors provide a snapshot of the local degree of nonuniformity (i.e., one measure of the defectiveness of the cloud). With a nonuniform cloud, examination of the detectors' data over a period of time provides a qualitative measure of the degree of quiescence. It should be noted that in a perfectly uniform cloud, the detectors are incapable of determining the degree of quiescence.

The optical detectors have small amounts of drift and noise susceptibility, measured to be on the order of 1 percent. Recognizing the practical limitations of achieving a uniform cloud, the scales of the combustion processes, and the realistic degree of instrument error, a goal of concentration uniformity of $\pm 10$ percent of their common mean was established. In the purest sense, this is a goal, not a scientific requirement.

The detectors, being line-of-sight instruments, are also incapable of distinguishing between suspended and wall-adhered particles. It is only the suspended concentration of particles which affect the combustion process. Ideally, either a negligible number of particles should be wall-adhered, or the wall-adhered particle density should be known, so that the suspended concentration can be easily determined. Additionally a known and uniform distribution of wall-adhered particles would be advantageous, in that a nonuniform wall density implies a nonuniform cloud concentration (not fundamentally true, but accurate for practical purposes). Reference 6 states the requirement for "wall saturation effects (to be) small as well as quantitatively determinable." In order to minimize effects of wall-adhered particles, a goal was established to keep their percentage of the total number of particles below 10 percent.

The flame shape and speed involving a particle cloud are more "quasi-steady" than absolutely steady. This is due to the discrete nature of the particles and the nonuniformity of the cloud. Thus examination of the flame shape and speed on a local basis may reveal somewhat unsteady behavior. However when viewed over sufficient lengths of the tube, the average flame speed should be constant and reproducible.

# Experimental Test Apparatus

## Drop Tower Experimental Apparatus

In the drop tower facility, the experimental hardware, as shown in figure 3, is mounted within the confines of a drop rig (maximum allowable dimensions of approximately 38 in. long by 14 in. wide by 28 in. high. The drop rig itself is placed inside a drag shield; both the drag shield and drop rig are suspended by a music wire at the top of a 100-ft open shaft. When the wire is cut pneumatically, both drag shield and drop rig fall for 2.2 sec, landing in an aerated sand pit. During the fall, the drag shield absorbs most of the air drag, while the drop rig falls freely inside (fig. 4). In this way, the low gravity level cited previously is achieved during the fall.

The drop tower experimental hardware consisted of (1) a 25-in.-long, 2-in.-diameter tube containing 480-mg lycopodium (an equivalence ratio of about 3), (2) a 1-in.-long, inline igniter section, (3) a 2-in. heat exchanger to cool the combustion products as they escape through the open tube end, and (4) an 80-W capacity acoustic speaker mounted inline on the end of the tube opposite from the igniter.

Instrumentation consisted of (1) two high-speed movie cameras each filming one-half of the tube from above and through a mirrored side view at a rate of 128 frames/sec and (2) four concentration detector assemblies mounted 4, 17, 31.5, and 45.5 cm from the igniter end of the tube. Each assembly, shown in figure 5, contains a light-emitting diode (820 nm), filters and collimating lenses, and a photodiode to measure the strength of the 3.5-mm-diameter light beam. The signal strength was determined by the particle concentration in the beam path. In order to improve accuracy, each beam was split to provide an unattenuated reference voltage signal. In addition, the LED was pulsed on/off to account for any ambient light leaks and drift. To account for possible circumferential effects, the four detector assemblies were mounted at different angles passing through the tube axes. The signals from the detector assemblies, normally between 0 and −10 V, were halved and inverted to be compatible with the central data acquisition system described as follows.

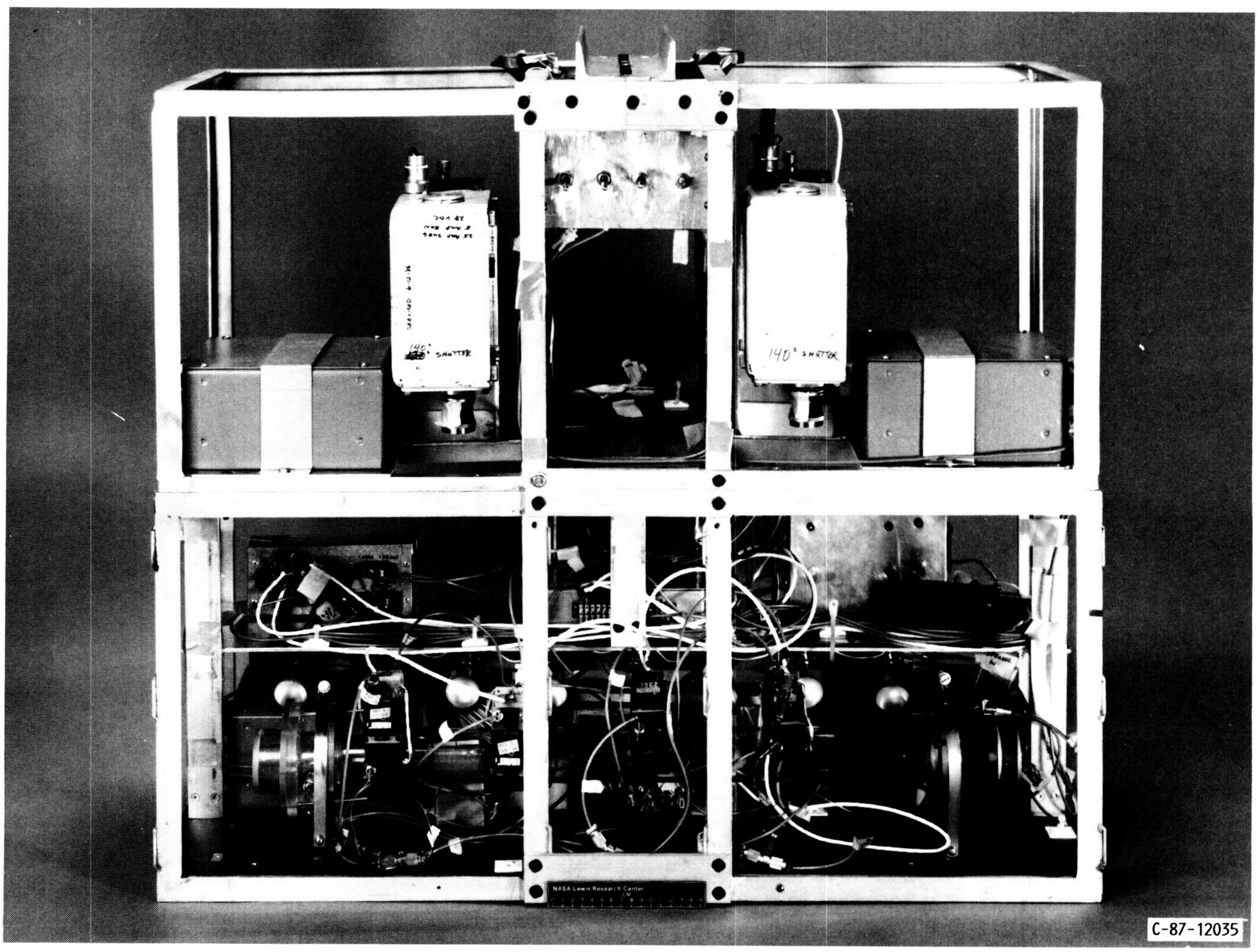
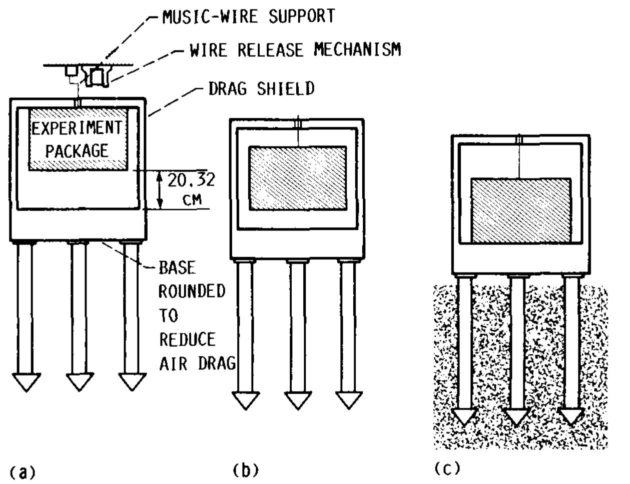



Figure 3.—Particle-cloud combustion experimental drop tower rig.




(a) Before test drop.
(b) During test drop.
(c) After test drop.

Figure 4.—Position of experiment package and drag shield before, during, and after test drop in 2.2.-sec drop tower.

Prior to the experiment the fuel was positioned in the tube via a small grooved rod. The fuel particles were arranged in a thin row (4 to 10 mm wide), running the full axial length of the tube. The experimental sequence was as follows: (1) While still hanging from the music wire, the cameras and lights were powered and brought to normal operating speed; during this period the detector assemblies were sampled at a rate of 12.5 Hz; (2) the music wire was cut, and the package began to fall; (3) at 0.05 sec into the reduced gravity period, the acoustic speaker was turned on; it was driven with a square wave signal at 140 Hz for a period of 0.5 sec; (4) immediately after the speaker was turned off, the detector assemblies were sampled at a rate of 25 Hz (25 "LED on" readings and 25 "LED off" readings); and (5) at 2.1 sec into the drop, the sampling and cameras were stopped.

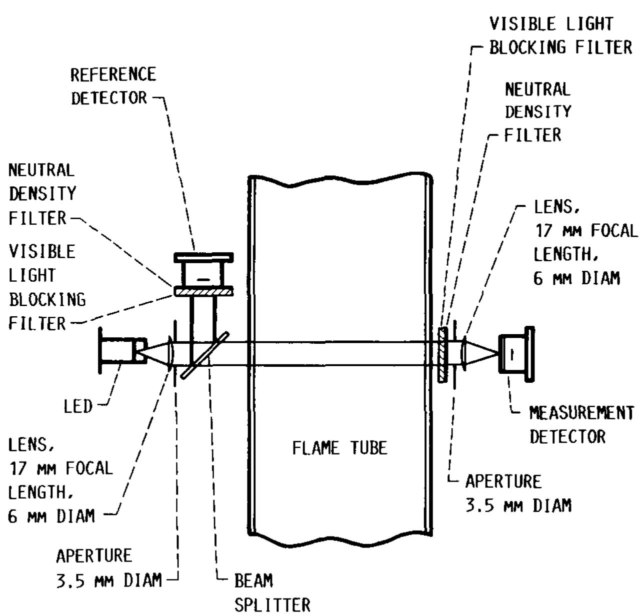



Figure 5.—Schematic of the optical detectors mounted on flame tube (25 in.).

All data acquisition and control functions were provided by a battery-powered microprocessor-based system, based on a commercially available board. After the drop was completed, detector data stored in memory on this board was downloaded to a personal computer and processed via a standard spreadsheet program. The data collected prior to the drop provided the unattenuated reference voltage and were compared to the drop measurements of the signal attenuated by the suspended particle cloud.

A program of roughly 40 drops was conducted to optimize mixing techniques and to determine approximate flame propagation rates through the tubes. A complete list of test conditions is given in table III. Nineteen drops were dedicated to mixing testing only. Twelve drops were dedicated to ignition and flame propagation tests only (no detector data). The other tests were specialized to examine mixing phenomena or to check out subsystem performance. None of these tests involved the full-scale test of the experiment. It should also be noted that after the 40th drop, several welds on the drop rig failed because of a "hard hit" in the aerated sand pit. At the time of this writing, a second generation drop rig is being built.

### Learjet Experimental Apparatus

Experiments were also performed on the NASA Lewis Learjet. This facility provides about 20 sec of reduced gravity at a level of less than 0.02g by flying a Keplerian trajectory (ref. 12). It also allows a researcher to observe the experiment in real time.

Figure 6 displays the experimental hardware on the Learjet. A secondary containment chamber was required for safety reasons. Its volume was 64 times that of the flammability tube. Calculations suggested a negligible pressure rise in the containment chamber as a result of combustion.

With the following exceptions, virtually all other instrumentation and procedures described were the same in the Learjet.

(1) A more precise acoustic mixing control was utilized.

(2) Detector data were collected every 0.07 sec and stored on a different data acquisition and control system.

(3) The detector positions were varied axially in some tests, but were more evenly spaced than in the drop tower tests.

(4) The waiting time for secondary airflow decay was increased from 0.35 sec in the drop tower to 3 to 10 sec in the Learjet.

(5) As described later, different mixing frequencies were required to achieve satisfactory cloud uniformity.

(6) An extra 12 mg of lycopodium was loaded into the first 4 cm of the tube nearest the igniter to ensure a robust ignition.

(7) The camera framing rate was 200 frames/sec, instead of the 128 frames/sec used in the drop tests.

TABLE III.—TEST CONDITIONS FOR PARTICLE CLOUD COMBUSTION EXPERIMENT (PCCE) STUDIES

| Test | Equivalence ratio, Φ | Purpose | Results |
|---|---|---|---|
| 1 | 3.3 | Mixing subsystem checkout | OK |
| 2 | | Camera subsystem checkout | OK |
| 3 | | Mixing and camera checkout | Abort |
| 4 | | Repeat 3 | No speaker |
| 5 | | Repeat 4 | OK |
| 6 | ↓ | Repeat 5 | OK |
| 7 | 3.0 | Two detectors installed | OK, good agreement |
| 8 | 2.5 | Mixing only, no detectors | OK |
| 9 | ? | Repeat 8 | OK |
| 10 | 3.0 | Four detector checkout | Program bug, data from two detectors only |
| 11 | 3.1 | Repeat 10 | OK, good agreement |
| 12 | | Ignition test | OK, full propagation |
| 13 | | Four detector mixing test | M4 bad, else good |
| 14 | | Ignition test | OK, full propagation |
| 15 | | Repeat 11 and 13 | M4 bad, else good |
| 16 | ↓ | Repeat 12 and 14 | OK, full propagation |
| 17 | 3.6 | New presssure measurement, fuel loader, time delay on camera ignition test | OK, poor mix, no pressure rise, bad adhesion |
| 18 | 3.7 | New fuel loader, same as 15 | M4 bad, else good |
| 19 | 3.7 | Repeat 18 | M4 bad, else good |
| 20 | (a) | Visualization of fuel segments | OK |
| 21 | 1.1 | Four detector mixing test | Detector 3 data bad |
| 22 | 1.1 | Repeat 21 | Detector 3 data bad |
| 23 | 1.2 | Ignition test | OK, full propagation |
| 24 | 1.1 | Repeat 23 | OK, full propagation |
| 25 | 1.1 | Repeat 22 | Detector 3 data bad |
| 26 | 1.4 | No camera or lights; noise test | Poor mix due to fuel loading |
| 27 | 1.4 | Increase speaker power | Cloud moves to middle |
| 28 | 1.6 | Same as 27, less ontime | Detector 1 data bad, else OK |
| 29 | 1.2 | Repeat 25 | Detector 4 data bad? else OK |
| 30 | .95 | Ignition test | OK, full propagation |
| 31 | .62 | Ignition test | Bad igniter |
| 32 | .65 | Repeat 31 | OK, full propagation |
| 33 | .65 | Repeat 32 | Flame died 4 in. from igniter |
| 34 | 1 | Mixing test | OK |
| 35 | 2.2 | Ignition test | OK, full propagation |
| 36 | 2 | Ignition test | OK, speaker camera ran out of film |
| 37 | 1 | Repeat 34 | OK, good mix |
| 38 | 1 | Repeat 34 and 37 | OK, good mix |
| 39 | 1.05 | Repeat 38 | OK, good mix |
| 40 | 1 | Adhesion test | No powder on tube |
| 41 | 6 to 7 | Ignition test | Rig broke because of hard hit |

[a]Not applicable.

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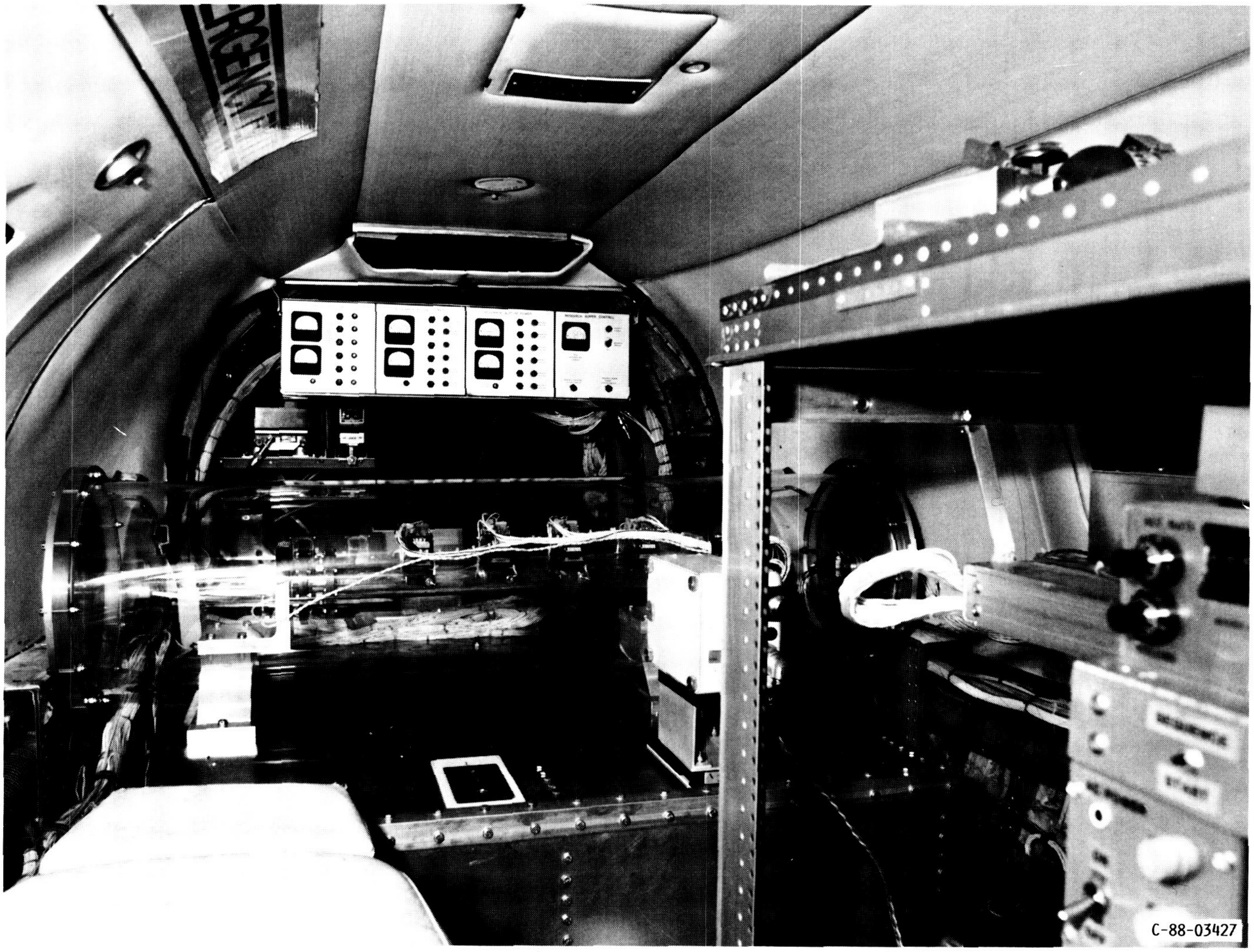



Figure 6.—Particle-cloud combustion experimental Learjet rig.

(8) A triaxial accelerometer system that is part of the Learjet facility recorded the acceleration levels for every flight. Unfortunately, the sensing heads were not mounted near the experimental apparatus.

A total of 31 Lear flights were performed. A complete list of flight tests is given in table IV. Because of the long waiting periods, fewer flights were dedicated strictly to mixing tests. Instead, most flights involved full-scale testing of the experimental hardware, with mixing data taken on all flights, including those with ignition.

In the flight sequence, a few problems occurred. Three operational failures were traced to software error. Some early flights revealed adhesion levels to be excessive. In a series of twelve flights, tube handling procedures were varied to try to reduce adhesion levels. Eventually, the handling procedure used in the drop tower tests was reutilized. Perhaps most importantly, the first flight revealed that a different mixing frequency from that used in the drop tower was required. The probable reason was that the flammability tube was being held by different mounting brackets inside a secondary containment. The new frequency, which was selected based on limited normal gravity testing, was 170 Hz. While this frequency resulted in a robust cloud on some occasions, ignition failures occurred often. A more detailed normal gravity test program was then undertaken, resulting in the selection of a warbling between two frequencies, 170 and 330 Hz, at a rate of about 30 Hz. This procedure resulted in successful ignition and flame propagation in 13 of 14 attempts, the one failure being due to an igniter wire breakage.

### Tube Cleaning, Handling, and Preparatory Procedures

After combustion tests, flammability tubes were placed in an ultrasonic cleaner filled with tap water and nonsudsing clean-room detergent. The solution was heated to approximately 40 °C. After 30 min of cleaning in each half, the tubes were removed, rinsed with ethanol, and allowed to dry in room air.

TABLE IV.—FEASIBILITY FLIGHT SUMMARY

| Flight number | Equivalence ratio, $\Phi$ | Purpose | Results |
|---|---|---|---|
| Flights 1 to 4 | | | |
| 1 | 3.10 | Mixing | Frequency 140 Hz, 30 W (0.5 sec) |
| 2 | 1.30 | Mixing | Frequency 170 Hz, 30 W |
| 3 | 1.10 | Flame propagation | Burn, (10-sec wait to ignition) |
| 4 | 2.16 | Flame propagation | Burn |
| Flights 5 to 7; mixing parameters (frequency, 170 Hz, 20.8 W); varying tube cleaning procedures | | | |
| 5 | 0.98 | Mixing | No data, operational problem |
| 6 | 1.15 | Mixing | No data, operational problem |
| 7 | 1.21 | Mixing | Poor mixing |
| 8 | 1.24 | Flame propagation | No burn, bad mixing |
| 9 | 1.09 | | No burn, fair mixing |
| 10 | 1.19 | | Successful burn |
| 11 | 1.12 | | No burn, fair mixing |
| 12 | 2.17 | | No burn, fair mixing |
| 13 | 1.21 | | Successful burn |
| 14 | 1.20 | | No burn, bad mixing |
| 15 | 1.18 | Flame propagation, no heat exchanger | No burn, bad mixing |
| 16 | 1.18 | Flame propagation | No burn (7-sec wait to ignition) |
| 17 | 1.15 | Flame propagation | No burn |
| Flights 18 to 31; mixing parameters (frequency, 170/330 Hz, 20.8 W, alternating 30 Hz); same tube cleaning procedure | | | |
| 18 | 1.16 | Flame propagation | Successful burn, new mixing |
| 19 | 1.23 | | Successful burn |
| 20 | 2.32 | | Successful burn |
| 21 | 1.98 | | Successful burn, poor mix and adhesion |
| 22 | 2.19 | | Successful burn |
| 23 | 2.18 | | Successful burn, chatters near speaker |
| 24 | 2.20 | Lights, flame propagation, no heat-exchanger | Successful burn, chatter |
| 25 | 3.35 | Lights, flame propagation | Successful burn, negative-g lifted fuel |
| 26 | 3.35 | | Broken ignitor wire, good mixing |
| 27 | 3.29 | | Successful burn |
| 28 | 1.16 | | Successful burn |
| 29 | 1.18 | Lights, flame propagation, moved detector | Successful burn, chatter |
| 30 | .97 | Lights, flame propagation, | Successful burn, chatter |
| 31 | 1.61 | Lights, flame propagation | Successful burn, chatter |

After tests involving only acoustic mixing, the ultrasonic cleaning step was replaced with a tap water rinse to remove particles.

Several different tubes were used in this study. Prior to their first use, they were heated under vacuum for 30 to 60 min. This step potentially provided stress relief as well as removed surface-bound water. In general, this treatment was done only once; however this treatment was used in several cases between Learjet flights 5 to 17. It was abandoned as being unnecessary and/or ineffective.

When preparing tubes for drop or flight testing, care was taken to touch only the flanges on the tube ends. It was believed that touching the body of a tube could promote electrostatic adhesion of particles to the tube walls.

# Acoustic Mixing Test Results

### Mixing Description and Detector Signals

Figure 7 shows selected frames from the film records of the drops. Immediately after the speaker is turned on, the fuel particles are scrubbed off the tube bottom, bursting into regularly spaced, narrow airborne particle columns. Each column quickly merges with its nearest neighbor, creating regular spaces of clouds and voids. Nearest neighbors then merge again, creating broader, but still distinguishable columns of fuel and voids. While the speaker is still running (i.e., within the first 0.5 sec of reduced gravity) the columns and voids can be seen to oscillate axially in phase with the speaker. However during this same time period, the void spaces are filled partially as the columnar clouds diffuse and overlap with their nearest neighbors, and the cloud can be seen to move across the full tube diameter. When the speaker is turned off, the persisting secondary airflow swirls the particles sufficiently to fill in the remaining void spaces. This airflow then begins decaying, and the particle cloud tends toward quiescence. However, complete quiescence is not achieved in the 2.2 sec of available reduced-gravity time, based on qualitative observations of the film.

Figure 8 displays the data collected by the detectors in several different drop tests. No data are collected during the time in which the speaker is powered, because of restrictions of the data acquisition and control system. The predrop data show that the detectors are quite stable (less than 1 percent variation), providing a reference unattenuated signal. The post-drop data show that mixing occurs even after the speaker is turned off, via the secondary airflow mechanism. Though not steady, the detector signals are relatively unchanged for the last 0.5 to 1 sec of the drop. The figure shows an axial uniformity of ± 10 percent of a common mean in the attenuated signal, which was achieved in some cases in 2 sec of reduced-gravity time.

The "speaker on" time was varied in a few uninstrumented drop tests. If the speaker was powered for too short a time period, the scrubbing process was incomplete, and puddles of fuel unmoved from their initial position could be seen both on film and upon post-drop examination of the tube. Earlier tests in normal gravity revealed that excessively long "speaker on" time caused both severe particle adhesion to the tube wall and voids near the ends of the tube. At this point, the appropriate "speaker on" time has been found to be between 0.5 and 0.8 sec.

During most of the Learjet tests, the mixing process could not be observed well because of lighting restrictions. However in the last eight flights, a lighting system was installed which provided excellent visualization of the cloud.

Despite the change in operating frequency, the mixing process generally appeared as in the drop tests. Jetlike lamina rose from the tube bottom and merged eventually into a cloud which appeared quite uniform to the eye. A slight migration of particles away from the speaker could be seen. During the waiting period, holes in the cloud were seen to be filled in by secondary airflows carrying fuel particles. These flows tended to be less cellular, especially near the ends of the tube where secondary air flows swirled over a larger scale. By the end of the quiescence waiting period, no particle motion and no defects in the cloud uniformity were visible.

Figure 9 shows detector data from several flight tests. The energizing of the speaker is indicated by the sharply increased attenuation. The speaker was energized for 0.5 sec, followed by a typical waiting period of 7 sec (varied occasionally from 3 to 10 sec). The igniter was energized for 0.5 sec, though it burned through the diaphragm in about 0.1 sec. The flame then proceeded down the tube. The detector data shows first a rise in attenuation due most likely to the strongly refracting temperature field just in front of the flame front. It then shows an apparently sharp decrease in attenuation as the flame itself serves as a light source superposed on the LED signal. Then the attenuated signal again rises, because of absorption by the combustion products.

### Relationship of Detector Signal Attenuation to Concentration

The detector readings of light attenuation must be converted to particle concentration. Reference 14 describes calibration methods. Summarizing, the transmitted light decays exponentially with increased particle concentration, according to the Bouguer-Lambert law:

$$\text{transmission} = \exp[-K(\text{concentration})\text{pathlength}]$$

and

$$\text{attenuation} = 1 - \text{transmission}$$

The factor $K$ can be estimated theoretically or experimentally. The theoretical estimate is usually based on single scattering, an assumption which is invalid at large particle concentrations, as may be the case for rich mixtures. Buchele has estimated $K = 1.27$ based on diffraction theory and

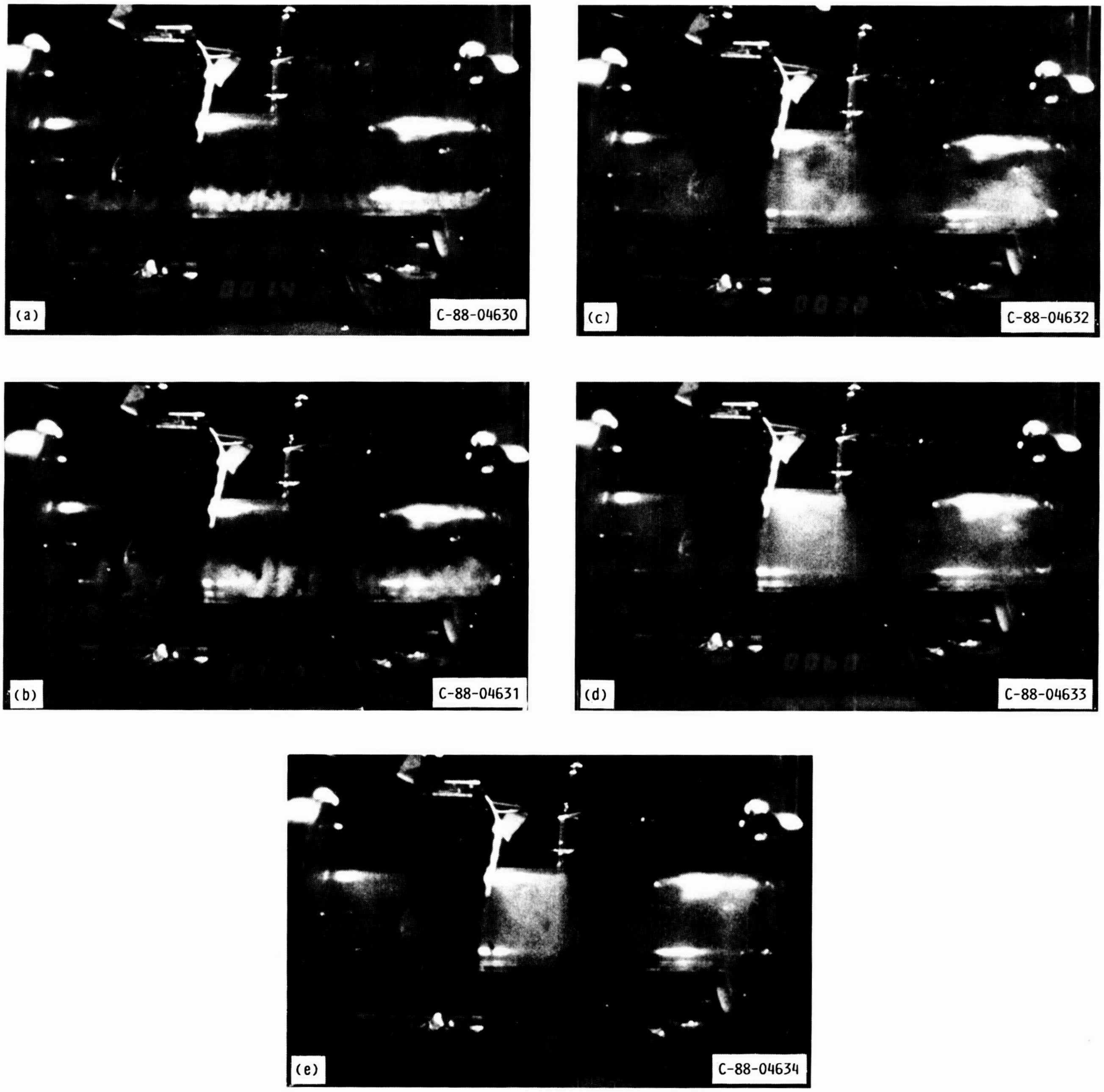
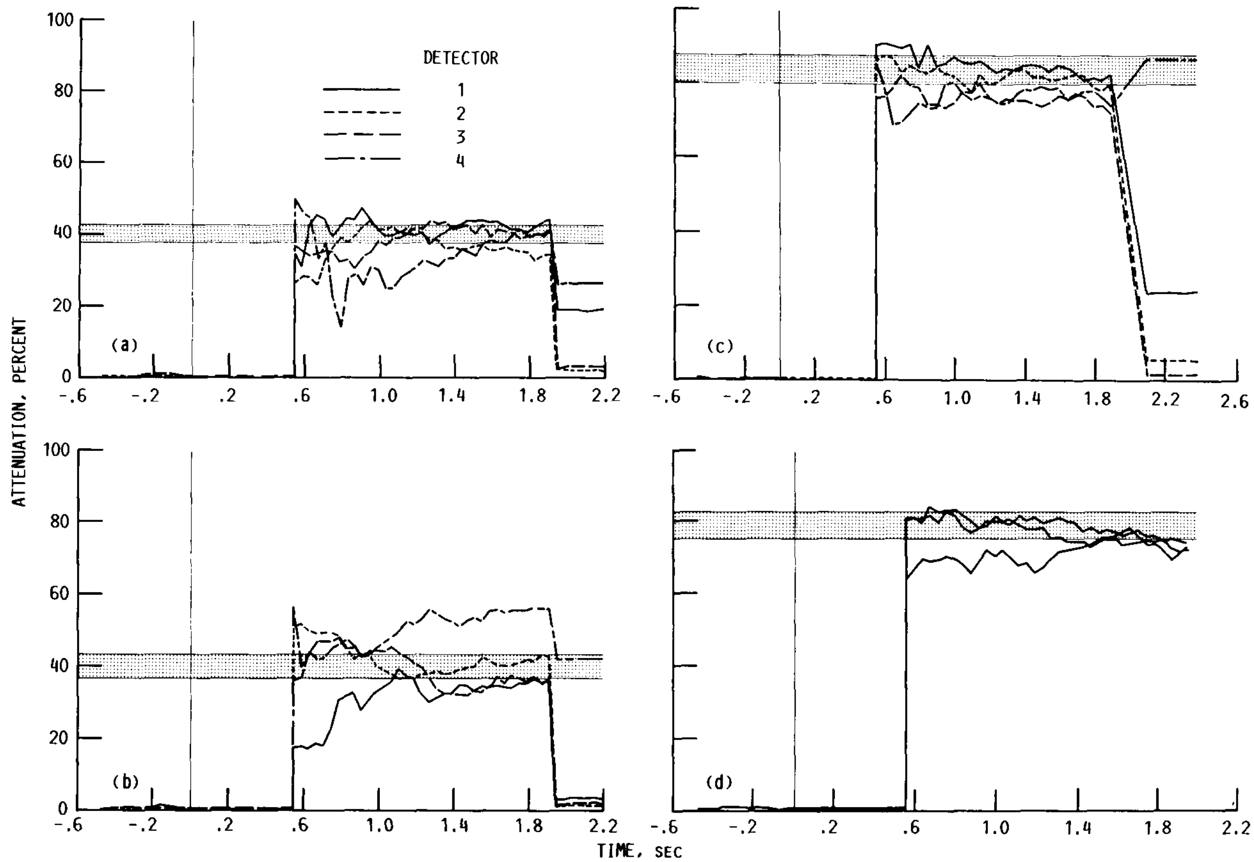



Figure 7.—Sequence of mixing events, 10-in. tube (side view). Spacing is about 0.09 to 0.12 in. with a thickness of 0.09 to 0.11 in. at $t$ = 0.15 sec into the drop. At $t$ = 0.20 sec, spacing is 0.18 in. and thickness is 0.25 in. Speaker is turned off at 0.8 sec.




(a) Drop 34; equivalence ratio, 1.0.
(b) Drop 37; equivalence ratio, 1.0.
(c) Drop 18; equivalence ratio, 3.7.
(d) Drop 13; equivalence ratio, 3.1.

Figure 8 .—Drop tower detector data. The gray band represents ±10 percent of a common mean, centered at an attenuation level based on $K = 1.6$ and the known amount of fuel.

assuming single scattering of the light. Reported experimental estimates of the concentration are rarely more precise than ±10 percent. The empirical value of $K = 1.6$ best fit the detector data, based on the known particle mass used in the drop tests and the assumption that the cloud uniformly fills the tube. The validity of this assumption was only determined qualitatively, by observation of the cloud on the camera films.

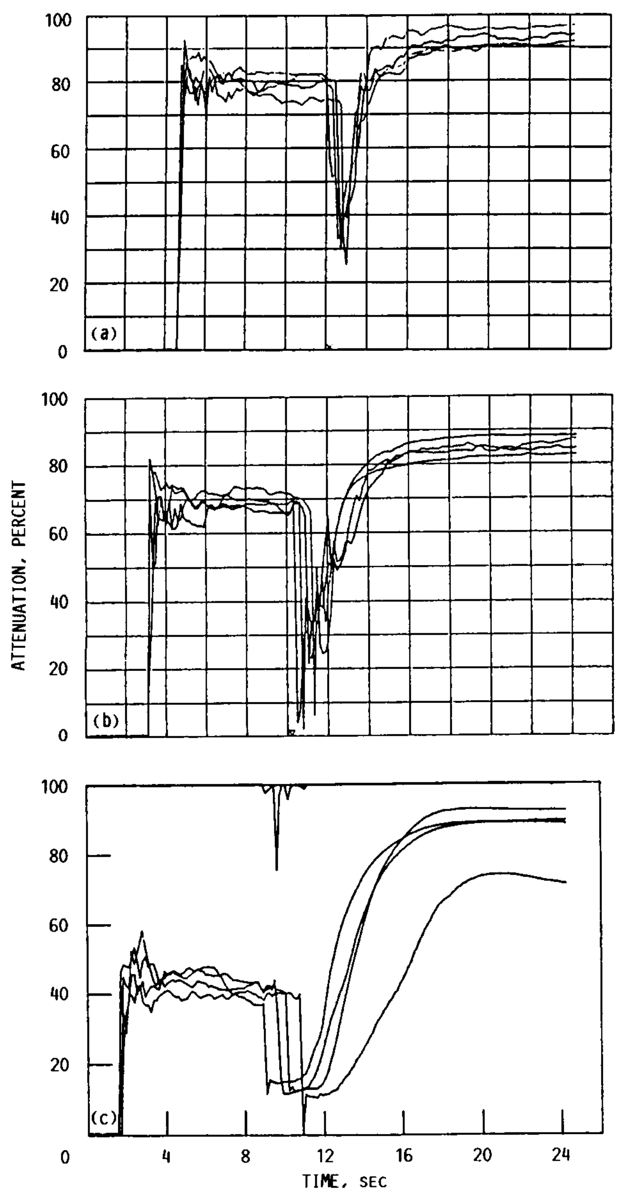
Therefore, a more complete test is required to define the $K$ factor more precisely. Nonetheless, these values may be used to provide an accurate estimate of the cloud uniformity, based on the differences in detector signals. A detailed analysis of the use of optical attenuation methods for determination of particle cloud concentrations has been given by Tangirala and Berlad (ref. 13).

## Analysis of Mixing Uniformity

Figure 10 shows the attenuation-concentration relationship for various $K$ values, including those described above. Using $K = 1.6$, the uniformity in concentration which was achieved was about ±10 percent of the common mean for the drop tests.

The detector data from the last Learjet test sequence were studied in detail. As described above, the earlier tests were primarily developmental. The most significant data are those in the last four seconds prior to ignition which represent the cloud into which the flame will propagate. This time period is longer than the total flame propagation time which ranged from 1.5 to 3 sec for the rich to lean cases, respectively. Figure 11 displays the average deviation and one standard deviation of the detector data (shown as a circle with an error bar), as well as the ±10 percent requirement on uniformity (shown as squares), based again on a factor of $K = 1.6$ to convert the attenuated signal into concentration. Shown also is the nominal equivalence ratio (shown as a dashed horizontal line), based on the known mass of lycopodium which was loaded into the tube.

A degree of test-to-test reproducibility may be seen in the figure. When the square falls within the error bars, the




(a) Flight 27 (3.29 stoichiometric) mix/burn.
(b) Flight 20 (2.32 stoichiometric) mix/burn.
(c) Flight 18 (1.16 stoichiometric) mix/burn. Data at time ~9 sec and attenuation between 80 and 100 percent is due to flame passage when detector light source is off, providing a measure of flame speed.

Figure 9.—Learjet detector data. Ground-based feasibility tests.

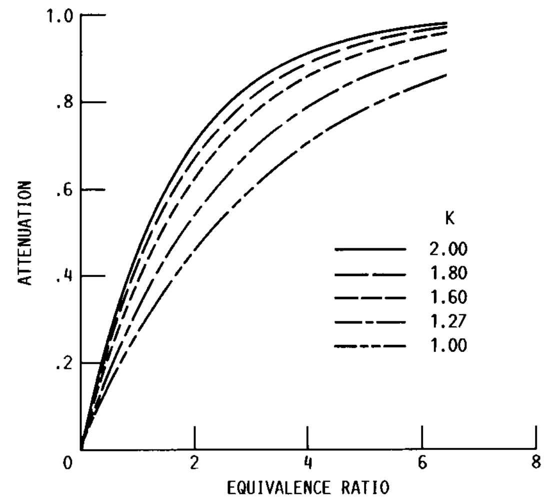



Figure 10.—Effect of *K* factor on equivalence ratio.

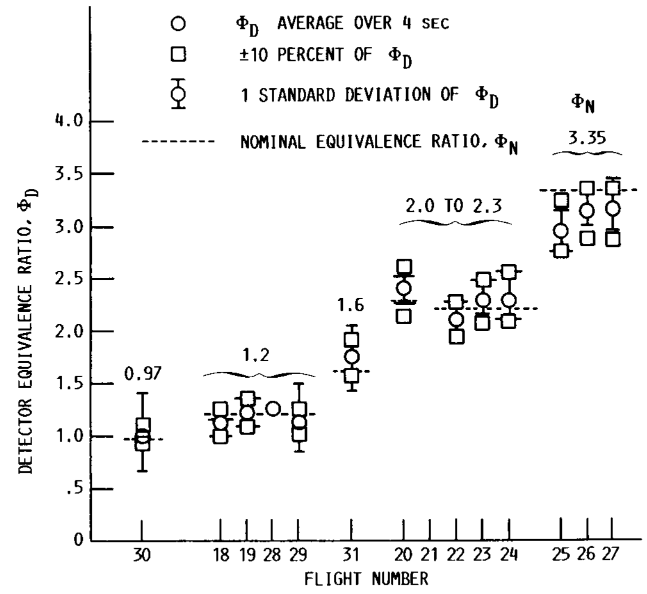



Figure 11.—Flight results: mixing uniformity.

uniformity requirement has been met. Conversely, when the square falls outside the error bars, the mixing uniformity is not considered satisfactory. The requirement is met regularly for the richer mixtures, and met sometimes for an equivalence ratio of about 1.2. However, the 5 percent uniformity requirement for mixtures of equivalence ratio less than 1.3 was never achieved.

Flight 26 was a "mixing only" test with the final 4 sec of mixing being displayed here. Flight 29 shows a wider standard deviation because of the placement of the detectors. They were moved 7 to 8 cm closer to the speaker for this flight. Detectors 1 through 3 showed similar values as on other flights; however detector 4, placed within 8 cm of the speaker diaphragm, showed much lower attenuation. This information, along with the visualization and observed flame behavior, strongly suggests that the cloud concentration is diminished in the neighborhood of the speaker.

Lost in the averaging process is the time dependence of the data. However, appendix A displays the detector data, and shows that the detector signals are little changed in the last few seconds prior to ignition or while the flame propagates toward the detector stations.

## Particle-Wall Adhesion Test Results

### Maximum Permissible Surface Area Density of Adhered Particles

The goal for adhesion levels was less than 10 percent of the total fuel loading. It might be added that it was desirable for the adhesion levels to be uniform throughout the tube to minimize axial variations in concentration. The 10 percent criterion may be converted to a maximum permissible surface area density (MPSAD) based on the particle volume and density.

The volume estimate was determined as follows. The literature usually treats lycopodium particles as being 28- to 30-$\mu$m spheres. However, the supplier describes their shape as pyramidal. Figure 12 shows our scanning electron microscope pictures of lycopodium. The lower half of the particle is hemispherical while the upper half reveals a complex pyramidal structure. The volume of the particles was approximated by assuming a hemisphere with a 14-$\mu$m radius below a cone with a 14-$\mu$m radius and height.

The particle density estimate was determined as follows. Joshi reported a specific gravity for the particles equal to that of water (ref. 14). However the manufacturer states that the particles float on water (ref. 15), but does not discuss the role of surface tension in these observations. Experiments by Tangirala (ref. 16) revealed that the particles remain suspended in benzene and toluene (specific gravity of about 0.85 to 0.88)

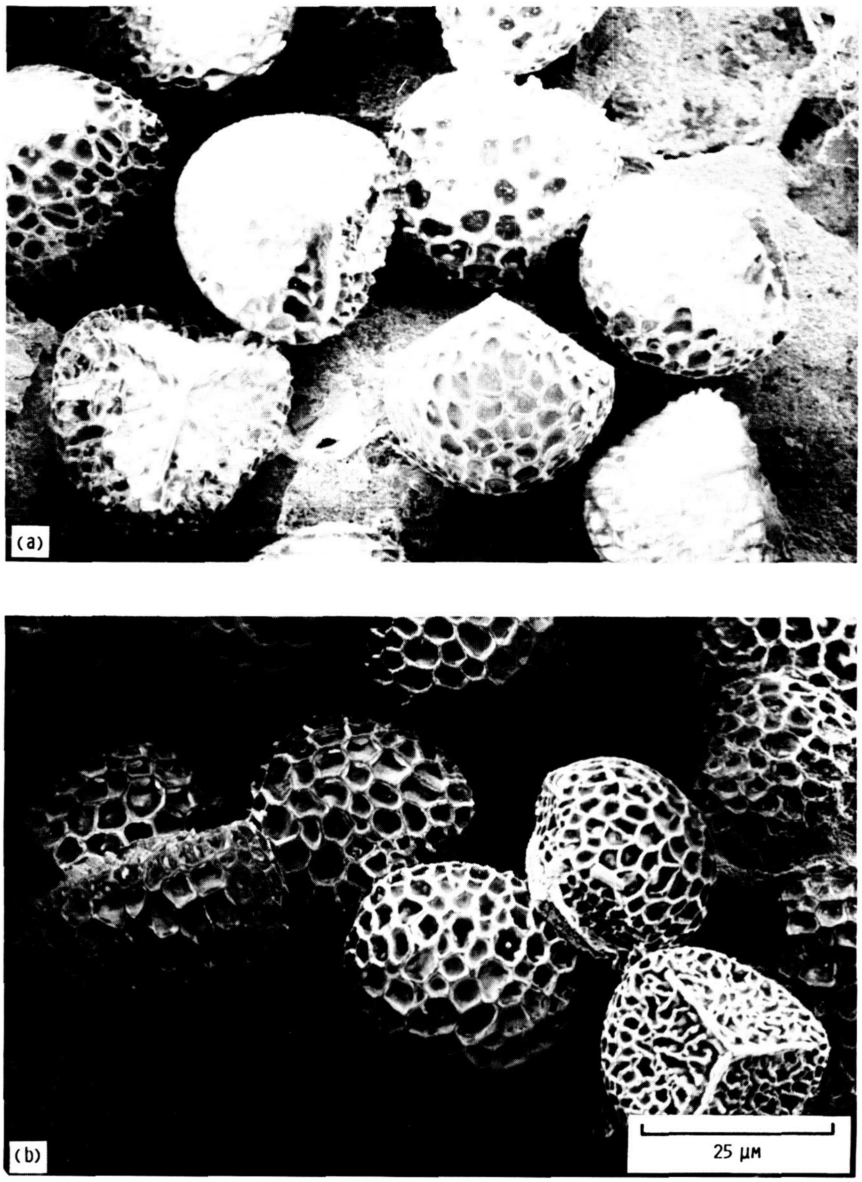



Figure 12.—Lycopodium particles.

for long periods of time but eventually settle to the container bottom. The value of 0.95 for the specific gravity of the particles was selected based on these tests.

From the above information, the MPSAD was determined to be 19, 38, and 57 particles/mm$^2$ for equivalence ratios of 1, 2, and 3, respectively. The 5 percent criterion of the shuttle flight project may be found by halving these values.

### Drop Tower Test Results

It was difficult to determine true adhesion levels in the drop tower tests since the experimental test rig experiences a 30 to 50g deceleration. However, measurements of the attenuation were taken following mixing experiments and are displayed on the far right portion of figure 8.

In the "mixing only" drop tests, virtually no particles were seen adhered to the walls in the upper half of the tube. A detector mounted horizontally showed adhesion levels to be less than 2 percent of the total concentration of fuel. These results should be viewed as necessary but not sufficient proof that adhesion levels were controlled acceptably. In the ignition drop tests, a monomeric layer of particles remained on the entire tube wall, even after the 30 to 50g deceleration. These particles remained "glued" to the wall by the combustion products. The number of particles was observed to increase with increasing stoichiometry. It was unresolved whether these particles were adhered to the wall prior to combustion or whether, in the rich mixture cases, they were blown onto the wall by the expanding combustion products. No measurements of the surface area density were taken at this stage. Instead, Learjet tests were deemed necessary to determine adhesion levels in reduced gravity.

### Learjet Flight Test Results

Following some Lear flights, the tube was examined under a microscope. In general the tube appearance was as in the drop tests with a monomeric coating of particles along the entire inner surface of the tube. In some cases, small clusters of particles appeared in a few spots and in any scratches on the inner wall surface. Tubes with scratches were generally not reused.

After some flights, the particle adhesion levels were photographed at 12 to 16 locations on the tube. Figure 13 displays a typical picture for a mixing-only test and for one in which combustion took place. In the latter case, unburned lycopodium can be seen clinging to the tube wall surrounded by many small particulates of ash. Scanning electron microscope pictures showed the unburned lycopodium was completely unaffected by the combustion process.

The number of particles in each photograph was counted, and the overall results are displayed in table V. Shown in the table is the MPSAD, as well as three values of the measured surface area density (SAD).

The column listed "SAD—Unburned" displays the average SAD for areas of the tubes not subjected to flame propagation. Flight 26 was a "mixing only" test, and the tabulated value is an average of measurements taken along the top surface of the tube. In flights 28 through 30, the flame extinguished a few inches away from the speaker. This allowed an examination of the tube in this area of particles also subjected to a "mixing only" process. In each of these cases, the measured SAD is less than the MPSAD.

The column listed "SAD—Burned" displays the average SAD from combustion tests. Flights 23 through 27 suggest that 15 to 20 percent of the total particles were adhered to the wall. However, these results are very misleading in the sense that for the rich mixtures, many suspended particles are expected to be unburned and will be deposited on the tube wall after the flame passage. Flights 28 through 30, however, are for near-stoichiometric mixtures, where all of the suspended particles should be consumed in the combustion process. These results should be comparable to the "SAD—Unburned" column, but are slightly higher. They are still close to the MPSAD. One possible explanation of the difference may be the nature of the chattering flame, which tends to segregate the particles into columns that, of necessity, must be fuel-rich (chattering flames are discussed in the next sections). In this case, excess particles might survive the combustion process and be deposited on the wall after the flame passage.

The column listed "SAD—Ignition" displays the average SAD in the igniter region. Recall that this area had an extra loading of fuel for all near-stoichiometric tests. The extra loading made the local nominal equivalence ratio equal to 2.2. The SAD in this region is comparable to the SAD in those tests where the entire tube was filled with the same nominal equivalence ratio.

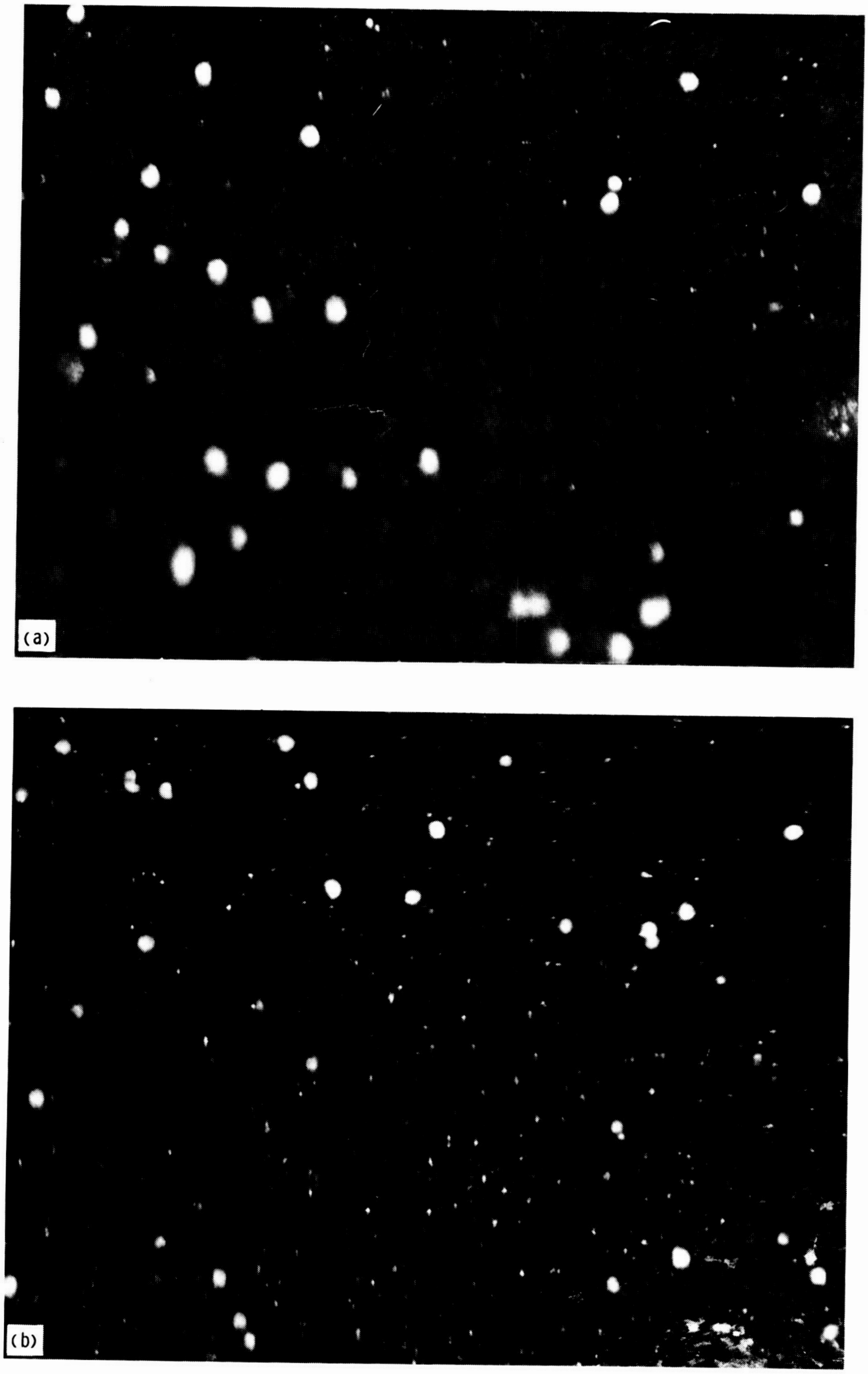
All of the adhesion results must be viewed with some caution, since the photographed areas were very small. Each picture captured only 2.1 mm$^2$ of the tube area. The total photographed area is then on the order of 30 mm$^2$, which is being used to represent the entire inner surface area of 101 341 mm$^2$ (i.e., only 0.03 percent of the total area was measured). Given the large standard deviations, the measurement area should be increased. Unfortunately, the current method for collection of these data is very tedious and time consuming.

## Ignition and Flame Propagation Test Results

### Ignition System Performance

The ignition system tested successfully in both the drop and Learjet tests: of 12 drop and 27 Learjet tests, only 2 igniters failed to burn through the mylar diaphragm.

In one drop test of a very lean mixture (less than 0.7 equivalence ratio), the flame extinguished about 4 in. from



(a) Unburned (flight 29, position 1).
(b) Burned (flight 29, position 7).

Figure 13.—Adhesion test results. Total photographed area is 2.1 mm².

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TABLE V.—ADHESION MEASUREMENT

| Flight | Nominal equivalence ratio, $\Phi_N$ | MPSAD[a] (10 percent), particles/mm$^2$ | SAD[b], particles/mm$^2$ | | |
|---|---|---|---|---|---|
| | | | Unburned | Burned | Ignition |
| 23 | 2.2 | 42 | (c) | 64±46 | (d) |
| 24 | 2.2 | 42 | (c) | 55±39 | ↓ |
| 25 | 3.35 | 64 | (c) | 127±88 | ↓ |
| 26 | 3.35 | 64 | 56±21 | (d) | ↓ |
| 27 | 3.35 | 64 | (c) | 96±49 | ↓ |
| 28 | 1.2 | 23 | 19±10 | 35±14 | 60±45 |
| 29 | 1.2 | 23 | 13±2 | 18±7 | 59±49 |
| 30 | .97 | 20 | 7±5 | 24±14 | 49±24 |

[a]Maximum permissible surface area density.
[b]Surface area density.
[c]Unavailable.
[d]Not applicable.

the ignition end of the tube. Thus in 10 of 12 drop tests, the flame propagated through the entire drop time.

In Learjet test flights 1 through 17, only 4 of 11 ignition attempts resulted in flame propagation. An extra loading of fuel in the first 4 cm of the tube was attempted but was insufficient. The problem was traced not to the nitrocellulose igniter performance, but to inadequate mixing of the cloud in the neighborhood of the igniter. When the mixing frequency selection was changed to the 170/330 Hz warble, successful ignitions were achieved in 13 of 14 flights.

### Qualitative Observations of Flame Behavior

The results from the drop tests revealed several novel features. First, a flame was observed to propagate down the tube despite gross defects in the cloud uniformity for a mixture thought to be outside the flammability limits. At times, the flame front was discontinuous across the tube diameter, and advanced down the tube in a leaping fashion. Figure 14 shows the flame shape roughly two-thirds of the length from the igniter. This flame propagated more slowly than richer flames. Its mode of propagation was unsteady; its forward progress proceeded via a sequence of jumps, thereby yielding a quasi-steady rate of propagation. This result suggested an entirely new mode of flame propagation down the tube, so-called chattering flames (discussed later).

When a stoichiometric flame was observed, it also tended to develop a ''chattering flame'' structure, identified by a spatially discontinuous flame front. Figure 15 shows an excellent example of the tail structure. The separation distances between flame front laminae are on the order of the initial spacing of the fuel jets during mixing.

When rich mixtures were ignited, the flame maintained a continuous tail, as shown in figure 16, for nearly the full tube length. However in some cases, a ''chattering'' structure was observed very near the speaker section.

As in the drop tests, the Learjet flames propagating through rich fuel mixtures were classical in nature, with long continuous luminous tails behind a rough flame front. The frontal shape varied, with the leading edge sometimes appearing in the upper tube half, and other times appearing in the bottom tube half. In a few flights, the leading edge remained in the bottom half, suggesting either a concentration gradient or consistently negative gravity effects. The most symmetric flame front was achieved on flight 22, and examples of its appearance are shown in figure 17.

In every test of mixtures of equivalence ratio less than 1.3, the flame front propagated in a leaping, or chattering, fashion. The first appearance of the chatter varied from test to test, sometimes occurring only a short distance from the igniter and sometimes waiting till near the speaker end of the tube. Figure 18 displays a typical series of luminous lamina from flight 10. In most cases, the flame front shape is flatter than those observed for the richer flames.

In the one Learjet test with a nominal equivalence ratio of 0.97, the number of luminous lamina was distinctly reduced. However the flame front was exceptionally flat. This flame actually extinguished prior to propagating the full tube length.

Since the ''chattering flame'' structure was observed throughout much of the tube length for near-stoichiometric mixtures, and did not appear for equivalence ratios near 2.0, one test was performed with a nominal equivalence ratio of 1.6. This test showed a classical flame structure for most of the tube length, then ''chattered'' near the speaker end of the tube.

### Flame Speed Measurements

Flame speed measurements may be attempted either from camera film records or from the change in detector signals. Figure 7 shows consistently that the detector signals experience a brief increase in attenuation, followed by a sharp decrease when the flame front passes, followed finally by a slow rise in attenuation. The initial increase in attenuation is believed to be due to the LED beam being refracted away from the detector in the preheat zone of the flame. In this zone, there exists a steep refractive index field due to the steep temperature gradient. The decrease in attenuation results from the emission from the combustion process of a substantial amount of infrared radiation (i.e., the flame serves as a second source for 820-nm radiation). The final slow rise in attenuation is due primarily to absorption by water vapor, carbon dioxide, and other products of the combustion process. The flame speed may be estimated from the time each detector first sees the sharp decrease in attenuation, and the known separation between the detectors. Unfortunately, this estimate is inaccurate because of the relatively slow sampling rate, every 7/100 sec, compared with the flame speed.

A better estimate of flame speed is derived from the camera film records, which provide snapshots of flame position every 1/128 and 1/200 sec in the drop and Lear films, respectively. The films were viewed on a motion analyzer, which projects the image onto a digitized screen. The position of the flame

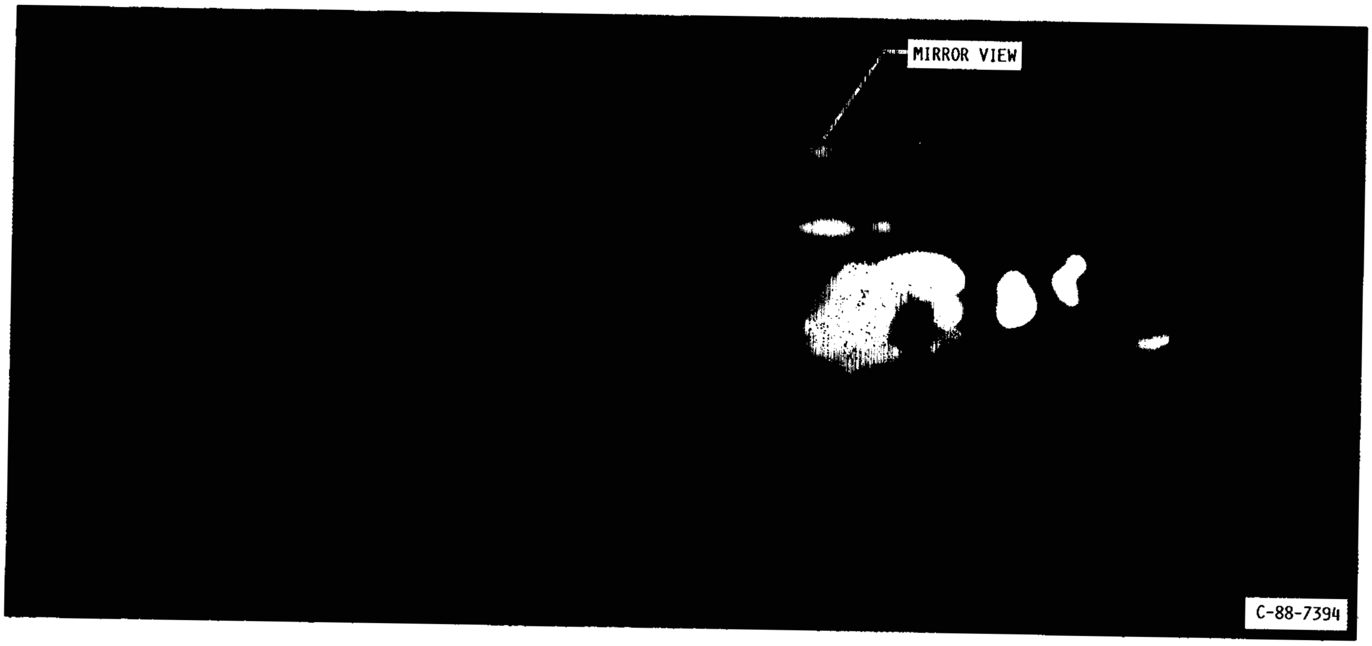



Figure 14.—Drop tower flame propagation with an equivalence ratio of 0.65 (right to left).

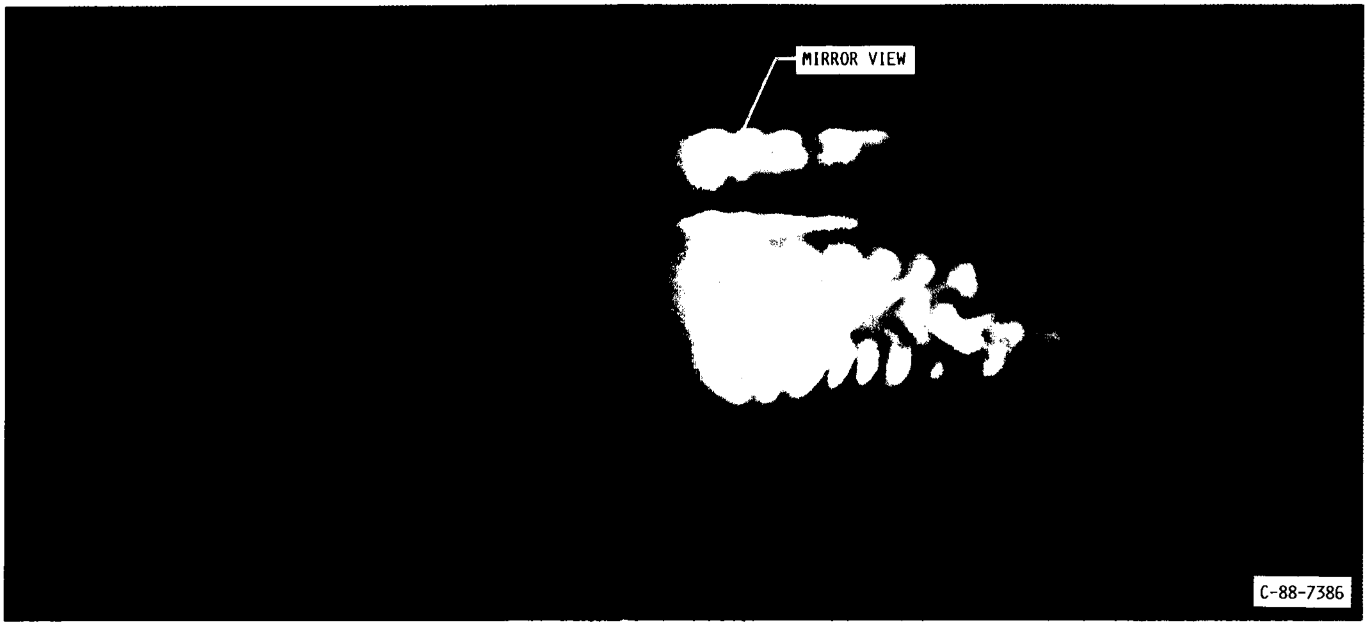


Figure 15.—Drop tower flame propagation with an equivalence ratio of 0.98 (right to left).

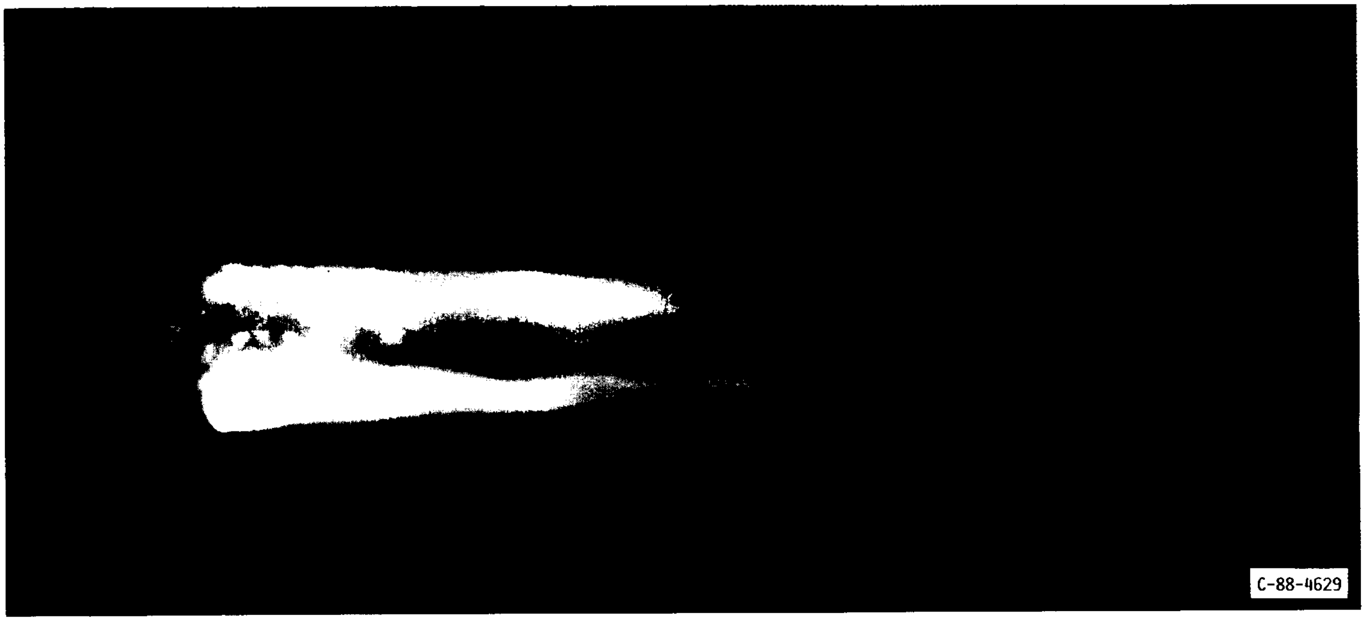


Figure 16.—Drop tower flame propagation with an equivalence ratio of 3.1 (right to left).

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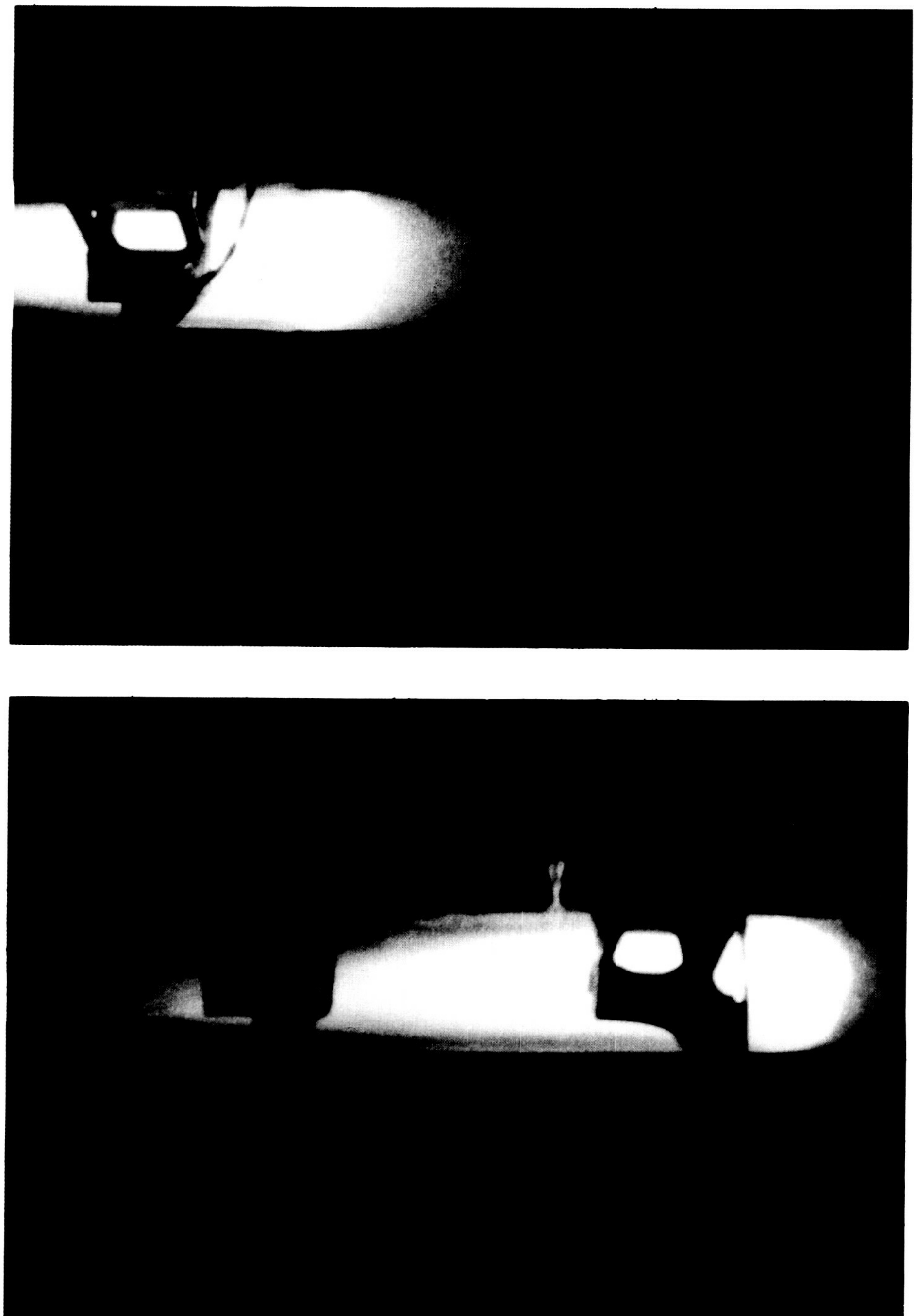

Figure 17.—Learjet flame propagation with an equivalence ratio of 2.2 (left to right).

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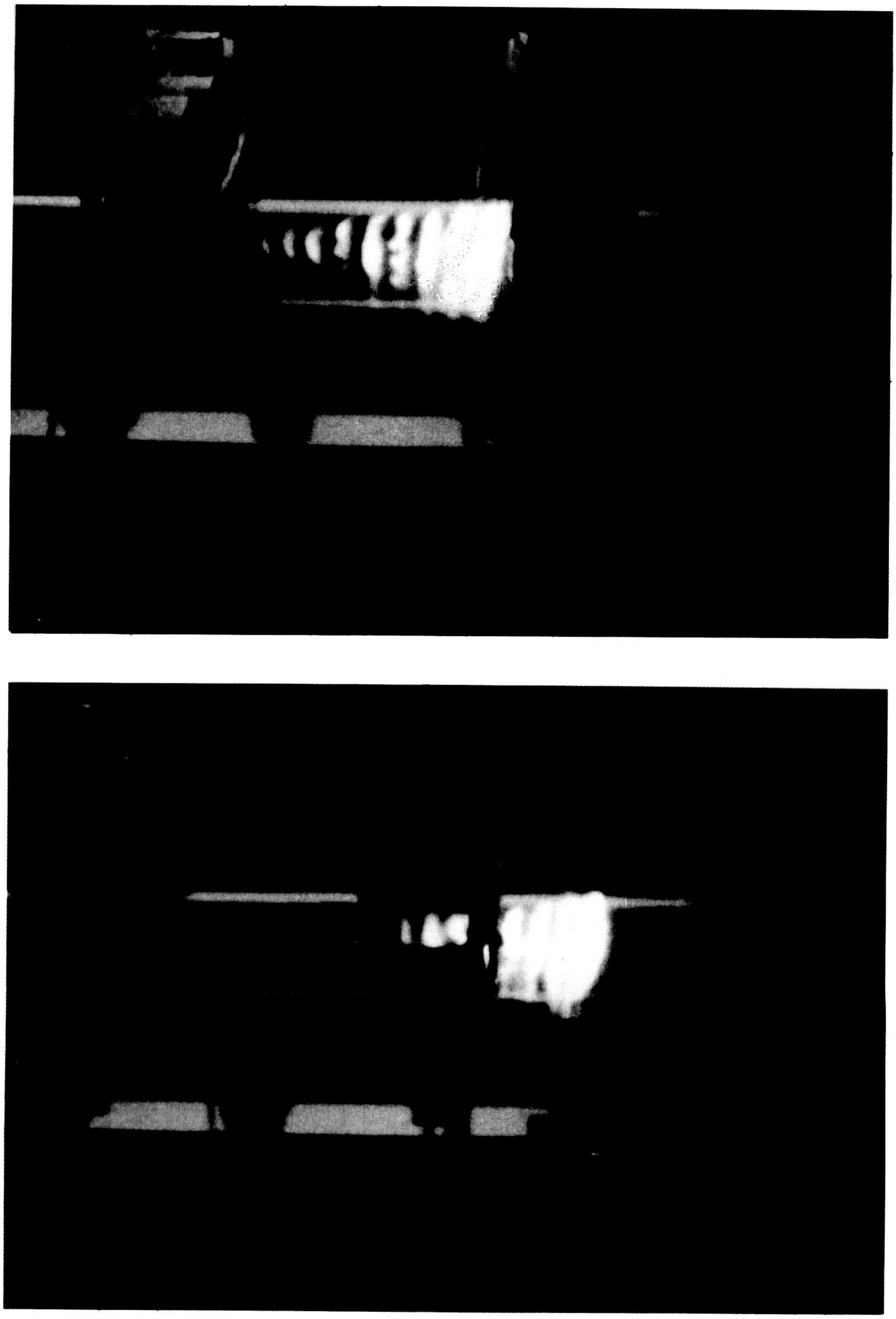
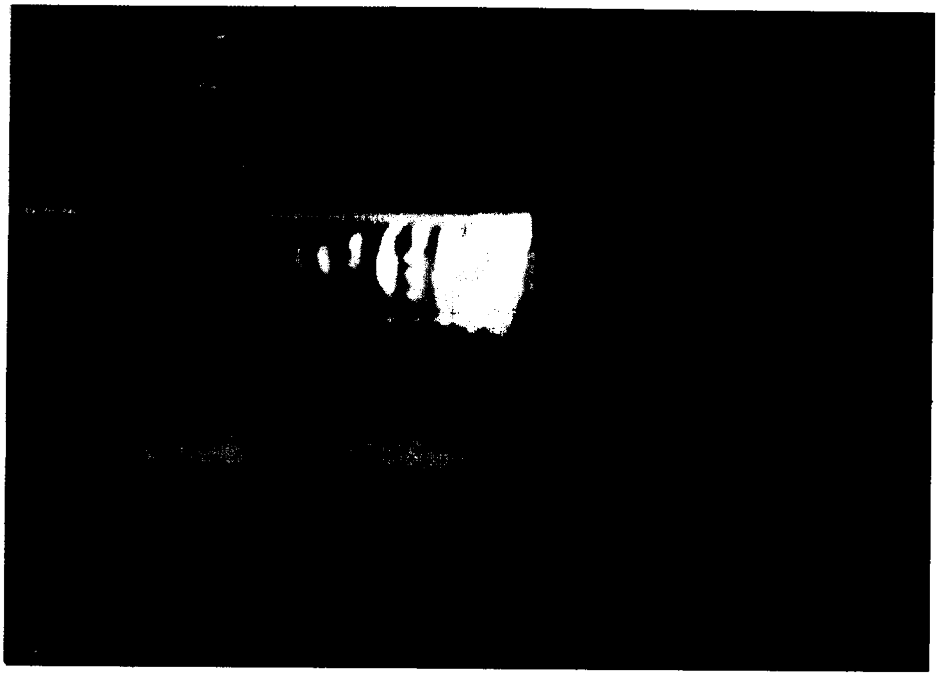


Figure 18.—Concluded.



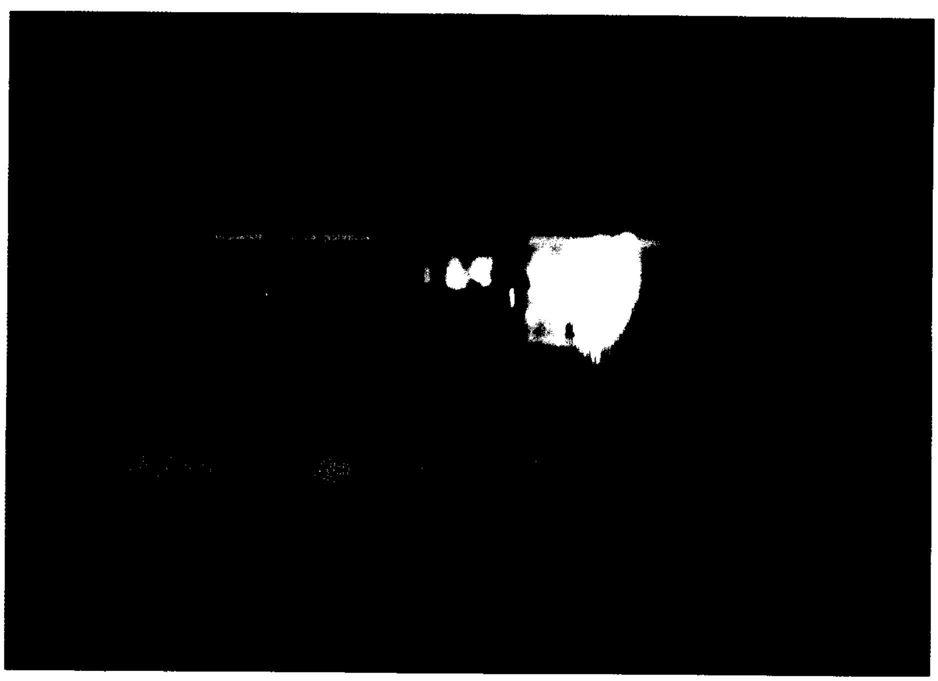


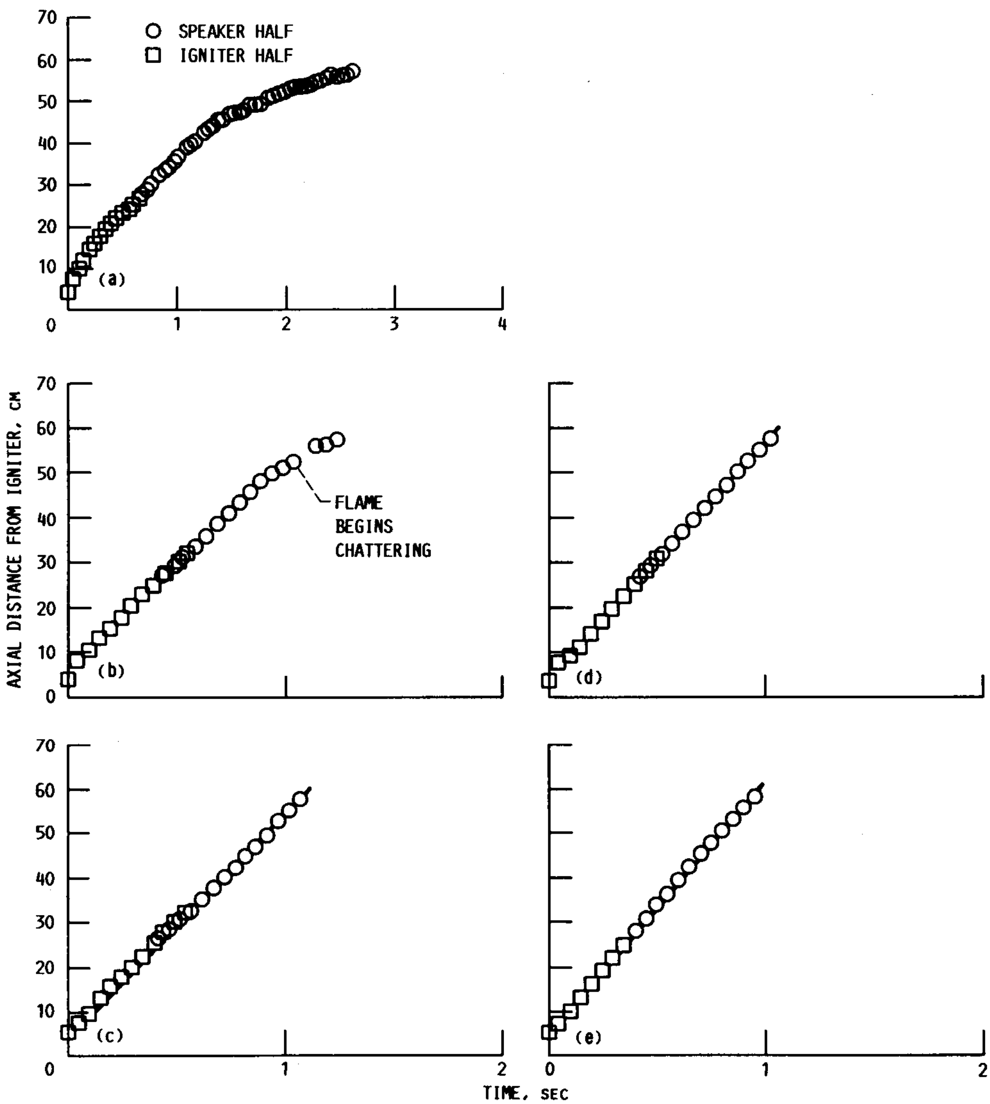
Figure 18.—Concluded.

was recorded every 6 frames in the drop tower tests and every 10 frames in Learjet flights. The digitized reading was converted to the axial position down the tube, and then plotted as a function of time. In general, only the centerline position was used since the flame front shape was variable in time because of concentration gradients and gravity level fluctuations.

Figure 19 shows that the flame speeds for rich mixtures from the Learjet flights are quite steady. Linear regression was performed on these data, with the resulting flame speeds displayed in figure 20. Flame speeds of about 40 cm/sec (±5 percent) were obtained repeatedly for clouds with equivalence ratios above 2.0. These flame speeds are not fundamental burning velocities.

The leaner, chattering flames propagated in an unsteady fashion, slowing particularly in the neighborhood of the speaker. This behavior is probably due to the poorer mixing in this region of the tube and to the strength of the flame-induced acoustic disturbance (Berlad, A.L., et al.: Particle Cloud Flames in Acoustic Fields. Combust. Flame, 1988, submitted for publication). A determination of these flame speeds was done by considering only the flame propagation in the first 75 percent of the tube length. Linear regression of these data showed approximate flame speeds of 20 cm/sec (±10 percent).

Both of the quoted flame speeds derived from film records agreed well with the optical detector estimates (21 and 45




(a) Flight 19; equivalence ratio, 1.2.
(b) Flight 31; equivalence ratio, 1.6.
(c) Flight 22; equivalence ratio, 2.2.
(d) Flight 25; equivalence ratio, 3.3.
(e) Flight 27; equivalence ratio, 3.3.

Figure 19.—Flame speed data.

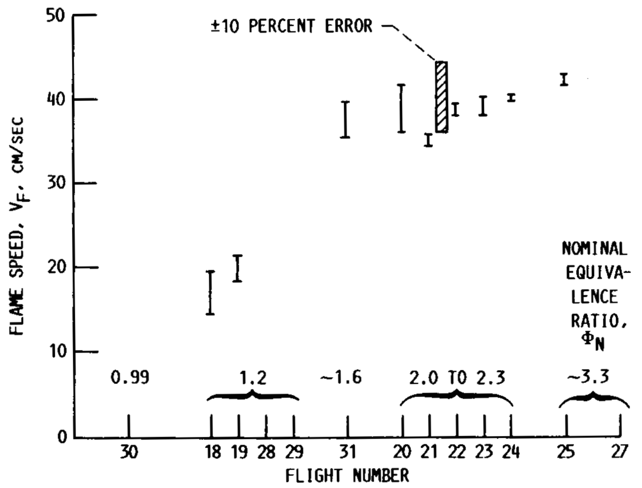


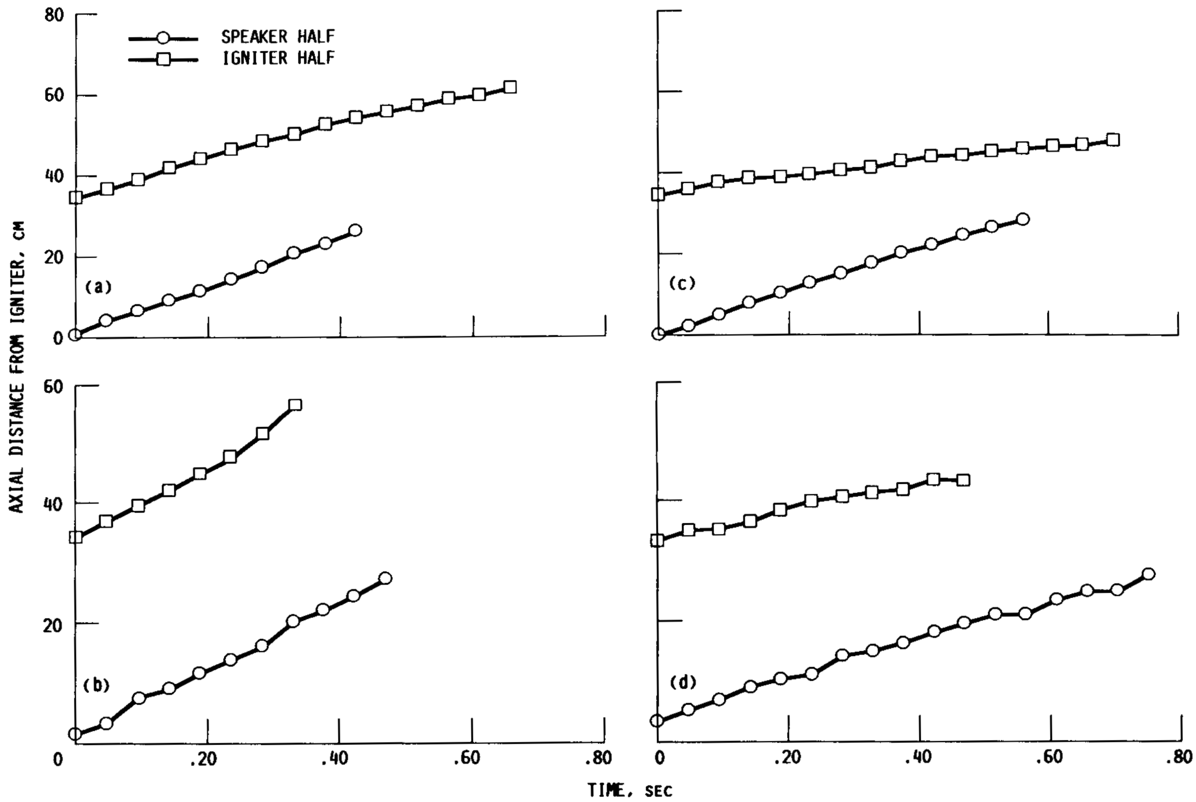

Figure 20.—Quasi-steady flame speeds versus nominal equivalence ratio.

cm/sec, respectively) derived from the time required for the flame to travel from the first to the last detector.

It is interesting to compare these results with those obtained in the drop tower tests. Figure 21 displays typical raw and reduced data from these tests. The flame speed is less steady with different values in the igniter and speaker halves of the tube, except for the $\Phi = 2.2$ case. At this stoichiometry, the flame speed is 30 to 50 percent higher, which may be due to the lack of quiescence and/or perhaps lesser adhesion of particles. The lack of steadiness, quiescence, and detector information makes the drop tower data difficult to interpret, as such it is discounted in this report.

## Flame Speeds Versus Suspended Concentration

Figure 20 displays the flame speed at the nominal concentration, defined as the known mass of fuel loaded into the tube divided by the known tube volume. The nominal equivalence ratio was then the nominal concentration divided by a stoichiometric concentration. However the suspended concentration is of principal interest, defined as the nominal concentration less the average particle adhesion level as determined from table V. Typically the suspended concentration




(a) Drop 35; equivalence ratio, 2.2.
(b) Drop 16; equivalence ratio, 3.1.
(c) Drop 30; equivalence ratio, 1.0.
(d) Drop 32; equivalence ratio, 0.65.

Figure 21.—Drop tower flame propagation. Slope = centerline velocity, cm/s.

was 10 percent less than the nominal concentration. Uncertainties in the suspended equivalence ratio may be derived from variable particle adhesion, variable detector attenuation, and unknown detector calibration.

The uncertainty in the suspended concentration was estimated by adding the standard deviation associated with the average detector signals and the standard deviation associated with particle adhesion.

The uncertainty in flame speed measurements is associated with the linear regression used to determine the slope of the distance versus time plots. In general the regression fit was excellent in each tube half. The average flame speed was taken as the average of the flame speed in the igniter and speaker halves of the tube. The uncertainty was taken as half of the difference in these speeds.

There appears to be little dependence on stoichiometry for mixtures above an equivalence ratio of 1.4 to 1.5. Below this value, the flame speed is diminished. More testing needs to be done to complete the curve.

# Discussion of Findings

This section is dedicated to technical discussions of the results described previously and their implications on combustion science.

The chattering flames found in these reduced gravity experiments have not been previously observed. A possible explanation for the novel structures is as follows: First, partial confinement encourages flame-acoustic interactions (ref. 16). Second, clouds of particles may segregate in laminae, along the nodal surfaces prescribed by a complex acoustic field. Third, the flame's radiative flux density penetrates far into the unburned particle cloud regimes.

### Mixing Phenomena

Although the speaker was operated nominally at a frequency near the first fundamental mode of the tube, the discrete and regularly spaced columns observed early in the mixing process suggest higher frequency excitation of the particles. The high-power "sloppy" diaphragms and the flexure of the tube walls make the acoustic resonator a highly nonlinear system. Wandering of energy among longitudinal, radial, and tangential modes is a well-known phenomenon characterizing nonlinear systems. That is, seemingly orthogonal normal modes do interact.

The higher harmonics of the longitudinal mode appear to be stimulated in a manner that corresponds closely to the striations observed in the classical Kundt's tube experiment (ref. 16). The correspondence of Kundt's tube striations (of cork dust) and those observed herein for lycopodium is striking. To quote from reference 18, "...Perhaps the most striking of all effects of alternating aerial currents is the riblike structure assumed by cork filings in Kundt's experiment. Close observation, while the vibrations are in progress, shows that the filings are disposed in thin laminae transverse to the tube and extending upwards to a certain distance from the bottom. The effect is a maximum at the loops, and disappears in the neighborhood of the nodes. When the vibrations stop, the laminae necessarily fall..." In microgravity, the thin laminae can rise to the top of the horizontal tube. When vibrations stop, our observed laminae do not necessarily fall.

Reference 16 provides an historical observation of the higher frequency excitation, but not a physical explanation of the process. The reasons for the appearance of the thin laminae in Kundt's tube experiments are varied, with radiation pressure (ref. 17) and wall effects (ref. 18) having been cited in the literature. When our tube was clamped at different places, the mixing process was observed to change, verifying the participation of the tube wall in the excitation of the higher harmonics. Quoting reference 18, "If the duct walls are not perfectly rigid, or if thermal and viscous effects at the surface are not neglected, some of the higher modes will be excited, even if the driving surface is a perfect piston...."

The observed behavior near the ends of the tube also suggest acoustic streaming as participating in the mixing process. The streaming serves to disrupt the columns of particles and form a more cloudlike structure.

The nonlinearity of the overall system permits energy coupling (destruction of the orthogonality) of the vibrational modes, permitting energy to be pumped into both radial and tangential modes. It is well known (ref. 19) that the tangential modes correspond to higher frequency spinning waves near walls and that radial waves may involve sloshing. Three-dimensional flows of this kind appear to provide the secondary flow conditions needed for good particle mixing, after cessation of the acoustic source.

### Autoignition Time Calculation

During the mixing process, jetlike laminae are formed by the acoustic driver and then destroyed by the secondary airflows in the quiescence waiting period. Then after ignition, the propagating flame may interact with the tube's acoustic properties to again excite the particles into closely spaced laminae. If this occurs, both the unburned (27 $\mu$m) and pyrolyzed (6 $\mu$m) particles become segregated (ref. 16). The unburned reactants then consist of alternate laminae of high concentration and low concentration fuel-air mixtures. The nomenclature $\Phi_o$ corresponds to the overall equivalence ratio of the system and $\Phi_L$ the average equivalence ratio in the high-concentration lamina. In general, $\Phi_L > \Phi_o$.

Figure 7 shows the early development of the lamina during the acoustic mixing burst. Figure 18 shows the structure of the radiatively emitting particle cloud of the combustion products of a chattering flame. The cold particle laminae do not emit strongly in that the pyrolysis of particulates is essentially complete at temperatures below 700 K. The vaporization-pyrolysis kinetic rates for lycopodium have been determined experimentally by Tangirala and Berlad (ref. 20).

The lycopodium-air flame of figure 18 is propagating from left to right. The overall equivalence ratio $\Phi_o$ for this flame is 1.1 to 1.2. The chattering flame could progress through a series of radiatively induced autoignitions (Berlad, A.L., et al.: Particle Cloud Flames in Acoustic Fields. Combust. Flame, 1988, submitted for publication)

where

$$\overline{U_f} = \left(\delta_1 + \delta_2\right)/\tau$$

where $\delta_1$ is the (cold) width of the particle-concentrating laminae and $\delta_2$ of the particle-depeleted neighboring space. Based on the $\overline{U_f}$ values observed, the autoignition time $\tau$ is about 30 msec.

The lycopodium autoignition data of Conti and Hertzberg (ref. 20) have been used in conjunction with autoignition theory to derive an overall reaction rate law for lycopodium-air combustion (Berlad, A.L., et al.: Particle Cloud Flames in Acoustic Fields. Combust. Flame, 1988, submitted for publication)

$$\dot{\omega}''' = P^2T^{-2}Y_FY_oA \exp\left(-E_a/RT\right)$$

where $E_a = 150\,000$ K/kmol, $A = 4.3\times10^{17}$ (m$^3$/kg)sec$^{-1}$, and $Y_F$ and $Y_o$ are the fuel and oxidizer mass fractions; $\dot{\omega}'''$ is given in kg-m$^3$ sec$^{-1}$.

For the near-adiabatic case, the model of a chattering flame is taken to consist of a sequence of initially cold, particle-enriched laminae, illuminated by hot combustion products whose infrared radiative flux penetrates far upstream. Based on the optical extinction studies for lycopodium described in reference 12, an optical beam loses only about half its intensity, in penetrating a $\Phi_o = 1.2$ cloud, in a distance of about 0.10 m.

The experimental data of reference 21, the optical opacities of lycopodium clouds, the kinetics of equation (2), and time-dependent autoignition theory (ref. 22) have been employed to compute an autoignition time characteristic of the chattering lycopodium flame's rate of propagation. The radiatively driven ignition of a given particle lamina is considered to proceed via a series of radiative bursts, each of duration $\tau$ and of an intensity that is determined by the flame-generated radiative flux and the location of the layer of unburned particles with respect to the hot combustion products. The optical attenuation law for lycopodium particles has been measured (Berlad, A.L., et al.: Particle Cloud Flames in Acoustic Fields. Combust. Flame, 1988, submitted for publication) and is given by

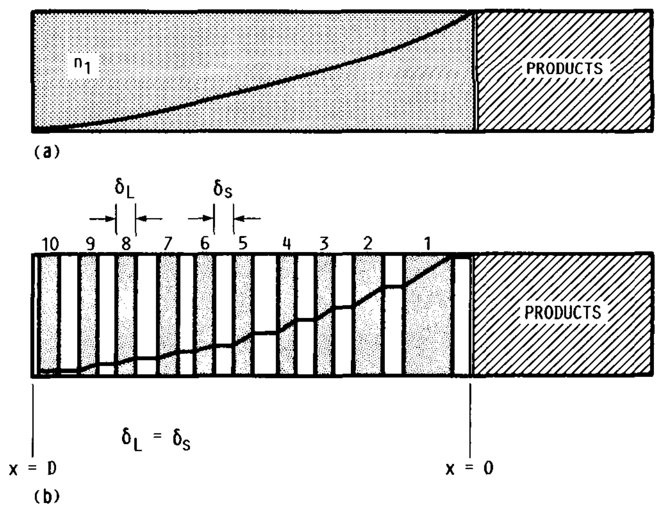
$$I_t = I_o \exp\left(-53.0\ c_X\right)$$

where $I_t$ is the transmitted radiant heat flux, $I_o$ is the initial radiant heat flux, $c$ is the concentration (kg/m$^3$) and $X$ is the space variable ($m$).

For adiabatic lycopodium-air flames, $I_o$, $c$, and $X$ are all known. For $\Phi_o = 1.2$, we take $\delta_1 \simeq \delta_2 \simeq 0.01$ m and calculate the temperature history (the time-dependent method of ref. 22) of particle layer 10 as it is radiatively driven along a supercritical trajectory to particle layer 9, 8, 7, . . ., 1. A particle layer designated initially as number 10, becomes 9 after a time, $\tau$. After each period $\tau$, the particle layer number is reduced and the radiative flux density is increased, as illustrated in figure 22. The computationally acceptable value of $\tau$ is found by an iterative process. A computational guess of $\tau$ that is too large will yield a particle layer temperature-composition history that leads to autoignition for $j > 1$. A guess of $\tau$ that is too short will fail to provide autoignition of a particle cloud layer within the $j = 1$ regime. For the conditions selected, the calculated value of $\tau$ is found to be 35 msec, in good agreement with experimental observation.

## Fire Safety Implications

The reported experiments are the first of a series. It is not too early, however, to note the fire and explosion safety implications of these findings. For particles in confined spaces, uncontrolled fire and explosion may be a threat even where $\Phi_o$ values (averaged over a large regime) are below some apparent lean limit. For small particles, such threats may be real, even for normal gravitational conditions (e.g., flour mills, etc.) and for large containment vessels.




(a) Intensity, $I(X)$, for uniform distribution of particles.
(b) Intensity, $I(X)$, for nonuniform distribution of particles.

Figure 22.—Theoretical particle distribution ahead of flame front.

# Feasibility Assessments for Particle Cloud Combustion Experiment Ground-Based and Space-Based Experiments

### Ground-Based Experiment Feasibility

Prior to this study, three technical obstacles existed which permitted questioning of the feasibility of the experiment. First, the formation of a sufficiently uniform cloud had not been demonstrated. Second, particle-wall adhesion was observed to be excessive. Third, as a result of the first two problems, quasi-steady flame propagation had never been observed.

This study showed that a cloud uniformity on the order of $\pm 10$ percent of the mean concentration can be achieved regularly for rich mixtures, and occasionally for lean mixtures, throughout most of the tube. This degree of uniformity met the stated goal for the experiments in reference 6.

This study also showed that particle-wall adhesion levels on the order of 10 percent ($\pm 5$ percent) can be achieved for both lean and rich mixtures. This level is comparable with the stated goal for the experiments.

Most importantly, quasi-steady flame propagation was observed for fuel-rich mixtures. The observed shape of the flame front and wake structures were as anticipated but not previously obtained. For near-stoichiometric mixtures, a new mode of flame propagation was observed, the so-called chattering flame. These flames did not propagate steadily through the tube, but instead may have induced an acoustic disturbance which could segregate the upstream particles into alternating fuel-rich and fuel-lean columns, modifying dramatically the forward movement of the flame front through these columns.

Flame propagation was also observed in tubes loaded with an amount of fuel thought to be outside the lean flammability limit. This finding has potential fire safety implications. It implies that an amount of fuel particles which, if uniformly distributed in a volume would not be flammable, will still allow flame propagation throughout that volume if the particles are located properly. Locating the particles into small packets separated by large distances does not necessarily serve to impede flame propagation where radiative fields are intense and physical scales are large.

New theory was developed which begins to explain these findings. The adiabatic case has been developed substantially, and the nonadiabatic cases are under present analysis.

The measured flame speeds were more rapid than anticipated, particularly for the near-stoichiometric tests. Deduction of burning velocities from flame speed and flame shape data are in progress. Also, the total mixing time was found to be less than 10 sec. These findings reveal that the Learjet facility provides a sufficient amount of low gravity time to conduct the complete experiment.

Each of these findings represents an advance to the state of the science. Also, each of the experimental goals was achieved in more than one instance. While improvements in the experimental methods can be made, and are recommended below, the findings are such that further significant advances to fundamental scientific understanding are probable and the planned ground-based science program should therefore be considered feasible.

### Space-Based Experiment Feasibility

Unlike the conclusions of the previous section, it is more difficult to consider favorably the feasibility of the space-based experiment. The tighter constraints on cloud uniformity and particle-wall adhesion were never met. Furthermore, the required reduced gravity time and level for some of the tests planned originally for the space-based experiment might be available in ground-based facilities. If this is accomplished, it would then be necessary to reevaluate the assumptions used to determine the eventual benefit-cost ratio of the space-based experiment.

The potential need for a space-based experiment is not disputed, in that (1) further ground-based studies will clarify the need for space and may improve the experimental methods to reach the previously stated goals; (2) related experiments can be envisioned, which if performed in concert with the present experiment, might produce successful results in space; and (3) the propagation of very lean mixtures will likely require a reduced gravity time unavailable in the aircraft facilities. If the current experiment is to be pursued for study in space, then some new hardware needs to be developed, specifically an automatic initial particle positioner with a higher degree of precision than the device used successfully in Learjet-mounted experiments. Other recommendations are described in the next section of this report.

# Potential Improvements and Specific Recommendations for the Ground-Based Experiment

The first activity which should be undertaken is the revision of the science requirements document to incorporate the findings of this study, and the development of a project plan for the collection of scientific data. The remaining items in this section, offered without prioritization, should be considered for inclusion in the project plan.

### Drop Tower Test Rig Utilization

Although most of the scientific data collection requires more reduced gravity time than available in the drop towers, the existing test rig may be used for several purposes. First, a series of tests should be performed with coal, cellulose, and very rich lycopodium clouds prior to comparable experiments on the Learjet. These tests will ensure safety on the Learjet and may reveal unusual flame behavior.

Certain specialized tests should also be performed. Flammability tubes of different dimensions may be studied in the test rig. Also ignition of still leaner clouds of lycopodium should be attempted. The initial positioning of fuel should be varied in several tests. Small segments of fuel should be loaded various distances apart, then mixed to see if they may be ignited radiatively. A larger proportion of fuel might also be loaded near the speaker in some tests to see if the chattering flame behavior observed frequently in this section of the tube might be eliminated.

The use of gold-coated flammability tubes was tried but failed to control particle-wall adhesion levels. However, these tubes have the additional benefit of reducing radiant heat losses from the flame to the tube wall. It is anticipated that the system will behave closer to an adiabatic one with the use of gold-coated tubes. These should be tried in tests near the lean limit. Reference 6 specifically requires the use of an infrared barrier coating in some ground-based tests.

### Additional Detectors to Determine Cloud Uniformity

The cloud concentration was measured at only four discrete locations. As in any experiment, it was impossible to measure everywhere and this introduced some uncertainty in the uniformity determination. As described earlier, the mixing process was observed to be multicellular. To minimize false agreement between detectors, care was taken to position the detector assemblies to view through different axes of the tube diameter and with uneven axial spacing.

However, in about one-third of the drop tests, a few small (less than 1 cm) puddles of unmixed fuel were observed on film and in post-drop tube examination while the detector data suggested a uniform cloud. The size of these puddles was on the order of the initial column spacing seen early in the mixing time. These puddles were confined to less than 5 percent of the tube volume, did not appear in every test, and were not sufficient to prevent flame propagation. They also never appeared in the final sequence of Learjet tests. The puddles were not predicted by examination of the detector data. Many more detector assemblies would be necessary to observe this phenomena directly.

Also, on one Lear flight the detectors were moved toward the speaker end of the tube. This revealed that the mixing near the speaker was less robust than elsewhere in the tube. Flame behavior in this region also suggested a leaner suspended mixture. Again more or better placed detectors are necessary to characterize quantitatively the entire cloud structure.

The camera films displayed readily gross defects in the cloud formation and uniformity. However, neither direct observation of the experiment nor of the films could distinguish concentration differences on the order of 10 to 20 percent. Thus a combination of more detectors and films is required as a minimum to better evaluate the cloud.

Even so, it is impossible for enough detector assemblies to be mounted on the tube to characterize the cloud uniformity completely. However improvement in the characterization can be made via repeated mixing tests performed with the detectors at different locations on the tube.

The detectors should also be sampled more frequently in the combustion tests to provide better measurement of the flame speed.

### Detector *K* Factor to Determine Concentration

The theoretical *K* factor for the flame tube hardware was calculated to be 1.27, based on simple diffraction theory and drawings of the optical detector hardware. However the value which best fit the reduced gravity data was about 1.6. The discrepancy may be due to (1) a different positioning of the lens, LED's, and photodiodes than was used in the calculation; (2) multiple scattering effects; and (3) the presence of a concentration gradient in the tube either axially or radially. The last possibility allows the calculated *K* factor to be correct, but requires substantial migration of fuel toward the detector positions. Inward migration was observed in normal gravity testing when the speaker remained energized for long periods of time (greater than 1 sec). Also, the lower attenuation and flame extinction observed near the speaker suggest that this area of the tube contained a diminished concentration of fuel.

Despite these uncertainties, either *K* factor may be used to determine cloud uniformity. The more difficult task is to determine cloud concentration, which requires a more accurate calibration, the methods for which are discussed in reference 12. Two different techniques (single layer slide data and drop tests) for calibrating the detectors were tried. In each technique, several assumptions were made which introduced an uncertainty in the results. A new calibration method might involve the use of liquid suspension tests with NASA detector hardware. These tests are particularly important for fuel-rich mixtures where multiple scattering effects are likely to be observed.

Consideration should also be given to modifications to the detector hardware to decrease the theoretical *K* factor to a value as close as possible to 1.

### Surface Area Density Measurements

A new means to determine the number of adhered particles in a given wall area should be developed. One possible technique would be the use of light extinction measurements as is done with the current optical detectors. Large light-emitting diodes and photodiodes could be mounted such that relatively large surface areas could be measured. An entire assembly might be mounted to a stepping motor to scan the entire length of the tube.

There are some potential difficulties with the measurement system just described. First, the stability and sensitivity of the system must be such that it can measure precisely small changes in light transmission corresponding to attenuation by a single layer of relatively few particles. Second, a wavelength must be selected which is absorbed by fuel particles and not by the combustion products. Third, ash and unburnt fuel particles must be distinguishable by the system.

Despite these difficulties, it may be worthwhile to develop such a system which would both conserve time and provide more representative measurements of the adhesion levels.

### Additional Measurement Capability

The unsteady shape of the flame front was due in part to the variable acceleration levels on the Learjet. The Learjet triaxial acceleration measurement system should be synchronized with the detector and film data. Newly developed systems at Lewis and GTE could be used for these measurements. In addition to these systems, the existing Learjet accelerometer system should be enhanced with a simple data acquisition system which would store digitized readings at a higher rate than the existing system.

### Time Display and Camera Framing Rates

It would be helpful if the time with 0.001-sec accuracy would be displayed on the camera films. Also, the framing rate of the cameras should be increased in some tests to provide better resolution of the "chattering flame" behavior.

A pressure transducer should be installed near the speaker end of the tube to determine if any significant pressure rise occurs during the test, and to measure the flame-induced acoustic disturbance with near-stoichiometric mixtures.

### Tube Preparations

The adhesion levels seemed to be affected by the temperature and humidity conditions in the room where the tube was prepared. A better controlled location should be considered for further tests.

Also, consideration was given in this study to the use of a spark ionization device to reduce residual electrostatic charge in the tube prior to testing. Such a device was purchased but never tested. Follow-on testing should be performed.

Plans now exist for the testing of adhesion levels at various humidities. These tests should be conducted and, if a positive finding occurs, employed in the tube preparations.

### Initial Particle Positioning

Repeated loadings into the slotted rod revealed a variation on the order of 5 percent in the total mass of fuel, most likely due to different packing densities. Some axial variation in the fuel mass is also suggested which, because of the cellular mixing process, affects the potential cloud uniformity. As such, it is unlikely that the cloud uniformity will be better than ±5 percent.

Some axial variation must be accepted because the slotted rod cannot easily be manufactured to a tolerance which will further reduce this variation. In an attempt to minimize this variation, a semiautomated particle loading and positioning device was designed during this study. Owing to a delivery failure by its manufacturer, it arrived too late for use. However, it should be tested for repeatability and axial uniformity.

### Very Rich Fuel Mixtures

The experiments which were conducted represent only a portion of the overall desired test matrix. Mixtures near the rich flammability limit were not examined owing principally to the inability in this region of the optical detectors to assess the cloud uniformity. The attenuation is nearly 100 percent, with changes in the suspended concentration of 10 percent corresponding to changes in the attenuated signal of less than 1 percent. Recalling that the optical detector instrument error is on this order, the interpretation of the measurements is difficult if not impossible. Measurements of clouds with equivalence ratios above 4.0 are not best interpreted by currently employed optical absorption measurements.

Nonetheless, experiments with mixtures richer than 4.0 should be studied for their qualitative benefit and to provide an approximation of the rich flammability limit.

One measurement scheme to determine the cloud uniformity would be to use the optical attenuation technique but shorten the path length. This approach, however, would require a major revision to the hardware design and fabrication. Alignment and therefore calibration difficulties would also increase.

## Acknowledgments

The authors wish to acknowledge the substantial contributions of several individuals. Eric Neumann and Ray Sotos contributed immensely to the detailed design and smooth operation of the Learjet flights tests. Earle Boyer and William Rieke piloted the Learjet for most of the test flights, providing reduced gravity conditions of consistently high quality. Mike Brace volunteered needed electrical design and troubleshooting support on several occasions. Don Buchele analyzed in depth the optical detector design as well as provided insight on potential changes to that design.

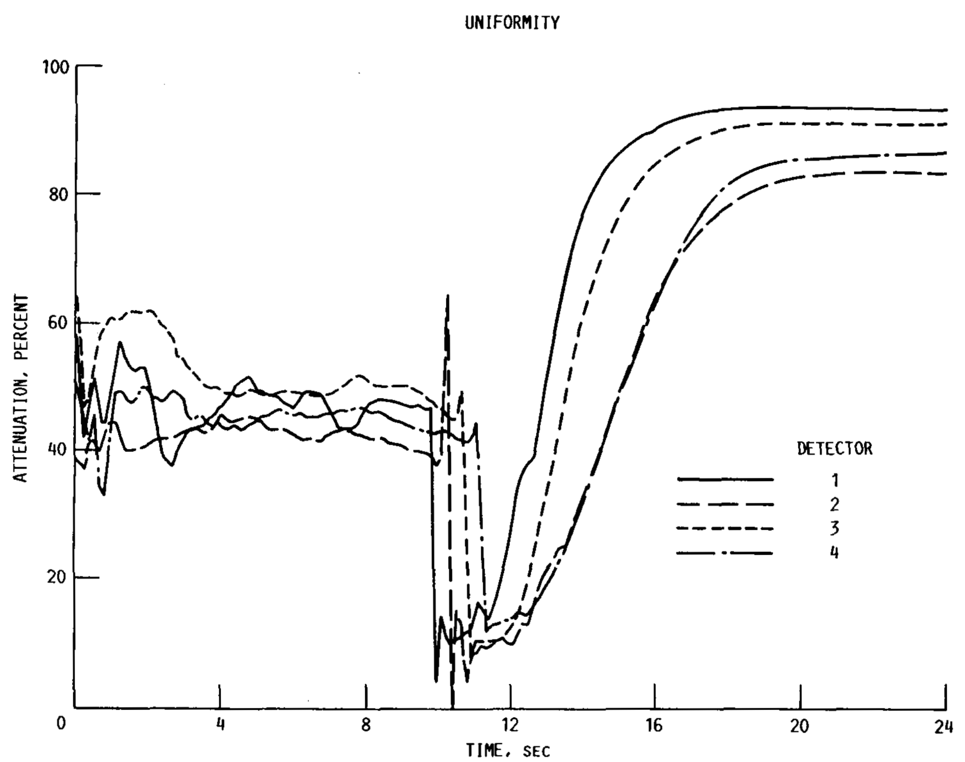
# Appendix—Summary of Flight Data

Three sets of data are shown for each Learjet flight. The first displays the optical detector data which determined both the uniformity of the cloud concentration and the flame propagation rate. The second set shows the flame position as a function of time, as determined from the movie films. This data was collected by use of a digitized motion analyzer. The data labeled ''Igniter half'' was taken from the camera viewing the early portion of flame propagation. The data labeled ''Speaker half'' was taken from the camera viewing the flame as it approached the speaker. The third set shows the accelerations recorded by the Learjet accelerometer system during the experiments. These accelerations are in each direction: along the axis of the fuselage, along the axis of the wings (i.e., perpendicular to the fuselage axis), and along the floor-to-ceiling axis of the airplane.

Any result particular to the experiment is shown along with these data sets.

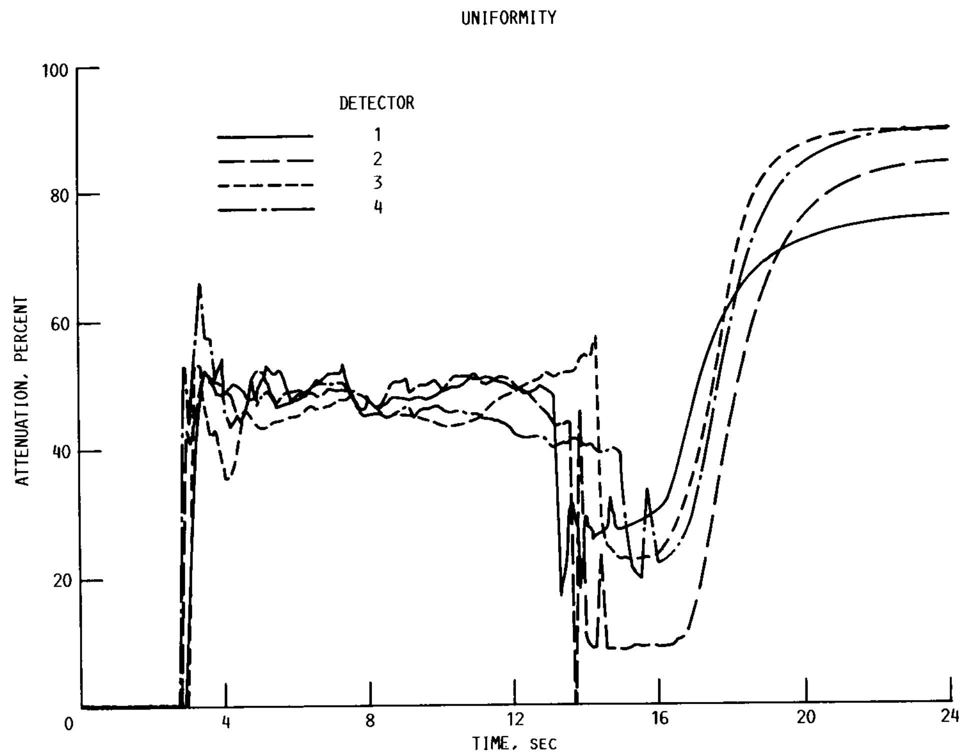
## Flight Test 10

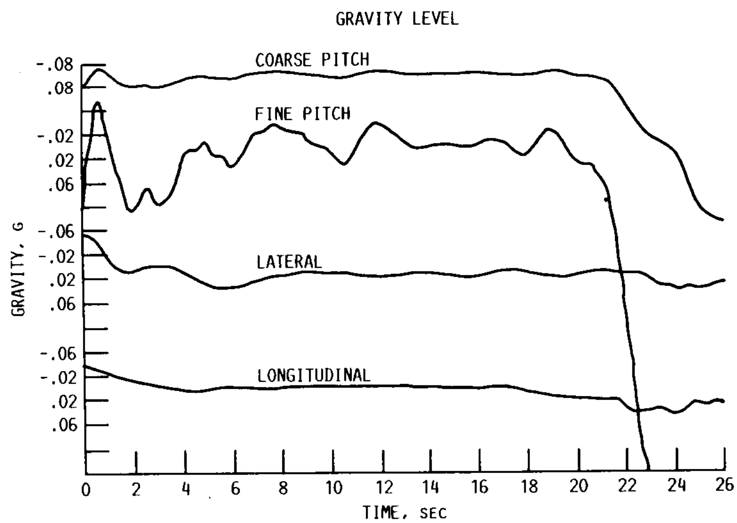
Flight date, 5/31/88
Equivalence ratio, 1.19
Average attenuation over 4 sec prior to flame, 45±8 percent



## Flight Test 13

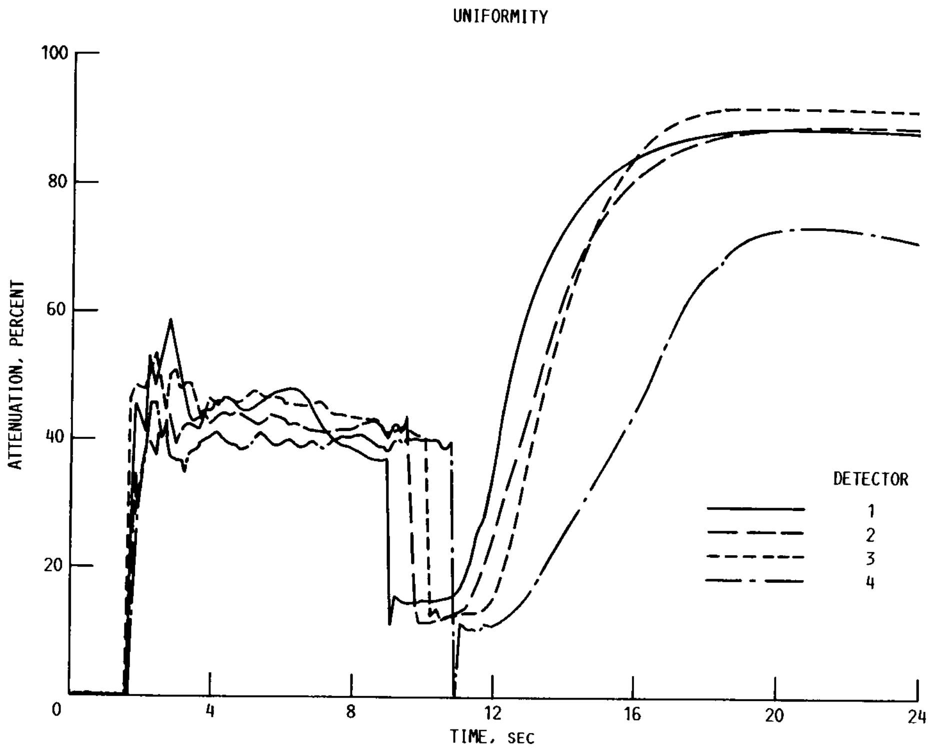
Flight date, 6/03/88
Equivalence ratio, 1.21
Average attenuation over 4 sec prior to flame, 47±8 percent

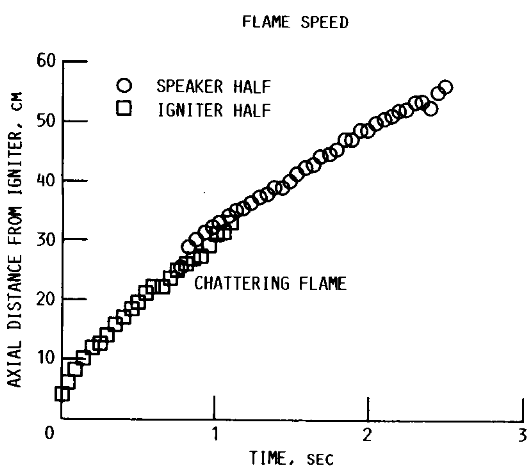


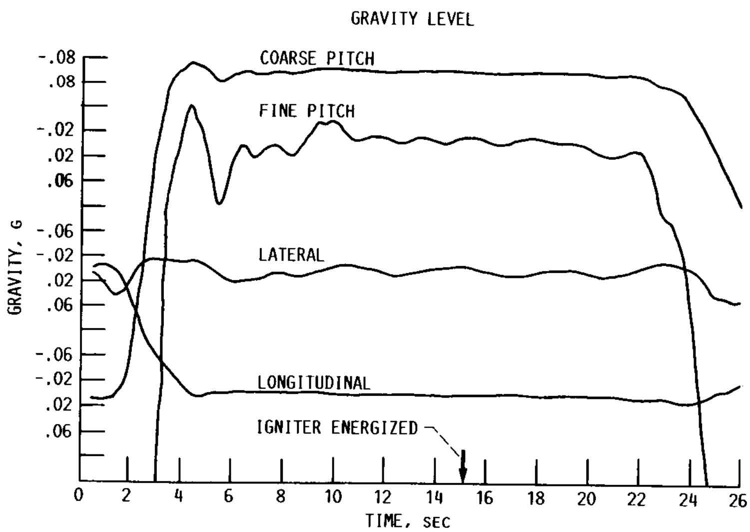



## Flight Test 18

Flight date, 7/01/88
Equivalence ratio, 1.16
Temperature during fuel loading, 70 °F
Relative humidity during fuel loading, 40 percent
Adhesion level, low
Average attenuation over 4 sec prior to flame, 43±5 percent

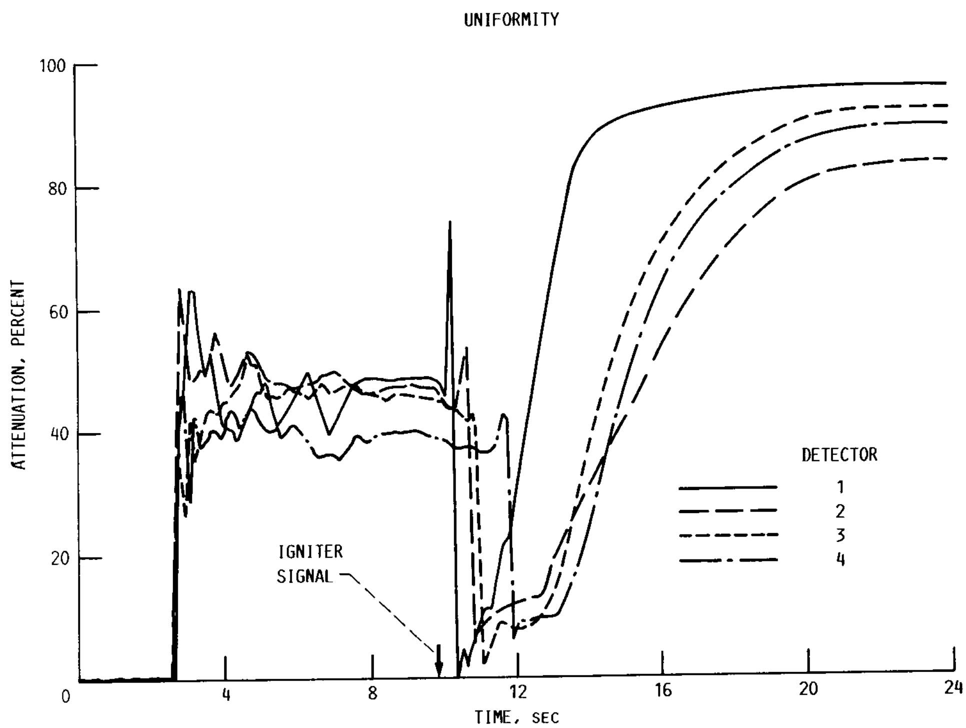


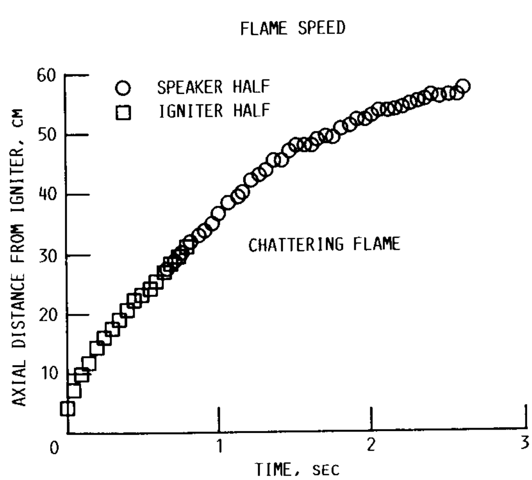



**Flight Test 19**

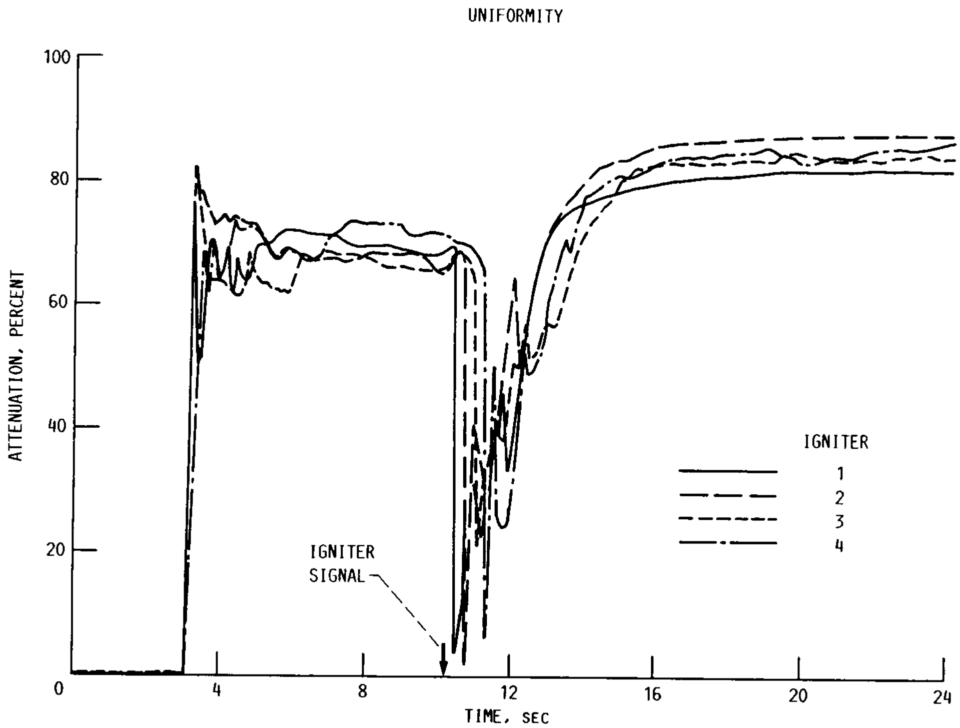
Flight date, 7/06/88
Equivalence ratio, 1.23
Temperature during fuel loading, 80 °F
Relative humidity during fuel loading, 40 percent
Adhesion level, low
Average attenuation over 4 sec prior to flame, 45±8 percent

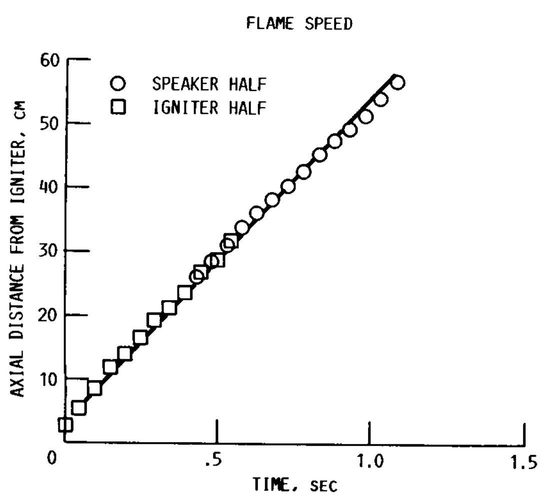


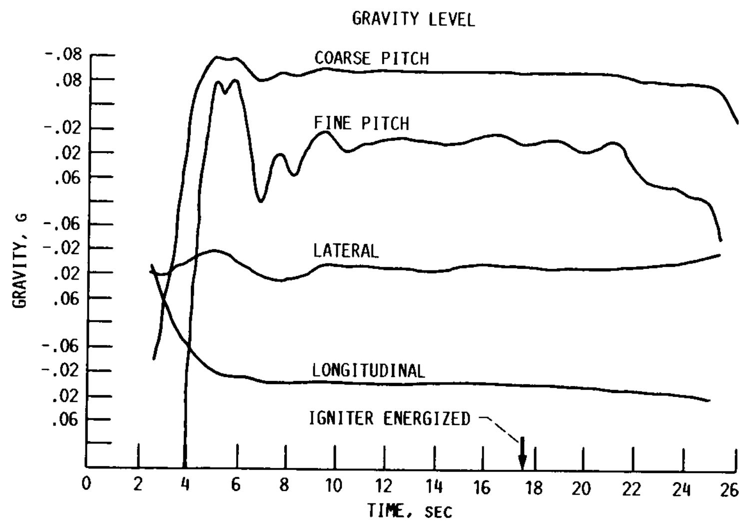



**Flight Test 20**

Flight date, 7/07/88
Equivalence ratio, 2.32
Temperature during loading, 80 °F
Relative humidity during loading, 40 percent
Adhesion level, low
Average attenuation over 4 sec prior to flame, 69±2.7 percent

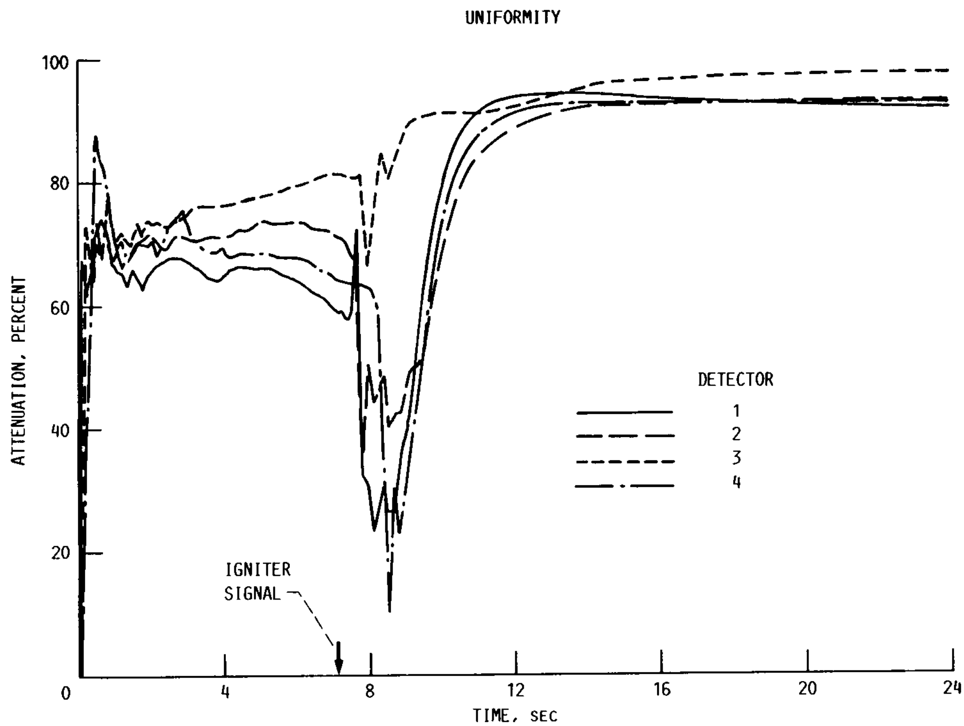


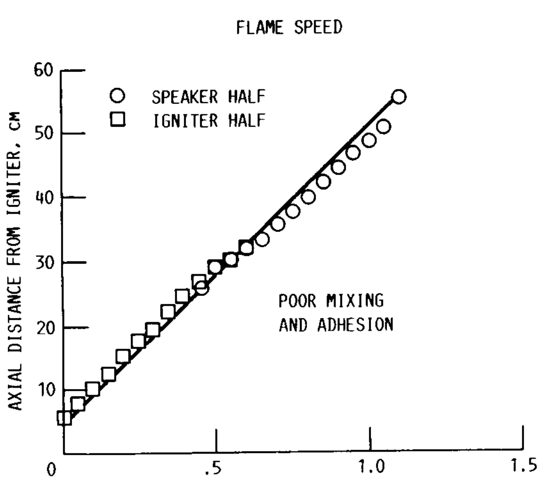



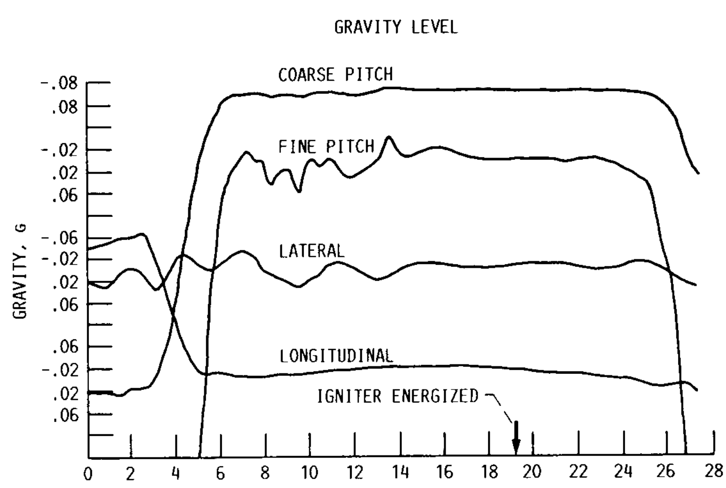



## Flight Test 21

Flight date, 7/12/88
Equivalence ratio, 1.98
Temperature during fuel loading, 75 °F
Relative humidity during fuel loading, 40 percent
Adhesion level, low
Average attenuation over 4 sec prior to flame, 70±9 percent

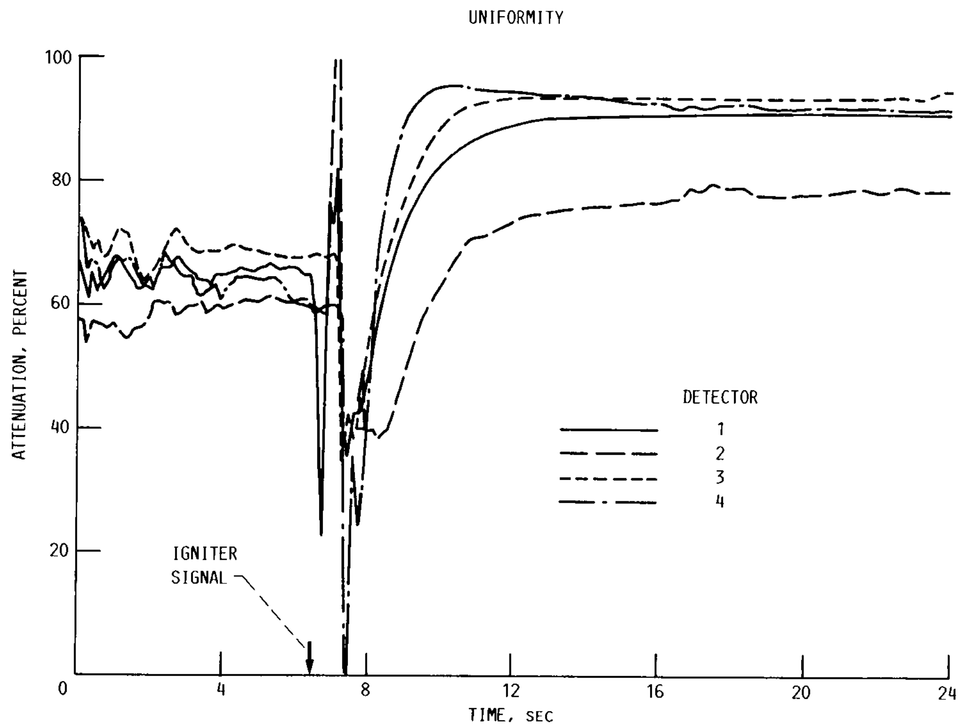


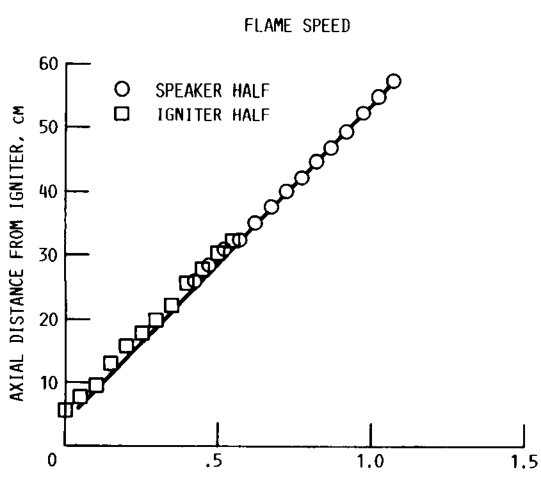



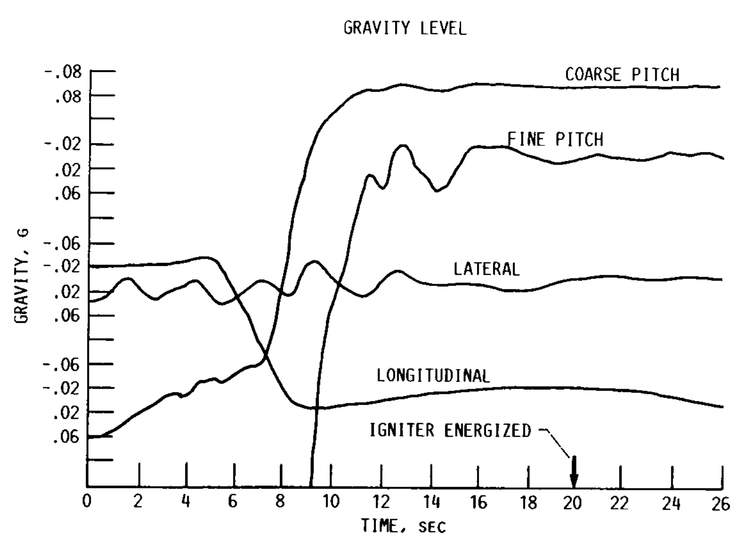



## Flight Test 22

Flight date, 7/13/88
Equivalence ratio, 2.19
Temperature during fuel loading, 76 °F
Relative humidity during fuel loading, 50 percent
Adhesion level, moderate
Average attenuation over 4 sec prior to flame, 63±5 percent

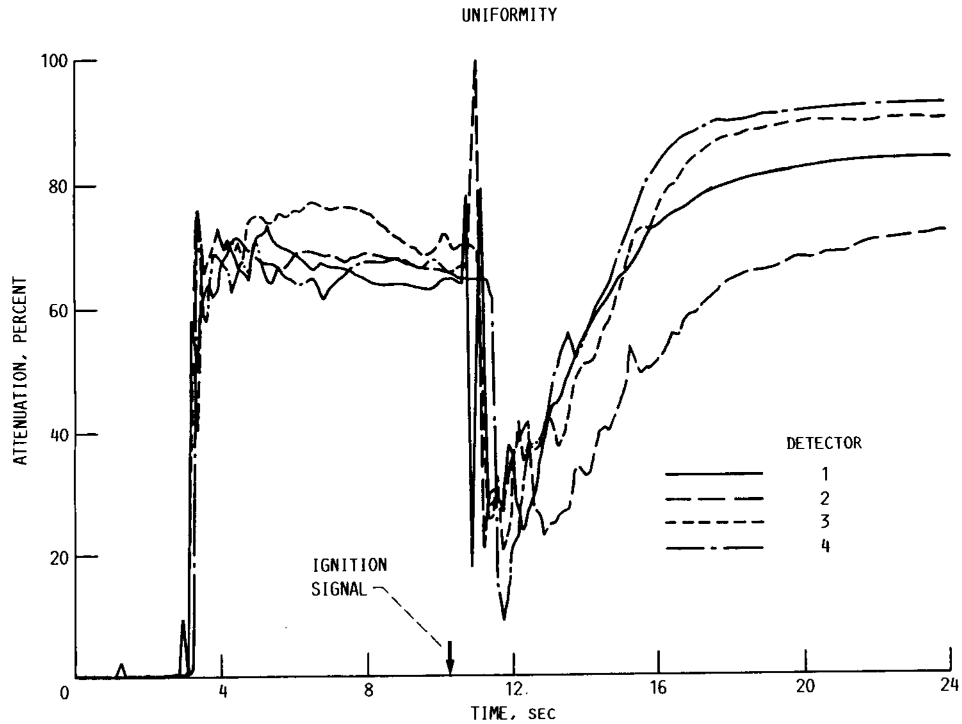


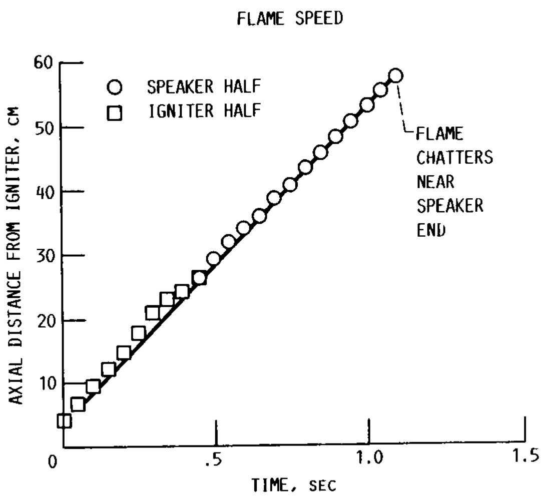



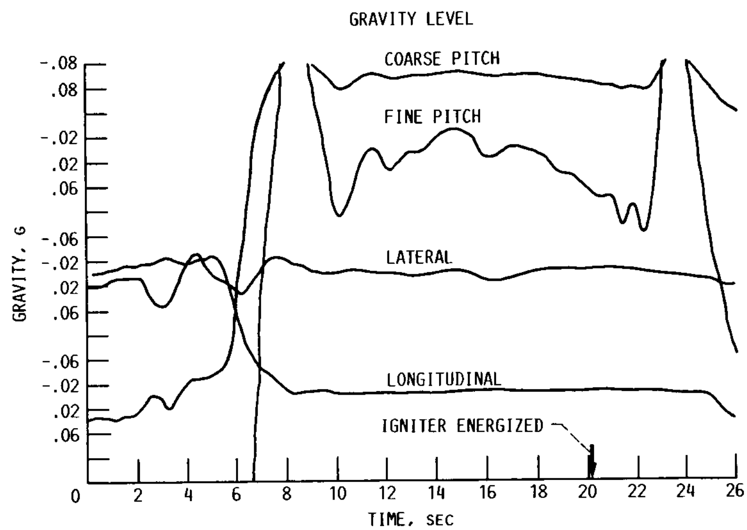



## Flight Test 23

Flight date, 7/14/88
Equivalence ratio, 2.18
Temperature during fuel loading, 78 °F
Relative humidity during fuel loading, 58 percent
Adhesion level, very low
Average attenuation over 4 sec prior to flame, 68±3.8 percent

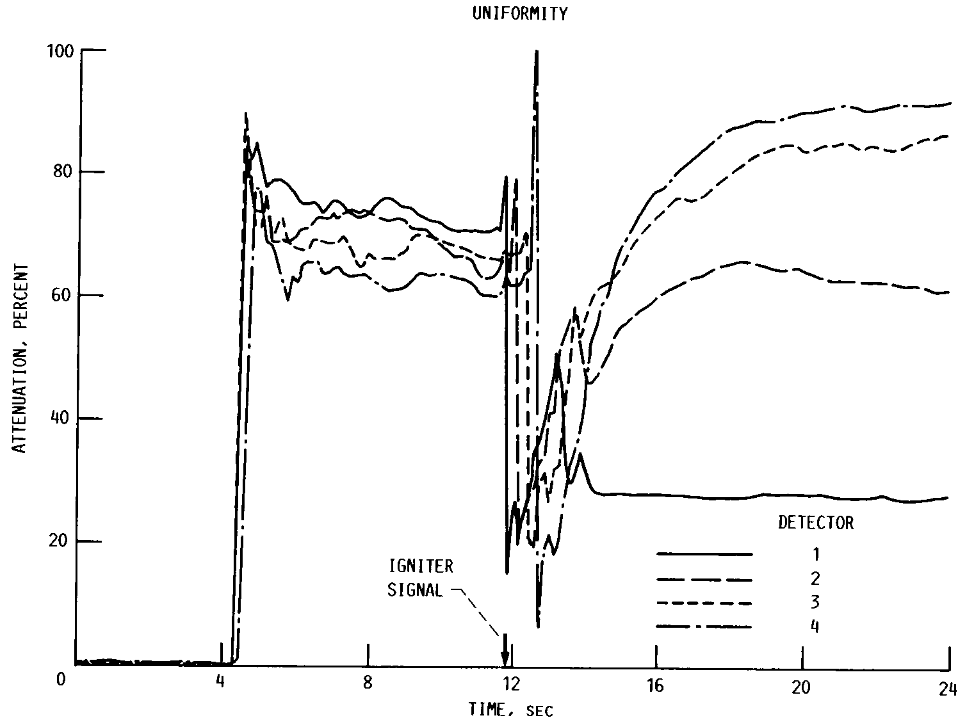


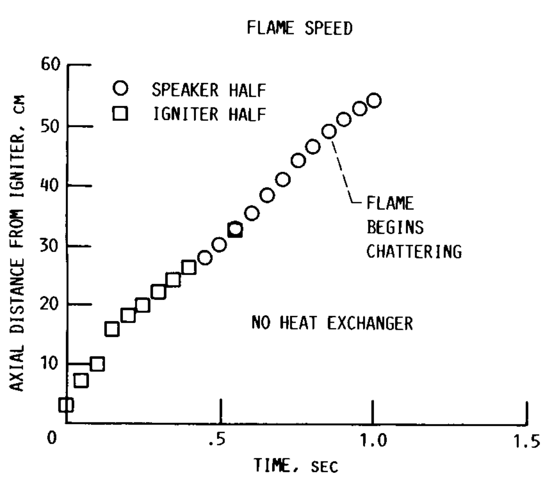



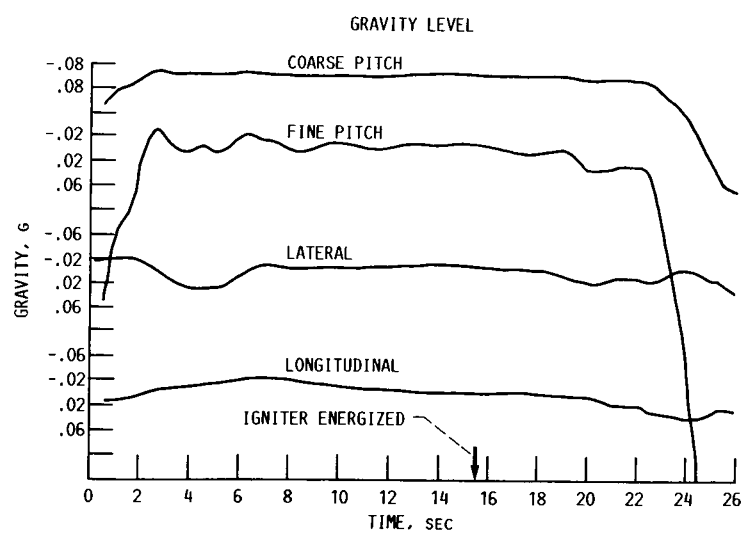



**Flight Test 24**

Flight date, 8/02/88
Equivalence ratio, 2.20
Temperature during fuel loading, 77 °F
Relative humidity during fuel loading, 45 percent
Adhesion level, 55±39 particles/mm$^2$
Average attenuation over 4 sec prior to flame, 68±5.5 percent

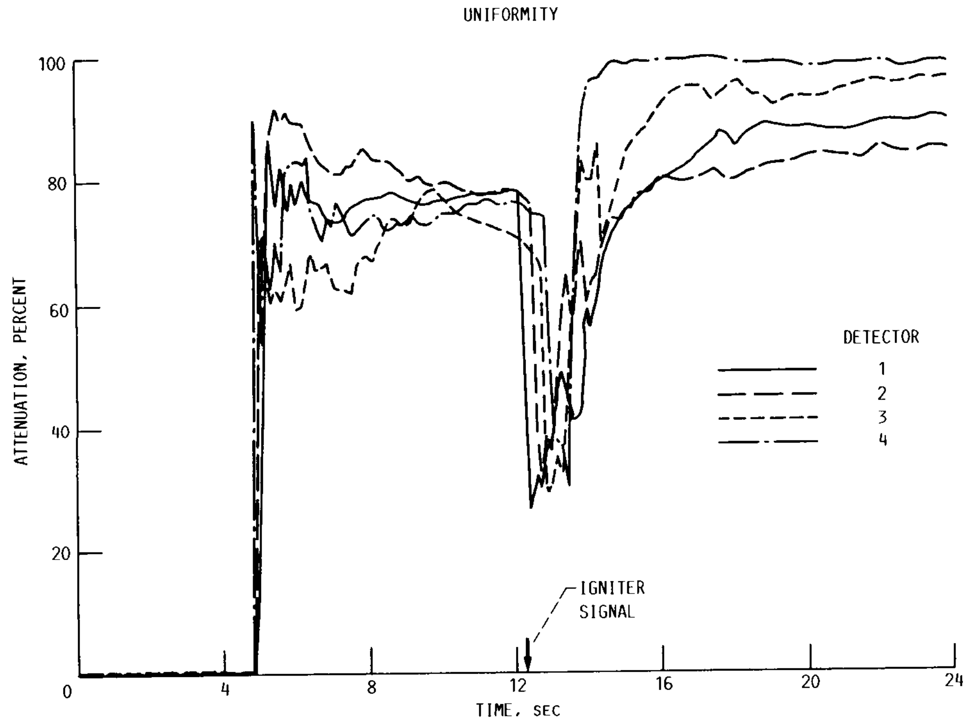


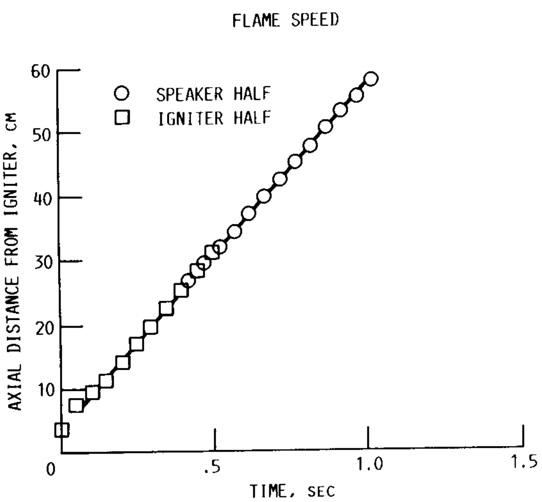



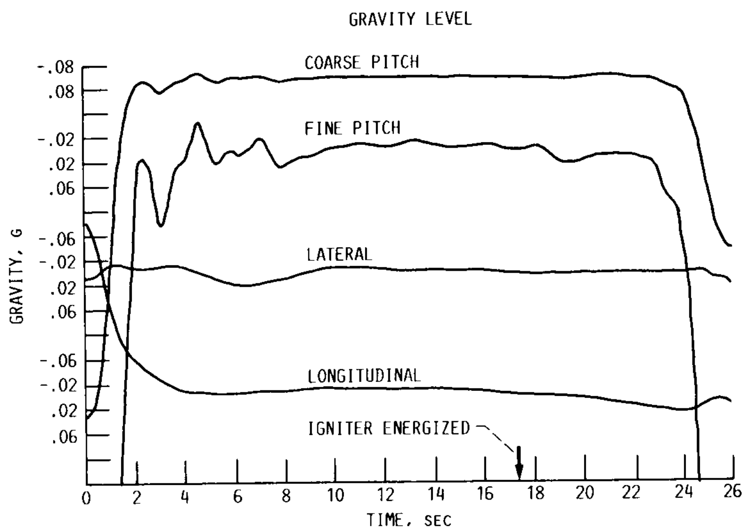



## Flight Test 25

Flight date, 8/03/88
Temperature during fuel loading, 76 °F
Relative humidity during fuel loading, 60 to 50 percent
Adhesion level, 127±88 particles/mm$^2$
Average attenuation over 4 sec prior to flame, 76±3 percent

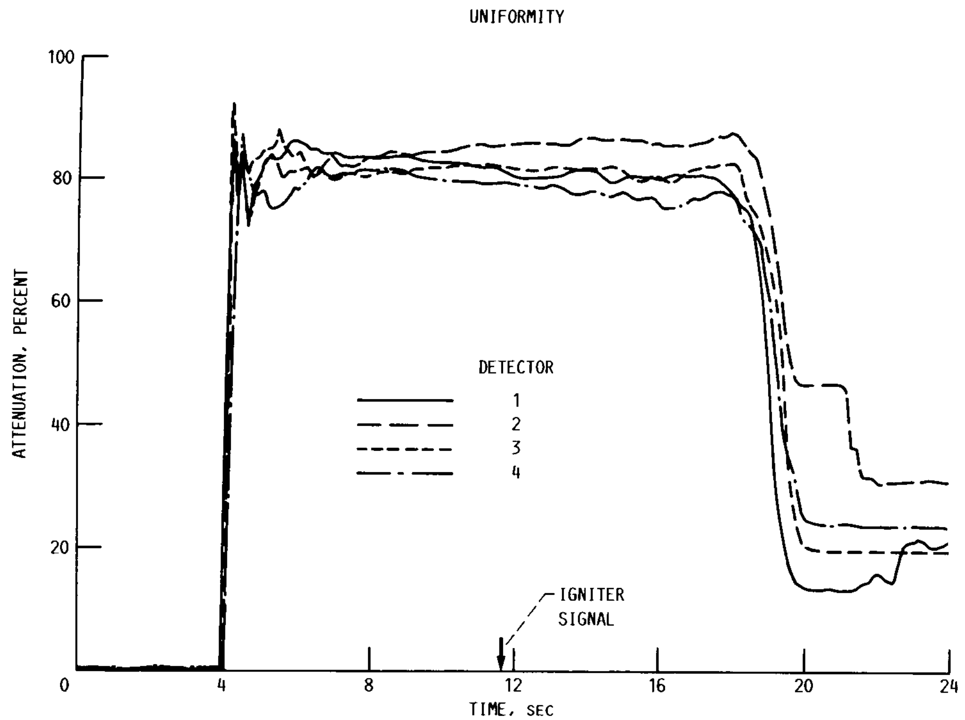


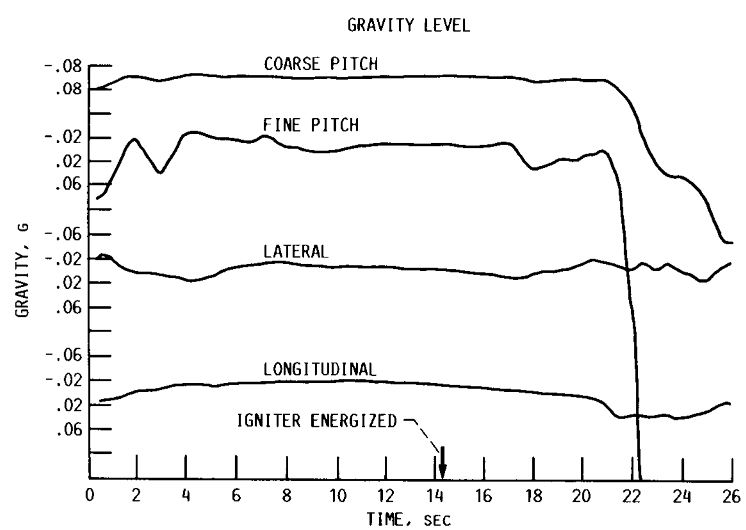



## Flight Test 26

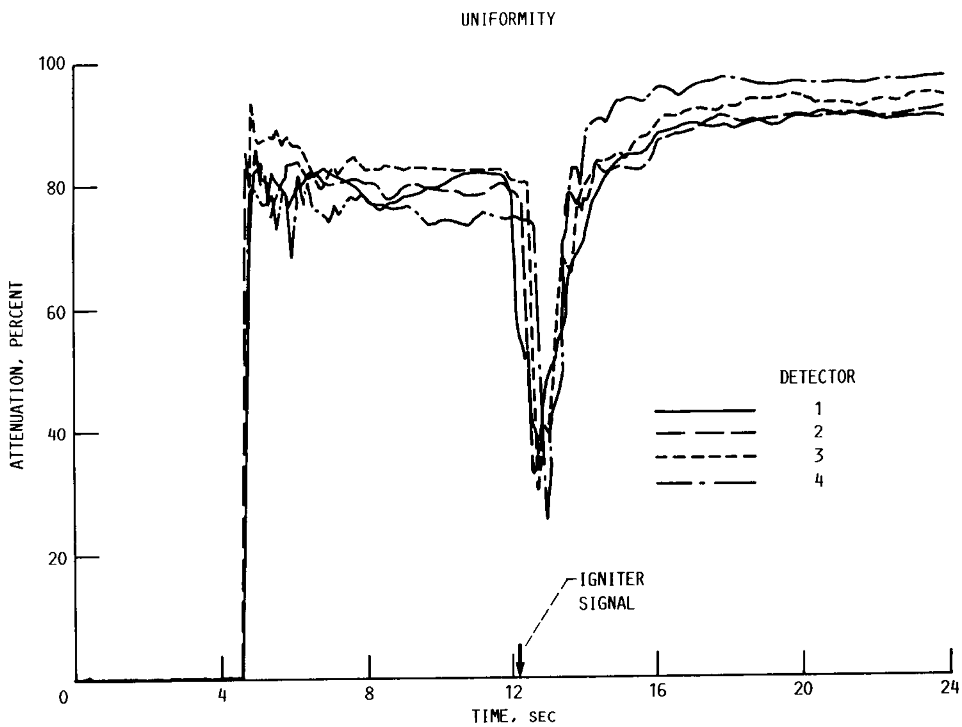
Flight date, 8/04/88
Equivalence ratio, 3.35
Temperature during fuel loading, 76 °F
Relative humidity during fuel loading, 55 percent
Adhesion level, 56 ± 21 particles/mm$^2$
Average attenuation over 4 sec prior to flame, 79 ± 2 percent

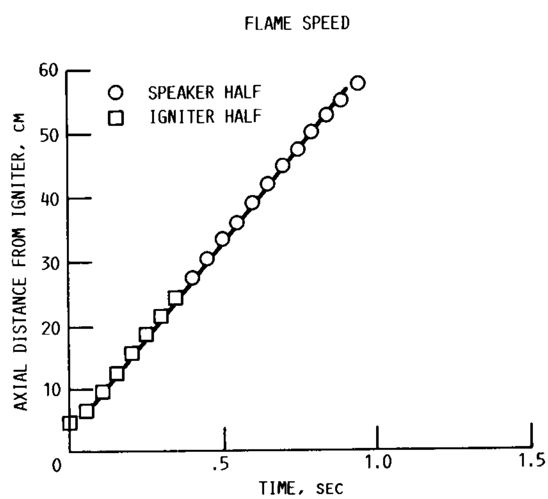


### Flight Test 27

Flight date, 8/05/88
Equivalence ratio, 3.29
Temperature during fuel loading, 78 °F
Relative humidity during fuel loading, 54 percent
Adhesion level, 96±49 particles/mm$^2$
Average attenuation over 4 sec prior to flame, 79±3.5 percent

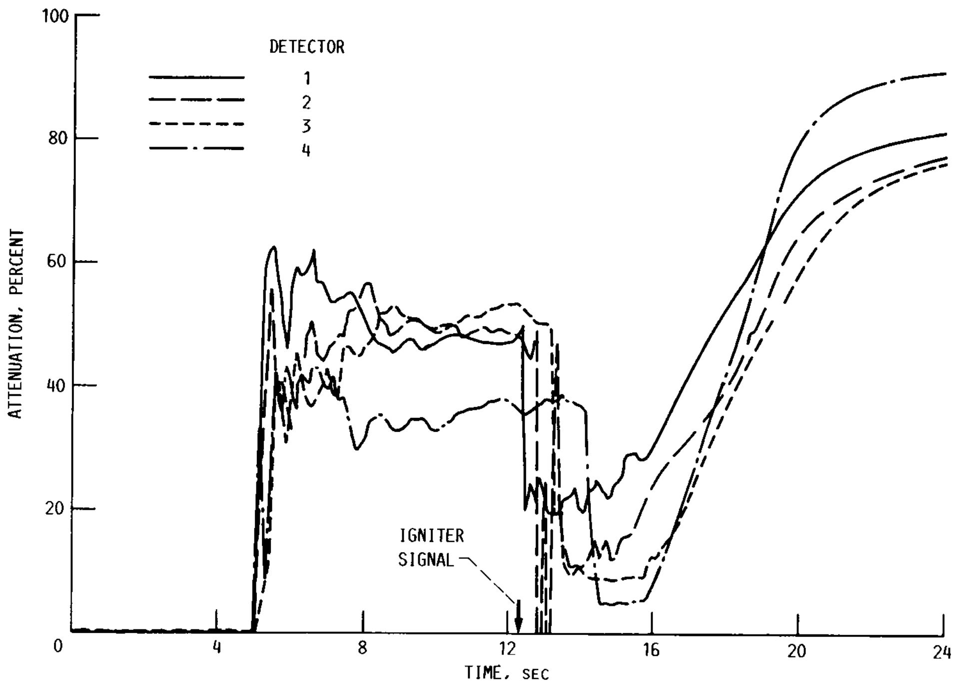


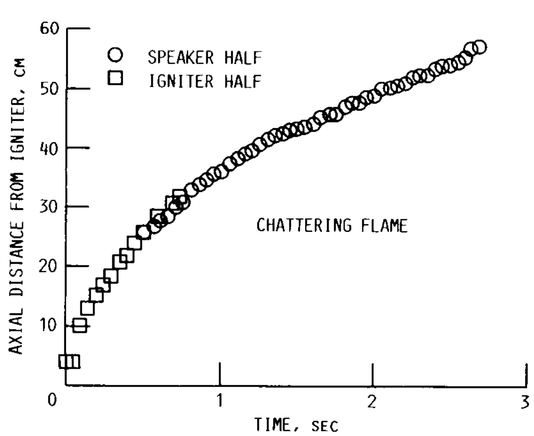
## Flight Test 28

Flight date, 8/08/88
Equivalence ratio, 1.16
Temperature during fuel loading, 78 °F
Relative humidity during fuel loading, 54 percent
Adhesion level, 96±49 particles/$mm^2$
Average attenuation over 4 sec prior to flame, 46±2.5 percent

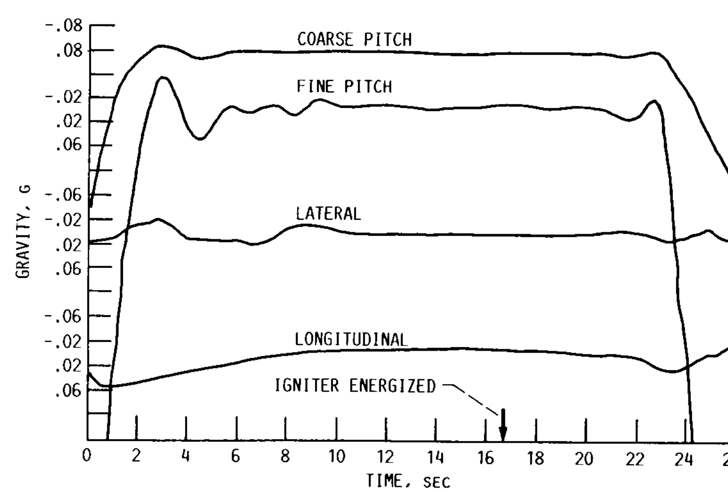
UNIFORMITY




FLAME SPEED

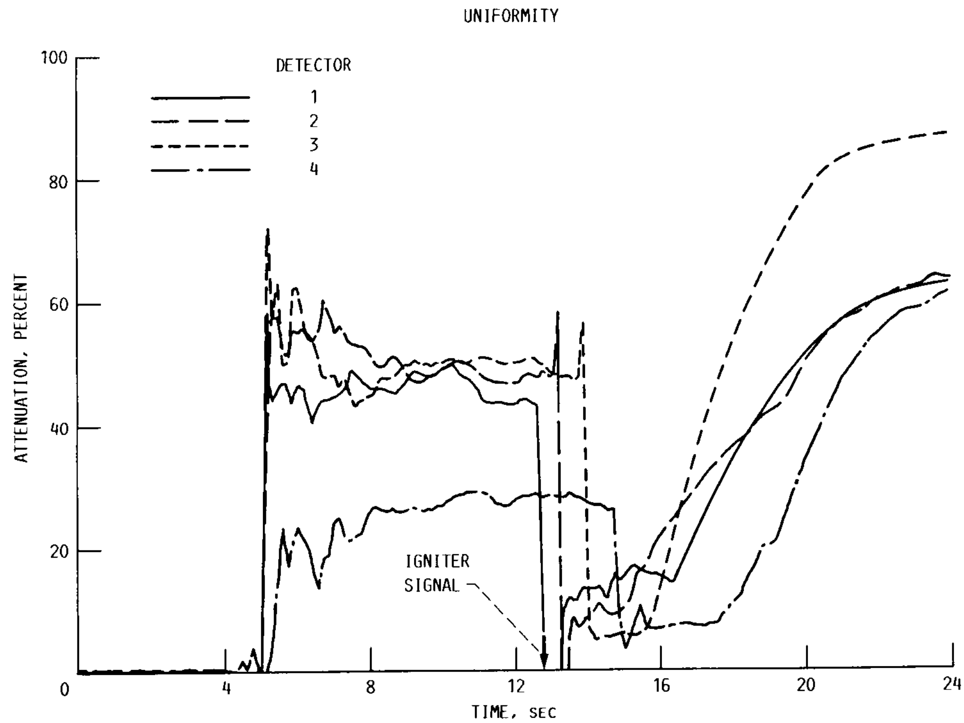


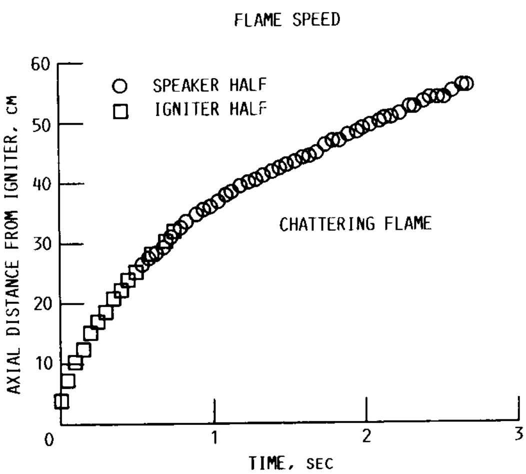

GRAVITY LEVEL

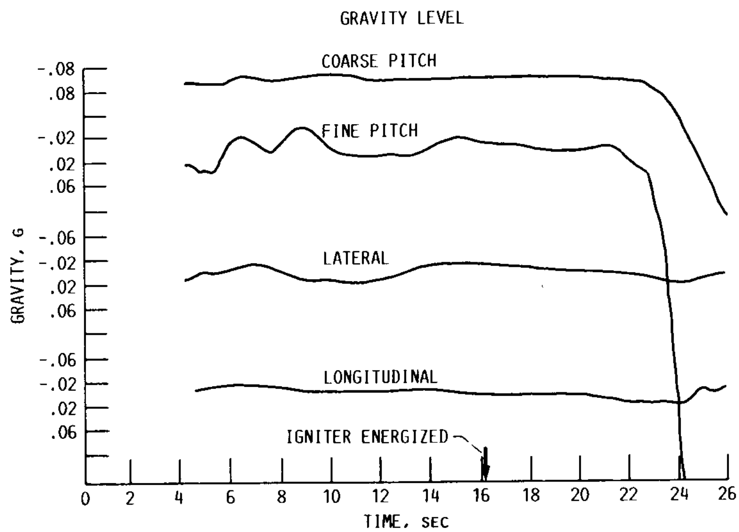


## Flight Test 29

Flight date, 8/09/88
Equivalence ratio, 1.18
Temperature during loading, 80 °F
Relative humidity during loading, 45 to 50 percent
Adhesion level, 18±7 particles/mm$^2$
Average attenuation over 4 sec prior to flame, 43±20 percent

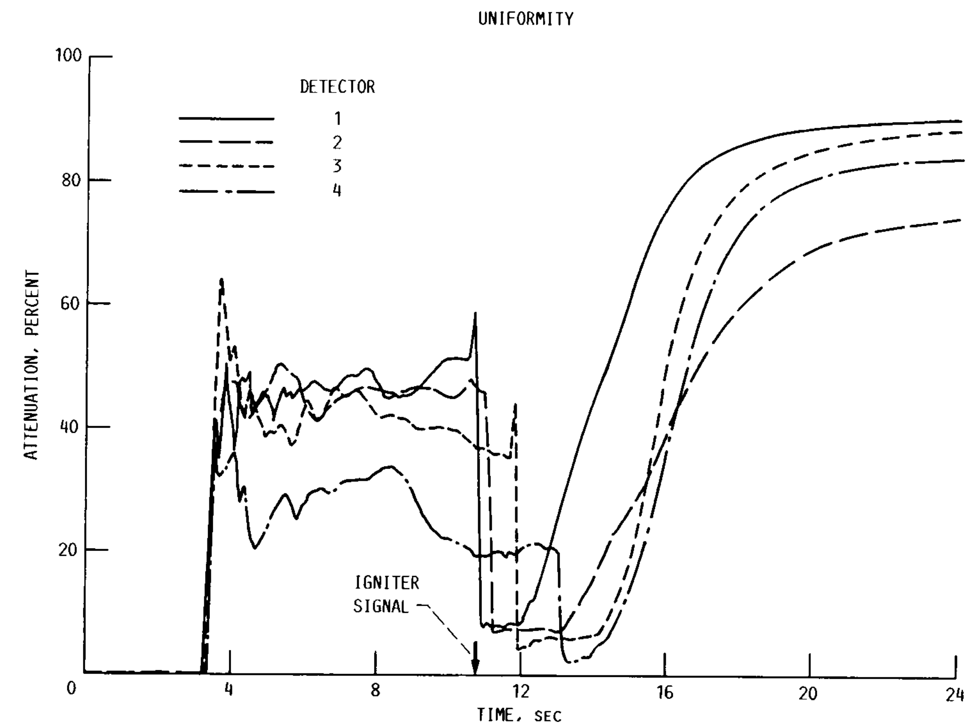


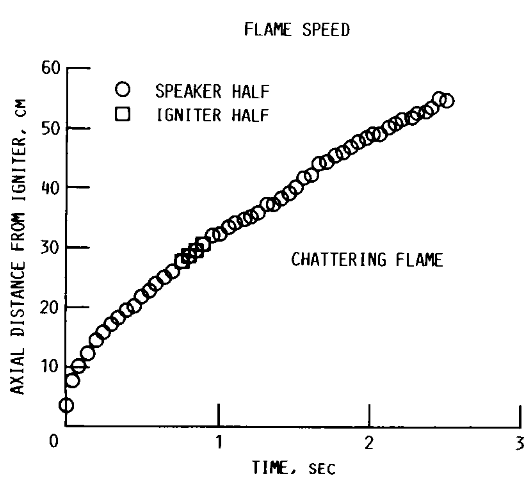



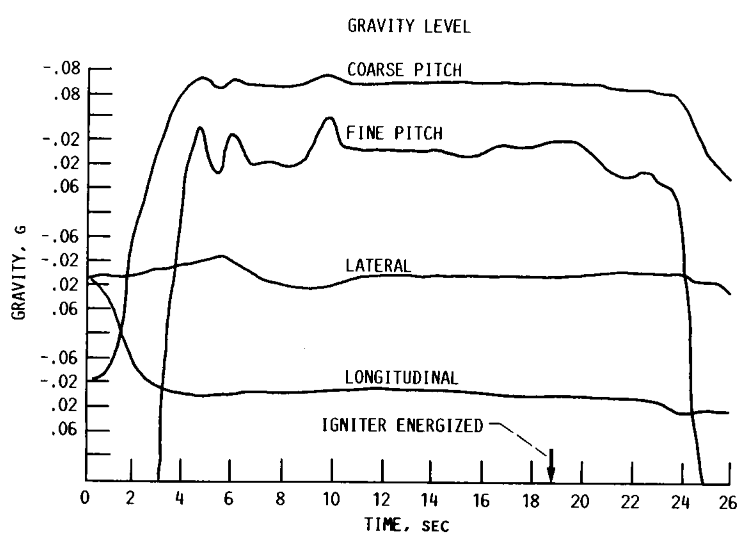



## Flight Test 30

Flight date, 8/11/88
Equivalence ratio, 0.97
Temperature during fuel loading, 79 °F
Relative humidity during fuel loading, 65 to 53 percent
Adhesion level, 24±14 particles/mm$^2$
Average attenuation over 4 sec prior to flame, 39±28 percent

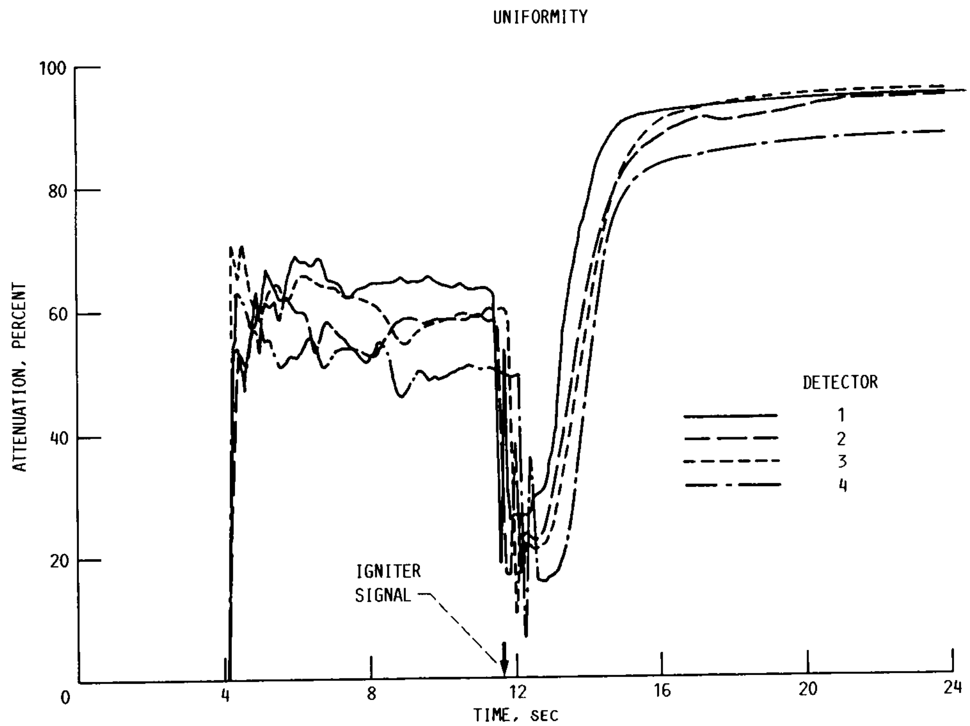


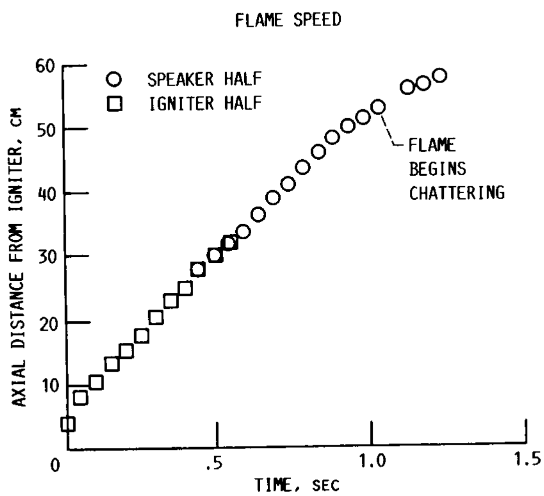



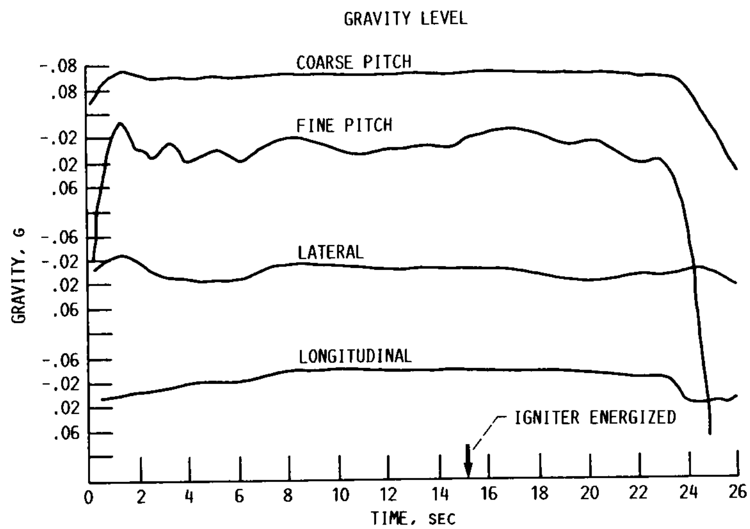



## Flight Test 31

Flight date, 8/12/88
Equivalence ratio, 1.61
Temperature during fuel loading, 78 °F
Relative humidity during fuel loading, 65 percent
Adhesion level, low
Average attenuation over 4 sec prior to flame, 58±8.6 percent



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15. Supplementary Notes

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16. Abstract

The study of combustible particle clouds is of fundamental scientific interest as well as a practical concern. Such clouds spread fires in underground mining operations and contribute to the fire and explosion hazards of grain storage and handling facilities. The principal scientific interests are the characteristic combustion properties, especially flame structure, propagation rates, stability limits, and the effects of stoichiometry, particle type, transport phenomena, and nonadiabatic processes on these properties. The feasibility tests for the particle cloud combustion experiment (PCCE) were performed in reduced gravity in the following stages: (1) fuel particles were mixed into cloud form inside a flammability tube; (2) when the concentration of particles in the cloud was sufficiently uniform, the particle motion was allowed to decay toward quiescence; (3) an igniter was energized which both opened one end of the tube and ignited the suspended particle cloud; and (4) the flame proceeded down the tube length, with its position and characteristic features being photographed by high-speed cameras. Gravitational settling and buoyancy effects were minimized because of the reduced gravity environment in the NASA Lewis drop towers and aircraft. Feasibility was shown as quasi-steady flame propagation which was observed for fuel-rich mixtures. The observed shape of the flame front and wake structures were as anticipated but had not been previously obtained. Of greatest scientific interest is the finding that for near-stoichiometric mixtures, a new mode of flame propagation was observed, now called a "chattering flame." These flames did not propagate steadily through the tube. Our current explanation is that the flame induced an (Kundt's tube) acoustic disturbance which could segregate the air-suspended particles into alternating fuel-rich and fuel-lean laminae. The flame then would propagate in a leaping, or chattering, fashion from one fuel-rich regime to the next. Chattering modes of flame propagation are not expected to display extinction limits that are the same as those for acoustically undisturbed, uniform, quiescent clouds. A low concentration of fuel particles, uniformly distributed in a volume, may not be flammable but may be made flammable, as was observed, through induced segregation processes. A new theory was developed which showed that chattering flame propagation was controlled by radiation from combustion products which heated the successive discrete laminae sufficiently to cause autoignition.

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