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ON

INVESTIGATION OF CRITICAL BURNING
OF FUEL DROPLETS

by

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16. Abstract

An earlier analysis for the combustion response of a liquid monopropellant strand was extended to consider individual droplets and sprays. While small drops gave low or negative response, large droplets provided response near unity at low frequencies, with the response declining at frequencies greater than the characteristic liquid phase frequency. Temperature gradients in the liquid phase resulted in response peaks greater than unity. A second response peak was found for large drops which corresponded to gas phase transient effects. Spray response was generally reduced from the response of the largest injected droplet, however, even a small percentage of large droplets can yield appreciable response.

An apparatus was designed and fabricated to allow observation of bipropellant fuel spray combustion at elevated pressures. A locally homogeneous model was developed to describe this combustion process which allows for high pressure phenomena associated with the thermodynamic critical point.

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1975 Annual Report on the Investigation

of Critical Burning of Fuel Droplets

Summary

This report discusses activities under NASA Contract NGR 39-009-077 for the period January 1, 1975 to December 31, 1975. During this period the work was divided into two phases: (1) Combustion response of monopropellant droplets and sprays and (2) High pressure combustion of bipropellant sprays. The accomplishments of each phase of the study for the present report period may be summarized as follows:

1. Combustion response of monopropellant droplets and sprays. Earlier results for the response of burning liquid monopropellant strands were extended to consider monopropellant droplets and sprays. The theory employs perturbation analysis with calculations through first order to yield the linear response. Physical properties were chosen to simulate hydrazine decomposition due to the availability of data for this material to test the model. The zero-order or steady state calculations gave predictions in good agreement with earlier measurements of liquid temperatures and burning rates. A simple, approximate formula was developed which estimates actual droplet burning rates with a maximum error of 10%; this formula is readily integrable and convenient for use in the analysis of spray combustion.

The response of individual droplets was examined. Small droplets gave low or negative response at all frequencies. Large drops provide a response near unity at low frequencies, with the response declining at frequencies somewhat in excess of the characteristic frequency of the liquid phase thermal wave. If temperature gradients are present in the liquid phase, this decline can be preceeded by a response peak in excess of unity. A second response peak is also present for large droplets which is associated with gas phase transient effects, however, the frequency range of this peak is generally higher than the frequency range normally associated with combustion instability.

The response of a monodisperse injected spray is less than the response of the initial droplet size, due to the reduced response of small droplets near the end of their lifetime. The response characteristics of a polydisperse

injected spray depends strongly on the size distribution and several cases were considered. Notably, even a very low percentage of large droplets can yield appreciable response, due to their relatively long lifetimes and high response.

Work in this area of the investigation has been concluded.

2. <u>High pressure spray combustion</u>. An apparatus has been designed and fabricated to allow observation of fuel spray combustion at pressure levels where thermodynamic critical phenomena are important. The apparatus provides for spray shadowgraphs, dark field flame photographs and gas temperatures in the region downstream of the spray region.

Modeling of this process is based on an integral-entrainment model which allows for density variation in the two-phase flow and high pressure thermodynamic characteristics, but neglects slip between the phases. This type of model is most accurate at high pressures and initial theoretical and experimental comparisons are considering this regime.

The assembly of the apparatus is nearing completion and testing will begin early in the next report period. Initial development of the theory has also been completed.

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1975 Annual Report on the Investigation
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1. Introduction

The objective of this investigation was to continue earlier work on the steady and unsteady combustion of liquid fuel droplets under rocket engine conditions. Emphasis has been placed on consideration of combustion at elevated pressures and temperatures, representative of typical combustion chamber environments. The results of this study have technical application to the design of liquid fueled rocket engines and the determination of the combustion instability characteristics of these engines.

This report gives a summary of progress on the investigation for the period January 1, 1975 to December 31, 1975. During this report period, the work was divided into two phases, as follows:

1. Combustion response of monopropellant droplets and sprays. This portion of the study is concerned with extending the analysis of the "open loop" response of burning liquid mono-propellant strands (1,2), to the more practical case of drop-lets and sprays. The theoretical approach employs a perturbation analysis allowing for both liquid and gas phase transient effects. For conditions of technological interest, the gas phase was found to be largely quasisteady and present calculations have emphasized this condition. The analysis of spray response was limited to the quasisteady gas phase approximation. The procedure of the study involved considering the steady combustion and the response of individual droplets first, followed by analysis of the steady combustion and response of sprays. Work in this area was concluded during the report period.

2. High pressure spray combustion. An investigation was begun on the characteristics of burning fuel sprays at elevated pressures where critical phenomena are important. The modeling of this process is based upon an integral-entrainment model, with provision for including the high pressure thermodynamic characteristics of the liquid gasification process. During this report, an apparatus to test the theory was designed and fabricated, and initial development of the theory was begun.

Reports and papers issued during the period of this report are as follows:

G. M. Faeth and S. Chanin, "1974 Annual Report on the Investigation of Critical Burning of Fuel Droplets," Contract NGR 39-009-077, The Pennsylvania State University, University Park, PA, February 1975.

C. B. Allison and G. M. Faeth, "Open-Loop Response of a
Burning Liquid Monopropellant," AIAA J 13,10,1287-1294 (1975).

G. S. Canada and G. M. Faeth, "Combustion of Liquid Fuels in
a Flowing Combustion Gas Environment," Fifteenth Symposium
(International) on Combustion, pp. 419-428, The Combustion
Institute, Pittsburgh (1975).

2. Combustion Response of Monopropellant Droplets and Sprays.

2.1 Introduction

The objective of this investigation is to study the burning rate response of monopropellant droplets to imposed pressure oscillations, followed by consideration of the total response of a spray. Knowledge of the frequency ranges where the combustion response is high, allows the designer either to adjust combustion geometry to avoid having characteristic chamber frequencies in this region, or provide damping tuned to this frequency range.

The present work is a continuation of earlier efforts which treated the response of a burning monopropellant strand to imposed pressure oscillations (1,2). Using these findings as a basis, the more practical case of droplet combustion was investigated. By utilizing a model generally substantiated by strand combustion results, the case of droplet combustion could be approached with some confidence.

In the following, only a brief summary of the oscillatory combustion of monopropellant droplet work is given. A complete discussion of this investigation may be found in Reference 4.

2.2 Theory

The theoretical model under consideration involves a droplet that is burning in the absence of convection, yielding a spherically symmetric flow field. While convection is important under actual combustion chamber conditions, there is evidence to indicate that the region where the droplet has a low (or zero) relative velocity with respect to the ambient gas, is a very critical zone in determining combustion instability characteristics (5). For simple evaporation without decomposition, the response due to velocity effects has been found to be quite low (6). In addition, the decomposition process near the droplet surface reduces the influence of convection over a fairly wide range of conditions (7,8). This occurs since convection only affects the process when the outer edge of the flow field interacts with the reaction zone, a situation that is limited to very weak reactivity or very high Reynolds numbers. Therefore, neglecting convection for monopropellant droplets puts fewer limitations on the practicality of the calculations, than would be the case for bipropellants.

Similar to earlier response studies (1,2,6), the ambient pressure is assumed to be oscillating with a wavelength that is long in comparison to the dimensions of the combustion field of the droplet. The period of oscillation, however, is assumed to

be short in comparison to the total droplet lifetime so that
large changes in the position of the surface during a pressure
oscillation are not considered. This assumption allows the
analysis to proceed while only examining oscillatory solutions.
The low frequency regime where this assumption breaks down is
associated with the range of frequencies where both liquid and
gas phases are quasi-steady.

Since the combustion rate of monopropellant droplets is much
higher than bipropellants, the usual assumption of a constant
liquid phase temperature (in the zero order) is less valid than
for bipropellants. Therefore, the presence of mean liquid phase
temperature gradients is considered in the analysis. Examination
of constant mean temperatures is also made, in order to include
the conventional steady combustion model, by equating the bulk
liquid temperature to the wet bulb temperature at a given pressure.

A sketch of the theoretical model is shown in Fig. 1. The
process is examined at an instant of time when the droplet radius
is r_s^* (quantities with an * are dimensional). Formally, this
radius is taken to be fixed so that the mass flux of fuel is time
varying. This actually corresponds to porous sphere combustion;
however, the two cases are equivalent as long as the density in
the liquid phase is large compared to that of the gas phase; and
the period of oscillation is small in comparison to the lifetime
of the droplet (9). When this is true, the motion of the surface
with respect to the mean surface position is negligible and can
be ignored. Exceptions to this assumption arise near the critical
point and the present analysis is not valid in this regime. The
response portion of the analysis is invalid at frequencies having
an oscillation period comparable to the lifetime of the droplet.

For generality, gas phase transient effects are included in
the model. The effect of variable properties is also included,
so that the model is equivalent to the earlier strand combustion
analysis (1,2). Hydrazine was the fuel studied, since earlier
information was available for both oscillatory (1,2) and steady
droplet burning (10) characteristics.

The remaining assumptions of the analysis are similar to
those of Refs 1 and 2. They are as follows:

1. The process is spherically symmetric with a Mach number
much less than unity and negligible body forces. Inertial and
viscous terms in the momentum equation are neglected.

2. The reaction process is premixed and laminar. A one-step,
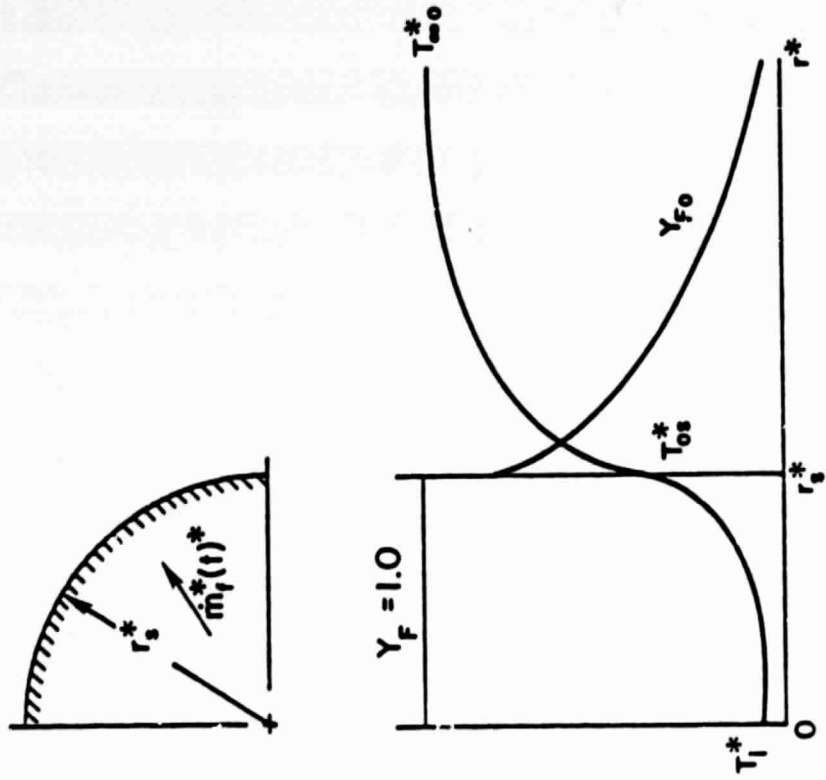irreversible chemical reaction takes place in the gas phase and

Figure 1 Sketch of the Droplet Combustion Response Model.

any time lags associated with the chemical reaction itself are negligible, i.e. the chemical reaction is locally quasi-steady and obeys an Arrhenius equation. Chemical reaction is neglected in the liquid phase.

3. Radiation heat transfer is neglected.

4. The gas phase is taken to be an ideal gas and the Lewis number is assumed to be unity.

5. All gas diffusion coefficients are equal, all molecular weights are equal, all gas phase specific heats are equal and constant, the gas phase thermal conductivity is independent of composition and varies linearly with temperature, and the liquid is composed of a single chemical species having constant properties.

6. The combustion products are assumed to be insoluble in the liquid phase and the gas phase fuel mass fraction at the liquid surface is given by the Clausius-Clapeyron equation. As in the case of the gas phase reaction, the equilibrium at the surface is assumed to occur rapidly in comparison to other transient effects in the system.

7. The wavelength of any periodic pressure disturbance is assumed to be long compared with the diameter of the zone involving active combustion. Consideration of the momentum equation, along with Assumption 1, then implies that pressure is only a function of time.

A discussion of the applicability of these assumptions is provided in Refs. 1 and 2.

Utilizing the above assumptions, the conservation equations and boundary conditions are written in spherical coordinates. After nondimensionalizing, a perturbation solution is used with the amplitude of the pressure oscillation being the perturbation parameter, ε (a small quantity). The resulting equations are separated into like powers of ε. The zero order problem describes the steady state situation, and the first order problem describes the effect of oscillating pressure. Reference 4 should be consulted for the details of the analysis.

2.3 Steady State Results

The physical property values and the chemical kinetic parameters used in the calculations are summarized in Ref. 2.

A second order reaction correlates the strand burning rate of hydrazine at pressures above 1 atmosphere (1,2). For steady

state conditions, the theoretical burning rate is relatively insensitive to variations in the activation energy. However, for oscillatory combustion, the activation energy influences both the amplitude and phase of the combustion response of strands. Allison and Faeth (2) found that the value of E* (activation energy) gave good agreement between theoretical and experimental response determinations over their test range.

In order to check the accuracy of the zero-order model, predicted and measured liquid surface temperatures were compared as a function of pressure. These results are shown in Fig. 2. The agreement is good throughout the pressure range of the measurements (.51-19.8 atm).

The test conditions shown in Fig. 2 involved a liquid temperature of 298°K far from the liquid surface. This is representative of a non-wet bulb condition, with the liquid temperature increasing as the surface is approached. A theoretical calculation for the wet bulb state, where the liquid temperature is constant, is also presented in Fig. 2. For the wet bulb case, no energy is required to raise the liquid to the vaporization temperature, resulting in a higher surface temperature than the non-wet bulb case, for a given pressure.

Steady state calculations were completed over a range of A (dimensionless parameter proportional to droplet diameter squared) and pressure for both non-wet bulb (with a centerline droplet temperature of 298°K) and wet bulb conditions.

The mass burning rate of a liquid droplet depends on the size of the droplet (at a given pressure) and approaches two asymptotic limits: the large drop and small drop limit burning rates. The small drop limit represents a droplet vaporizing without reaction, and the large drop limit approximates a one-dimensional liquid strand with the flame very close to the liquid surface.

Figure 3 shows the dimensionless steady state mass burning rate per unit solid angle, $\dot{m}_o$, as a function of A at 1 atmosphere pressure for non-wet bulb conditions. The complete steady state solution clearly approaches the large and small drop limits. In order to plot $\dot{m}_o$ as a function of A at the large drop limit, values of the burning rate eigenvalue were obtained from the strand combustion calculations, (1,2) and converted to the present notation. The small drop limit mass burning rate, $\dot{m}_{o_{SDL}}$, is
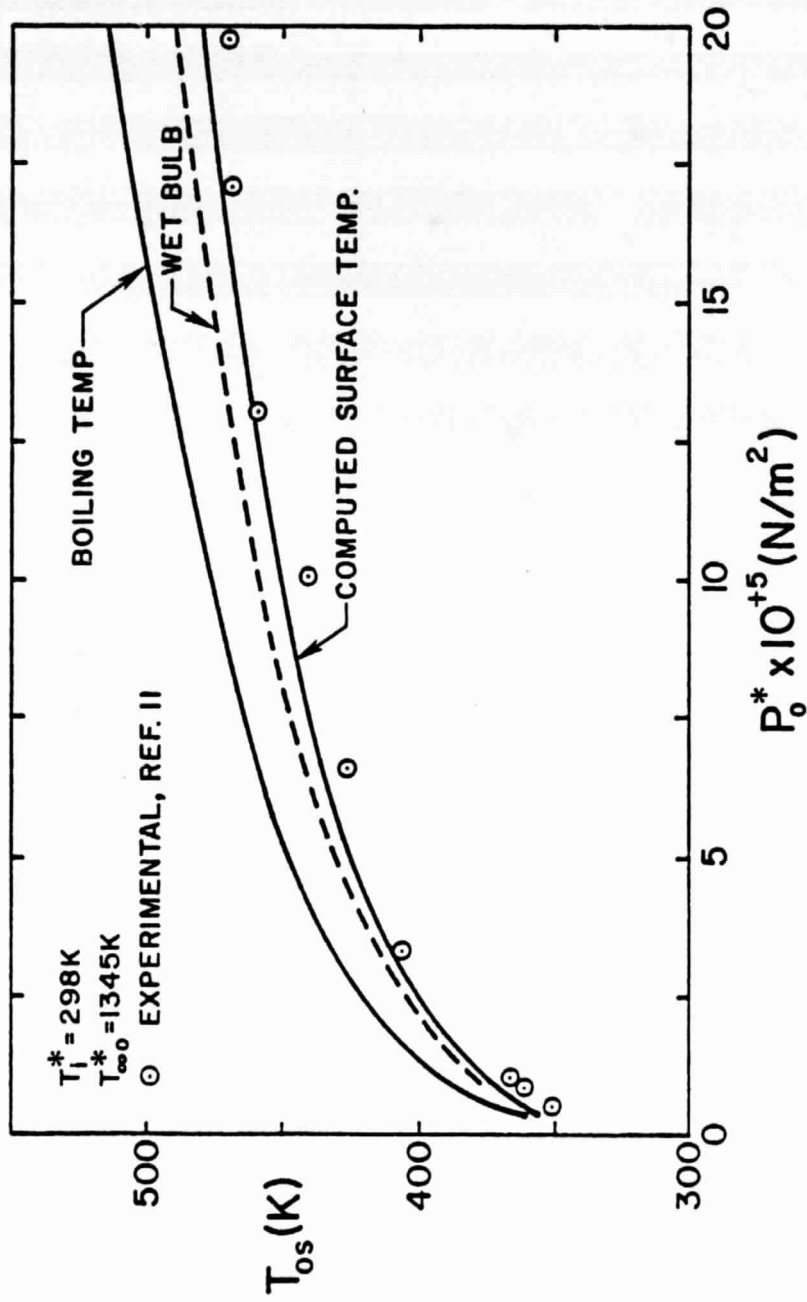
Figure 2   Theoretical and Experimental Liquid Surface
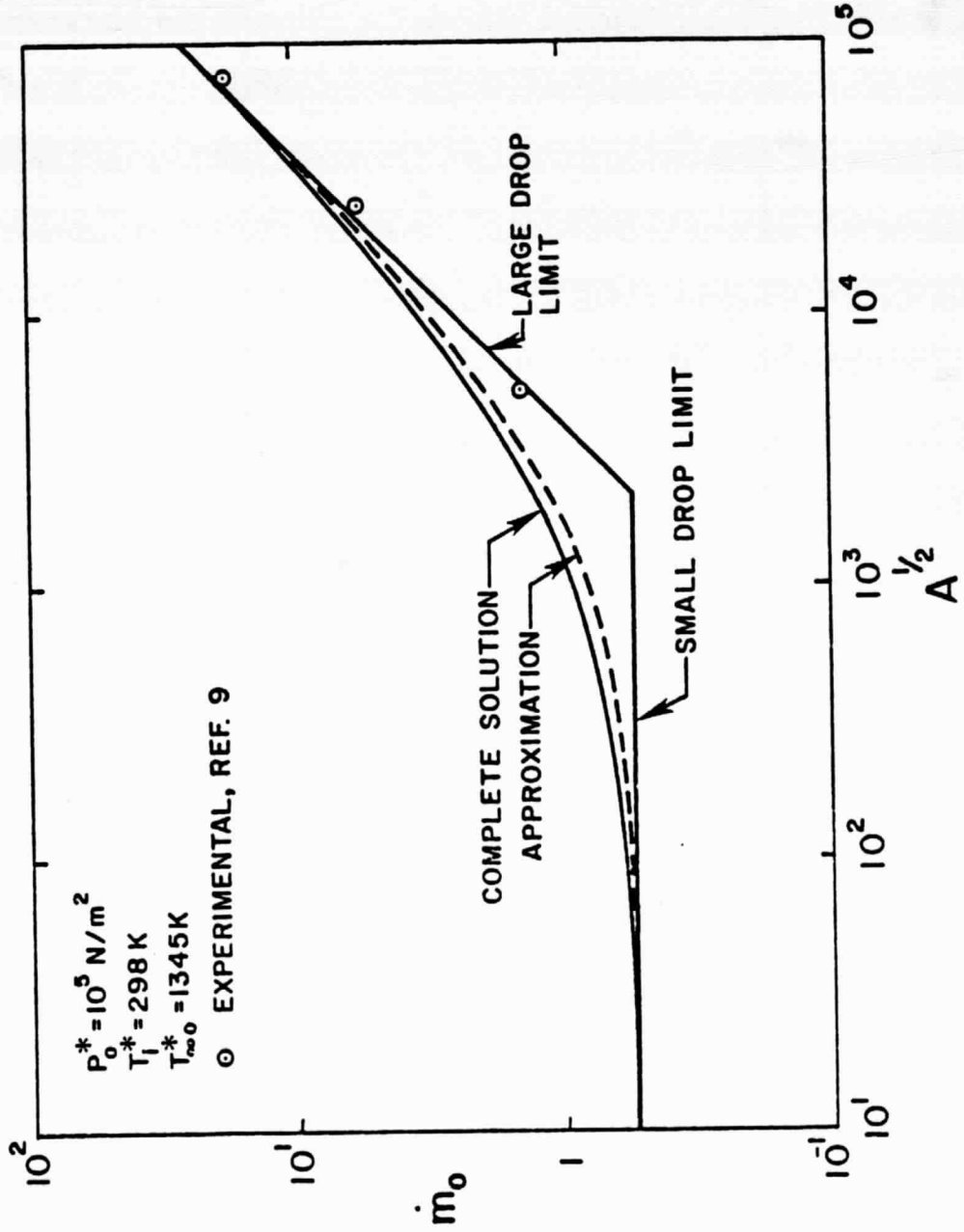Temperature as a Function of Pressure

Figure 3 Theoretical and Experimental Steady State Droplet Gasification Rates at Approximately 1 atm. Pressure (Non-Wet Bulb Conditions)

calculated directly from the theory for A=0.

An approximation to the complete steady state solution is shown in Fig. 3. The approximation was obtained by simply adding the small and large drop mass burning rates at each value of A, as follows:

$$\dot{m}_o = \dot{m}_{o_{SDL}} + \dot{m}_{o_{LDL}}$$

This approximation yields a maximum error of approximately 12% over the entire range of A, and it will be used later to evaluate spray combustion characteristics since it can be readily integrated to determine droplet lifetimes.

Data on hydrazine combustion was available from experimental work done by Allison and Faeth (10). This study involved droplet burning in a combustion gas under decomposition conditions, for various droplet sizes, at atmospheric pressure. The data was limited to the ambient temperature range $1660-2530^oK$; therefore, it was necessary to extrapolate the measurements to the 1345^oK ambient temperature which correspond to adiabatic decomposition for an initial fuel temperature of 298K. The agreement between the predicted and measured burning rates is seen to be reasonably good, lending confidence to the theoretical model.

Burning rate results for wet bulb conditions are similar to the non-wet bulb conditions; the major difference involves a slight increase in the burning rate throughout the entire range of A. Theoretical mass burning rates at pressures of 10 and 100 atmospheres also gave results very similar to Fig. 3 for both wet and non-wet bulb conditions. In all cases the transition region between the large and small droplet limits falls approximately in the range $10^4<A<10^9$.

In order to employ the approximate burning rate expression, it is necessary to have values for $\dot{m}_{o_{SDL}}$ and the strand burning rate eigenvalue, A_s. These quantities, along with surface temperature predictions, are summarized in Table 1 over a range of pressures, for both wet bulb and non-wet bulb conditions.

With increasing pressure, the liquid surface temperature, $T_{os}*$, increases in all cases. As noted earlier, the wet bulb surface temperature slightly exceeds the non-wet bulb surface temperature at each pressure.

Table 1

Summary of Steady State Calculations

P_o^* (N/m^2)	T_{os}^* (K)	T_∞^* (K)	$\dot{m}_{o_{SDL}}$	A_s
Non Wet Bulb Conditions[a]				
10^5	374	1345	.544	1.432×10^7
10^6	450	1345	.509	1.432×10^7
10^7	562	1345	.454	1.432×10^7
Wet Bulb Conditions				
10^5	376	1417	.603	6.205×10^6
10^6	457	1498	.629	2.660×10^6
10^7	582	1623	.668	8.162×10^5

[a]center temperature 298K.

While A_s is relatively constant with pressure at non-wet bulb conditions, A_s decreases with increasing pressure for the wet bulb case, which significantly increases the mass burning rates for the larger drops at a given value of A. This effect is due to increased reaction rates for the higher flame temperatures of wet-bulb combustion, at elevated pressures.

At non-wet bulb conditions, $\dot{m}_{o_{SDL}}$ decreases with increasing pressure due to the reduction in the temperature difference between the ambient gas and the liquid surface. For the wet bulb case, the increased ambient temperature compensates for this effect and there is a slight increase in $\dot{m}_{o_{SDL}}$ with increasing pressure.

Using the properties from Ref. 4, the droplet size range corresponding to the transition region (taken to be $10^4 < A < 10^9$) is shown in Table 2. As the pressure increases, the droplet size for the onset of the large drop limit is reduced. Notably, the size range of technological importance for actual combustors falls largely in the transition region. At higher pressures, however, a greater percentage of the droplets present in a spray can be represented by large drop limit results.

2.4 Droplet Response

In order to analyze response, the burning rate response function, P_r, is utilized (5). In the present notation this quantity is

$$P_r = Re \; \{\dot{m}_1/\dot{m}_o\}$$

where Re denotes the real part; i.e. that portion of the burning rate oscillation, $\dot{m}_1$, that is in-phase with the pressure oscillation. For instability, P_r must be positive and of order unity (the exact value depends upon the degree of damping present) at a point in the combustion chamber where the pressure is varying. It must be understood that a droplet with $P_r \geq 1$ will not in itself cause instability, but rather the sum of the responses of all the droplets within the combustion chamber must be greater than the available damping, in order for the combustion oscillation to grow.

At low frequencies for the small droplet or evaporative limit, the response function is negative, with a relatively small

Table 2

Droplet Size Range of Transition Region[a]

$P_o^* \times 10^{+5}$ (N/m^2)	$d_{s_{min}}^* - d_{s_{max}}^*$ (μ)
1	25 – 7500
10	2.5 – 750
100	.25 – 75

[a]Corresponding to $10^4 < A < 10^9$

magnitude and with increasing pressure, the response function
becomes more negative (4). This is in contrast to results for
bipropellant combustion where the response function generally
approaches zero or a positive limit for small ω.

Moving from the evaporative limit (small drop limit) to the
large drop limit, much greater response is observed for mono-
propellant droplets. Figure 4 illustrates the non-wet bulb
response as a function of frequency ω_s (dimensionless frequency
for strand combustion from Refs. 1 and 2 for the large droplet
limit at a mean pressure of 10 atmosphere. Figure 5 shows
similar results at wet bulb conditions. In addition to the
quasi-steady gas phase approximation, results for the completely
unsteady gas phase are also shown. The non-wet bulb results are
replotted from the calculations of Ref. 1, while the wet bulb
results were calculated during the present investigation.

In all cases, the response approaches unity at low fre-
quencies, where both liquid and gas phases are quasi-steady.
This follows from the fact that the burning rate is proportional
to pressure, under steady conditions, for a second-order reaction
(1).

With increasing frequency, at non-wet bulb conditions, a
peak is observed in the response plot at frequencies near the
characteristic frequency of the liquid phase. Beyond this peak,
the quasi-steady gas phase solution gives a continuously de-
clining response. The peak is absent in all wet bulb cases, with
the response showing a noticable decline at the liquid phase
characteristic frequency. This interesting contrast between
the two cases will be discussed later in more detail.

At higher frequencies, the analysis allowing for transient
gas phase effects begins to diverge from the quasi-steady gas
phase solution. Substantial differences between the two models
are encountered for values of ω_s on the order of 10^{-1}, which

represents frequencies near the characteristic frequency of the
gas phase. At dimensionless frequencies on the order of unity,
a second response peak is observed, in all cases, for the com-
plete unsteady gas phase solution. This peak is clearly associ-
ated with gas phase transient effects and yields maximum values
of P_r on the order of unity. With increasing pressure, the

frequencies of the two response peaks approach one another due
to the increase in gas density.

Table 3 lists the frequencies where large droplets have
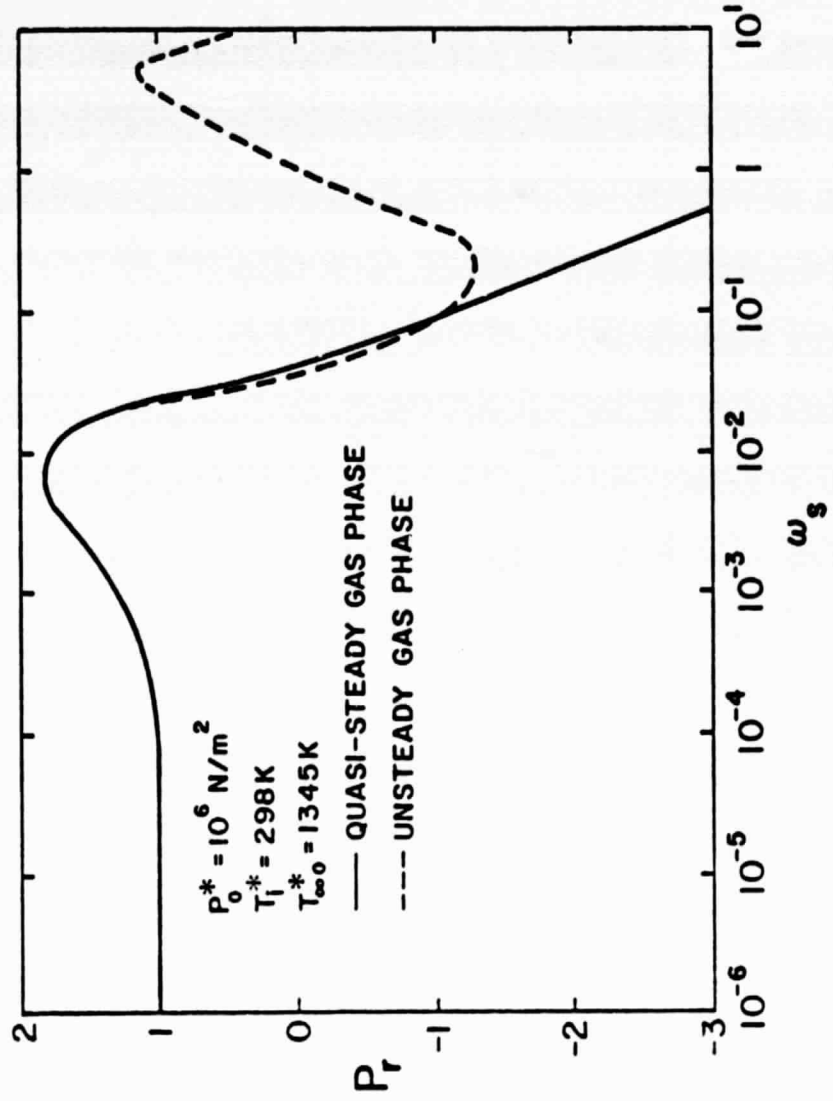response peaks. In considering this table, it should be recalled

Figure 4 Response as a Function of Frequency at the Large Droplet Limit at Approximately 10 atm. Pressure (Non-Wet Bulb Conditions).
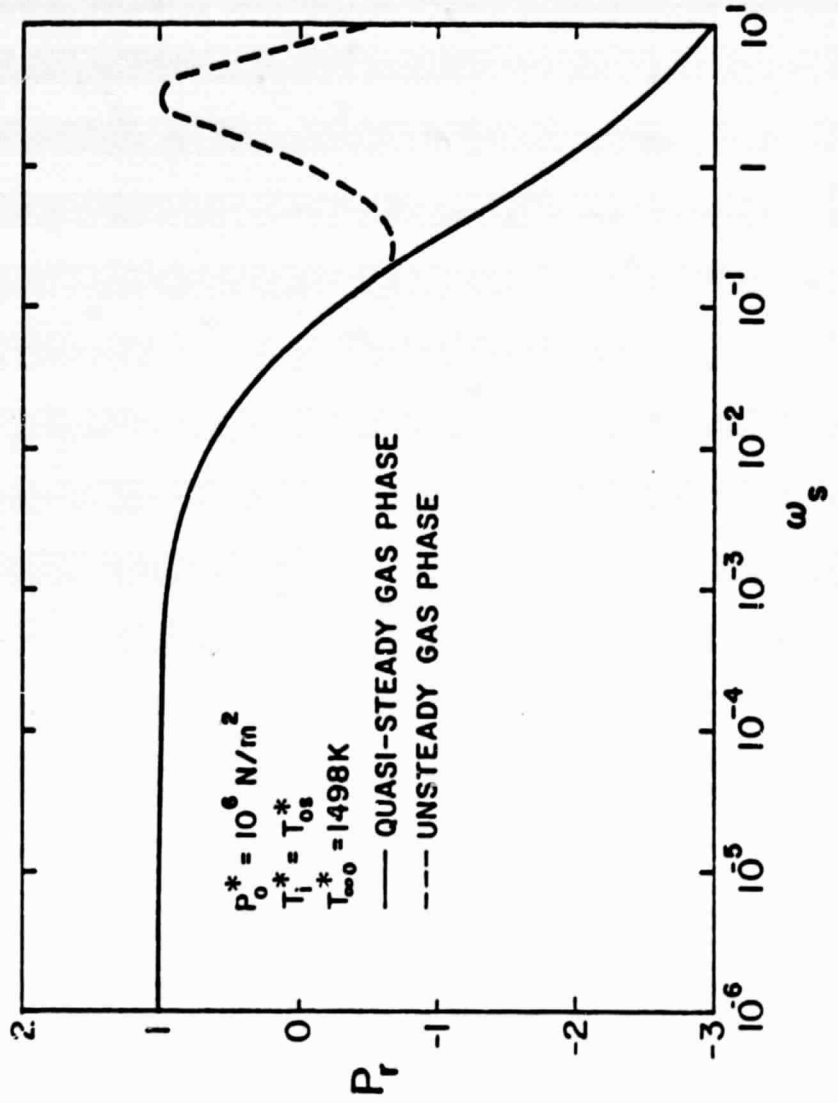
Figure 5 Response as a Function of Frequency at the Large Droplet Limit at Approximately 10 atm. Pressure (Wet Bulb Conditions).

Table 3

Frequencies of the Unsteady Gas and Liquid Phase Response Peaks

Mean Pressure (N/m^2)	Liquid Transient Peak (Hz)	Gas Transient Peak (Hz)
(Non-Wet Bulb Condition)		
10^5	0.04	528
10^6	17	11,000
10^7	1100[a]	110,000
(Wet Bulb Condition)		
10^5	—	670
10^6	—	6,700
10^7	—	67,000

[a]Corresponds with first gas phase transient analysis peak

that acoustic instability in rocket engine combustion chambers is generally associated with the frequency range 500-30,000 Hz (5). At pressures below 10 atmospheres, response peaks due to gas phase transient effects largely fall within this range. At pressures above 10 atmospheres, response peaks due to gas phase transient effects decline in importance since they are associated with very high frequencies. In this pressure range, liquid phase phenomena are more significant, providing response peaks in the critical frequency range. Since the pressure range usually encountered in rocket engines is above 10 atmospheres, gas phase transient effects do not appear to be a major factor in causing instability for hydrazine fueled engines. Based on this finding, further analysis in the transition region, between the large and small droplet regimes, was limited to the case of quasi-steady gas phase effects.

Figure 6 shows the quasi-steady gas phase non-wet bulb response as a function of frequency, ω, (which is proportional to ω_s) at various drop sizes, ranging from the small drop to the large drop limit. As A, or drop size, increases, the response increases, caused by the combustion zone moving closer to the liquid surface. At an A of approximately 10^7, a peak in the response curve develops, increasing in magnitude and frequency as the drop size increases, until the large drop approximates the one-dimensional strand near the value of $A=10^{10}$. As the pressure increases, the peaks increase in magnitude and move to higher frequencies.

The quasi-steady gas phase wet bulb responses are plotted in Fig. 7, as a function of frequency for the complete range of drop sizes at 10 atmospheres pressure. As in the non-wet bulb case, the response increases with increasing A; however, no response peaks are observed. Droplet combustion response is well approximated by the one-dimensional strand at values of A greater than 10^{10}.

The only two types of monopropellant droplets which have been considered, are the wet bulb droplet with a zero mean temperature gradient (constant mean temperature) and the non-wet bulb droplet with a steep mean temperature gradient. For the parameters used, a response peak is only observed in the non-wet bulb case. Under realistic conditions, the droplets will have temperature gradients ranging between the wet and non-wet bulb limits.

From the present study it can be concluded that a response peak will only occur when the mean temperature gradient near the

Figure 6 Quasi-Steady Gas Phase Response as a Function of Frequency and A at Approximately 10 atm. Pressure (Wet Bulb Conditions).
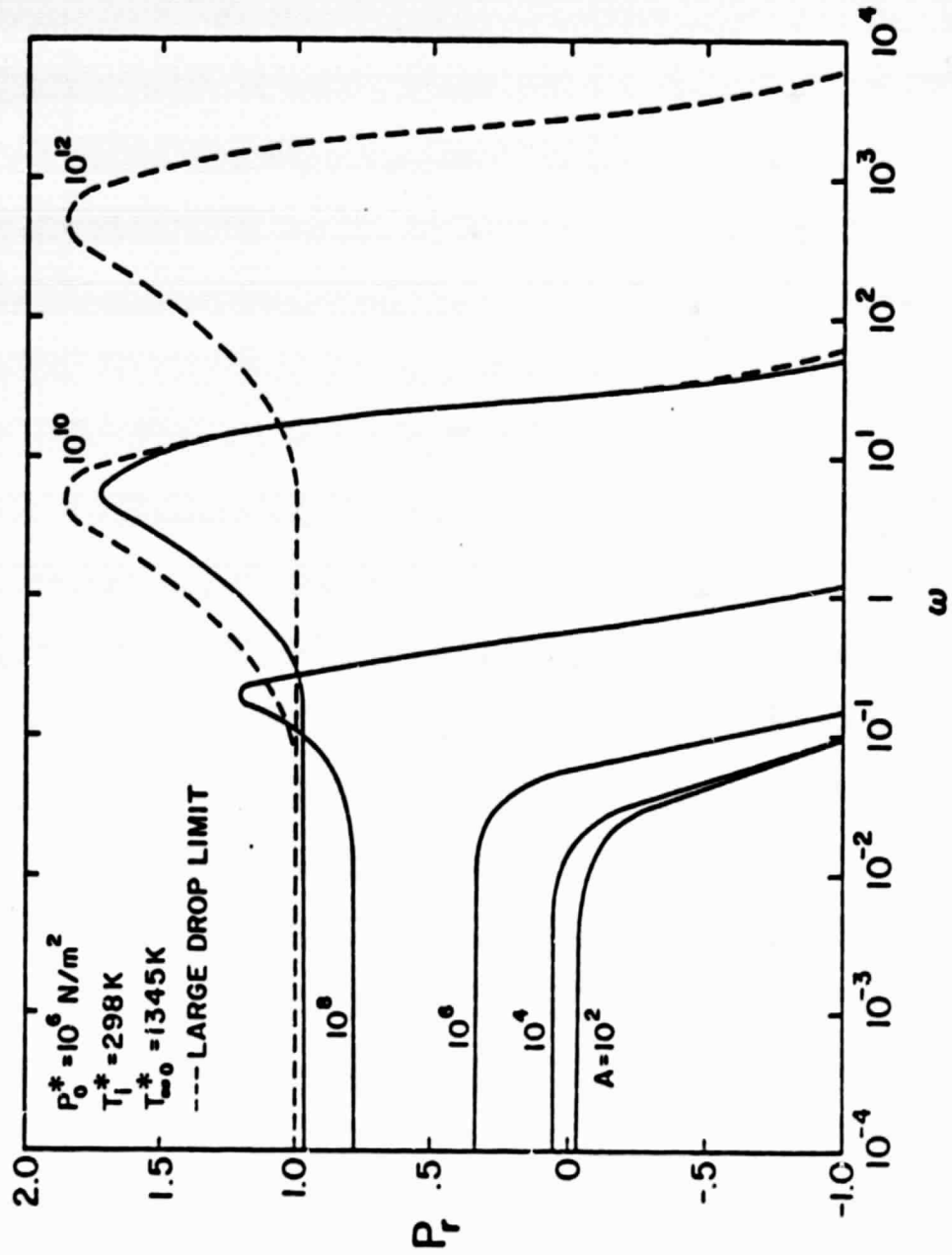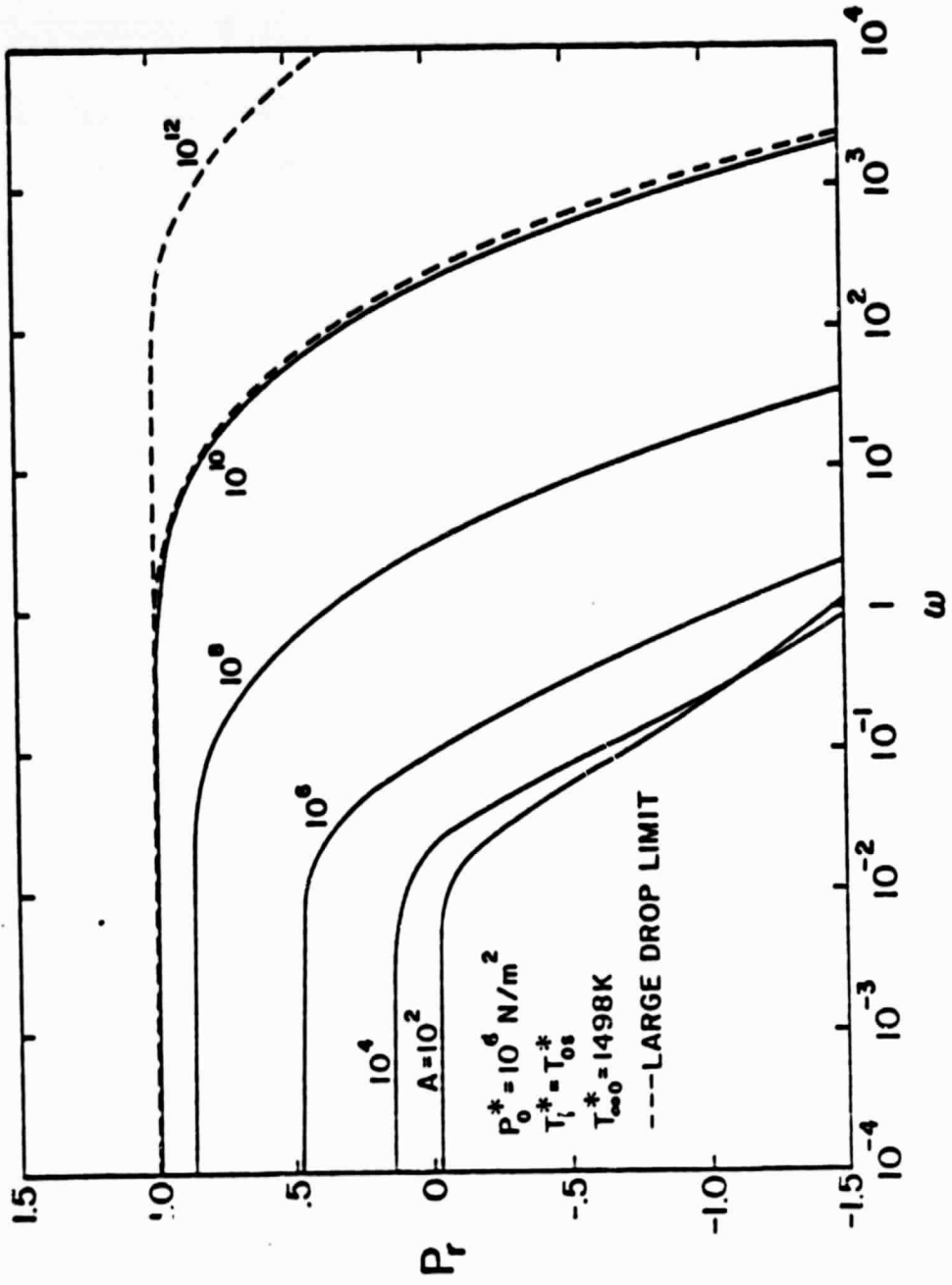
Figure 7 Quasi-Steady Gas Phase Response as a Function of Frequency and Λ at Approximately 10 atm. Pressure (Wet Bulb Conditions)

droplet surface has sufficient steepness so that enough energy
will flow from the surface towards the center of the drop, caus-
ing the perturbation surface temperature to lead the pressure.
When the mean temperature gradient is not steep enough, the per-
turbation surface temperature will never lead the pressure. Also,
as the droplet size decreases while it is reacting, the liquid
temperature gradient will tend to approach the wet bulb limit;
thus, eliminating the response peak.

2.5 Spray Response

A combustion chamber will become unstable when the total
response of all the droplets in the spray exceeds the available
damping. Using the droplet response results, an analysis of
spray response was undertaken. A one-dimensional spray combustion
model was used, in which the pressure field is identical for all
parts of the spray.

Droplet lifetimes were calculated using the steady state
mass burning rate approximation. Table 4 lists the droplet life-
times as a function of pressure and initial drop radius.

The wet bulb droplets consistently have shorter lifetimes
because of their higher mass burning rates. For all cases, at a
given initial radius, the lifetime decreases with increasing
pressure. This is caused by the fact that a given radius cor-
responds to a larger value of A at higher pressures, yielding
a greater mass burning rate. At a constant pressure, the life-
time increases with drop size, which is to be expected.

The response portion of the present analysis is not valid
at frequencies having an oscillation period comparable to the
lifetime of the droplet. This provides a minimum droplet size
that can be considered by the present analysis. The probable
oscillation periods of instability range from 2×10^{-3} to
3×10^{-5} seconds/cycle (corresponding to the 500-30,000 Hz range
indicated in Ref. 5). At the oscillation period limit of
2×10^{-3} seconds/cycle, the minimum drop radius is approximately
13 μ at the non-wet bulb condition, and approximately 95 μ for
the wet bulb case. At the other limit of 3×10^{-5} seconds/cycle
the minimum droplet radius is approximately 2 μ at all pressures
and both wet and non-wet bulb conditions. This indicates that at
low frequencies, appreciable response may be generated by droplet
lifetime characteristics, a mechanism that has not been considered
in the present investigation.

Table 4

Dimensional Droplet Lifetimes as a Function

of Initial Radius and Pressure

$P_o{}^*(N/m^2)$	$r_{so}{}^*(\mu) = 10$	100	1000
	(seconds)		
Non-Wet Bulb			
10^5	0.00158	0.128	4.79
10^6	0.00135	0.0489	0.728
10^7	0.000507	0.00734	0.0788
	(seconds)		
Wet Bulb			
10^5	0.00141	0.109	3.61
10^6	0.000955	0.0272	0.361
10^7	0.00179	0.0020	0.0229

If a monodisperse spray is injected into the combustion chamber, the total response, P_{rt}, is the weighted sum of all drop sizes existing in the chamber. Figure 8 illustrates the non-wet bulb total response of a monodisperse spray as a function of frequency, ω_o, and A_o (dimensionless parameters based on the injected size) for a pressure of 10 atmospheres. The solid lines correspond to the entire spray while the dashed lines correspond to the situation when it is assumed that all drop sizes are approximated by a constant drop size corresponding to A_o. For these two cases, the peaks occur at approximately the same frequency, while the magnitude of the peak is slightly larger when the drop size is assumed constant. The reduction in the response peak of the spray is due to the reduced response of the smaller droplets.

Figure 9 is the wet bulb total response for a monodisperse spray as a function of ω_o at 10 atmospheres pressure. The same conclusion can be drawn as from the non-wet bulb case. The total response at pressures of 1 and 100 atmospheres for both wet and non-wet bulb conditions give similar results. The shapes of the total response curves in Figs. 8 and 9 are very similar to the shape of the individual response curves for A_o.

When a polydisperse spray is introduced into the combustion chamber, the spray is separated into discrete spray sets, each with its own A_o, and the calculations proceed as before. Figure 10 is a plot of a non-wet bulb polydisperse spray at a pressure of 10 atmospheres, consisting of three spray sets with A_o's of 1.234×10^{10}, 1×10^9, and 1.234×10^6. The response from each size group is weighted and summed in order to obtain the total response. The mass fractions of the spray sets and injection rates were varied, as listed in Fig. 10. The total response is greater than unity when the larger A_o spray sets comprise about 30% of the injected spray mass. The results indicate, however, that even a very small percentage of large drops in the injected spray can result in substantial response peaks. Findings at other pressures for both wet and non-wet bulb conditions are similar; however, for the wet bulb case, no peaks greater than unity are observed.

2.6 Summary

The response of monopropellant droplets and sprays was considered using an analysis based on earlier strand combustion work. For individual droplets, small droplets gas low or
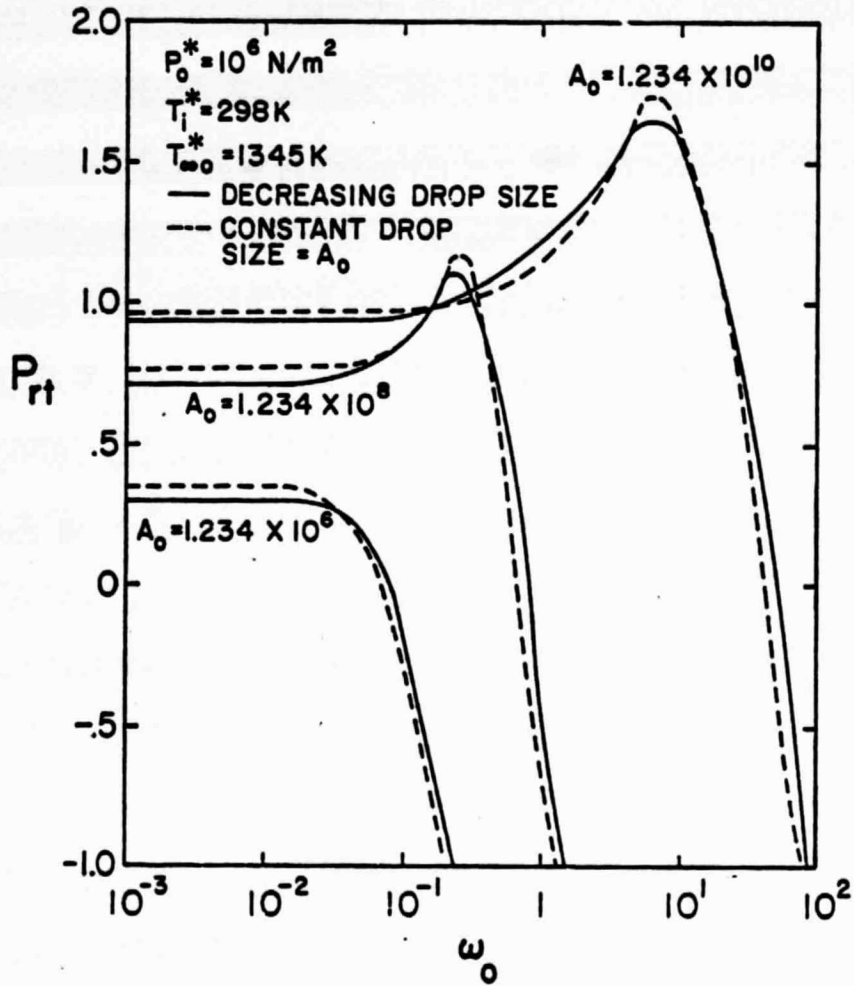
Figure 8   Total Response as a Function of ω_o for a Monodisperse
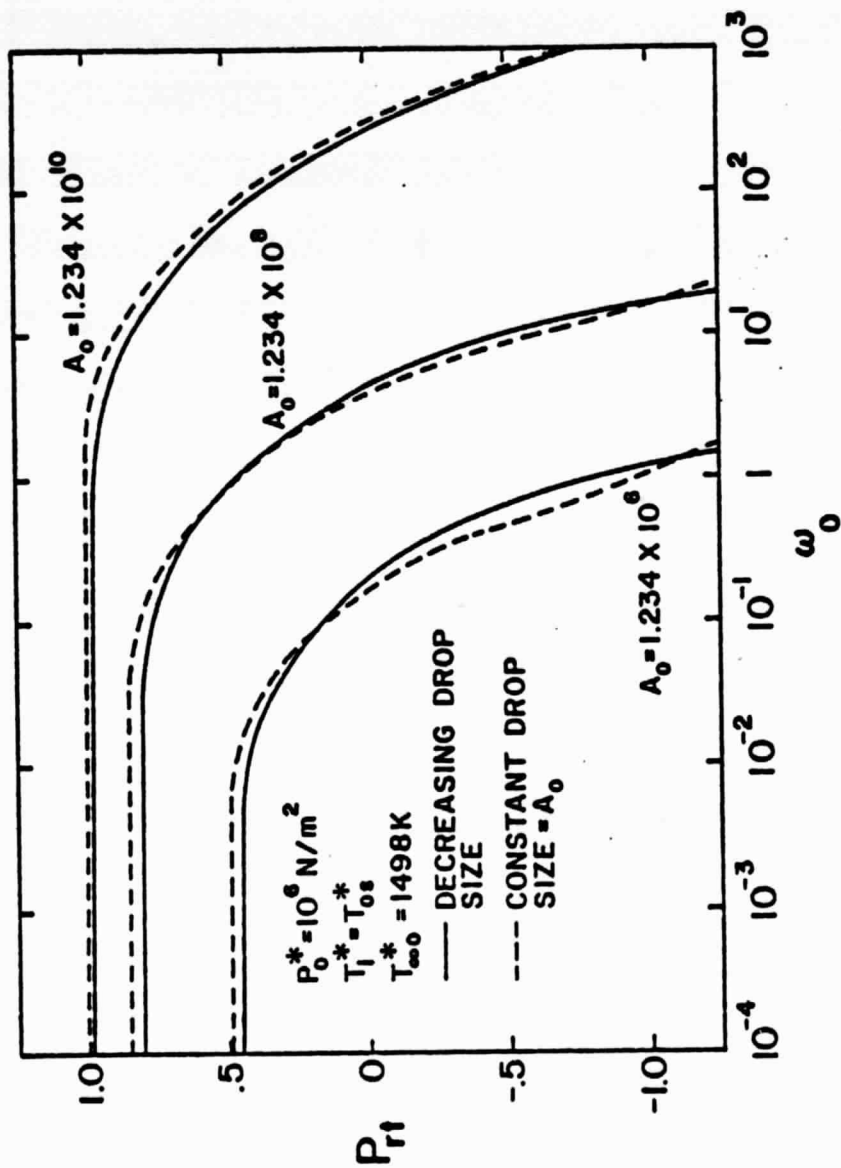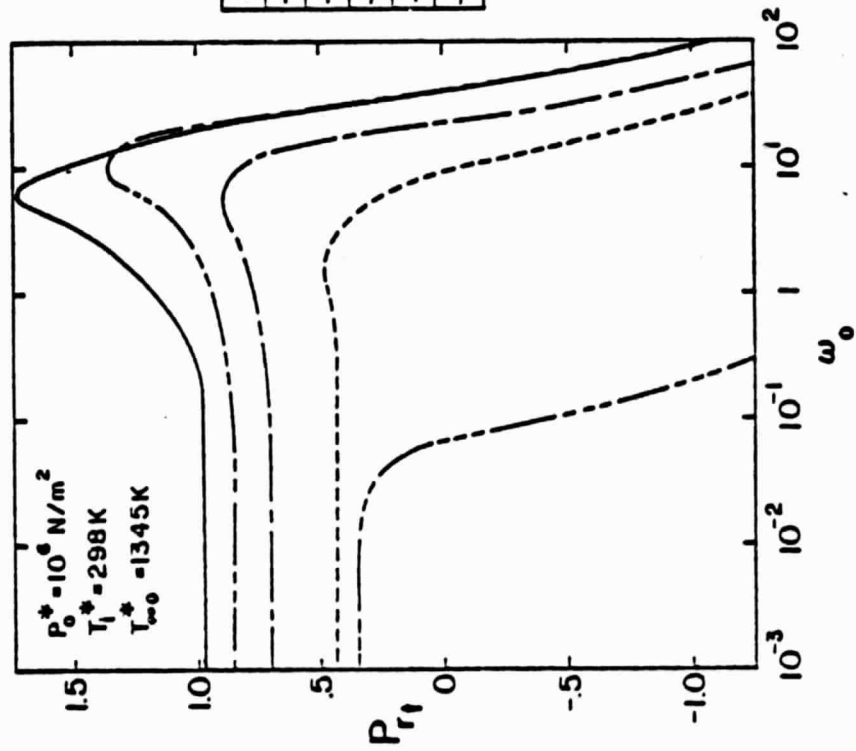Spray at Approximately 10 atm. Pressure (Non-Wet Bulb
Conditions)

Figure 9 Total Response as a Function of ω_o for a Monodisperse Spray at Approximately 10 atm. Pressure (Non-Wet Bulb Conditions).

	% MASS IN CHAMBER			% DROPS/SEC. INJECTED			% MASS/SEC. INJECTED		
A_o (X10⁶)	123	10	.0123	123	10	.0123	123	10	.0123
——	100*	0	0	100*	0	0	100*	0	0
—·—·	10	30	60	.001	.053	99.946	.1	1.4	98.5
———	60	30	10	.005	.315	99.68	3.4	7.7	88.9
—·—·	49.5	49.5	1.0	.05	4.98	94.97	11.47	51.78	36.75
—··—··	0	0	100*	0	0	100*	0	0	100*

*ALL DROPS IN THE SPRAY ARE AT A CONSTANT SIZE A_o

$P_o^* = 10^6 \text{ N/m}^2$
$T_i^* = 298K$
$T_{\infty o}^* = 1345K$

Figure 10   Total Response as a Function of ω_o for a Polydisperse Spray at Approximately 10 atm. Pressure for Varying Spray Set Mass Fractions and Injection Rates (Non-Wet Bulb Conditions).

negative response at all frequencies. Large drops provided a
response near unity at low frequencies, with the response de-
clining at frequencies somewhat in excess of the characteristic
frequency of the liquid phase thermal wave. If there was a
temperature gradient in the liquid phase, a response peak in
excess of unity was determined. For large droplets, a re-
sponse peak resulting from gas phase transient effects was also
observed, but at frequencies generally higher than the range
normally associated with combustion instability.

Spray response was also considered for several specific
cases. The response of a spray is generally lower than that
of the largest injected droplet, however, even a small percent-
age of large droplets can yield appreciable response.

Work in this area of the investigation has been concluded.

3.   **High Pressure Spray Combustion**

3.1   **Introduction**

Knowledge of the gasification process of individual drop-
lets is vital to understanding the entire spray combustion pro-
cess. This aspect of the problem has already been considered
in some detail. The results have provided a capability for pre-
dicting gasification rates and critical combustion conditions
in environments typical of spray combustion processes.

In order to apply the results of individual droplet studies
to sprays, the structure of the spray must be determined in order
to specify the local environment of the droplets. In spite of
its importance, investigations of spray structure during com-
bustion have only recently appeared due to the experimental dif-
ficulty of this type of work.

Chigier and coworkers (11-13) have measured the structure
of spray combustion processes at atmospheric pressure. Gas
temperatures and droplet sizes and velocities were determined
within the spray for several injector types. Onuma and
Ogasawara (14) conducted similar measurements at atmospheric
pressures, with additional results on species concentrations.

These studies indicate some similarities between the struc-
ture of spray combustion processes and turbulent gaseous dif-
fusion flames. The similarity is most apparent when the droplets

are finely atomised so that droplet velocities quickly come into
equilibrium with local gas velocities. Under these conditions,
models analagous to homogeneous two phase flow (negligible slip
conditions) are suggested, although they have not been pursued
as yet.

At high pressures, where the density of the liquid phase
approaches that of the gas, the condition of negligible slip
between the two phases becomes more appropriate. If this is the
case, the combustion of a spray at high pressures would be similar
to that of a turbulent gas jet with greater density variations due
to the presence of liquid in the early stages.

Newman and Brzustowski (15) considered the evaporation of
carbon dioxide sprays at elevated pressures. Experimental re-
sults were compared with a homogeneous two phase flow model, which
did not consider high pressure thermodynamics and employed an early
version of the integral model for a jet. The success of the pre-
cictions was limited, but it is encouraging that results were of
the correct order of magnitude.

Avery and Faeth (16) considered a rather different problem,
involving the combustion of a high velocity gaseous oxidizer jet
submerged in a liquid metal fuel. In this case, the gas is the
distributed phase. Since the gas has low interia in a liquid
surroundings, the local slip between the two phases is small and
the homogeneous model is a good representation of the process.
The major uncertainty involves the proper treatment of the
enormous density variation of the flow as mixing and reaction pro-
ceeds. The density variation was handled using a coordinate trans-
formation and a variable density entrainment model proposed by
Morton (17).

The results of the procedure were very encouraging. A
unified correlation of flame length, temperatures and velocities
was achieved for both the two-phase system and earlier work on
forced turbulent diffusion flames (18). Figure 11 gives an
example of the flame length results. The gas-liquid combustion
process is compared with the gas-gas measurements of Hawthorne, et
al (18) and Wohl, et al (19). Using a similar approach it was
also possible to correlate the measurements of length of con-
densing vapor jets in subcooled liquids (20, 21) in the same manner
as shown in Figure 11.

These findings suggest that under conditions where the slip
between the two phases is small, the model of Ref. (16) can handle
the large density variations of a two phase flow during a mixing
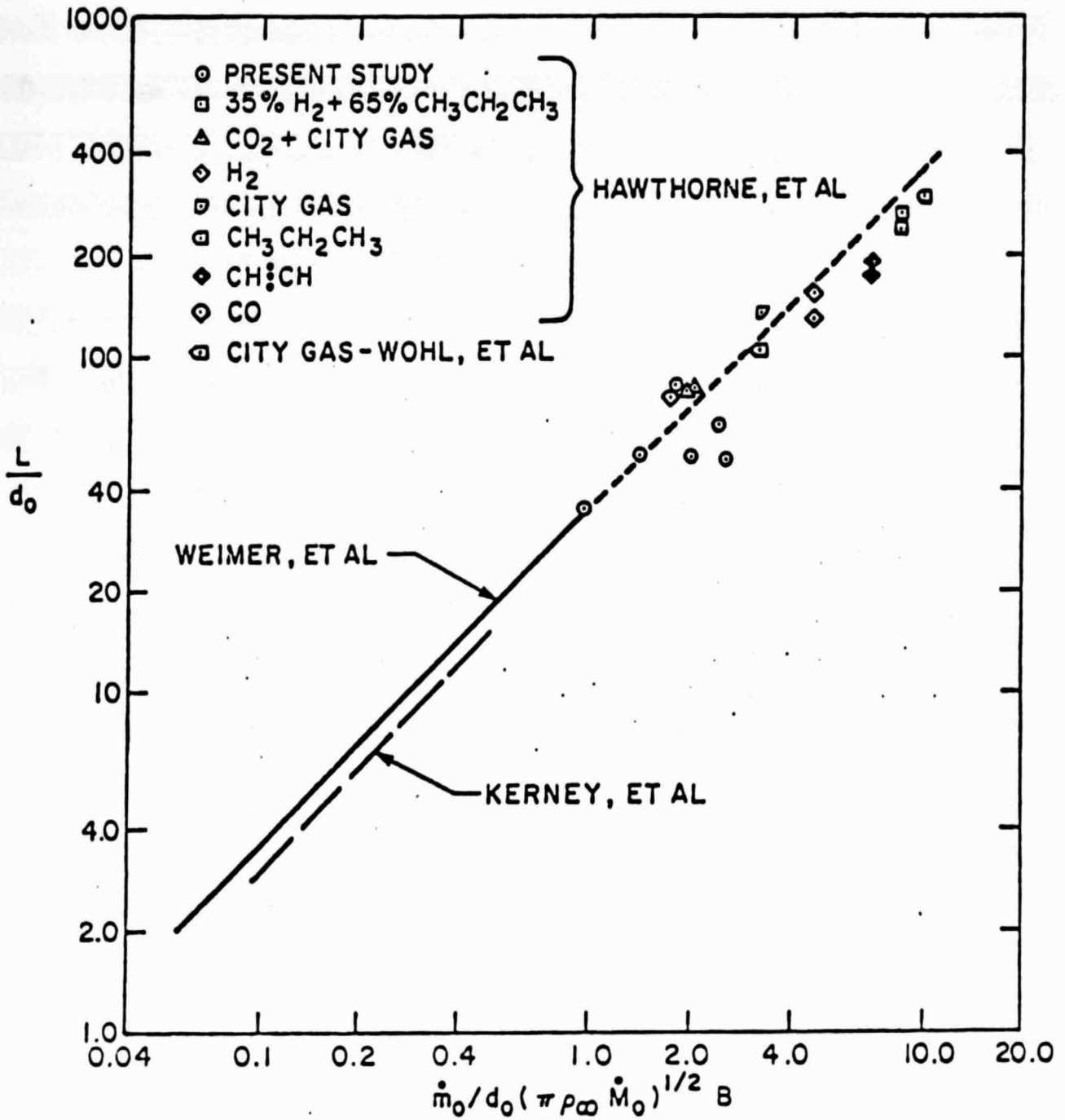and combustion process. The model provides information on the

Fig. 11 Comparison of predicted and measured flame lengths for
gas-liquid and gas-gas turbulent jets, Ref. 16.

structure of the process including temperature, density, velocity
and species concentrations. The mean position of the diffusion
flame is also predicted as well as the length required for complete
combustion. The input variables are well defined and include in-
jector size, injection momentum, injector flow rate, ambient dens-
ity, stoichiometry and ambient velocity. These parameters can be
specified unambiguously for most practical combustion processes.

The objective of the present study is to investigate the
validity of the integral-entrainment model for spray combustion
at elevated pressures where the assumptions of the model are most
valid. During this report period, major emphasis of the investi-
gation was placed on the design and fabrication of the experimental
apparatus.

3.2 Theory

A complete description of the basic theoretical model is pre-
sented in Ref. 15, only a qualitative description will be given here.
A sketch of the present process is given in Fig. 12. A liquid fuel
jet is injected into a large stagnant gas region at elevated pres-
sure. It is assumed that buoyancy forces can be neglected. Since
gas and liquid densities approach one another at high pressures, it
is assumed that fuel droplets produced by the spray are in local
kinematic equilibrium with the gas, i.e. slip is neglected.

Under these assumptions, integral equations of conservation
of mass, momentum, energy and species are written. The entrainment
of gas by the jet is described by Morton's variable density entrain-
ment expression (17). The equations can be integrated in closed
form to yield the variation of absolute enthalpy, allowing for
heat of formation, Δh, velocity u, and concentration, Δy, through-
out the flow field. The problem is closed by specifying the
equations of state for the system which relates concentrations and
enthalpies to temperature, the presence or absence of liquid and
density. In regions some distance outside the spray boundary,
an ideal gas model may be used. Within the spray boundary, and
particularly to define its extent, the high pressure thermodynamic
models, of Refs 22-24 must be employed.

Aside from mean quantities, the outer spray boundary and outer
flame boundary are characteristics of interest. The interpretation
of these factors, however, is somewhat complicated for turbulent
jets due to local unmixedness or property fluctuations. For ex-
ample, the flame zone is relatively thick for turbulent flow and
profiles of mean fuel and oxidizer concentrations overlap to a con-
siderable extent. Therefore the outer flame limit corresponds to
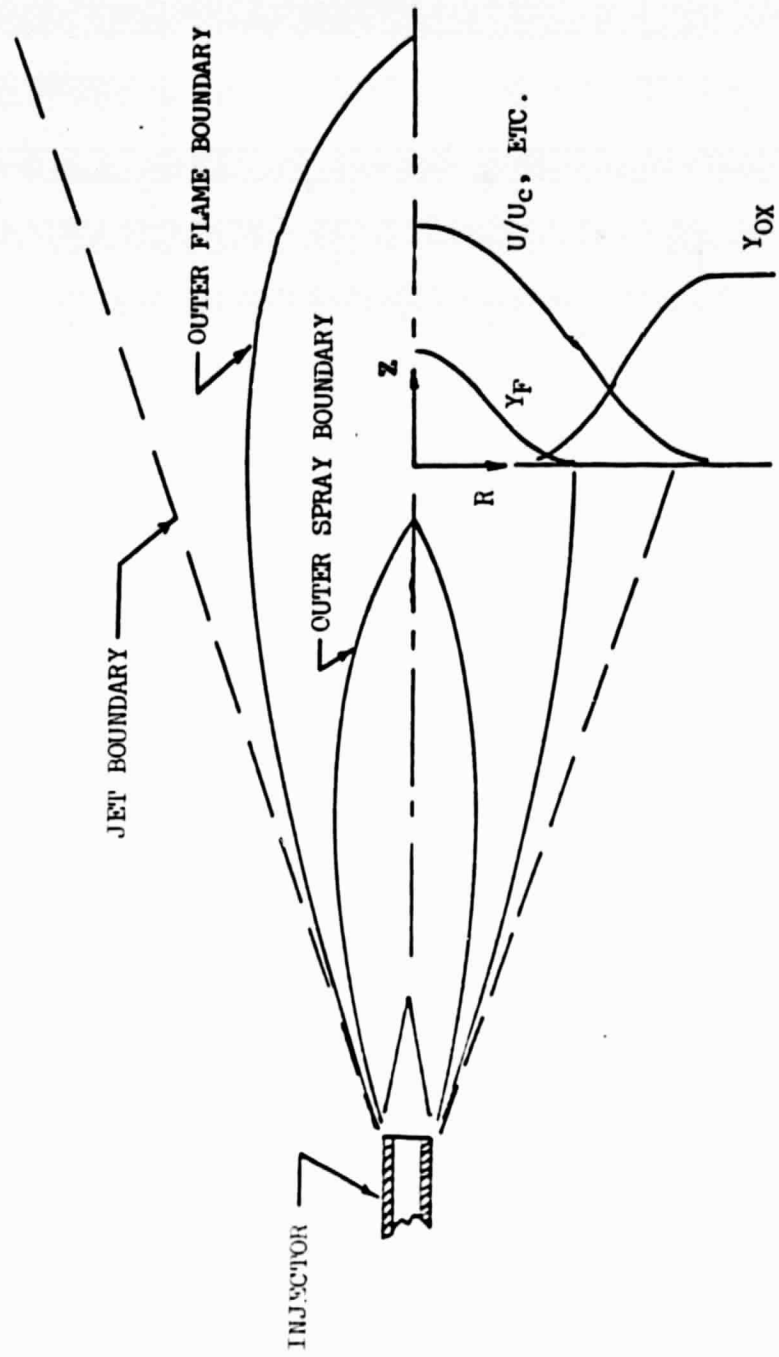the point where all the fuel is consumed, which is beyond the

Fig. 12 Sketch of the spray combustion process

equivalent laminar stoichiometric flame position. Similar behavior also holds at the outer spray boundary. It has been found, however, that a constant ratio allows outer boundaries to be specified from mean quantities for both thermodynamic and reactive processes (15).

3.3 Experimental Apparatus

Initial evaluation of the theory for the noncombusting case can employ existing data in the literature (15). An apparatus has been designed and fabricated for tests involving the combustion case. A sketch of the apparatus is presented in Fig. 13.

The apparatus consists of a windowed pressure vessel which can operate at pressures in excess of 100 bar. The internal volume of the chamber is approximately 11 liters.

A given volume of fuel is placed in a loop in the injector supply line. This sample is forced into the chamber by opening the solenoid valve between the injector and the air supply which is maintained at selected pressures higher than the test chamber. The spray is ignited with a hydrogen gas jet which, is ignited by a hot wire. Injector passage diameters are small to reduce wall effects, on the order of .2-.4 mm. Differential pressure gages are used on the fuel feed and hydrogen supply, an absolute pressure gage is used for the chamber pressure.

The process is photographed with a motion picture camera, using a dark field for flame positions, or back-lighting and filters for spray positions. Measurements can also be made of gas temperatures in the jet using thermocouples recorded by an oscillograph.

The time sequencing of injection, ignition, shutdown, etc., is controlled automatically using a programmable timer. Initial work is considering methanol and heptane as fuels, due to availability of developed thermodynamic models for the high pressure characteristics of these materials (22-24).

3.4 Summary

A theory for high pressure spray combustion has been obtained by modifying an analysis developed for gas-liquid and gas-gas combustion and condensation processes. Modification of earlier high pressure thermodynamic analysis is in progress for use in predicting spray boundaries with this model. Initial model evaluation is being undertaken using existing data in the literature.
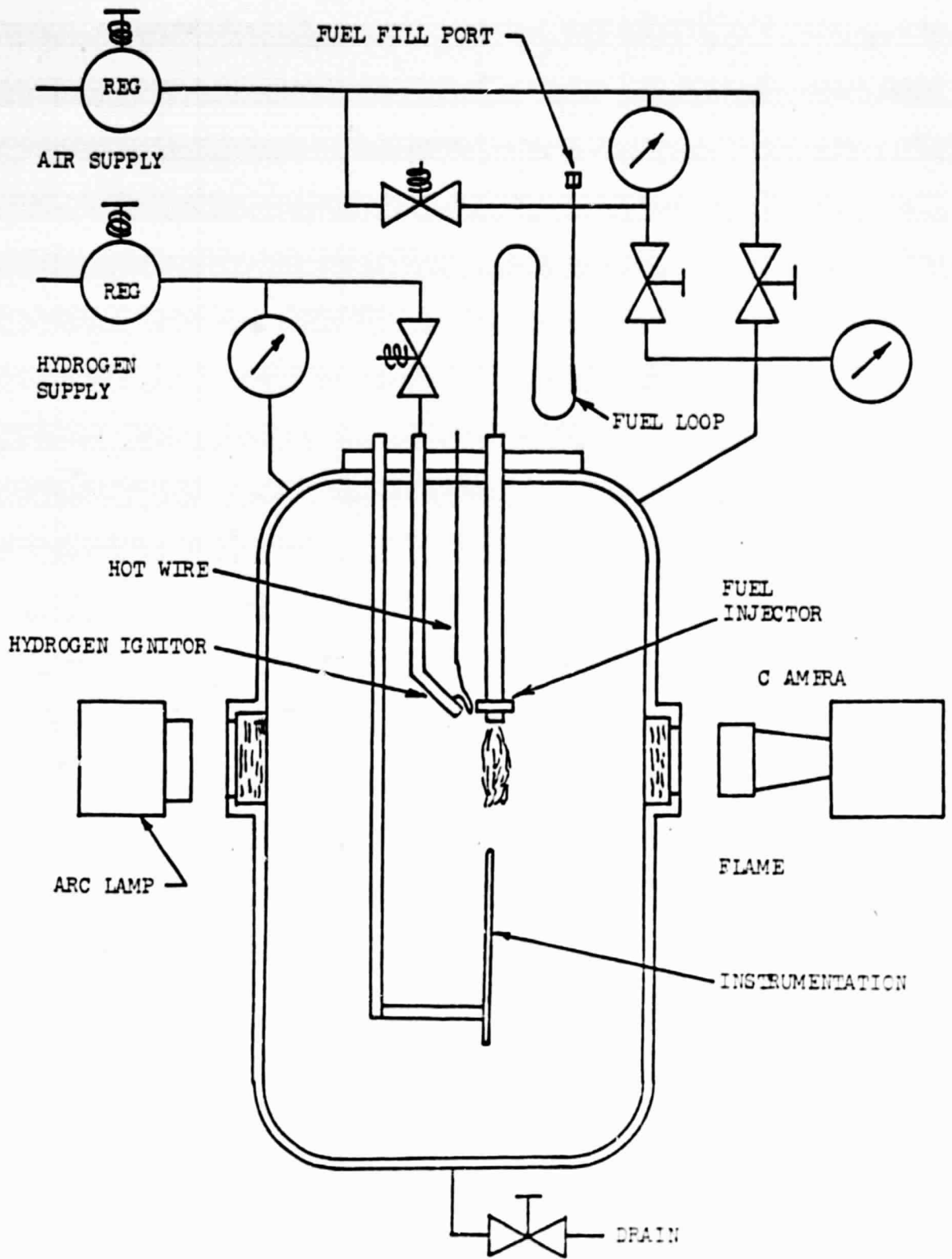
Fig. 13 Sketch of the high pressure spray combustion apparatus

An apparatus has been designed and fabricated to allow ob-
servation of combusting fuel sprays at high pressures. The
apparatus provides measurements of spray shadowgraphs, dark
field flame photographs and gas temperatures in the region
downstream of the spray. Assembly of the apparatus is nearing
completion and testing will begin early in the next report
period.

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