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# DROPLET COMBUSTION AT REDUCED GRAVITY

by

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## Extended Abstract

The science of droplet combustion is an applied science of current interest. Improvements in understanding of droplet combustion could lead to enhanced performance of combustors that employ liquid or slurry fuels. Although much is known about droplet combustion, various aspects of the subject are in need of additional fundamental knowledge. The research in progress addresses some of these aspects.

In applications of droplet combustion use is made of the now-classical theory developed in the early 1950's. Properties are approximated as uniform throughout the liquid, and steady-state conservation equations in spherical symmetry are employed to describe the gas on the basis of a reaction-sheet approximation, in which the combustion occurs at a spherical surface (the flame) surrounding the droplet. Fuel and oxygen diffuse into this surface from opposite sides, and heat liberated there is conducted back to the liquid to cause fuel vaporization. It is predicted that the square of the droplet diameter decreases linearly with time, and the ratio of the flame diameter to the droplet diameter remains constant during combustion.

The classical theory provides a good approximation to reality in many circumstances. However, phenomena neglected by this theory can be important in practical situations. The research is addressing various aspects of departures from the classical theory. These aspects include heating transients in the liquid, unsteady evolution of the gas-phase reaction zone, extinction of the gas-phase reactions, disruption of the liquid during combustion, and sooting behavior in the gas. The last three of these can be especially significant in applications; for example, liquid disruption through generation of gases in the droplet interior reduces burning times by producing collections of smaller droplets and can decrease yields of unburnt hydrocarbons and oxides of nitrogen.

Experiments under reduced gravity can aid in investigating many of these aspects of droplet combustion by decreasing buoyant convection. Although the individual combustion of each of the small droplets in sprays in practical combustion chambers often occurs with nearly spherical symmetry, for ease in data acquisition laboratory experiments on burning of individual droplets usually must employ larger droplets whose flames are displaced and elongated by buoyancy. Research taking advantage of reduced-gravity facilities, such as drop towers and space vehicles, affords the opportunity to study combustion of larger droplets with decreased buoyant influences. In the present studies, burning of individual droplets having diameters between 0.8 and 2.5 mm is being investigated at pressures between 0.5 and 2 atm in oxygen-nitrogen atmospheres having oxygen mole fractions between 0.18 and 0.50. The fuels are alkanes (initially decane and heptane), alcohols and (later) possibly mixtures, slurries and emulsions.

The current work involves theoretical analyses of the effects identified, experiments in the NASA Lewis drop towers and design of a flight apparatus for experiments to be performed in the middeck area of the Space Shuttle. In addition, there is laboratory work associated with the design of the flight apparatus. Calculations have shown that some of the test-matrix data can be obtained in drop towers, and some are achievable only in the space experiments. The apparatus consists of a droplet dispensing device (syringes), a droplet positioning device (opposing, retractable, hollow needles), a droplet ignition device (two matched pairs of retractable spark electrodes), gas and liquid handling systems, a data acquisition system (mainly giving motion-picture records of the combustion in two orthogonal views, one with backlighting for droplet resolution), and associated electronics.

Recent results from drop-tower testing of decane droplet combustion exhibit unexpected instances of disruptive burning. Theoretically, disruption does not occur for pure fuels. Earlier drop-tower tests encountered only two such events, both with small and unresolved satellite droplets burning in atmospheres having an oxygen mole fraction of 0.50. The recent tests demonstrate disruptions of larger, resolved droplets burning in air and suggest that disruption may be the rule rather than the exception under the experimental conditions. One hypothesis attributes the new results to improved achievement of spherical symmetry, allowing increased absorption of gas-phase fuel pyrolysis products in the liquid to form a multicomponent mixture susceptible to disruption. Future work includes evaluation of this hypothesis, further developments of theory for disruption, and exploration of ranges of conditions over which this mode of combustion occurs.

Theoretical studies have identified transient evolution of temperature profiles within droplets during combustion, through use of asymptotic analyses. Impulses delivered to droplets by sparks and by g-jitter have been calculated theoretically. Further theoretical investigations are planned on thermophoretic motion of soot particles formed around burning droplets, e.g. in relationship to disruptive burning.

Laboratory experiments have characterized spark transients and measured impulses delivered to droplets by sparks. Clarification of aspects of droplet formation on opposing needles also has been achieved in the laboratory. Future laboratory work will extend information on individual droplet ignition by sparks with attention paid to influences of fuel type, oxygen content of the atmosphere, and pressure. Analyses of soots collected under different laboratory combustion conditions also are planned. Future studies will devote special consideration to transients, extinction, soot and disruption.

## Introduction

Droplet burning has been the subject of intensive study over many years. The practical motivations for such investigations come mainly from a desire to achieve clean and efficient production of power through the combustion of liquid fuels. The fact that studies are continuing demonstrates that unknown factors remain at the basis of the subject.

Scientific studies of the topic first appeared at the Fourth International Combustion Symposium in 1953 [1,2,3]. A number of review articles on the subject have been prepared in recent years [4-8]. Much is known about the fundamentals of the subject, and good methods for calculating burning rates of droplets are available [9]. That these methods involve semiempirical procedures illustrates the need for further fundamental studies.

In the now-classical theory of droplet combustion, properties are approximated as uniform throughout the liquid, and steady-state conservation equations in spherical symmetry are employed to describe the gas on the basis of a reaction-sheet approximation, in which the combustion occurs at a spherical surface (the flame) surrounding the droplet. Fuel and oxygen diffuse into this surface from opposite sides, and part of the heat liberated there is conducted back to the liquid to cause fuel vaporization.

It is predicted that the square of the droplet diameter decreases linearly with time, and the ratio of the flame diameter to the droplet diameter remains constant during combustion. Specifically, the dependence of the droplet diameter d on time t is given by the "d-square law",

$$d^2 = d_0^2 - Kt \;, \qquad (1)$$

where K is called the burning-rate constant. In terms of the thermal diffusivity $\alpha$ of the gas, the ratio $\rho$ of the density of the gas to that of the liquid and the transfer number B, it was found that theoretically

$$K = 8\alpha\, \rho\, \ell n(1+B) \;. \qquad (2)$$

The transfer number is a thermodynamic quantity measuring the ease with which mass transfer can occur, viz.,

$$B = H/L , \tag{3}$$

where H is the enthalpy difference driving mass transfer and L is the enthalpy difference resisting it. The ratio of the flame diameter to the droplet diameter is predicted to be

$$R = \ell n(1+B)/\ell n(1+\nu) , \tag{4}$$

where $\nu$ is the product of the ambient oxygen mass fraction with the stoichiometric mass ratio of fuel to oxygen.

The classical theory provides a good approximation to reality in many circumstances. However, phenomena neglected by this theory can be important in practical situations. The current low-gravity research is addressing various aspects of departures from the classical theory. These aspects include heating transients in the liquid, unsteady evolution of the gas-phase reaction zone, extinction of the gas-phase reactions, disruption of the liquid during combustion, and sooting behavior in the gas. The last three of these can be especially significant in applications; for example, liquid disruption through generation of gases in the droplet interior reduces burning times by producing collections of smaller droplets and can decrease yields of unburnt hydrocarbons and oxides of nitrogen, thereby decreasing pollutant production.

## Liquid Heating Transients

The burning-rate constant K is affected by unsteady heat transfer within the liquid because the resistance enthalpy L includes, in addition to the heat of vaporization, the enthalpy conducted into the droplet interior. The variation of the latter with time introduces departures from the d-square law. Theories [10-12] have suggested that consequently K will gradually increase over the first 10% of the burning history, but recent studies [13-15] have identified the thermal diffusivity $\beta$ of the liquid and the ratio $\epsilon$ of sensible to latent enthalpy change of the liquid as parameters influencing this prediction. If $\beta < \alpha\rho\ell n(1+B)$ and $\epsilon > 1$, a thermal wave develops in the liquid at the droplet surface during combustion and causes L to increase with time, so that K decreases, contrary to expectation; instead of "heating up", the droplet "cools down". Experiments have shown heat-up behavior but have not been performed with parameters for which cool-down is predicted.

## Reaction-Zone Motion

There have been theoretical examinations of the classical result that the ratio R of flame to droplet radius remains constant during combustion [16-19]. In droplet burning, after an initial transient there is an outer transient-diffusive zone and an inner quasisteady convective-diffusive zone in the gas [16,17], and the flame should lie in the outer zone for low ambient oxidizer concentrations and in the inner zone for high concentrations, the specific condition for the latter being approximately $8\rho[\ell n(1+B)]^3 < [\ell n(1+\nu)]^2$. Thus, the theory predicts that the flame will remain unsteady in some cases but will achieve quasisteady behavior (flame radius proportional to droplet radius) in others. Good experimental tests of these theoretical predictions are unavailable. The burning rate of the droplet is influenced by this effect [17-19] such that, on the average, an additional factor $1 + [(2/\pi)\rho\ell n(1+B)]^{1/2}$ appears in the equation for K[8]. This result too lacks experimental scrutiny. The best available experimental indications are that under gravity-free conditions the ratio $R$ usually increases with time, at least initially [20-22].

## Reaction-Zone Extinction

The flame extinguishes if a Damkohler number D, the ratio of a residence time to a reaction time in the reaction zone, becomes too small. Since the reaction time is independent of the droplet diameter but the residence time is proportional to the square of the diameter, extinction is predicted to occur when the droplet becomes sufficiently small. Although extinctions have been observed in experiments with droplets suspended on fibers [9,23,24], interpretation of the results is difficult because of interference by the fiber. Depending on conditions, extinction is predicted to occur either before or after complete vaporization of the fuel [17,25]. Experimental tests of these extinction predictions for droplets currently are unavailable.

Extinctions in configurations of counterflowing fuel and oxidizer have been analyzed theoretically [26,27], and the results have been employed in conjunction with experiments to extract overall rate parameters [27-29]. Extinctions by convection have been inferred for free droplets [30], but data are insufficient to extract rate parameters. Published extinction analyses employ activation-energy asymptotics in a one-step approximation for the chemistry. More recent analyses [31,32] are addressing influences of full kinetic mechanisms on extinction. Since existing experimental methods for studying extinction can be applied only over a limited range of residence times, measurements of extinction for droplets burning with spherical symmetry as can be obtained in gravity-free conditions could extend capabilities of testing extinction theories.

## Liquid Disruption

Disruptive burning is a phenomenon whereby the fuel droplet disintegrates abruptly prior to completion of combustion. Experimental studies of the phenomenon have been performed, e.g. [30,33-35], and some theoretical understanding of the mechanisms of disruption has been obtained, e.g. [7,13,30,36], on the basis of ideas of homogeneous nucleation.

Deficiencies remain in abilities to predict disruption, and experiments at reduced gravity afford a means for addressing these deficiencies, as will be demonstrated below.

## Soot

Soot production in diffusion flames is a complicated chemical-kinetic process about which some qualitative concepts are available. The literature on the subject is vast, as may be seen from the citations in a recent publication [37], for example. In liquid-fuel combustors soot production in droplet burning may be a contributor to the soot levels in the combustion chamber. The soot may be beneficial for radiant energy transfer but detrimental for pollutant emissions. Soot formation has been observed in droplet-burning experiments, but quantitative measurements of soot concentrations or of rates of soot production in droplet burning are unavailable.

## The Role of Reduced Gravity

Experiments under reduced gravity can aid in investigating these aspects of droplet combustion by decreasing buoyant convection. Although the individual combustion of each of the small droplets in sprays in practical combustion chambers often occurs with nearly spherical symmetry, for ease in data acquisition laboratory experiments on burning of individual droplets usually must employ larger droplets whose flames are displaced and elongated by buoyancy. Research taking advantage of reduced-gravity facilities, such as drop towers and space vehicles, affords the opportunity to study combustion of larger droplets with decreased buoyant influences.

A droplet of diameter d exposed to an acceleration of magnitude g has an associated buoyancy-controlled residence time of order $\sqrt{d/g}$, which may be compared with the diffusion-controlled residence time $d^2/\alpha$. The square of the ratio of the second of these times to the first (viz. $d^3g/\alpha^2$) is proportional to a Grashof number that measures the importance of free convection relative to diffusive processes. Estimates show this number to be about unity under normal laboratory combustion conditions for $d \approx 1$ mm. Since gas diffusivities $\alpha$ vary inversely with the pressure p, reducing d, p or g decreases effects of buoyancy. Changing p also affects chemical-kinetic rates and mechanisms; reduction in g therefore is a more attractive way to achieve $d^3g/\alpha^2 << 1$.

With this last inequality enforced, changing d by a factor of five changes residence times by a factor of 25, which should be sufficient for investigating chemical-kinetic effects associated with extinction and soot production, for example. Changing d by a factor of three (as planned in the initial phase of the present program) changes residence times by a factor of nine, which still could reveal interesting phenomena.

To achieve these ranges of residence times, corresponding ranges of burning times are needed. The short-duration tests can be performed with drop towers, but the long-duration tests require the times available in space vehicles. Possible changes in controlling mechanisms, for example through changes in chemical-kinetic mechanisms, provide incentive for exploring the residence-time range indicated. The long-duration end of these residence times is relatively unexplored and therefore more likely to uncover unanticipated phenomena.

Reasons for Shuttle Tests

The present project involves plans to use the Space Shuttle, as a vehicle in which droplet combustion experiments are performed, primarily because of the extended test duration that it provides, at sufficiently low g-levels, with a hands-on observer present. The longer test durations afforded by the Space Shuttle are helpful for a number of reasons.

With respect to liquid heating transients, for example, experimental discrimination between heat-up and cool-down behavior is facilitated if the entire droplet burning history is accessible experimentally for droplets suffciently large to manifest anticipated differences. In tests where the reaction-zone motion is expected to approach quasisteady behavior, most or all of the combustion history of sufficiently large droplets must be observed to establish the quasisteadiness clearly; this could not be achieved in the earliest tests [20-22], but the planned use of larger drop towers can alleviate the difficulty, at least partially. To investigate reaction-zone extinction, the combustion history must be observed until extinction occurs. In sufficiently reduced-oxygen atmospheres, extinction times are accessible in drop towers (although the increased severity of ignition difficulties could degrade data), but interest in extraction of overall chemical-kinetic information dictates experiments in increased-oxygen atmospheres as well, at the same initial diameters $d_o$ used in reduced-oxygen tests, and this increases test times beyond drop-tower capabilities. Disruption shortens burning times, thereby promoting possibilities of full-data acquisition in drop towers, although use of larger droplets under conditions of slower onset of disruption (as would be possible in the Space Shuttle) could enhance resolution of the instabilities and other processes occurring. Observations of sooting behavior similarly could benefit from improved resolution afforded by study of larger droplets, and, moreover the residence-time variations achievable by use of the Space Shuttle can be beneficial in studying the chemical kinetics of sooting. Finally, at the longer test times approachable in the Space Shuttle, the observer may encounter unexpected and as yet unknown combustion events that may prove to be of fundamental scientific interest.

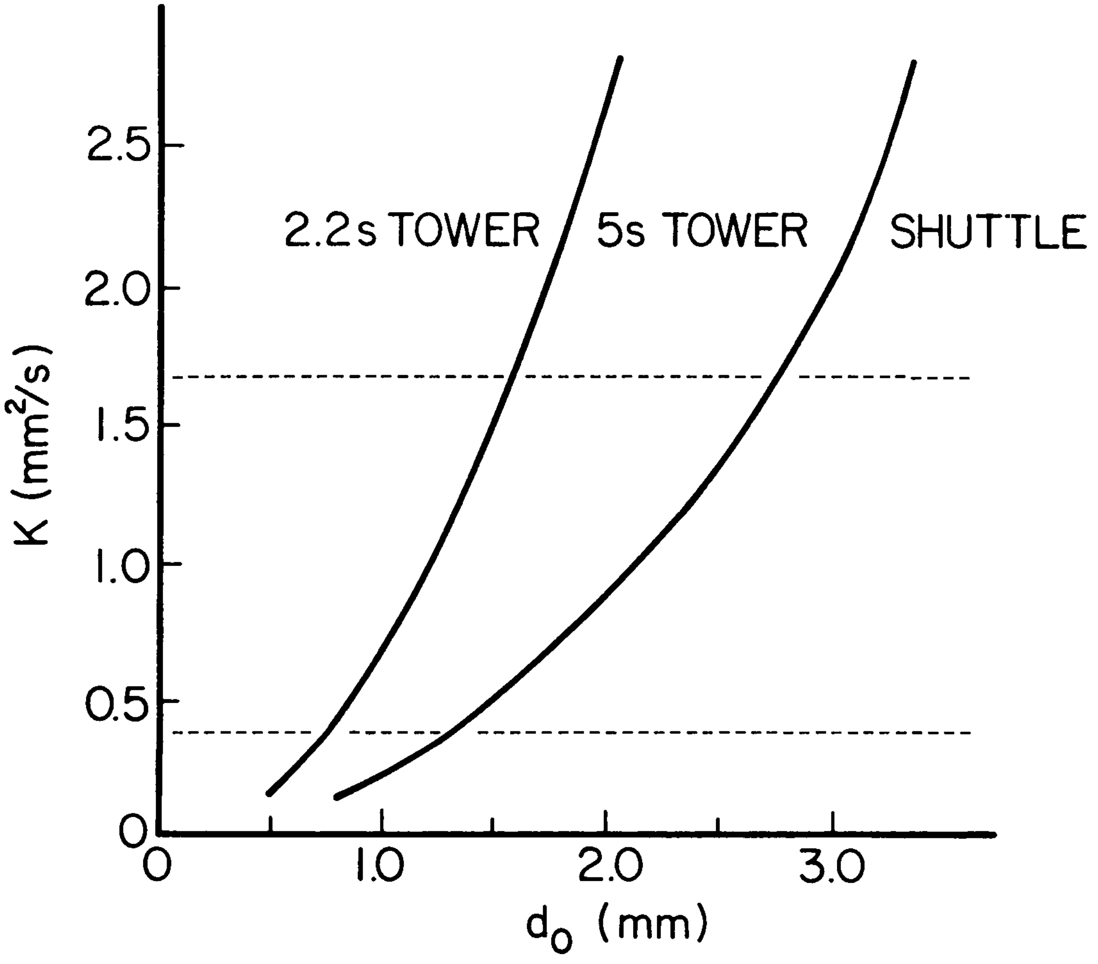

FIGURE 1. Ranges of conditions accessible to drop towers and to the Space Shuttle.

The easiest of the preceding considerations to quantify is a presumed requirement to observe the entire burning history of a droplet, with a specified initial diameter $d_o$, having a known burning-rate constant K. Figure 1 shows the ranges of $d_o$ and K accessible to the two NASA-Lewis drop towers and to the Space Shuttle. This figure allows for a preparation time of about 0.5 s prior to ignition. The range of values of K of interest is from about 0.4 $mm^2/s$ (a value estimated for the early period in recent drop-tower testing of decane in air) to about 1.5 $mm^2/s$ (a value representative of relatively volatile fuels in oxygen-enriched environments), as indicated by dashes in Fig. 1. In view of this range and the range of $d_o$ of interest, it is seen from Fig. 1 that some tests can be run in each of the drop towers, while some need the Space Shuttle.

Consideration was given to alternative options for obtaining the longer-duration test times assigned to the Space Shuttle in Fig. 1. Larger drop towers do not exist since the complexity and expense of drop tower operation increases rapidly with tower size (for example, more than ten drops per day have been made in the 2.2 s tower, but no more than two in the 5 s tower). Use of ballistic missiles would entail great expense for each data point. Aircraft flying "zero-g" trajectories offer the most attractive alternative to the Space Shuttle but pose special difficulties that render their utility problematic. Although reduced-gravity times on the order of 30 s or more are routinely achieved in such aircraft, their g-level fluctuations are appreciably greater than those in drop towers or in the Space Shuttle. Consideration of acceleration, velocity and displacement effects in the conservation equations for droplet combustion have indicated that g-levels on the order of $10^{-3}$ times normal earth gravity or less are needed in the droplet-burning experiments. These levels are readily obtained in drop towers and in the Space Shuttle, but in aircraft they would necessitate "free-floating" the experiment in the cabin (i.e., the apparatus could not be fastened to the wall). Free-floating reduces the test time appreciably, and moreover in these experiments the preparation time would be increased since the droplet would have to be formed as well as ignited during free-floating, and the formation time is on the order of 10 s. Thus it is uncertain that longer high-quality low-g burning times can be achieved in aircraft than in drop towers.

## History of the Program

The idea of an experiment on droplet combustion at reduced gravity was conceived in the early to middle 1970's when NASA-Lewis became interested in developing basic science of combustion experiments for the Shuttle. An overview committee was established which canvassed the combustion community to identify research areas benefiting from extended periods of near weightlessness or a buoyancy-free environment. The committee report [38] found ten major research areas including single-droplet combustion.

Kumagai [20-22] had pioneered gravity-free droplet-burning experiments with a drop tower giving 0.9 s test time. He had found in his experiments that the burning-rate constants were, in units of $mm^2/s$, 0.8 for benzene, 0.64 for ethyl alcohol, and 0.78 for n-heptane, approximately 82% of the corresponding normal-gravity rate constants. In an attempt to augment Kumagai's results on zero-gravity burning times, to test his burning-rate constants over a greater part of the droplet-burning history, and to extend the data base to other fuels (first decane), a test program (that acquired approximately 50 to 75 points) was undertaken in the 2.2 s NASA-Lewis drop tower [39]. These tests failed to produce burning droplets with less than 3 cm/s residual velocity upon deployment. The droplet deployment system used, a single-fiber-withdrawal technique, represented an attempt to implement the techniques that had been introduced by Kumagai. Critical timing difficulties between the instant of fiber withdrawal vertically upward and the subsequent instant of entry into zero-g is cited as the difficulty.

In 1984, after continuing investigations [39,40] and definition of droplet experiments to be flown in the Space Shuttle, a flight-hardware-development program was initiated with the award of a contract to TRW (NAS 3-23887). At the start of this hardware-development program the key feasibility issue of obtaining a single burning droplet in zero gravity with little or no residual motion was unresolved. This feasibility issue has now been solved by use of systems developed by TRW and testing accomplished in the NASA-Lewis drop tower, and the hardware has proceeded through a recently successful Preliminary Design Review.

## The Current Program

The current program involves continuation of the TRW work on development of a flight apparatus for experiments to be performed in the middeck area of the Space Shuttle, further testing in the NASA-Lewis 2.2 s and 5 s drop towers, and both theoretical studies and laboratory experiments at Princeton, associated with design of the flight apparatus and with the previously discussed outstanding problems in droplet combustion. In the present studies, burning of individual droplets having diameters between 0.8 and 2.5 mm is being investigated at pressures between 0.5 and 2 atm in oxygen-nitrogen atmospheres having oxygen mole fractions between 0.18 and 0.50. The fuels are alkanes (initially decane and heptane), alcohols and (later) possibly mixtures, slurries and emulsions. The current representative science-requirement test matrix is shown in Table I. Some of the entries in this matrix can be obtained from drop-tower tests, while others require longer test times. Continuing drop-tower studies are intended to lead to revisions of Table I, to identify those tests that are the best to be planned for a few flights of the Space Shuttle.

## Design of the Flight Experiment

Elements of the current design of the flight experiment for the Space Shuttle are shown in Fig. 2. The apparatus consists in general of a droplet dispensing device (special syringe mechanisms), a droplet positioning device (opposing, retractable, hollow needles), a droplet ignition device (two matched pairs of retractable spark electrodes), a gas handling system, a data acquisition system (mainly giving motion-picture records of the combustion in two orthogonal views, one with backlighting for droplet resolution), and associated

Table I

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TEST MATRIX

FLIGHT #1 - n-Decane fuel at 14.7 psia and cabin temperature.

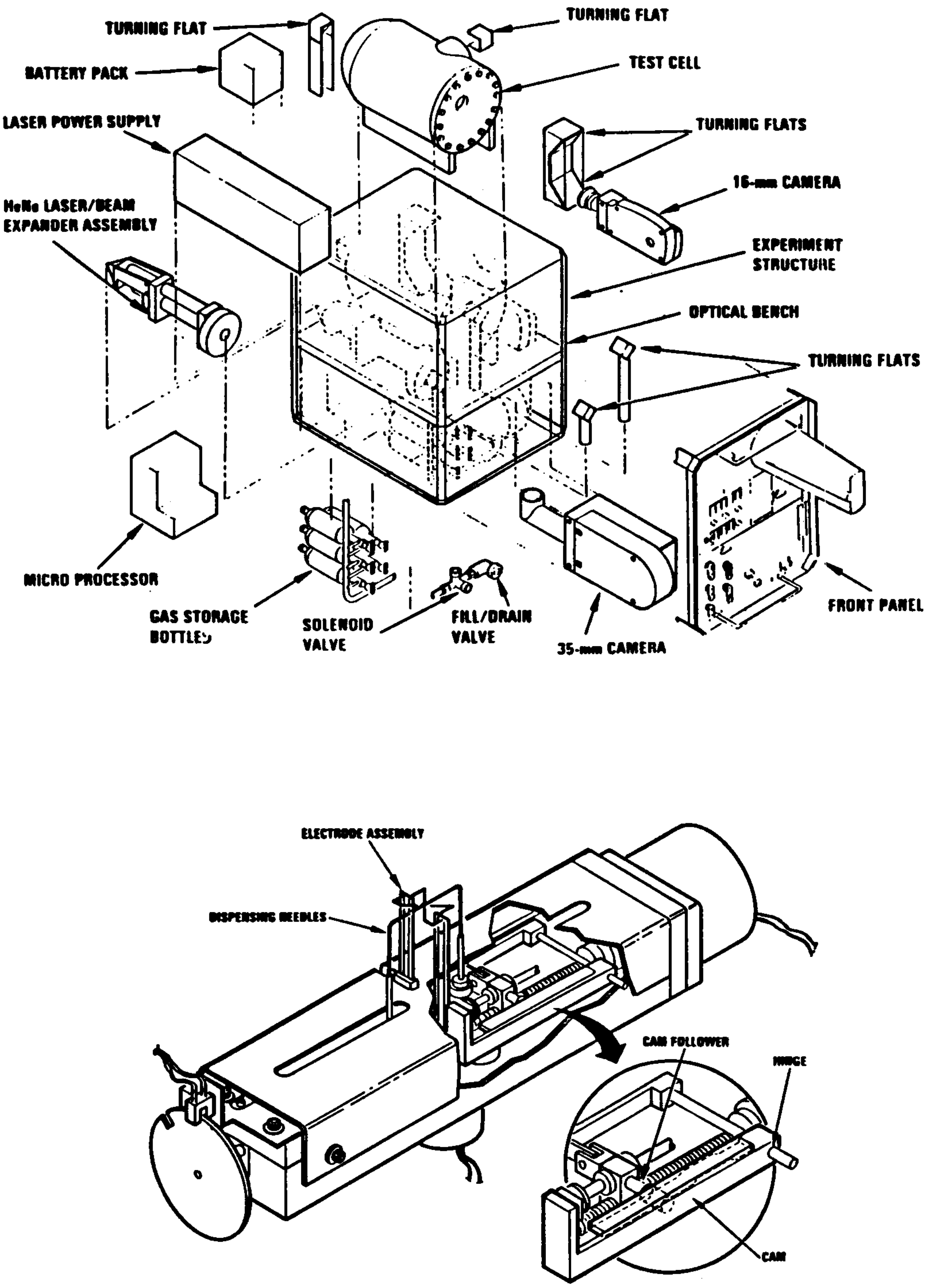
| Test # | Oxygen Concentration (mol %) | Drop Diameter - mm |
|---|---|---|
| 1 | .21 | 1. |
| 2 | .21 - Amt. consumed | 1.2 |
| 3 | .21 - " " | 1.4 |
| 4 | .21 - " " | 1.6 |
| 5 | .21 - " " | .8 |
| 6 | .21 - " " | 1. |
| 7 | .21 - " " | 1.6 |
| 8 | .21 - " " | 1.2 |
| 9 | .21 - " " | .8 |
| 10 | .21 - .021 = .189 | 1.4 |

FLIGHT #2 - n-Decane at cabin temperature.

| Test # | Oxygen Concentration (mol %) | Pressure - Atm. | Drop Diameter - mm |
|---|---|---|---|
| 1 | .21 | .5 | 1. |
| 2 | .21 - Amt. consumed | .5 | 1.5 |
| 3 | .21 - " " | .5 | .8 |
| 4 | .21 - " " | .5 | 1. |
| 5 | .5 | .5 | 1. |
| 6 | .5 - Amt. consumed | .5 | 1.5 |
| 7 | .5 - " " | .5 | .8 |
| 8 | .5 - " " | .5 | 2.5 |
| 9 | .5 - " " | .5 | 1. |
| 10 | .5 - " " | .5 | 1.6 |
| 11 | .18 | 1. | 1. |
| 12 | .18 - Amt. consumed | 1. | 1.5 |
| 13 | .18 - " " | 1. | .8 |
| 14 | .18 - " " | 1. | 1. |
| 15 | .25 | 2. | 1. |
| 16 | .25 - Amt. consumed | 2. | 1.5 |
| 17 | .25 - " " | 2. | .8 |
| 18 | .25 - " " | 2. | 2.5 |
| 19 | .25 - " " | 2. | 1. |
| 20 | .25 - " " | 2. | 1.6 |
| 21 | .35 | 1. | 1. |
| 22 | .35 - Amt. consumed | 1. | 1.5 |
| 23 | .35 - " " | 1. | .8 |
| 24 | .35 - " " | 1. | 2.5 |
| 25 | .35 - " " | 1. | 1. |

FLIGHT #3 - n-Heptane at cabin temperature

| Test # | Oxygen Concentration (mol %) | Pressure - Atm. | Drop Diameter - mm |
|---|---|---|---|
| 1 | .21 | 1. | 1. |
| 2 | .21 - Amt. consumed | 1. | 1.5 |
| 3 | .21 - " " | 1. | .8 |
| 4 | .21 - " " | 1. | 2.5 |
| 5 | .21 - " " | 1. | 1.6 |
| 6 | .21 - " " | 1. | 1. |
| 7 | .21 | .5 | 1. |
| 8 | .21 - Amt. consumed | .5 | 1.5 |
| 9 | .21 - " " | .5 | .8 |
| 10 | .21 - " " | .5 | 2.5 |
| 11 | .5 | .5 | 1. |
| 12 | .5 - Amt. consumed | .5 | 1.5 |
| 13 | .5 - " " | .5 | .8 |
| 14 | .5 - " " | .5 | 2.5 |
| 15 | .5 - " " | .5 | 1.6 |
| 16 | .5 - " " | .5 | 1. |
| 17 | .18 | 1. | 1. |
| 18 | .18 - Amt. consumed | 1. | 1.5 |
| 19 | .18 - " " | 1. | .8 |
| 20 | .18 - " " | 1. | 1. |
| 21 | .35 | 2. | 1. |
| 22 | .35 - Amt. consumed | 2. | 1.5 |
| 23 | .35 - " " | 2. | .8 |
| 24 | .35 - " " | 2. | 2.5 |
| 25 | .35 - " " | 2. | 1. |



Droplet Combustion Experiment
Experiment Components

FIGURE 2. Diagram of components of the flight experiment.

electronics. The component shown at the bottom of the figure is the dispensing, positioning and ignition assembly that is located inside the test cell. In this design, the test fuel is stored in two fuel systems at the base of the dispensing needles. An engineering model of the system at the bottom of the figure is to be employed in the drop towers to test its performance and to acquire data for the test-matrix points accessible to drop-tower experiments.

An earlier, development version of the apparatus shown at the bottom of Fig. 2 has been employed in experiments performed in the 2.2 s drop tower. Unanticipated results were obtained on droplet-combustion processes.

## Recent Results and Future Directions

Recent results from drop-tower testing of decane droplet combustion exhibit unexpected instances of disruptive burning [41]. Theoretically, disruption does not occur for pure fuels. Earlier drop-tower tests encountered only two such events [39,42], both with small and unresolved satellite droplets burning in atmospheres having an oxygen mole fraction of 0.50. The recent tests demonstrate disruptions of larger, resolved droplets burning in air and suggest that disruption may be the rule rather than the exception under the experimental conditions. One hypothesis attributes the new results to improved achievement of spherical symmetry (droplet velocities sometimes below 2 mm/s), allowing increased absorption of gas-phase fuel pyrolysis products into the liquid to form a multicomponent mixture susceptible to disruption. These pyrolysis products could be soot precursors or soot itself. Future work includes evaluation of this hypothesis, further developments of theory for disruption, and exploration of ranges of conditions over which this mode of combustion occurs.

Other results have been described in recent publications [41,43,44]. Theoretical studies have identified transient evolution of temperature profiles within droplets during combustion by use of asymptotic analysis. Impulses delivered to droplets by sparks and by g-jitter have been calculated theoretically. Further theoretical investigations are planned on thermophoretic motion of soot particles formed around burning droplets, e.g. in relationship to disruptive burning.

Laboratory experiments have characterized spark transients and measured impulses delivered to droplets by sparks [44]. Clarification of aspects of droplet formation on opposing needles also has been achieved in the laboratory [41]. Future laboratory work will extend information on individual droplet ignition by sparks with attention paid to influences of fuel type, oxygen content of the atmosphere, and pressure. Analyses of soots collected under different laboratory combustion conditions also are planned. Further consideration will be given to nonphotographic methods of data acquisition such as laser scattering for soot measurements. Future studies will devote special consideration to transients, extinction, soot and disruption.

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