Lean Combustion Characteristics of Hydrogen–Nitrous Oxide–Ammonia Mixtures in Air. Part I

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Abstract

We report experimental studies on the combustion of lean hydrogen-nitrous oxide-ammonia-air mixtures. This project is in support of the waste tank safety assessment for the storage facility at Hanford, WA. This study focuses on combustion limits, pressure histories, and flame speeds of flammable gas mixtures characteristic of this facility.

A facility was constructed to study the lean combustion characteristics of mixtures containing ammonia. This facility consists of a gas-handling system, a remotely-controlled 400-liter pressure vessel, a vacuum system capable of pumping and disposing of the unburned ammonia, and a data acquisition system.

A total of 208 experiments were conducted for this study. All experiments were performed using air as a primary oxidizer. Separate experiments were carried out for binary and ternary mixtures containing air, hydrogen, ammonia, hydrogen-nitrous oxide, ammonia-hydrogen, and ammonia-nitrous oxide. Other experiments examined quaternary mixtures of ammonia-nitrous oxide-hydrogen-air. Mixtures were burned under quiescent and turbulent conditions and, in some cases, with an inert substitute (nitrogen) for the nitrous oxide. The pressure and temperature were recorded in the tank throughout the combustion events. A schlieren video photography system was used to observe flame propagation and measure flame speeds. The final equilibrium pressures were also measured in the experiments.

The results demonstrate that nitrous oxide is inert in lean mixtures of hydrogen-air-nitrous oxide and reactive in lean mixtures of ammonia-air-nitrous oxide. For mixtures of hydrogen-nitrous oxide-ammonia-air, the reactivity of the nitrous oxide depends on the hydrogen-ammonia ratio. A correlation between the adiabatic, constant-pressure, flame temperature of the mixture and the reactivity threshold of the nitrous oxide is proposed. It was found that the nitrous oxide began reacting when the adiabatic flame temperature was between 1100 and 1300 K. It was found that for flame temperatures above this threshold, presence of nitrous oxide affects the flammability limit, the pressure history, and the flame speed.

Contents

List of Figures

List of Tables

Chapter 1 Background

1.1 Lean Flammability Limits

The flammability limits of a combustible mixture are those limiting compositions that will just support flame propagation when stimulated by an external ignition source. Identifying these mixtures is of great interest to the chemical industry and safety engineers, and compilations of flammability limits have been published by the Bureau of Mines [Coward and Jones, 1952, Zebetakis, 1976]. Although there is no widely accepted theoretical method of predicting flammability limits, there are a number of empirical rules and simple models, the classical results are summarized in Lewis and Von Elbe [1961] and updated in the series of reports by Hertzberg [1976]. The fuel type, mixture properties and mass diffusion of the deficient reactant are all factors [Abbud-Madrid and Ronney, 1990] in defining the limiting composition.

The primary reason [Spalding, 1957] for the existence of a flammability limit is heat loss (thermal radiation and conduction) from the hot products to the cooler surroundings. When the rate of heat loss exceeds the rate of energy generated by the chemical reactions, a flame cannot be supported. The composition at which balance exists between loss and generation determines the flammability limit. Thermal radiation from infrared-active species such as H_2O and CO_2 is one mechanism of energy loss from propagating flames. Thermal conduction to cold container walls is also a major loss mechanism in the standard flammability tests using the Bureau of Mines apparatus [Coward and Jones, 1952].

Mixtures that are either too rich or too lean are not flammable. In the present study, we are concerned with fuel-lean (excess oxidizer) mixtures, and therefore always mean lean flammability limit, known as LFL in the literature, when we refer to the flammability limit. Flammability limits are determined by a variety of techniques, each of which yields a slightly different value of the limiting composition.

Further complications are the effect of ignition energy and the buoyancy of the hot combustion products. If the ignition energy is too low, then although the gas may be flammable and a limited region will be ignited, a propagating flame will not result. In the present study, we have attempted to minimize the effect of ignition energy by using a high energy (10 J) spark of relatively long duration (100 μs).

The effect of buoyancy is to cause the initially spherical flame kernel, created by the spark, to rise and become distorted as it propagates outward. As a consequence, if the burning velocity is too low (less than about 5 cm/s), the flame is observed only to propagate upward. The gradients in the gas velocity induced by the rising flame also affect the flammability limit. The gradients and spherical expansion of the flame surface result in *flame stretch* which enhances combustion if the Lewis number Le (ratio of thermal diffusivity to mass diffusivity of the deficient reactant) is less than one and tends to quench the flame if $Le > 1$.

The limiting composition at which upward propagation of the flame begins is referred to as the upward propagation limit in this report. The composition at which the transition from upward to downward propagation takes place is known as the downward propagation limit. We have determined both upward and downward propagation limits.

Determining the flammability limits of mixtures containing multiple fuels and oxidizers has been largely confined to empirical studies. In the late 1800's, Le Chatelier [Le Chatelier and Boudouard, 1898] proposed a rule for mixtures of fuels: The flammability limit of a mixture can be approximated by using the weighted average of individual components:

$$1.0 = \frac{X_1}{LFL_1} + \frac{X_2}{LFL_2} \tag{1.1}$$

where X_1 is the mole fraction of component 1 and LFL_1 is the known flammability limit of fuel 1. For many compounds mixed in air, this rule is a reasonable approximation. The physical reasoning behind this model is that the reactants are compatible in kinetic and transport properties, and independently compete for oxidizer within the flame front.

1.2 Lean Flammability Limits of H_2 and NH_3

The mixtures of interest in the present study contain: hydrogen, H_2; nitrous oxide, N_2O; ammonia, NH_3; air, $.21O_2 + 0.79N_2$; and occasionally, methane, CH_4. The flammability limits of the individual components and some binary mixtures are well known, but more ternary and quaternary mixtures are not well characterized.

Hydrogen-air combustion has been extensively researched. The lean limits of flammability for H_2-air flames are 4.0% for upward propagation and 8.0% for downward propagation [Coward and Jones, 1952]. The stoichiometric concentration of H_2 is 28%.

Because ammonia has been used extensively as a refrigerant, the combustion of ammonia-air mixtures has been well studied [Fenton, et al., 1995]. Accepted limits of flammability for ammonia-air are scattered around 15% for upward and 18% for the downward limit [Ronney, 1987]. As discussed subsequently, N_2O appears to dramatically lower the limits for NH_3 , but H_2 is relatively unaffected. Ammonia is stoichiometric in air at 22%.

1.3 N_2O as an Oxidizer

Early researchers noticed [Danby, and Hinshelwood, 1940] that behavior of N_2O during combustion varies greatly. Depending on the mixture and ignition energy, the N_2O can behave as a diluent, or an oxidizer, or simply dissociate. Scott, Van Dolah, and Zebetakis [1954] experimentally determined that the upward propagation limit of H_2 is 3.1% in pure N_2O. Jones and Kerr [1949] found that the upward propagation limit of NH_3 in N_2O is 2.6%, considerably leaner than the upward propagation limit in air, which is 15%.

In their recent report, Cashdollar et al. [1992] found that in H_2-N_2O-air mixtures, the N_2O begins dissociating in the mixture when the H_2 concentration exceeds

10%. They noted the lack of participation of the N_2O in leaner mixtures. However, ammonia-rich samples of the mixtures were not investigated in this study, so the present report expands the range of mixtures tested to include ammonia rich mixtures.

Apparently, the differences in the effect of N_2O on NH_3 and H_2 mixtures is due to several factors. The main factor is temperature. Lean H_2-air flames have a very low product temperature (< 1100 K) and N_2O decomposes slowly under these conditions. The product temperature of lean NH_3-air flames is much higher and N_2O readily dissociates and reacts under these conditions. In addition, there appears to be some reactive intermediates characteristic of nitrogen chemistry that play a role in NH_3-N_2O combustion which are not a factor for H_2-N_2O combustion.

In the present study, we were not equipped to measure chemical composition. The combustion mechanism could only be evaluated indirectly by considering the overall reaction mechanism, considered next.

Major Product Models The major products for lean combustion of H_2-NH_3-N_2O mixtures are H_2O and N_2. If complete reaction of H_2 and NH_3 occurs and all the N_2O decomposes, the overall reaction is:

$$\begin{gathered}\alpha\ \mathrm{NH_3} + \beta\ \mathrm{H_2} + \gamma\ \mathrm{N_2O} + \delta\ \mathrm{air} \rightarrow \\ (\tfrac{3}{2}\alpha + \beta)\ \mathrm{H_2O} + (\tfrac{\alpha}{2} + \gamma + .79\delta)\ \mathrm{N_2} + (\tfrac{\gamma}{2} + .21\delta - \tfrac{1}{2}(\tfrac{3}{2}\alpha + \beta))\ \mathrm{O_2}\end{gathered} \tag{R1}$$

where one mole of air has been approximated as $0.21\ O_2 + 0.79\ N_2$. If the N_2O does not react or decompose in the combustion process, which is expected for some of the lean mixtures, the overall reaction will be

$$\begin{gathered}\alpha\ \mathrm{NH_3} + \beta\ \mathrm{H_2} + \gamma\ \mathrm{N_2O} + \delta\ \mathrm{air} \rightarrow \\ (\tfrac{3}{2}\alpha + \beta)\ \mathrm{H_2O} + (\tfrac{\alpha}{2} + .79\delta)\ \mathrm{N_2} + (.21\delta - \tfrac{1}{2}(\tfrac{3}{2}\alpha + \beta))\ \mathrm{O_2} + \gamma\ \mathrm{N_2O}\ .\end{gathered} \tag{R2}$$

Finally, if the oxidation of the fuel occurs preferentially by N_2O rather than O_2, this reaction is modified to

$$\begin{gathered}\alpha\ \mathrm{NH_3}+ \beta\ \mathrm{H_2} + \gamma\ \mathrm{N_2O} + \delta\ \mathrm{air} \rightarrow \\ (\tfrac{3}{2}\alpha + \beta)\ \mathrm{H_2O} + (2\alpha + \beta)\ \mathrm{N_2} + (\gamma - (\tfrac{3}{2}\alpha + \beta))\ \mathrm{N_2O} + \delta\ \mathrm{air}\ .\end{gathered} \tag{R3}$$

The first overall reaction (full dissociation of N_2O) corresponds to complete equilibrium and would be predicted by the usual equilibrium thermodynamic estimates by codes such as STANJAN [Reynolds, 1986], which is used for this study. A series of chemical equilibrium computations using a full set of product species and realistic thermodynamics has been performed using STANJAN. The constant volume, adiabatic combustion properties and the Chapman-Jouget detonation properties for a range of H_2-NH_3-N_2O-air compositions are given in Appendix E.

However, as discussed below, at low temperatures, the reaction rates are too slow and N_2O does not react. To simulate this, a series of equilibrium calculations were performed with the N_2O frozen, i.e., non-reacting. These computations, as well as experiments with N_2 substituted for N_2O, sheds light on the fate of N_2O in the reactions. These overall reaction models can be used to estimate the final pressure in a constant volume combustion situation. The ideal gas relation, $PV = NRT$ can be used to find the final pressure P_f in terms of N_f, the number of moles remaining in the system after combustion.

$$P_f = \frac{N_f \tilde{R} T}{V} \tag{1.2}$$

The number of moles, N_f, can be estimated by using the overall reaction balances discussed above, correcting for the condensation of water and resulting vapor pressure (26 mbar at 22 °C) at the measured temperature T_f. This method of analysis is a better method of determining the participation of N_2O than the comparing measured and predicted peak pressures because the result is not dependent on the heat transfer rate during the combustion process. However, it does depend on the combustion being complete in order to get reliable results.

Equilibrium models, though useful for estimating thermodynamic properties of combustion systems, cannot predict which oxidizer is preferred by the fuels in a multi-component system. Experimental measurements of the intermediate and product species are needed. Modeling based on detailed chemical kinetics considerations and known elementary reaction rates is a valuable alternative and supplement to experiments. A brief discussion of the issues is given below.

1.4 Chemical Kinetics

Radicals and reactive intermediates are key factors in determining flammability limits. Only a brief summary of previous results on flame chemistry is given here. A more detailed study of this aspect of flammability is currently being carried out at Los Alamos [Breshears, et al., 1996]. The differences in radicals and reactive intermediates are one obvious explanation for the differences in the lean flammability limit of NH_3 in air and N_2O. At high temperatures (> 1300 K), the primary reactions [Armitage, and Gray, 1971] responsible for the decomposition of NH_3 and H_2 are:

$$OH + NH_3 \rightarrow H_2O + NH_2 \tag{R4}$$

$$OH + H_2 \rightarrow H_2O + H \ . \tag{R5}$$

These reactions can proceed simultaneously without interfering with each other. It is known that at lower temperatures (less than 1100 K), the chain branching mechanism is not as important, but the following reaction

$$H + O_2 + M \rightarrow HO_2 + M \tag{R6}$$

is the primary path for H atom reaction. The primary mechanism for NH_3 consumption in lower temperature flames appears to be

$$NH_3 + OH \rightarrow NH_2 + H_2O \tag{R7}$$

$$NH_2 + OH \rightarrow NH + H_2O \tag{R8}$$

$$NH + NO \rightarrow N_2O + H \text{ or } N_2 + OH \ . \tag{R9}$$

The decrease in the LFL of NH_3, from 15% in air to an estimated 2.6% in N_2O, may be due to the decomposition of N_2O in the high temperature NH_3 flames.

$$N_2O + M \rightarrow N_2 + O + M \tag{R10}$$

and

$$H + N_2O \rightarrow N_2 + OH \ . \tag{R11}$$

1.5 Flame Speeds

When predicting the combustion behavior of multiple component mixtures, the flame speed of the pure mixtures in oxidizer can give some insight into deviation from ideal behavior. For example, when H_2 is mixed with CH_4 and burned in air, the difference in flame speeds causes CH_4 to act as a diluent for some stoichiometries. Flame speeds near the lean limit for these fuels are not very well known. Ronney [1987] performed flame speed measurements for lean NH_3-air mixtures in microgravity using the soap bubble method described in Andrews and Bradley [1978].

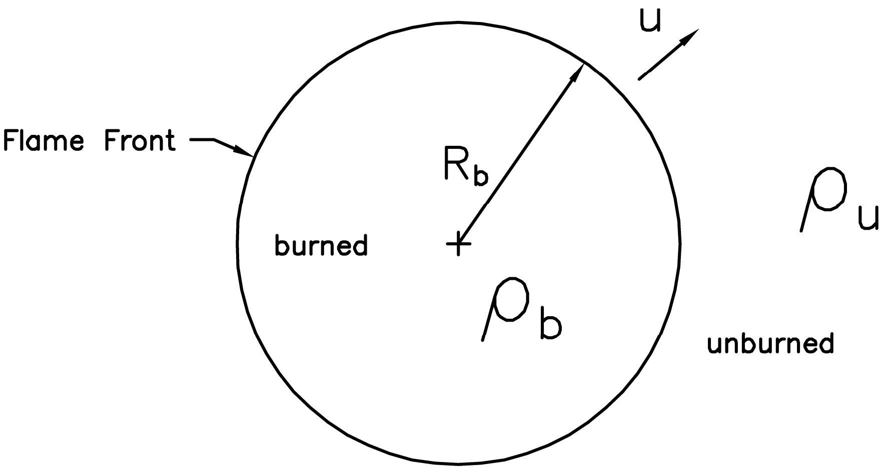


Figure 1.1: Radial expansion method for measuring flame velocity.

In the idealized "soap bubble" experiment, the pressure remains constant during combustion and the flame front is spherical. The flame front expands radially, and it is assumed that the burned gas inside the flame ball remains stationary. Therefore, the laminar burning velocity is the difference between the expansion rate of the flame front, V_f, and the velocity of the unburned reactants. The burning velocity S_b is therefore

$$S_b = V_f - u. \tag{1.3}$$

The continuity equation may be applied to obtain a relation between the burning velocity and the expansion rate of the bubble.

$$\rho_u S_b = \rho_b V_f, \tag{1.4}$$

where V_f is dR_b/dt. The final expression for the burning velocity is

$$S_b = \frac{dR_b}{dt}\frac{\rho_b}{\rho_u}. \tag{1.5}$$

The ratio ρ_b/ρ_u is the density of the burned material, evaluated by STANJAN [Reynolds, 1986] at constant pressure, over the density of the reactants at initial state. Normally this ratio is on the order of 0.2 for the mixtures studied in this report.

The uncertainty associated with measuring the burning velocity using this method is almost entirely due to the effect of buoyancy. The flame ball does not remain spherical, and initially the electrodes interfere with the flame front motion. As shown in Fig. 1.2 and video frames discussed subsequently, the flame moves upward as well as outward. The burning velocity was determined by measuring the horizontal growth of the flame in successive frames of the schlieren system video recording. Despite the effect of buoyancy, a very linear dependence of $R_b(t)$ was observed. An example of the raw data is shown in Fig. 1.3. The growth data was fit to a linear function $R_b = at + b$ and the slope was interpreted as the flame speed V_f. The slope can be determined quite accurately (the standard error is typically less than 5%) and the uncertainty in the flame speed is almost entirely due to unquantified effects of buoyancy. Comparisons with microgravity and two-kernel measurements are quite favorable.

Flame speed measurements provide a method of comparing reactivity of very lean mixtures which otherwise may not give much evidence of combustion. The flame velocity, V_f, is also useful for estimating the development of flames in explosion safety evaluations.

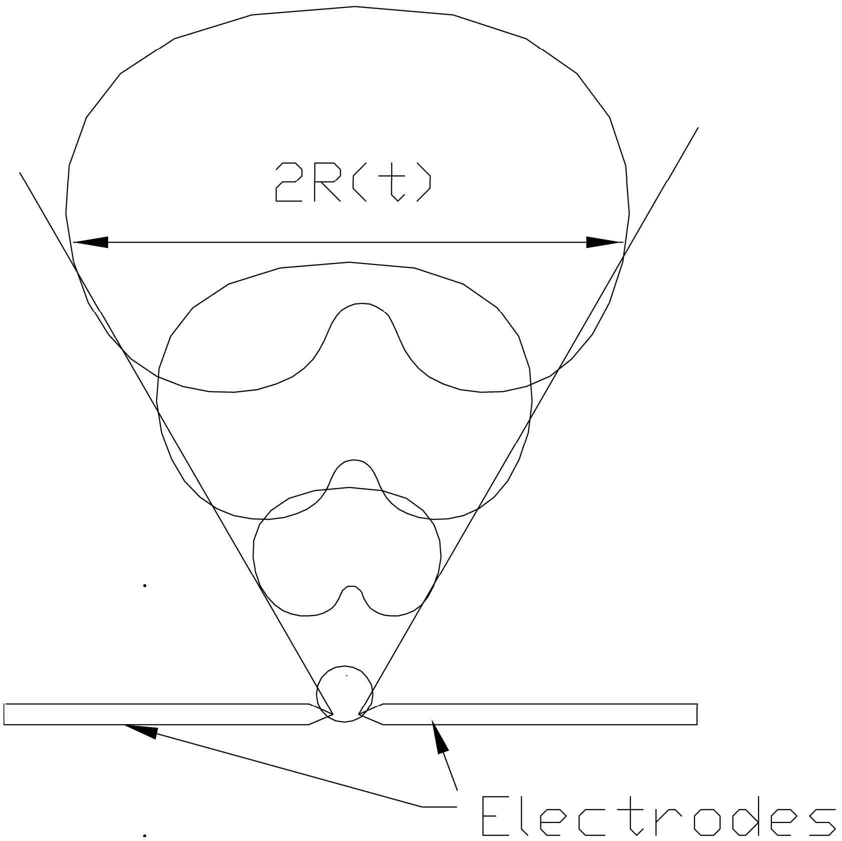


Figure 1.2: Experimentally observed flame development showing a typical buoyant flame near the flammability limit.

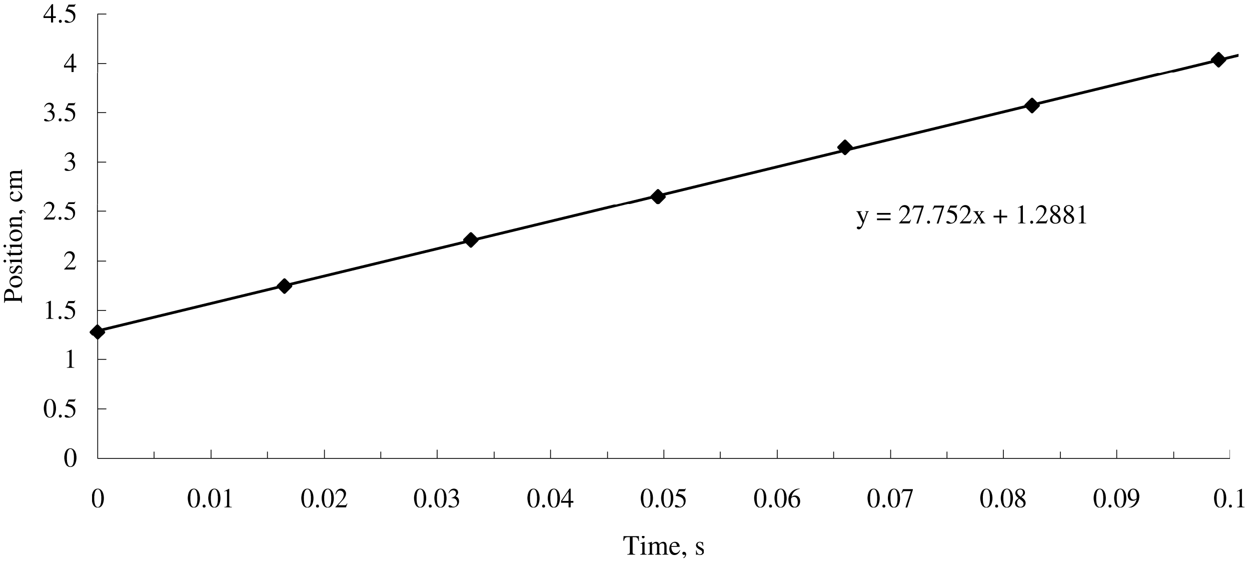


Figure 1.3: Experimentally measured flame horizontal growth and linear fit. Run 177.

Chapter 2 Apparatus

The facility (known as CONVOL) uses as a combustion vessel a cylindrical tank with a volume of 400 liters. The vessel is designed to study the combustion characteristics of lean flames of various mixtures. It is equipped with a gas dispensing system designed for the safe handling of combustible and hazardous mixtures. An evacuation and disposal system is designed to remove combustion products and safely dispose of unburned fuel. A plan view of the system is shown in Fig. 2.1.

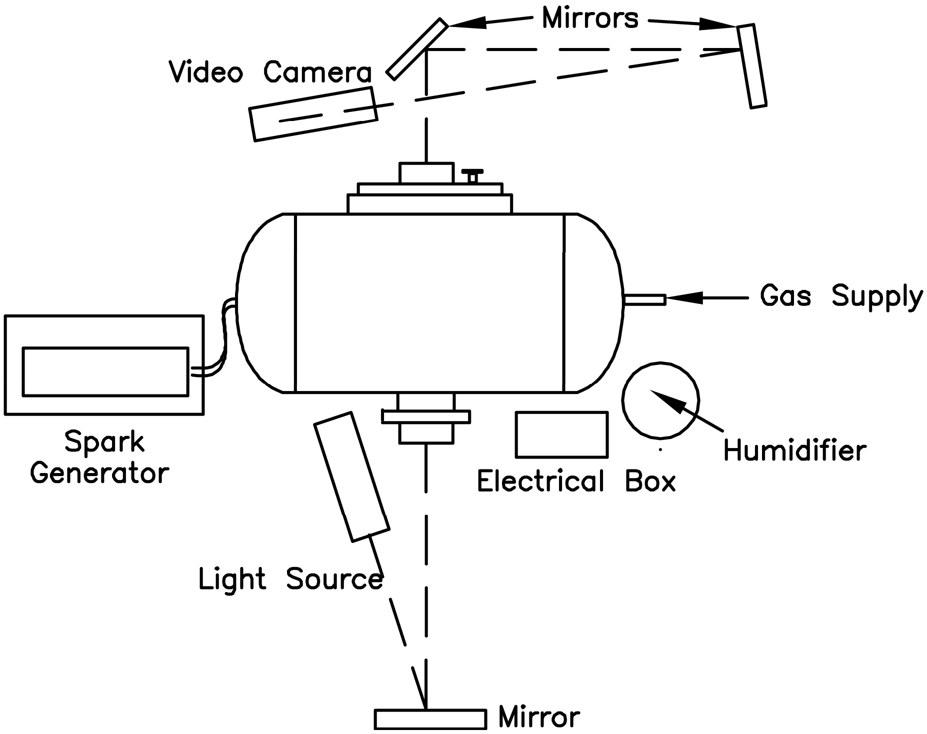


Figure 2.1: Caltech 400-liter combustion facility.

The system consists of three major parts: 1) the gas handling system; 2) the pressure vessel and instrumentation; 3) the exhaust system. The gas handling system consists of a bottle storage area (located outside) and the dispensing/metering system located in the control room. The pressure vessel and instrumentation includes the tank and associated control valves, the video system, the ignition systems, and the mixing fan. The exhaust system includes the vacuum piping, the pump, and the sparging system. Instrumentation includes pressure and temperature transducers and also a data acquisition system.

2.1 Gas Handling System

The bottle farm was constructed with primary consideration given to operator safety and minimizing the risk to building occupants. The main issues were ignition of the fuels and operator (or passerby) exposure to ammonia vapor or liquid. The fuels stored in the area are methane, nitrous oxide, hydrogen, and ammonia. All bottles are secured with seismic restraints. All tubing is thick-wall stainless steel, connected by stainless steel Swagelok fittings. All bottles are fitted with two-stage regulators. To prevent accidental dispensing of these gases in the laboratory, each line is equipped with an electro-pneumatic valve actuated by a pushbutton switch. If the operator leaves the control panel, these valves remain closed.

The ammonia is particularly hazardous because it is flammable, corrosive, and toxic. The ammonia bottle has a special storage cabinet in which the bottle is kept locked at all times. There is an active exhaust vent in the top of this cabinet to remove fumes and provide ventilation in the event of an accidental release. A bottle of nitrogen is attached to the side of the ammonia cabinet which is used to purge the ammonia line after the end of each day of experimentation.

A plan view of the gas handling system is shown in Fig. 2.2. This figure shows several of the safety features present in the laboratory. The gas detectors ensure that the fuel concentration levels present in the room stay below 1/100 of the LFL. In the event of a release that sets off the detectors, the emergency ventilation system is automatically activated, and air is exhausted (1500 cfm) through the overhead gas evacuation vents, shown in Fig. 2.2.

The gas supply system is designed for safe metering of the gases into the pressure vessel. A schematic of the system is shown in Fig. 2.3. The supply lines are thick-walled stainless-steel tubing, again connected with Swagelok fittings. Each line is

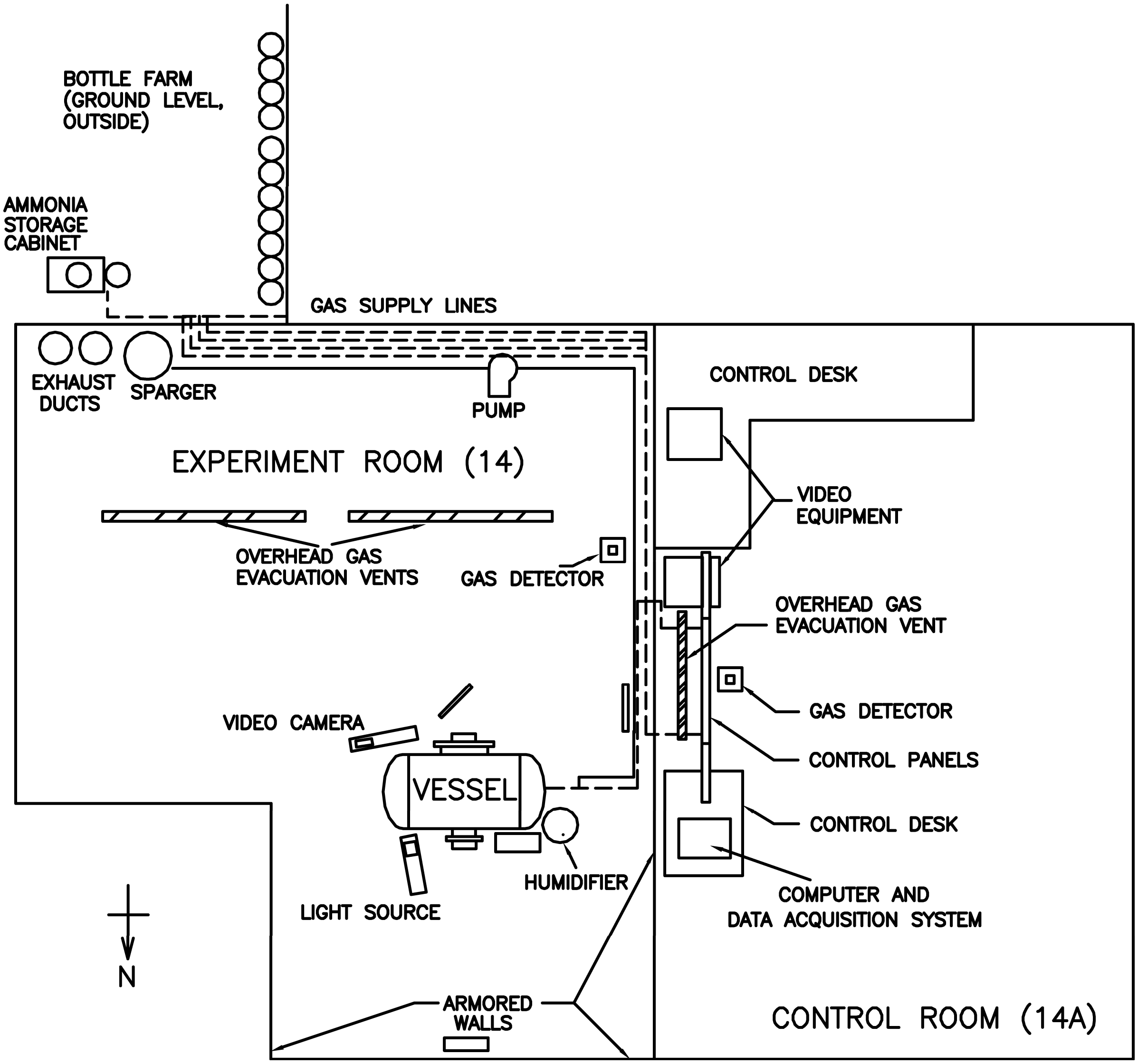


Figure 2.2: Explosion Dynamics Laboratory and CONVOL experimental facility.

protected by check valves, labeled “CV” on the schematic. All lines are opened and closed by stainless steel ball valves (SV1-6) mounted into the control panels. The lines converge after these valves, and pass through a needle valve (NV1), another stainless steel ball valve operated by a key switch (KS1), and into the tank through the tank isolation valve A1. Position indicators on the electro-pneumatic valves are interlocked through a logic control circuit to prevent accidental release of gas into the experimental area.

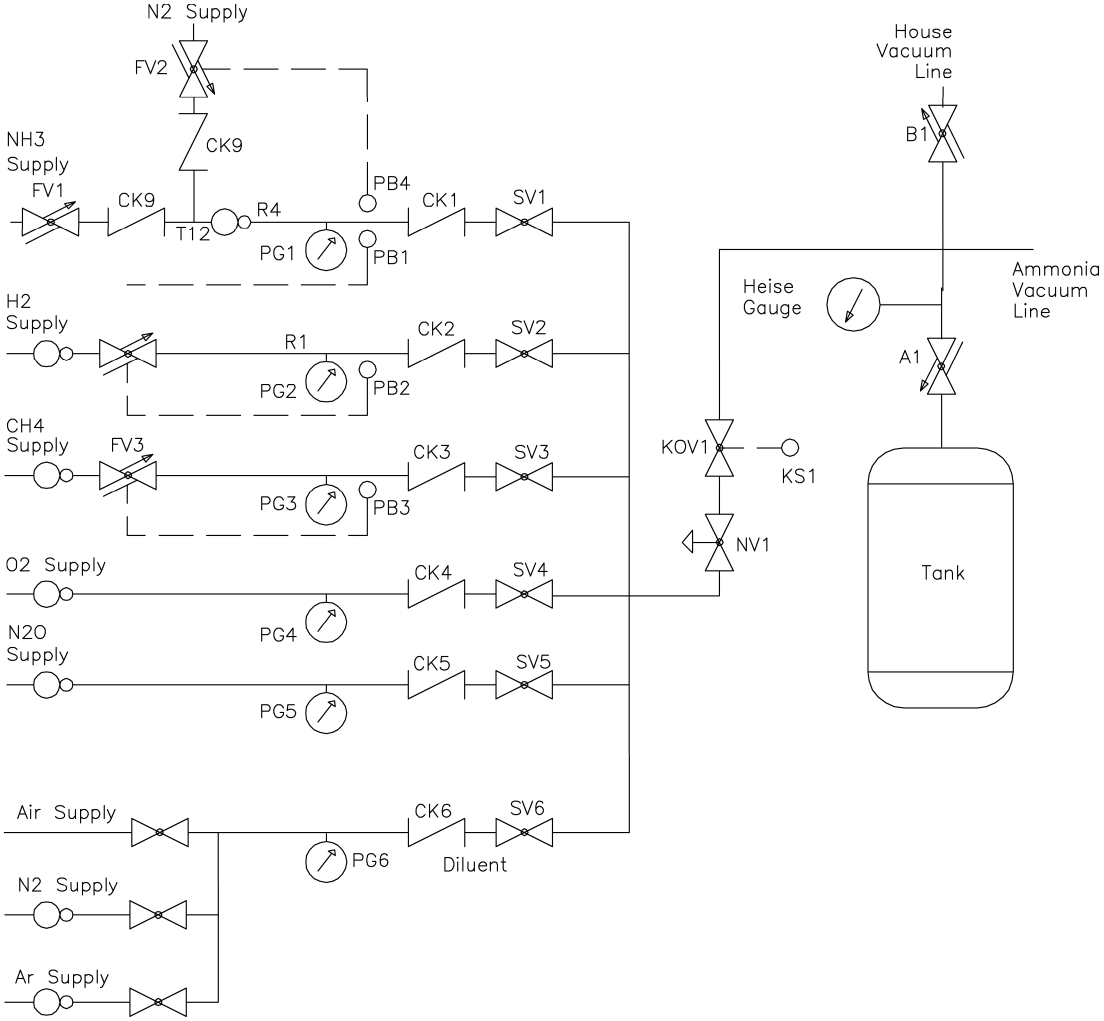


Figure 2.3: Schematic of the gas supply system.

2.2 Pressure Vessel

The pressure vessel was moved from Rensselaer Polytechnic Institute, Troy NY, after being used for experiments described in [Ross, 1993] and in [Krok, 1992]. The vessel (Fig. 2.4) is 1235-mm long and 711-mm in diameter, cylindrical with elliptical (2:1 aspect ratio) heads. The vessel is constructed of SA-212-B carbon steel, which has a tensile strength of 70,000 psi. The cylinder is 0.5-in thick and the heads are 0.614-in thick. The tank was constructed to ASME code rules for unfired pressure vessels and has a working pressure rating of 612 psi and has been hydrostatically tested to 920 psi.

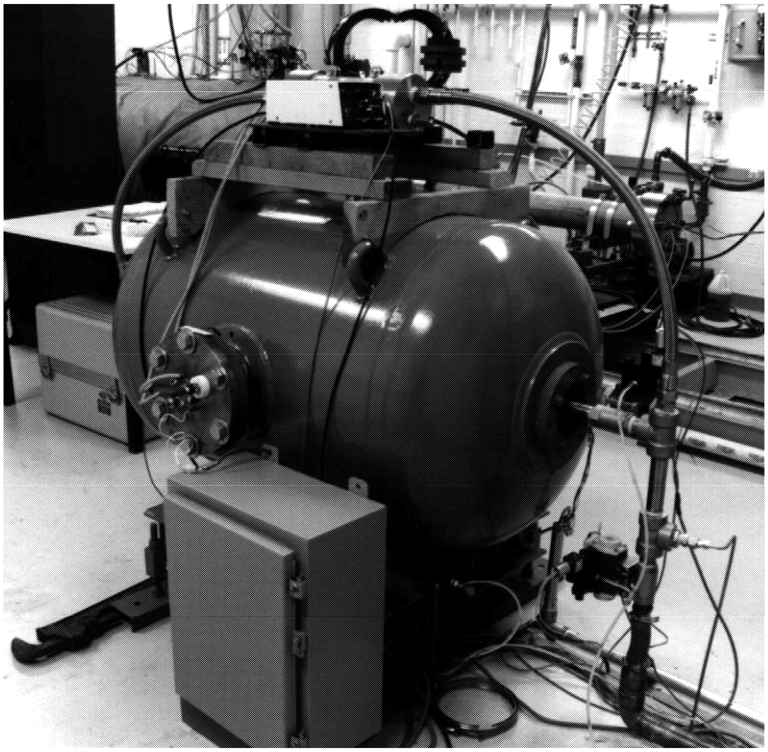


Figure 2.4: CONVOL pressure vessel.

There are 4 penetrations into the vessel. On the east and west ends, there is a 11-1/4-in OD, 6-1/2-in ID manhole closed with a flat plate and sealed by an O-ring. All seals used in the facility were made of buna-n, which is recommended for ammonia service. The plate on the west end of the tank is used for the gas-feed penetration. Here the gas-feed line, the ammonia vacuum line, and the main vacuum line are connected to the tank. The plate on the east end holds the support for the ignition source. There is a 10-3/4-in by 19-in manhole on the south side of the tank and a 6-in, Schedule 80 flange on the north side.

The electric spark generator is designed to store 10 J of energy, the amount delivered to the reactants is somewhat smaller. The spark gap is located near the tank center within the field of view of the video system. The electrodes are each 3.2 mm in diameter and 50-mm long, so the flame ball can expand with minimal interference from the electrode supports. The cathode of the spark source is a modified automotive spark plug which has the anode removed and a piece of steel rod welded onto the spark electrode. The spark plug is then threaded into a Teflon cap, which is sealed on the end of a 50-cm section of schedule 80 stainless steel pipe. The opposite end of this pipe is threaded with 1-1/4 pipe thread and screwed into the end cap on the tank. This provides a sturdy support for the spark assembly. The anode is a 4-inch stainless steel, 6-32 threaded rod screwed to a frame constructed to keep the anode centered with the cathode. The electrode spacing or gap for these experiments is 6.35 mm. A schematic of the system is shown in Fig. 2.5.

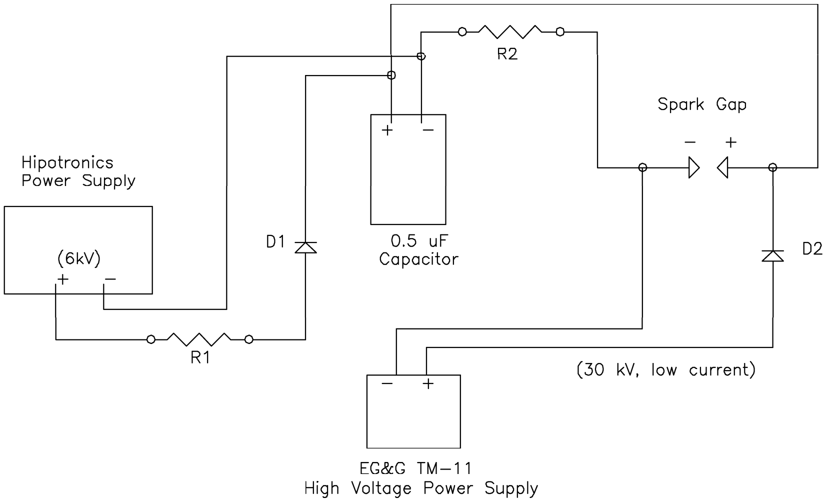


Figure 2.5: Ignition system for 10-J, 100 μs spark generation.

The power for the spark is provided by a capacitor discharge system which consists of two parts, an EG&G TM-11A Trigger Module, and a 0.5-μF capacitor charged by a Hipotronics 15 kV power supply. The circuit is similar to the design described in Ronney [1985]. When the system is turned on, the Hipotronics power supply charges the capacitor through charging resistor R1 and diode D1. Diode D2 prevents the charging current from being diverted through the TM-11 output transformer.

When the fire button on the control panel is depressed, the TM-11 is triggered producing a 30-kV pulse that passes through D2, but is blocked by D1. This pulse of about 10 mJ initiates the discharge across the gap. This provides a conduction path for the charge stored in the capacitor, and the main discharge occurs through R2 and the gap. Resistor R2 is chosen to give a time constant of about 100 μs, since this has been found to be most effective in initiating flames. The diode D2 prevents the capacitor from discharging into the TM-11 after the spark gap ceases conducting.

After the capacitor is discharged, the power supply then recharges it after a time constant of 5 seconds.

The penetration on the north end of the tank is closed by flange attached with 6, 7/8” UNC bolts on a 9.0-inch diameter bolt circle. On this flange is mounted a 6-inch diameter, 1.0-inch thick, 4.5-inch clear aperture BK-7 glass window used for the schlieren system. The second window for the schlieren system is located at the center of the access cover on the south side of the tank. A penetration for the mixer fan is located to the left of the window, and a hole for the pressure transducer to the right. The mixer fan is constructed of a Parr model A1120HC magnetic drive driven by a universal motor. The motor was run at about 250 rpm for all of the experiments. The impeller is simply two 8-in. blades mounted at a pitch angle of 45 degrees. The magnetic drive is connected to the motor by a belt and pulley system. The motor speed can be adjusted by a light-dimmer control.

A small penetration on the lower south end of the tank was used to support a diesel engine glow plug near the spark source at the center of the tank. The plug is mounted in a fixture and supported by a 19-inch length of 1-inch diameter schedule-80 pipe. The glow plug is used in the event that the spark source fails and a flammable mixture remains inside the tank. The glow plug is powered by a DC power supply that can be activated from the control room.

2.3 Vacuum System

A special exhaust and vacuum system was constructed to contain the ammonia mixtures and prevent gas releases/operator exposure. A schematic of the system is shown in Fig. 2.6. An important feature is a sparger which scrubs the gases of the ammonia before venting to the atmosphere. The sparger is a 5-gallon stainless-steel tank with an O-ring-sealed cover. A bubbler, consisting of a 10-inch length of PVC pipe drilled with 36 3-mm diameter holes, was installed in the bottom of the tank. During operation, the exhaust gases from the experiment are pumped through the bubbler, the sparger, and out the main exhaust vent to the roof level. Each day, the sparger

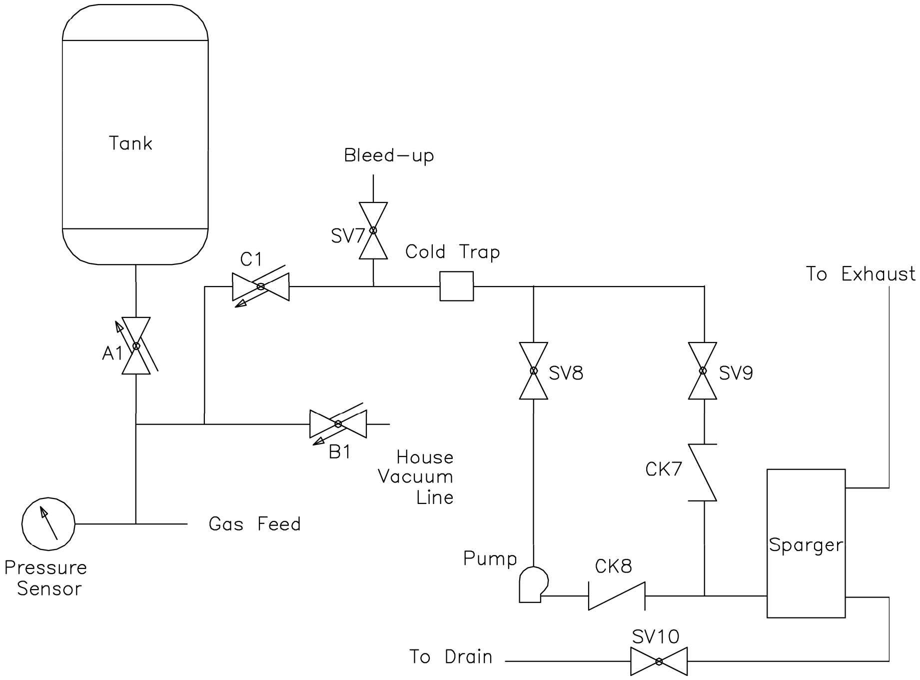


Figure 2.6: Ammonia exhaust system.

is inspected for pH level by an indicator strip. If the pH of the sparger solution is 10 or above, a weak acid (like vinegar) is added to neutralize the solution below to 9. The drain valve is then opened, and the mixture is then disposed of into the sewer. A stream of industrial water is injected into the drain with the sparger waste to dilute the mixture further.

All the plumbing used in the system is CPVC, except for the valves and nipples near the vacuum pump, which are stainless steel. The pump is a Sargent-Welch 1397 with a 17.7 cfm capacity, modified by sealing the exhaust and installing a water drain in the bottom. Since the condensates removed from the tank may contain ammonia, they were not trapped from the exhaust with the cold trap, and would become emulsified in the vacuum pump oil. Also, since the ammonia apparently chemically reacts with the pump oil, this necessitated changing the oil very frequently (every 10 tests when large concentrations of ammonia were used).

2.4 Instrumentation

The CONVOL combustion facility was instrumented with pressure and temperature sensors, as well as a schlieren video system for observing the flame initiation and measuring the flame motion. The location of the sensors is shown in Fig. 2.7. There are two pressure-measuring-devices in use, one static gauge for metering the reactants and measuring the final pressure of the products, and another dynamic gauge used to monitor the tank pressure during the combustion event. The metering gauge is a Heise model 901A digital pressure indicator with a 0-250 kPa range, and an accuracy of ±0.18 kPa (absolute). The gauge used to measure the pressure during the combustion process is a Kulite model XTME-190-250A. This is a piezoresistive type transducer which has a combined nonlinearity, hysteresis, and repeatability of 2.5 kPa. Calibration information is attached in Appendix D. This transducer is protected by two porous metal frits, which are sufficient to shield the instrument from temperature but do not affect the pressure reading.

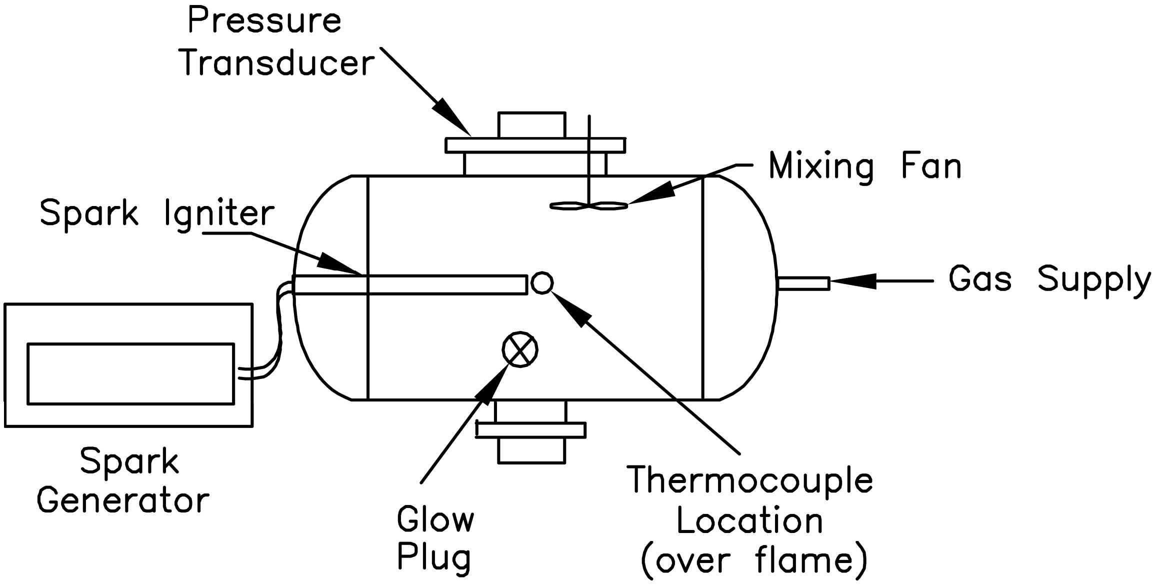


Figure 2.7: Pressure and temperature sensor location.

A thermocouple is installed 75 mm above the center of the spark source. This is an Omega K type thermocouple with a 0.125-in. metal sheath. Each wire is 24 AWG, and the weld bead size is approximately 1.5 mm. The thermocouple output is used to detect the presence of the flame ball as it rises from the spark source. The thermocouple output is also used for measuring the initial and final temperature of the tank contents. An Omega Model DP462 electronic cold-junction and temperature readout was used to convert the thermocouple output to temperature.

The flame ball is observed with a CCD camera at the output of a schlieren system and recorded with a Panasonic Model 1970 VHS system. The optical system is shown in Fig. 2.8. The primary components are the light source, two focusing mirrors, a turning mirror, a knife edge, and the video camera. The light source is an Oriel continuous filament-lamp, with a focusing lens and a pin hole to make a spherically diverging beam. Mirror 1 is an 8-inch diameter, spherical collimating mirror with a focal length of 1.473 m. This is mounted to the north wall of the experimental room, and adjusted so that a collimated beam of light passes through the center line of the tank. Mirror 2 (flat) is located 20 inches from the south window of the tank, and rotates the beam 45 degrees, diverting it to the second focusing mirror, 3, located on the west wall. The beam is focused on the knife edge 78 in. from mirror 3, and the light is directed into the CCD camera. The lens on the camera is a Fujinon model C6X18G-1 television zoom lens with a 6× zoom ratio and a 108-mm focal length. The camera is a Sony CCD model DXC-107A. The framing rate is a 2:1 interlace, 30 frames/sec, which translates into a frame every 16.67 ms. The camera is equipped with an electronic shutter, and the shutter speed of 1/10,000 s was used in the present study.

2.5 Data Acquisition

The pressure and temperature signals were recorded by Labview data acquisition software running on a Gateway P5-100 personal computer. Both the temperature and pressure signals were amplified by signal amplifiers. The thermocouple trace was amplified by a Trig-Tek model 205b, with gain of 100. The tank pressure signal is amplified by a Dynamics 7600A signal conditioner with a gain of 50. Signals are digitized by a National Instruments AT-MIO-64E-3 multi-purpose board sampling at

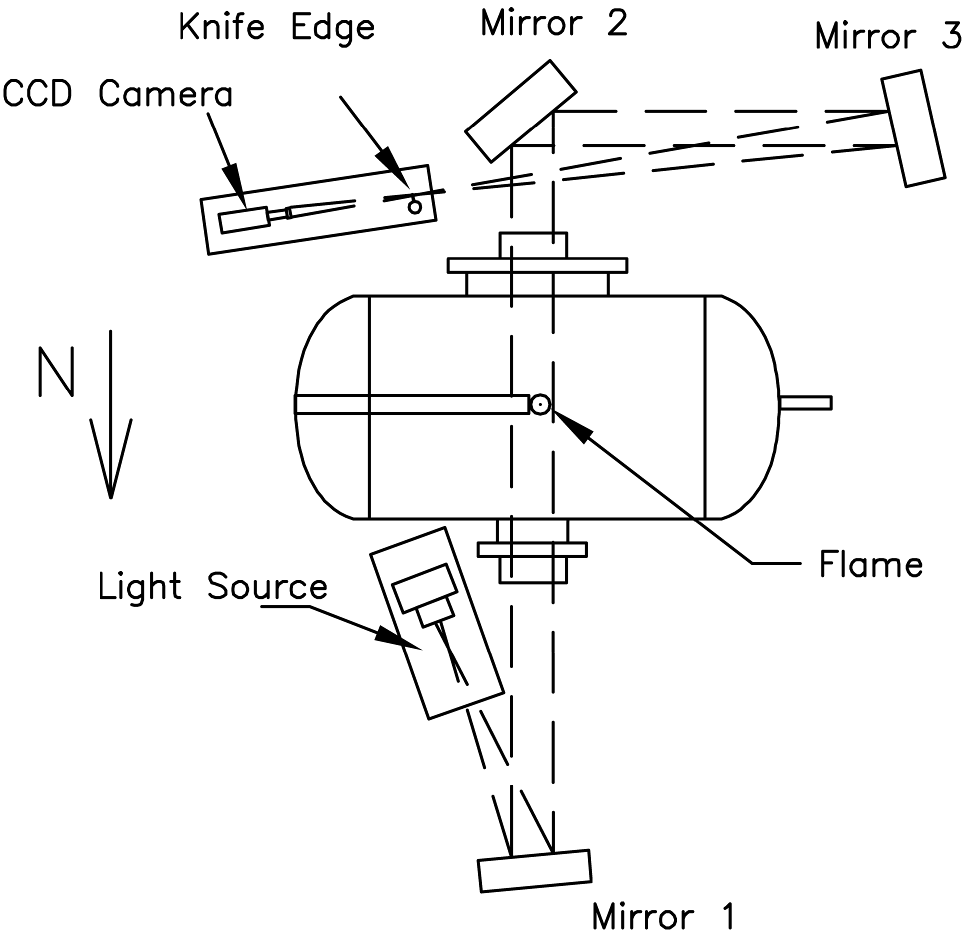


Figure 2.8: Layout of optical path and video equipment.

a rate of 1000 measurements per second. The data acquisition system was triggered by the fire control button for the spark source. The system records data for 16 seconds following the trigger command.

Chapter 3 Experimental Procedure

Each test conducted in the CONVOL facility had an initial pressure of 100 kPa and an initial temperature close to ambient. The mixtures were prepared by metering the gases by method of partial pressures. Checklists were used to ensure that startup, operation, and shutdown tasks were completed. Since the experiment involves many valves, the use of lists ensured that they were opened and closed in specific order. The checklists used in the experiment are shown in Appendix C.

The operator first selects the composition of the mixture and computes the corresponding partial pressures of each component. In the present experiment, the mixtures contained H_2, N_2, N_2O, CH_4, NH_3, and the balance was air. The experiment begins by evacuation of the system and zeroing of the pressure transducer. First, the gas supply plumbing is evacuated and the Heise gauge is set to zero. Second, the tank is evacuated until the pressure approaches .03 to .05 kPa, and the dynamic pressure transducer is zeroed. The operator then isolates the tank from the vacuum pump, and opens the tank air-bleed-up valve. Air is introduced into the tank until the pressure is close to the partial pressure of the air required for the experiment. The bleed-up valve is then closed, and the mixer fan is run to bring the air to thermal equilibrium with the tank. The final increment of air is dispensed using the supply system controls and the house compressed air. The temperature of the room air is then recorded. For this series of experiments, the temperature was normally between 21°C and 27°C. The relative humidity of the room air is controlled between 40 and 50%.

Once the air has equilibrated and the tank pressure has stabilized, the remainder of the gases are dispensed into the tank. Each gas is metered in to 0.15 kPa less than the precalculated value to account for the gas trapped in the supply lines. It was determined that the volume of the gas feed lines is approximately 0.15% of the volume of the tank. The gases are introduced in this order: air, N_2O, NH_3, CH_4, and H_2. Once the the tank has been filled, the tank isolation valve A1 is closed and the mixer is run for two minutes. If the experiment is to attempt a quiescent burn, then the mixer is turned off and the reactants are allowed to settle for one minute. The gas motion can be observed with the schlieren system. If the experiment is to attempt a turbulent burn, then the mixer fan runs throughout the test.

Just prior to ignition, the initial tank temperature is recorded, and the spark system is armed. After arming the data acquisition system (which is triggered by the firing circuit), and starting the video recorder, the fire button is pressed to create the spark discharge. The operator observes the video to determine if ignition took place. If the reactants do not ignite, he waits 5 to 10 seconds and presses the fire button again. This is repeated 4 to 6 times. If no burn is observed, he opens the tank valve and measures the pressure with the Heise gauge and the temperature with the in-tank thermocouple. The tank is then closed off and the mixer turned on. After resetting the DAS and cuing the video, the ignition procedure is repeated. If the reactants do not burn turbulently, fuel is added (usually H_2) and the ignition procedure is repeated. The mixing fan is allowed to run to cool the combustion products. Once the temperature decreases to ~ 30 °C, the fan is stopped and the main tank valve opened. The final pressure is recorded on the metering gauge.

After the final temperature and pressure are recorded, the NH_3 vacuum system is then opened and the products are removed from the tank and vented through the sparger. The video records the time interval from about 5 seconds before ignition to 10 seconds after.

3.1 Test Conditions

The mixtures chosen for the study were all relevant to the Hanford Waste Tank Storage Facility, so the basic constituents were H_2, NH_3, and methane. The oxidizers used are air and N_2O, the diluent used is nitrogen. For a complete listing of test composition, refer to Appendix A. The tests were sequentially numbered starting with 1 and are referred to by this number, also known as the "run number." In some cases, several ignition trials were made for a given mixture and the designator for each trial consists of the run number and an alpha suffix.

Tests previously conducted at the Bureau of Mines [Cashdollar, et al., 1992] on similar mixtures indicate that the N_2O does not participate in the combustion process with lean mixtures. This motivated detailed consideration of the effect of N_2O on lean H_2-air mixtures. The tests carried out can be divided into the following series: 1) H_2-N_2O-air, 2) NH_3-air, 3) H_2-NH_3-air, and 4) H_2-N_2O-NH_3-air mixtures (four sets) with various proportions of air. In some cases, nitrogen was substituted for the N_2O to determine the participation of the N_2O in the combustion process. For the H_2-N_2O series, the H_2 concentrations were fixed at 8 and 9%, with amounts of N_2O varying from 0 to 32%. A total of 13 tests were conducted with these mixtures. The objective of this test series was to determine if the presence of the N_2O affects the downward lean flammability limit of H_2-air mixtures.

The H_2-NH_3-air tests were used to determine the lean flammability limits of the binary mixture. Both the upward and downward propagation limits were determined. A total of 43 tests were performed. Tests 25-37 and 96-125 (see the tables in Appendix A) are designed to test the linear lean flammability rule of Le Chatelier. The flammability limit was bracketed by varying the H_2 concentration in one percent increments. The NH_3-N_2O test series examines lean NH_3-air mixtures with 4 and 8% added N_2O. Sixteen experiments were conducted with added N_2O. Peak pressures and flame speeds were measured to determine the lean limit for both upward and downward propagation.

Of particular interest were "fuel" blends comprised of H_2-N_2O-NH_3 mixtures. A matrix of "fuel" compositions was chosen to cover a broad range of NH_3-H_2 ratios. Four mixtures, defined in Table 3.1, were selected from the cases initially examined in the parametric study of Appendix E. These mixtures are labeled A, B, C and D and the corresponding numeric identifiers of Appendix E are given in Table 3.1. In addition to experimentally determining the peak pressure and pressure history of these mixtures, the objective of these experiments is to determine thresholds of participation for the N_2O in the combustion process.

Table 3.1: Compositions for the H_2-N_2O-NH_3 tests. Designator in parentheses refers to Appendix E.

Mixture	% Hydrogen	% Nitrous Oxide	% Ammonia
A (26)	42	36	21
B (11)	35	35	30
C (12)	25	25	50
D (20)	16.7	33.3	50

note: Mixture A included 1% Methane

Forty-five experiments were performed for mixture A, the conservative estimate for the gas release in Tank 101-SY. The release gas simulant is composed of 42% H_2, 36% N_2O, 21% NH_3, and 1% methane. In this experiment, turbulent combustion tests were performed from the point of no flame propagation up to 30% "fuel" in air. To determine the N_2O participation threshold, nitrogen was substituted for the N_2O for 12 of these tests. These experiments were used to locate the N_2O participation threshold. Finally, seventeen quiescent tests performed on this mixture, which were used to estimate the propagation limits and the flame speed.

Fifteen experiments were executed for mixture B, which contains 35% H_2, 35% N_2O, and 30% NH_3. Quiescent, turbulent, and nitrogen substitution tests were conducted for all of these compositions. Eighteen experiments were done on mixture C, composed of 25% H_2, 25% N_2O, and 50% NH_3. Finally, seventeen tests were performed on mixture D, containing 16.7% H_2, 33.3% N_2O, and 50% NH_3. The primary objective is to cover a range of H_2-NH_3 ratios to adequately test the participation of the N_2O in the combustion process. The mixtures studied can be represented by lines on a H_2-NH_3 composition plane, shown in Fig. 3.1.

The above tests composed the majority of the experiments performed. There was also a humidity study which was done for selected H_2-air cases, and two cases using mixture D. The air was saturated by use of a sparger (of similar design to the one used in the vacuum exhaust) containing water at 50 °C. The air was drawn through the sparger before entering the tank to ensure saturation. Eleven tests were conducted on the humidity experiment. Four on H_2-air (dry), five on H_2- air (saturated), and

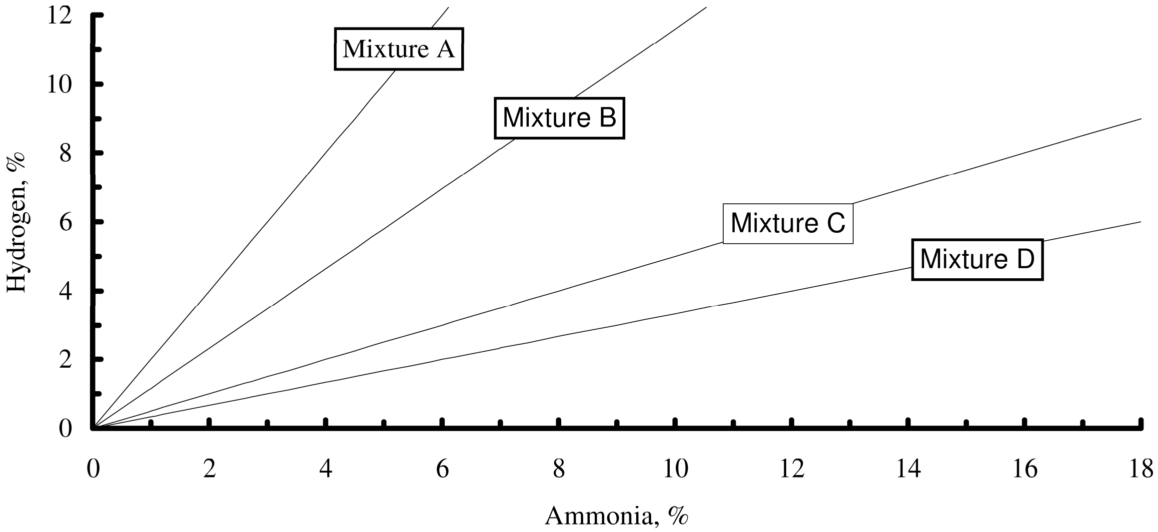


Figure 3.1: Mixtures examined in N_2O reactivity test series.

two on mixture D.

Finally, other miscellaneous tests performed include CH_4-air, and a mixture modeled after the retained gas sampler container [Shepherd and Ross, 1995]. For the CH_4-air case, the upward flammability limit was verified as 5.5% CH_4. The downward propagation limit was found for the retained gas sampler mixture, composed of 33% H_2, 53% N_2O, and 14% NH_3. Runs 38 - 44 (seven total) were performed for the retained gas sampler study.

Chapter 4 Results

The key results of the experiments are summarized in this chapter. A full listing of all experiments and key data are given in Appendix A. A complete set of data plots is given in Appendix F. The flame speed data are supplied in tabular format in Appendix B.

4.1 H_2-N_2O-Air

A series of tests were conducted to investigate the influence of N_2O addition on H_2-air mixtures near the downward propagation limit of H_2 (8 - 9%). The relevant run numbers are 11 - 24. The concentrations of N_2O tested were 8, 12, 16, 24, and 32%, and the balance of the mixture was air and H_2. Peak pressures as a function of N_2O concentration are shown in Fig. 4.1 for the 8% H_2 tests. All of these cases were ignited in a quiescent mixture, but turbulent motion was needed to propagate the flame throughout the volume and consume all of the fuel. In a quiescent mixture, a rising flame "ball" of limited extent (see Fig. 1.2) was produced. The flame quenched when it reach the top of the vessel so that only a small portion of the mixture actually burned. The pressure rise in those cases was extremely low, usually on the order of 0.1 bar.

Figure 4.1 reports the results of burns in turbulent mixtures. The results are compared with equilibrium adiabatic pressure computed by STANJAN. Various assumptions were made about the reaction of N_2O were made in these computations. The solid line represents a full dissociation of the N_2O, the middle line the H_2 only reacting with N_2O, and finally, the small dashed line with negative slope shows the pressure for no reaction with N_2O or dissociation, only reaction with oxygen.

Figure 4.2 shows the pressure histories as a function of time for selected 8% H_2 cases. The pressure histories are independent of N_2O concentration up to 32%. We

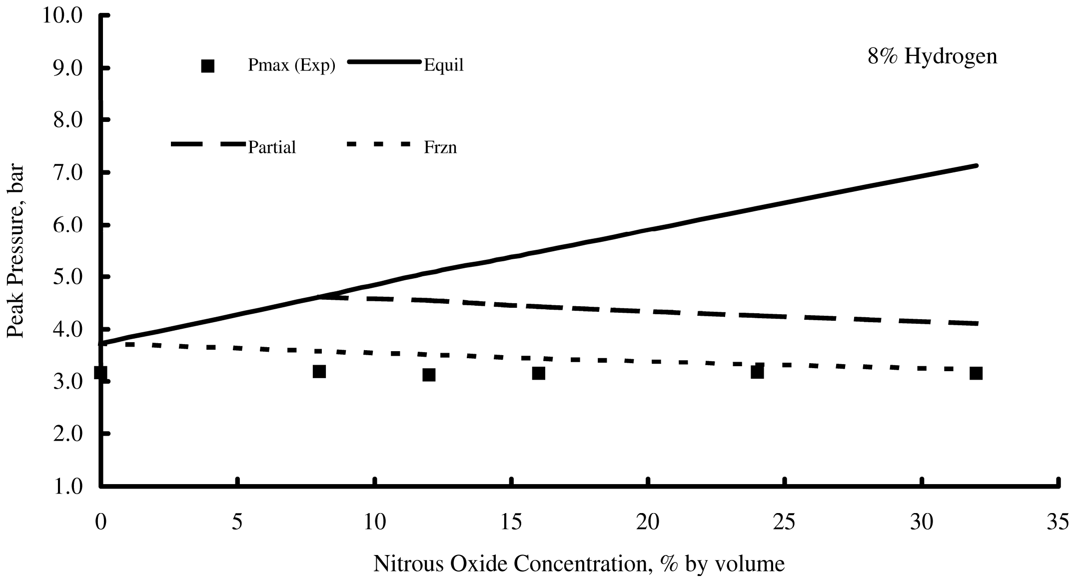


Figure 4.1: Peak pressure vs. N_2O concentration of 8% H_2 mixtures. The trend indicates little or no participation of the N_2O in the combustion process, especially no dissociation of the N_2O.

conclude that the molecular O_2 is serving as the oxidizer rather than the oxygen in the N_2O and that the N_2O does not decompose. This is confirmed by the final pressure results shown in Fig. 4.3. The final pressures are essentially independent of the N_2O concentration. The final pressures were estimated by constant volume equilibrium computations using the measured final temperature of about 30 °C. The three estimates shown correspond with full dissociation of the N_2O, H_2 reacting with the N_2O only, and H_2 reacting only with the O_2 molecules.

Similar tests with the H_2 concentration fixed at 9% were also performed using the same procedure. These cases, unlike the 8% cases, completely burned the tank contents under quiescent initial conditions. The measured peak pressures and computed adiabats are shown in Fig. 4.4. The adiabats were computed in the same manner as the 8% case. Here, a greater variation is observed with increasing N_2O concentrations. The pressure histories, shown in Fig. 4.5, are not coincident as in the 8% case. The measured and estimated final pressures vs concentration plot is shown in (Fig. 4.6). indicate minimal participation of the N_2O in the combustion process.

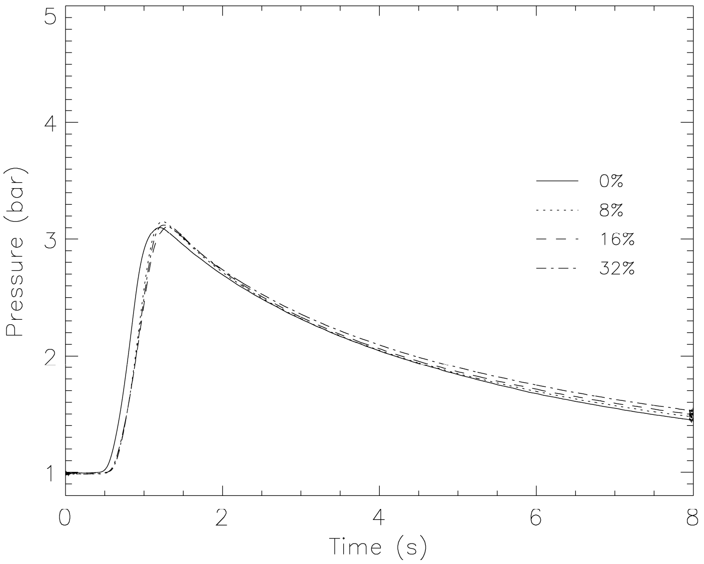


Figure 4.2: Pressure vs. time for the 8% H_2 in N_2O-air mixture. The fact that the histories overlap indicates the inert character of the N_2O in these mixtures.

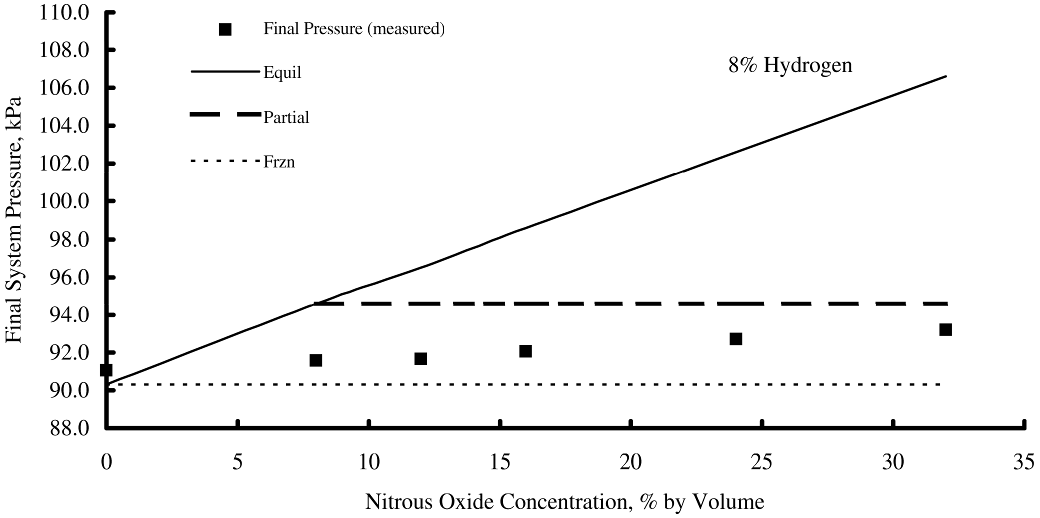


Figure 4.3: Final pressure vs. concentration of N_2O for 8% H_2 in air. This affirms the hypothesis that minimal dissociation of the N_2O occurs.

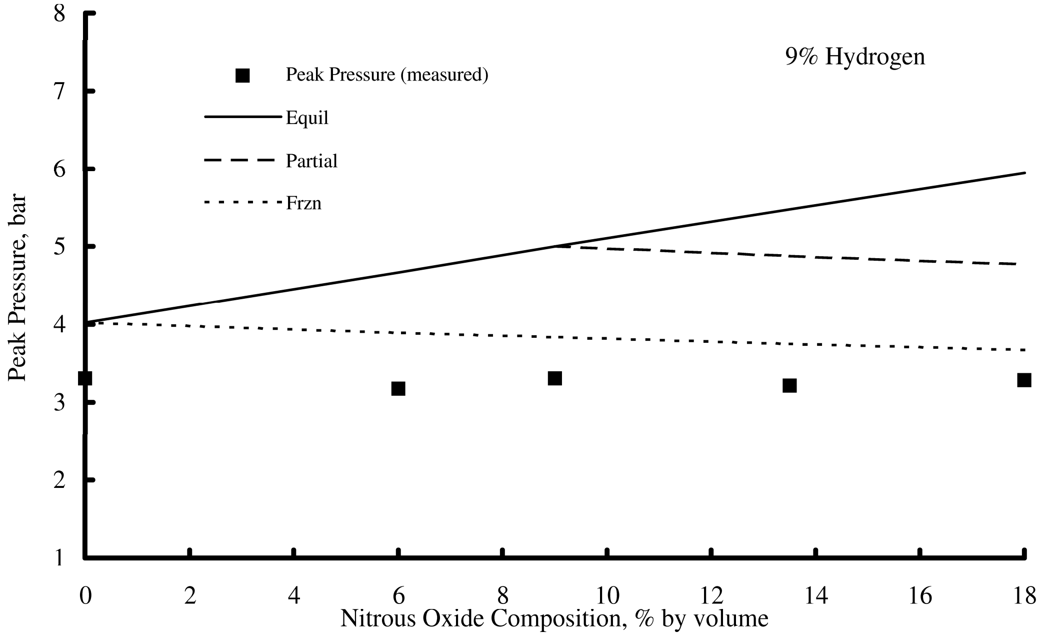


Figure 4.4: Peak pressure vs. concentration of N_2O for 9% H_2 in air, quiescent combustion.

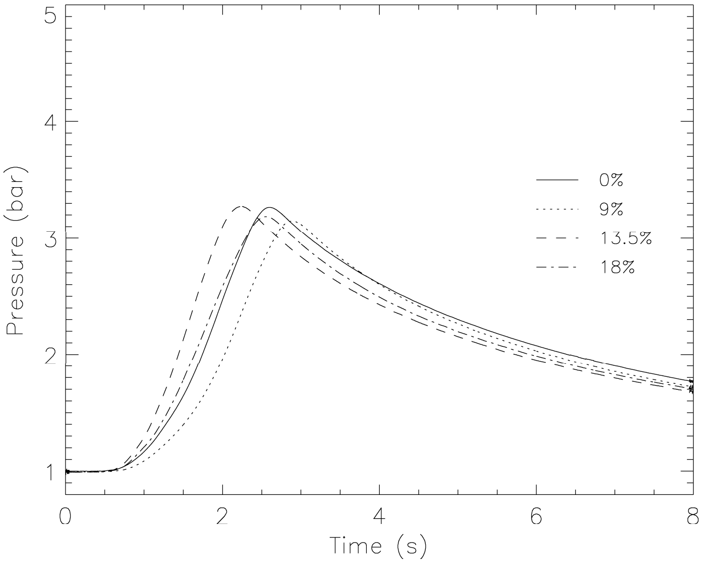


Figure 4.5: Pressure vs. time for 9% H_2 in N_2O-air mixture, quiescent combustion. Results indicate consistent peak values, but more variation in the histories than was observed in the 8% H_2, turbulent case.

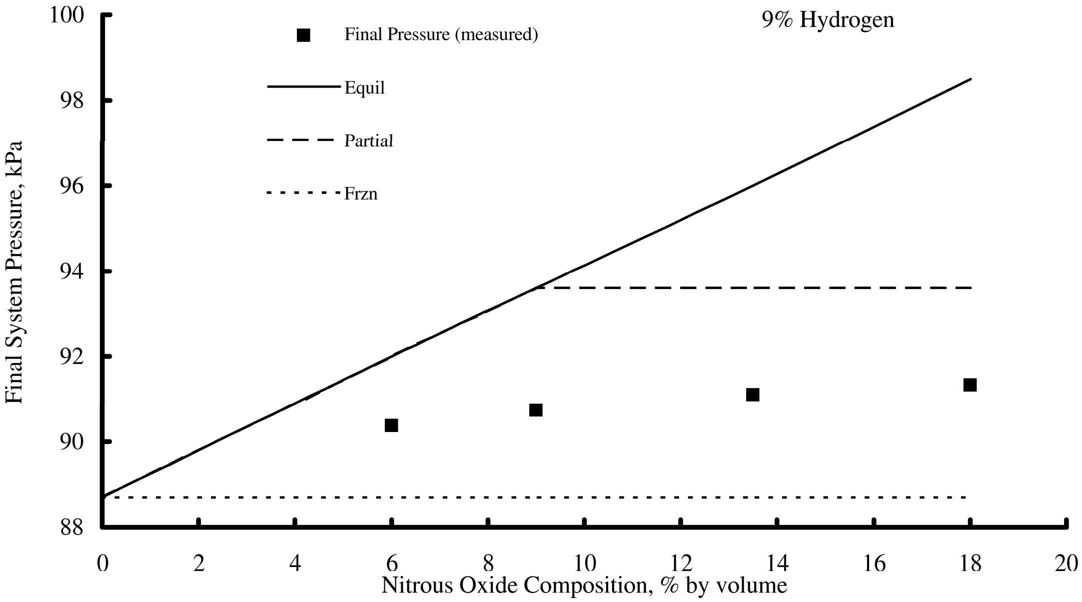


Figure 4.6: Final pressure vs. concentration of N_2O for 9% H_2 in air, quiescent combustion.

4.2 NH_3-H_2-Air

A series of experiments were designed to compare the flammability limits in the Caltech CONVOL vessel with those published in earlier work [Coward and Jones, 1952, Fenton, et al., 1995]. Experiments 25 - 37 and 96 - 125 were conducted to test the applicability of Le Chatelier's principle for the NH_3-H_2-air mixture. Published NH_3-air lean flammability limits were also verified. Measured peak pressures are shown in Fig. 4.7. The leanest mixture that would propagate throughout the vessel under quiescent conditions is 18%, which corresponds to the accepted value of the horizontal propagation limit (18.2%, [Coward and Jones, 1952]). The minimum NH_3 -air mixture concentration that would burn turbulently is 15%, which is close to the accepted value (16.1%, [Coward and Jones, 1952]) for the upward propagation limit. A propagating reaction was observed with the schlieren system at the 14% NH_3 level. This is below most accepted values of upward propagation of NH_3-air listed in [Fenton, et al., 1995], but our schlieren system is substantially more sensitive than previous techniques used to establish limits. No reaction was detected at 13%.

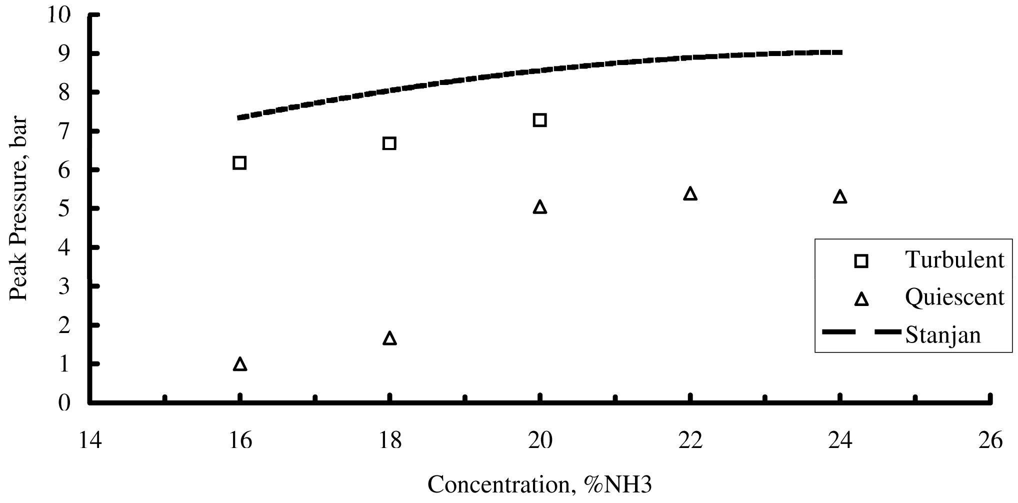


Figure 4.7: Peak pressure vs. concentration of NH_3 in air. Quiescent and turbulent cases.

Pressure histories are shown in Fig. 4.8 and flame speeds are shown in Fig. 4.9.

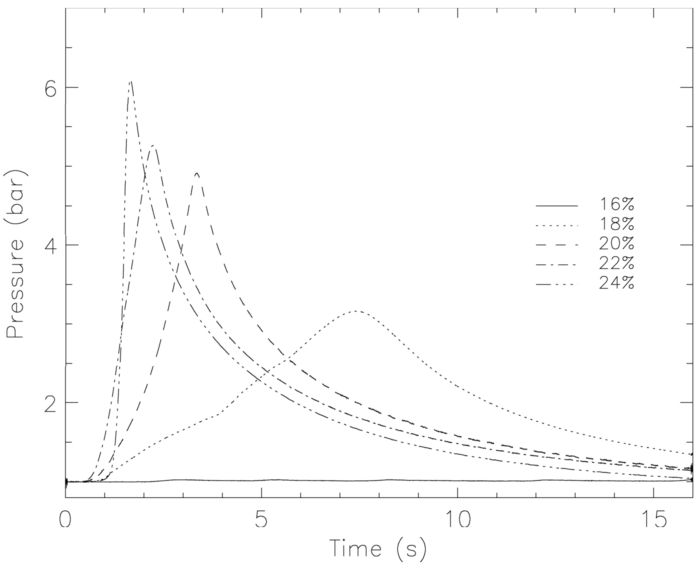


Figure 4.8: Pressure histories vs. time of NH_3 in air. Quiescent combustion. Results show a marginal burn at 18% NH_3, which agrees with the downward limit published in the literature.

Data from Ronney's study (1988) of NH_3-air flames in microgravity are also shown. The uncertainty in the burning velocity using our technique has not been quantified, but this comparison shows that our values are within ±1 cm/s of the microgravity measurements.

To complete this study, we examined the upward and downward propagation lean limits for the binary fuel H_2-NH_3. The concentration of H_2 was varied in 2% increments and the NH_3 in 1% increments. Using Le Chatelier's rule as a guide, the upward and downward propagation limits were bracketed. Results are shown in Fig. 4.10. The data symbols in this graph indicate the experimental conditions closest to the lean combustion phenomenon. The linear H_2-NH_3 relationship for the limits indicate that Le Chatelier's rule for binary mixtures is appropriate for this system.

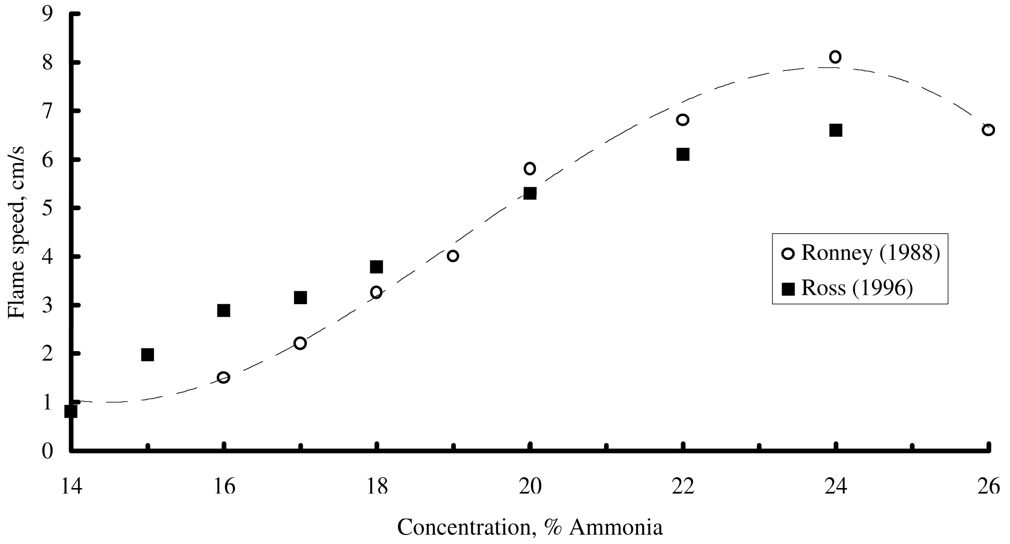


Figure 4.9: Burning velocity vs. concentration of NH_3 in air. Data from Ronney's microgravity experiments are also plotted.

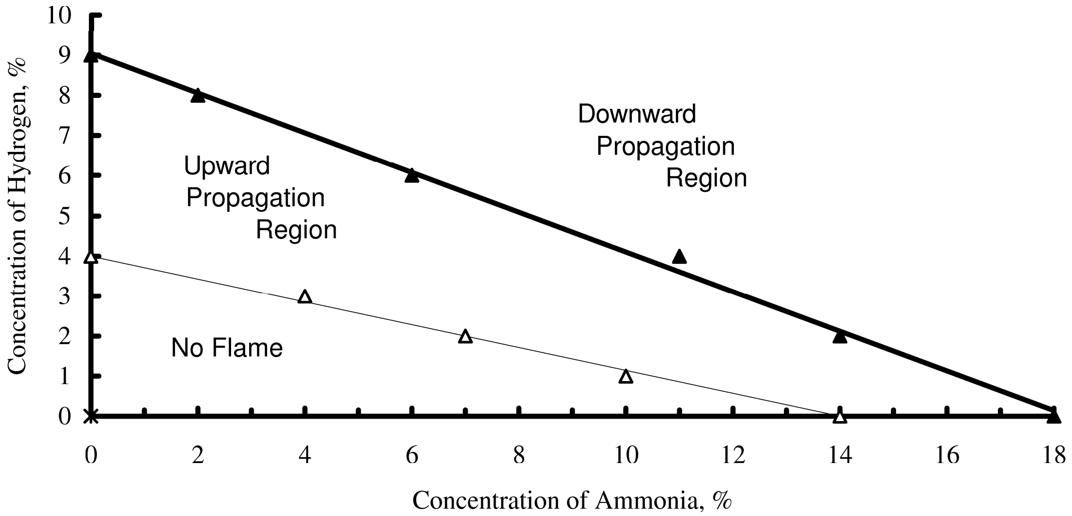


Figure 4.10: Upward and downward propagation limits for NH_3-H_2-air mixtures.

4.3 NH_3-N_2O-Air

NH_3-air-N_2O tests were conducted over the range of 12-18% NH_3. Two N_2O concentrations were used, 4% and 8%. All of these tests were carried out with quiescent initial conditions. Seventeen tests (175 - 179, and 186 - 197) were conducted. Peak pressure results are shown in Fig. 4.11. The peak pressure results for NH_3-air are also shown. The results indicate that the downward propagation limit of NH_3 is decreased as N_2O is added to the mixture.

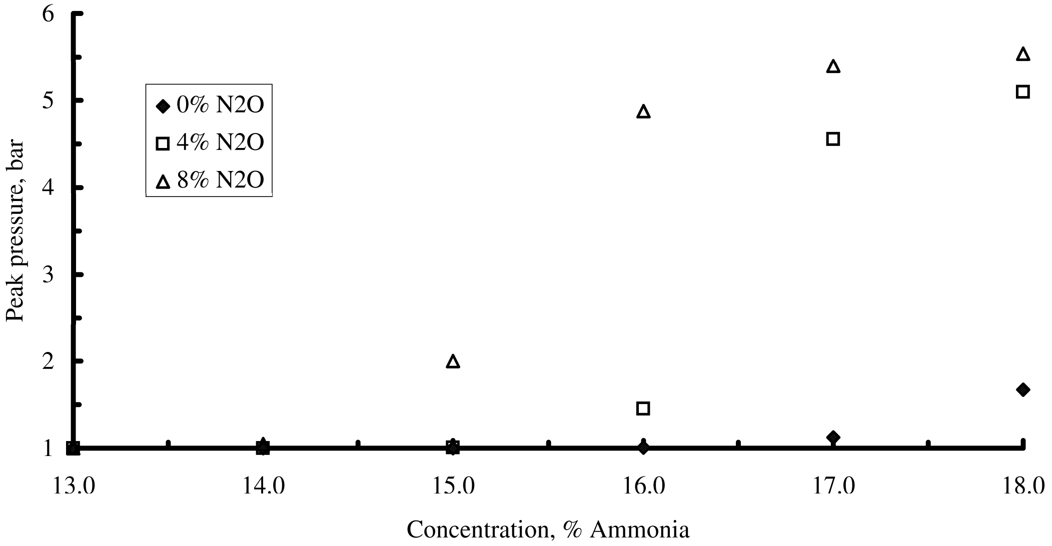


Figure 4.11: Peak pressure vs. NH_3 concentration for NH_3-N_2O-air mixtures.

Addition of N_2O resulted in a significant increase in the peak pressures for a given NH_3 concentration. The downward propagation limit decreased from 18% NH_3 to 15% with the addition of 8% N_2O. The peak pressures are still substantially lower (1-2 bars) than the computed adiabatic values, indicating that heat transfer and/or partial flame propagation through the volume occurred. We attribute the decrease in the downward limit as being due to an increase in the temperature of the combustion products as a result of N_2O addition. Burning velocity and density ratio (ρ_u/ρ_b) both increase with increasing flame temperature. This results in a higher value of apparent flame speed, dR/dt, and enhanced propagation. We expect that addition of larger amounts of N_2O will have an even greater effect on the downward flammability limit of NH_3-air. This explanation is based on the result of Jones and Kerr [1949] who found a downward flammability limit of 7% NH_3 in pure N_2O. Craven and Grieg (1968) were able to obtain a detonation in a 3-in. diameter, 100-foot-long pipe with 12% NH_3 in N_2O mixture. On the other hand, there have been no reported detonations in stoichiometric NH_3-air mixtures. Extrapolation of O_2-enriched N_2-O_2-NH_3 mixture data indicates a cell width of about 60 cm, comparable to stoichiometric CH_4-air mixtures, which are very difficult to detonate [Benz, 1988].

The pressure histories for 4 and 8% N_2O addition are shown in Figs. 4.12 and 4.13.

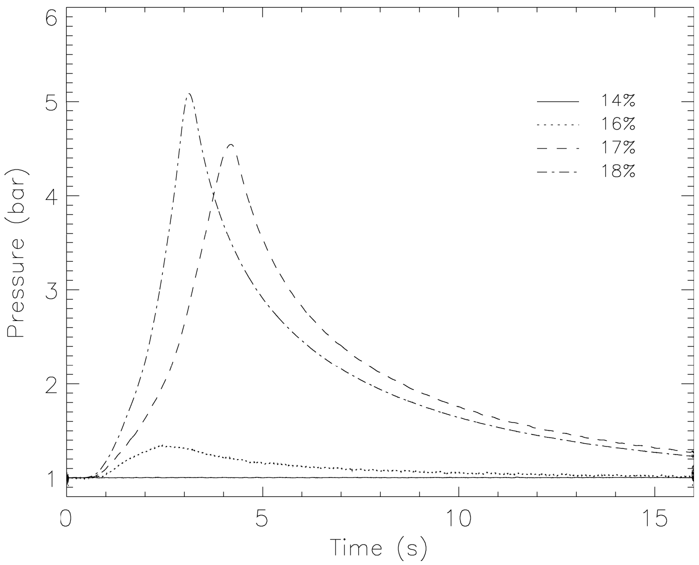


Figure 4.12: Pressure histories of NH_3-N_2O-air, 4% N_2O.

The burning velocities are summarized in Fig. 4.14. The addition of the N_2O appears to increase the burning velocity by a factor of 2 with the 8% N_2O from the NH_3-air case. The burning velocity is approximately 4 cm/sec at the downward propagation limit for this mixture.

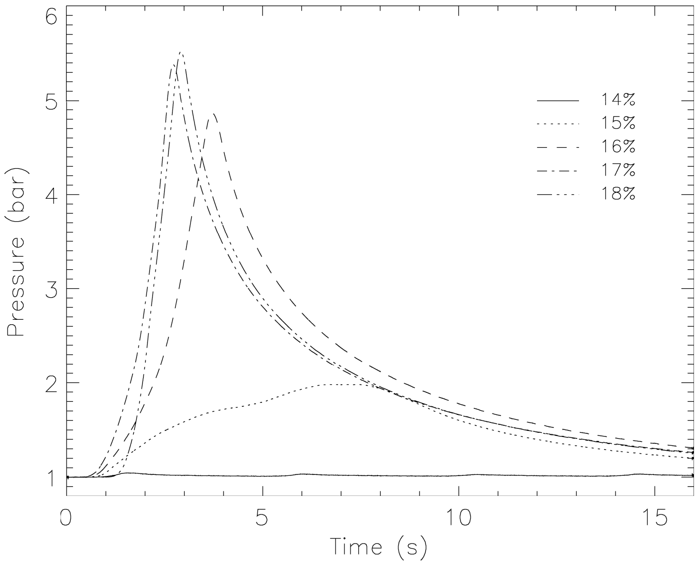


Figure 4.13: Pressure histories of NH_3-N_2O-air, 8% N_2O.

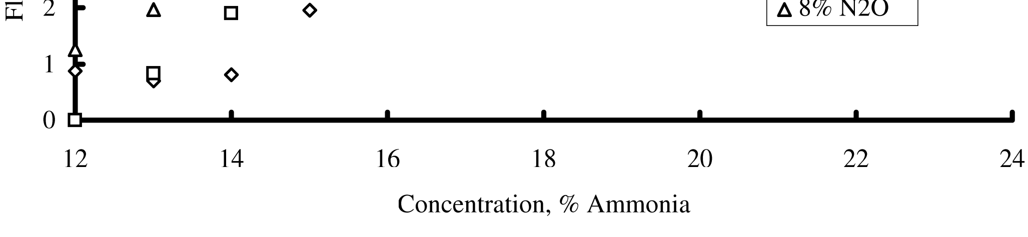


Figure 4.14: Burning velocity vs. concentration of NH_3 for NH_3-N_2O-air

4.4 H_2-N_2O-NH_3 Mixtures

In previous tests discussed in Section 4.1, it was shown that near the lean limit of H_2(8-9%), replacing air with N_2O had little effect. This is shown graphically in Fig. 4.15. However, near the lean limit of NH_3, the N_2O was found to participate readily in the reaction and substantially influences the lean limit, as shown in Fig. 4.16. Based on our results and data of previous investigations, a simple picture of the propagation limits emerges. In this approximate model the downward propagation limit for both the H_2 and the NH_3 decreases linearly with the N_2O concentration:

$$X_{H_2,DPL} = 0.08 - 0.02X_{N_2O} \tag{4.1}$$

$$X_{NH_3,DPL} = 0.18 - 0.15X_{N_2O}. \tag{4.2}$$

These are the approximations to the experimentally measured limits [Scott, et al., 1954, Jones and Kerr, 1949].

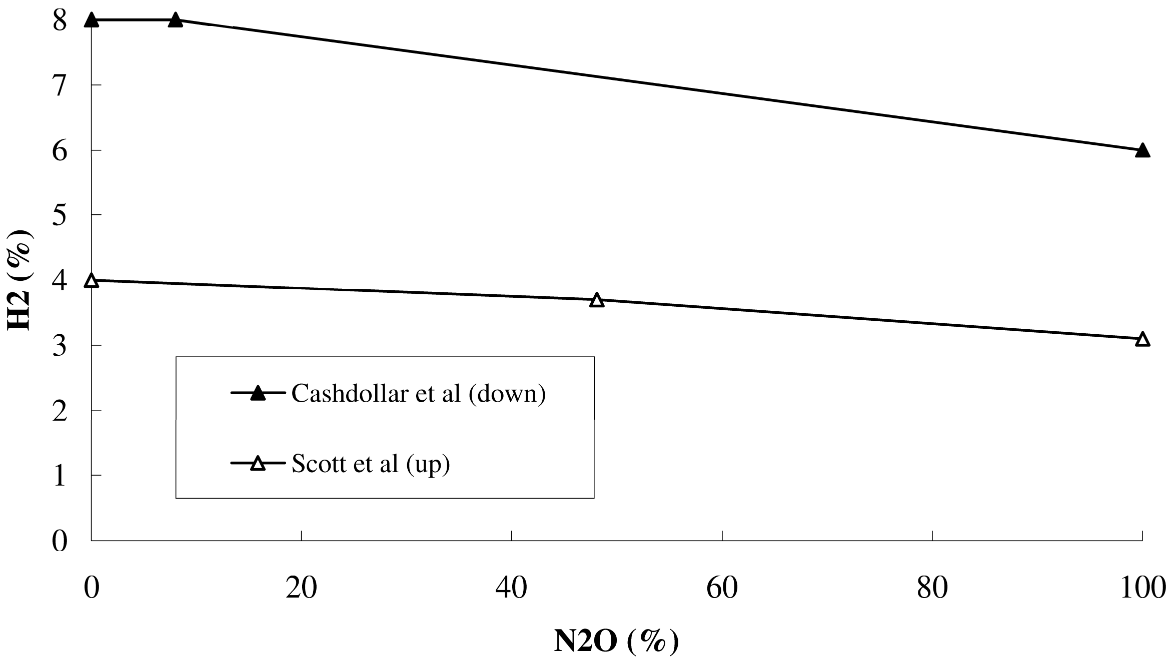


Figure 4.15: Propagation limits for lean H_2-N_2O-air mixtures

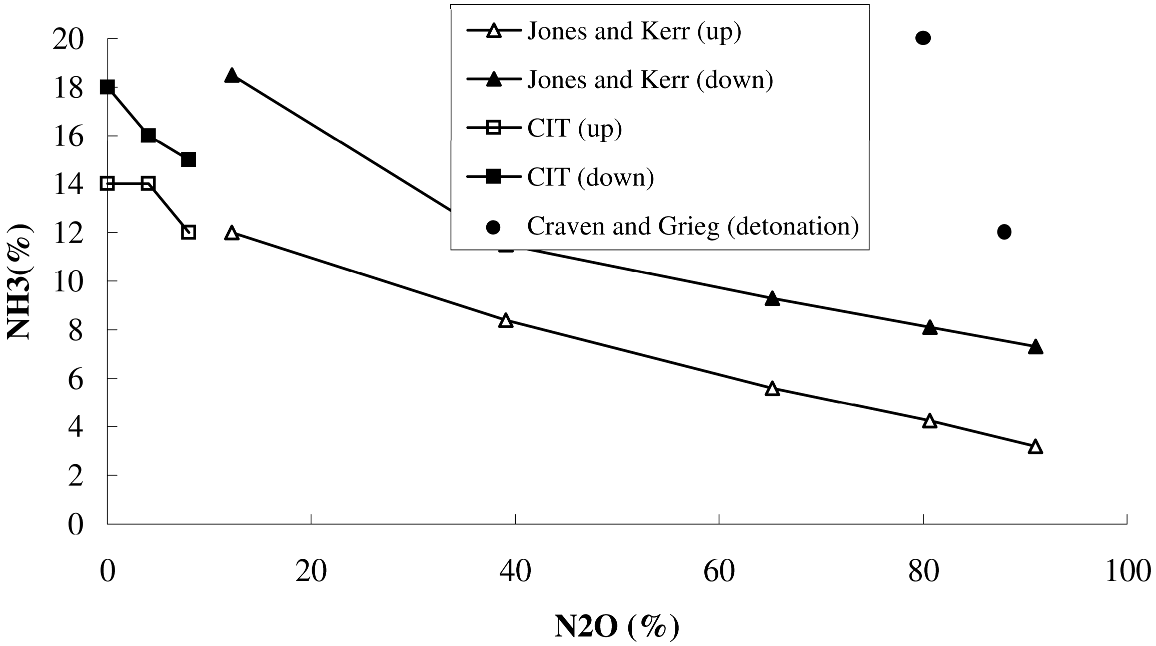


Figure 4.16: Propagation limits for lean NH_3-N_2O-air mixtures

In the absence of N_2O the present results imply that Le Chatelier's rule applies to the H_2-NH_3-air system. Making the admittedly crude approximation that this also applies to systems with added N_2O, the approximate limiting compositions for downward propagation can be estimated as shown in Fig. 4.17 and 4.18. Added N_2O clearly sensitizes all mixtures, but as observed in the experiments, has a much greater effect on the NH_3-air mixtures.

In order to examine the effect of N_2O addition systematically, four compositions were chosen for further study, described previously in Table 3.1. A series of tests were carried out to study the combination of each mixture with various amounts of air. The upward and downward propagation limits were measured for each mixture. Burning velocities were measured in quiescent mixtures. Peak and final pressures were measured for turbulent burns. Some tests are repeated with N_2 substituted for the N_2O to identify the participation limit of the N_2O. These points are indicated by the open symbols on the peak and final pressure graphs.

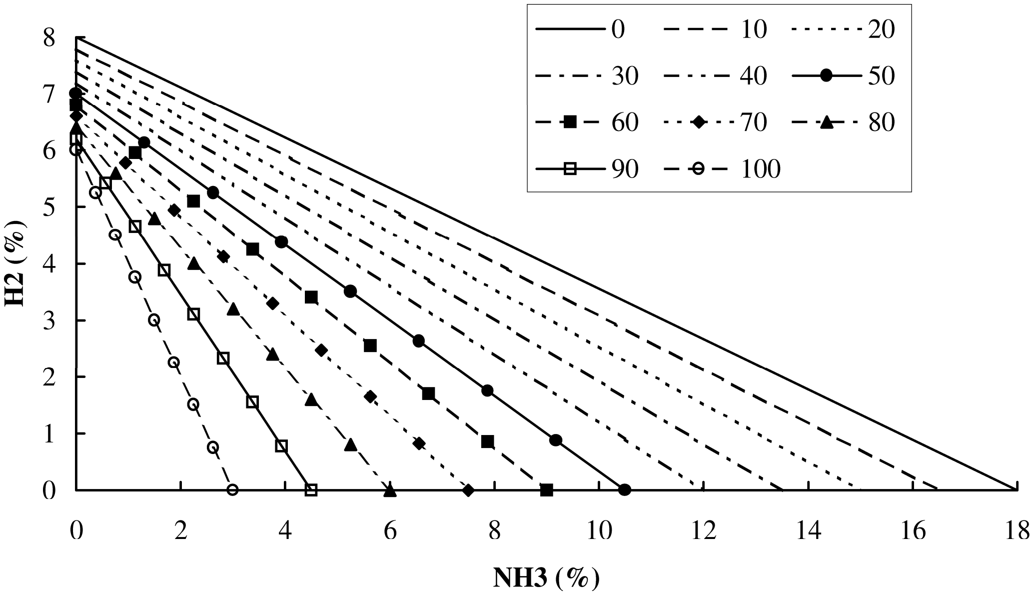


Figure 4.17: Downward propagation limit of H_2-NH_3-N_2O mixtures in air for 10% increments of N_2O.

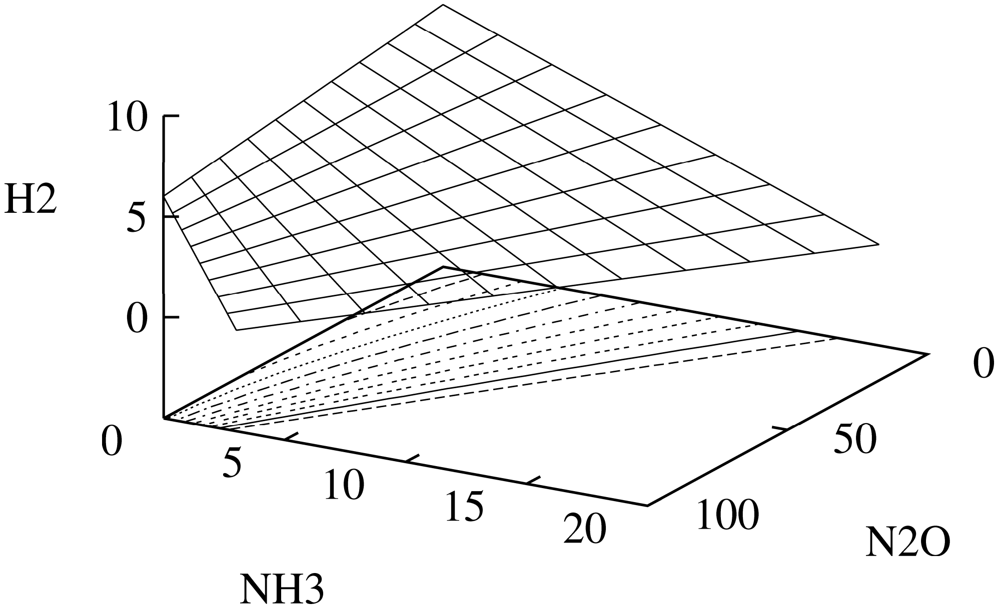


Figure 4.18: Three-dimensional surface of the downward propagation limit shown in Fig. 4.17.

4.5 Mixture A - 101-SY Estimate

Mixture A is a conservative estimate of the release gas composition from Tank 101-SY. The fuel composition is: 42% H_2; 36% N_2O; 21% NH_3; and 1% CH_4. Since this tank has been considered extensively in safety assessments, we have done a thorough study of the combustion behavior of this composition mixed with air. The mixture was burned under turbulent conditions in tests with between 7% to 30% mixture in air. Runs 51 - 95 were dedicated to studying mixture A. Nineteen experiments were conducted with the mixer fan on (turbulent burns). Seventeen experiments were quiescent and ten were turbulent conducted with N_2 substituted for the N_2O. Results are plotted in Fig. 4.19.

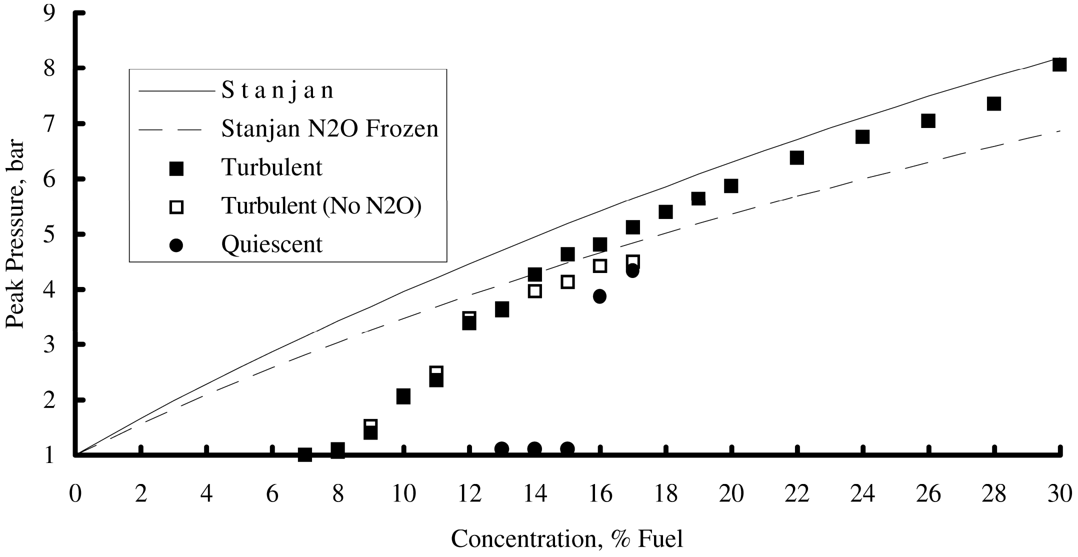


Figure 4.19: Mixture A. Peak pressure vs. concentration. Quiescent, turbulent, and turbulent with N_2 substituted for N_2O results are shown.

This figure and the final pressure results in Fig. 4.23 clearly indicate at 13% fuel, the N_2O begins participating in the combustion process. This is reflected in the pressure histories shown in Figs. 4.20-4.22. The dramatic change in pressure signal at the downward propagation limit is demonstrated in Fig. 4.20, where a complete burn is observed in the tank for 16% mixture. Further investigation showed the downward flammability limit to be closer to 15.25% (see runs 63, 64).

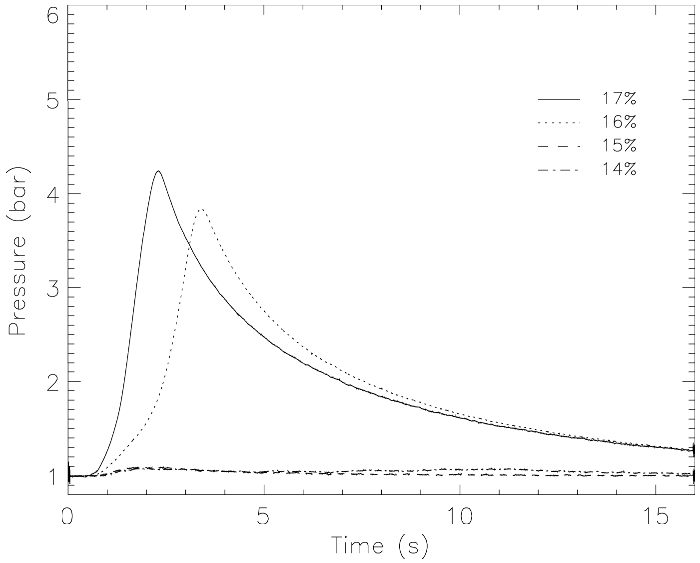


Figure 4.20: Mixture A. Pressure vs. time plots for quiescent cases. These include cases from 14 to 17% mixture, the lean flammability limit was determined to be near 15.25% for this mixture.

Figures 4.21 and 4.22 show a composite of pressure histories for mixture A, with fuel concentrations between 10% to 30% and the fan operating (turbulent burns).

The final pressure is shown as a function of concentration in Fig. 4.23. The dashed line is the value of the final equilibrium pressure predicted by STANJAN if the N_2O is inert, and the solid line corresponds with complete combustion. Only turbulent cases are plotted.

Figure 4.24 shows the burning velocity vs. concentration curve for mixture A. A burning velocity of 4 cm/s is measured at the downward propagation limit. For mixture A, the upward propagation limit is at 8%. No ignition was detected by the schlieren system at 7%. The downward propagation limit is 15.25%, where the flame propagated through the tank in a laminar fashion. Finally, the N_2O participation limit is near 13%, where peak and final pressure differences from the turbulent burns with and without N_2O are first observed.

Le Chatelier's rule based on the measured H_2-NH_3-air limits predicts the upward and downward limits reasonably well for this mixture. (see Fig. 4.34) The downward

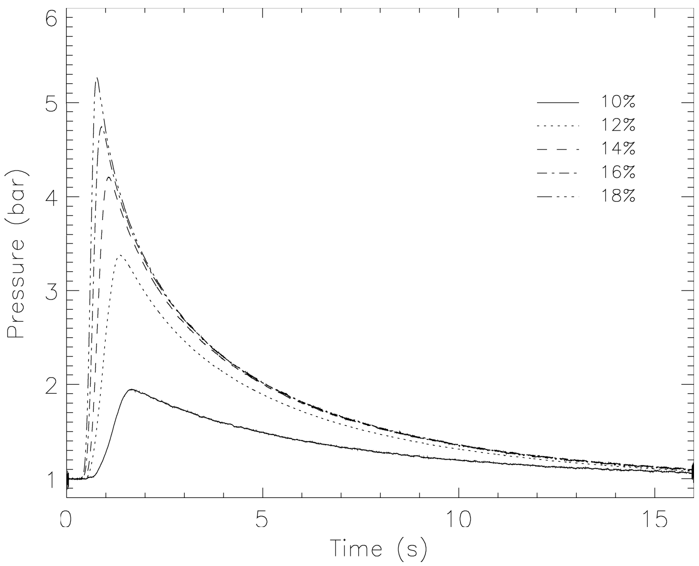


Figure 4.21: Mixture A. Pressure vs. time curves for lean turbulent cases (10 - 18%).

limit is slightly displaced from the limit line at 15.25% because N_2O is participating at this point and this affects the downward propagation limit.

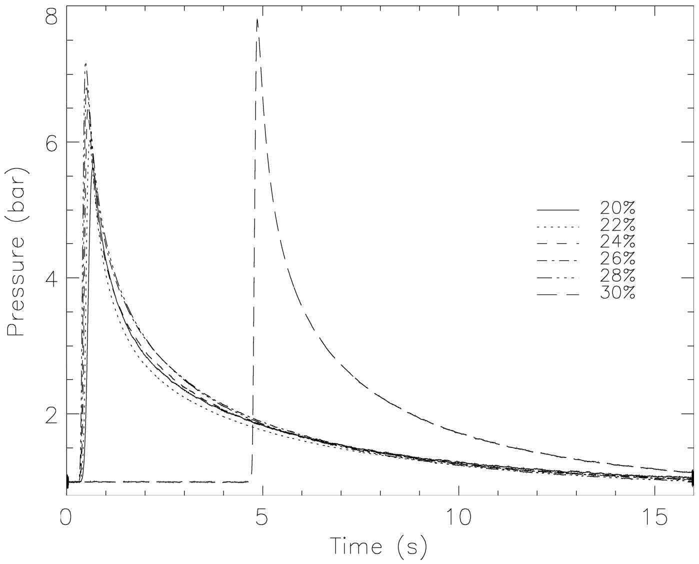


Figure 4.22: Mixture A. Pressure vs. time curves for richer turbulent cases (20 - 30%). The 30% case is offset because the spark generator did not ignite the mixture on the first attempt.

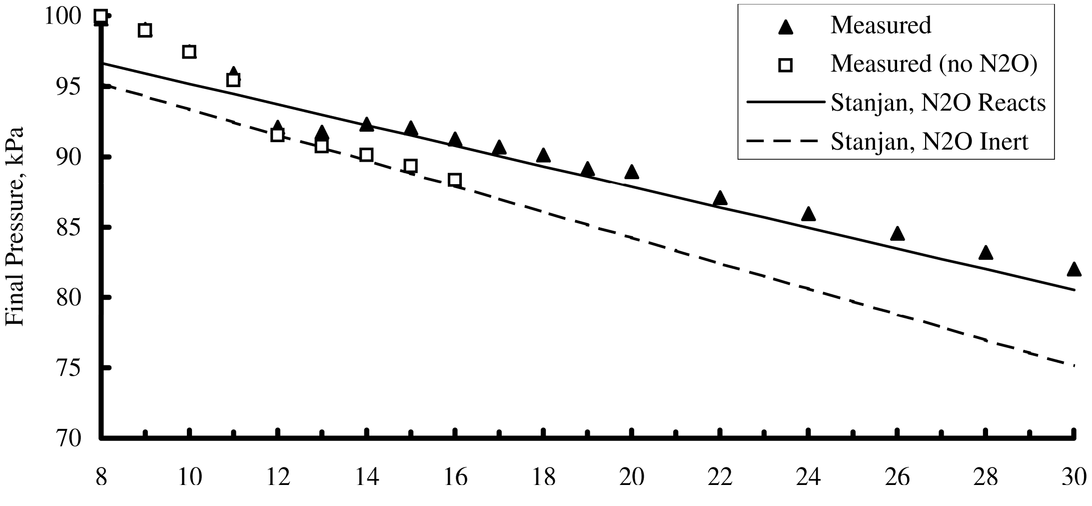


Figure 4.23: Mixture A. Final pressure vs. concentration for conservative estimate of release gas in tank 101-SY.

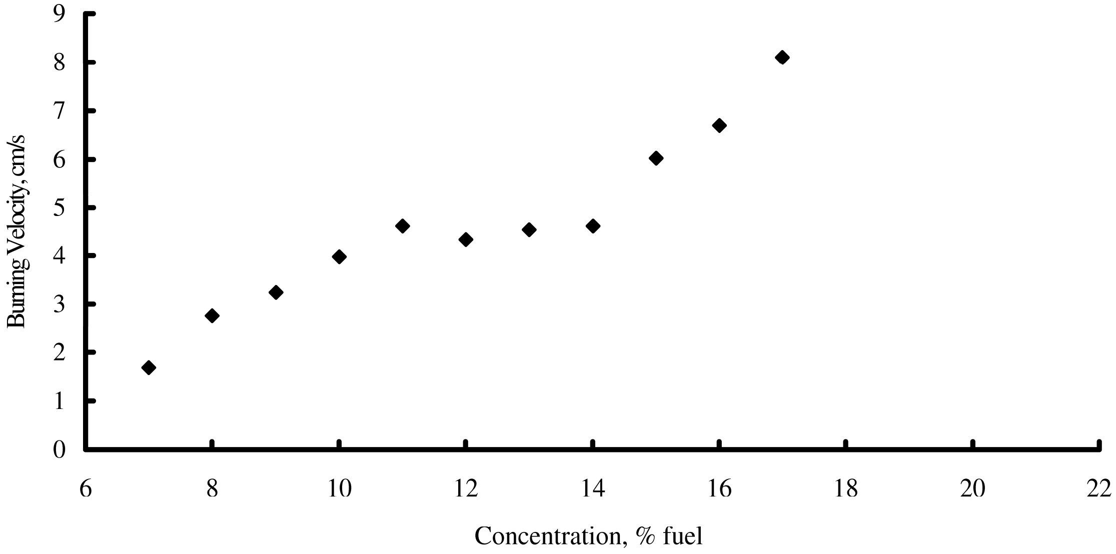


Figure 4.24: Mixture A. Burning velocity vs. concentration of fuel in air.

4.5.1 Mixtures B, C, and D

In order to more completely characterize the H_2-N_2O-NH_3 compositions, three other mixtures were tested.

Mixture B The fuel composition of mixture B was 35% H_2, 35% N_2O, 30% NH_3. This mixture has a higher NH_3 to H_2 ratio (approximately 1:1) than mixture A. Sixteen experiments on mixture B were conducted. Four were turbulent, seven were quiescent, and five were turbulent with N_2 substituted for the N_2O.

Peak pressure vs concentration is shown in Fig. 4.25 for turbulent and quiescent cases. These results indicate that the downward limit is near 15%, and the N_2O participation limit is also close to 15%. The upward propagation limit, determined by the schlieren system, was about 9%.

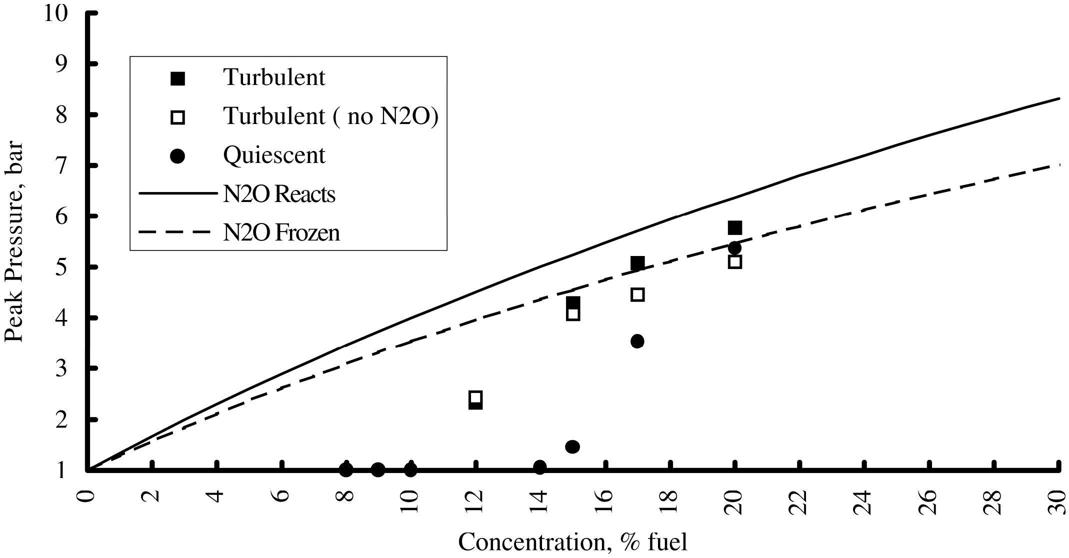


Figure 4.25: Mixture B. Peak pressure vs. composition. Fuel composition: 35% H_2, 35% N_2O, 30% NH_3.

Final pressures vs. concentrations for mixture B are shown in Fig. 4.26. Figure 4.27 shows the burning velocity vs. concentration curve for mixture B. The velocity corresponding to the downward propagation limit is about 4.5 cm/sec.

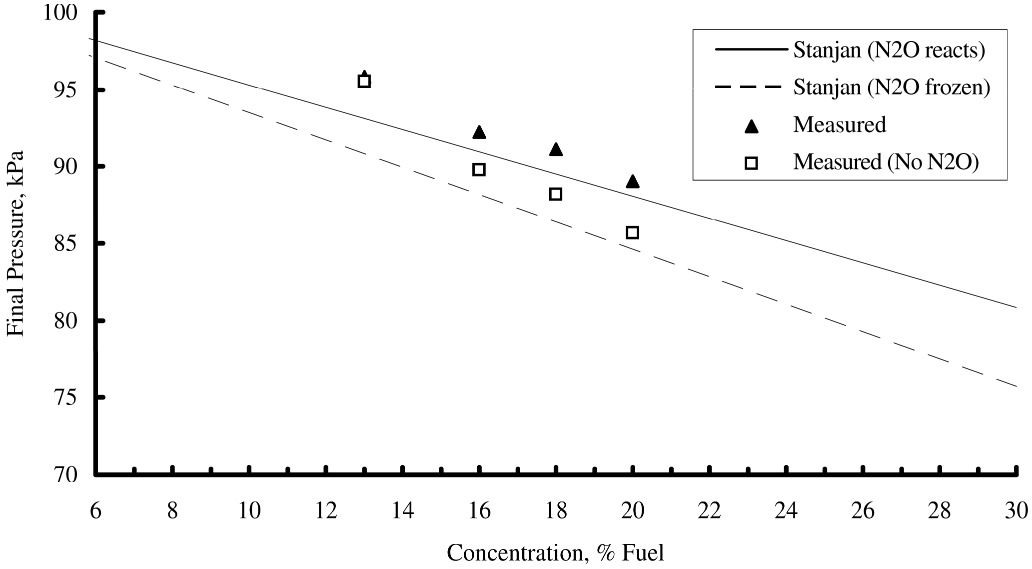


Figure 4.26: Mixture B. Final pressure vs. concentration. Fuel composition: 35% H_2, 35% N_2O, 30% NH_3.

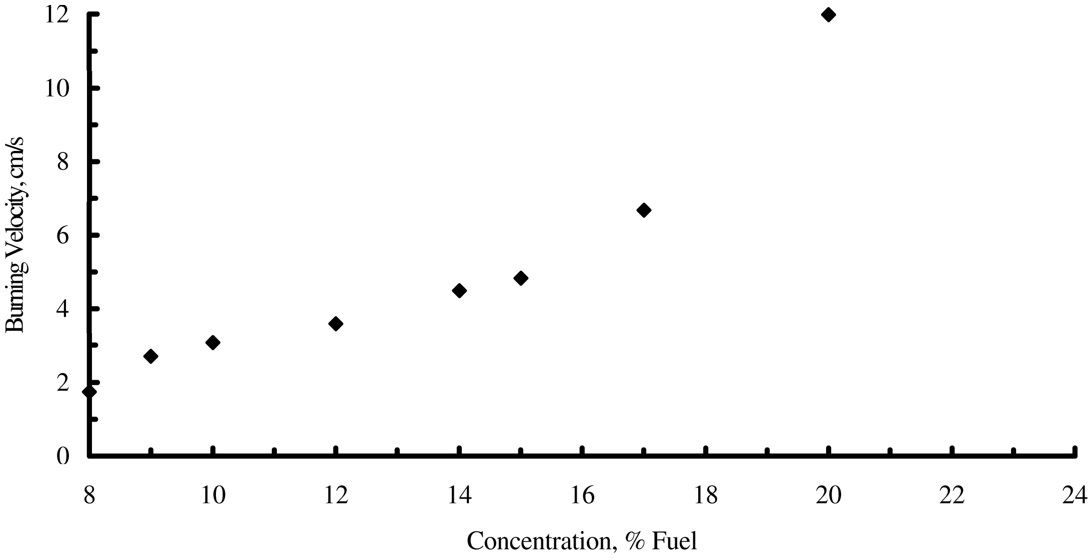


Figure 4.27: Mixture B: Burning velocity vs. composition. Fuel composition: 35% H_2, 35% N_2O, 30% NH_3.

Mixture C Overall, 17 experiments were conducted with mixture C, composed of 25% H_2, 25% N_2O, and 50% NH_3. Six were turbulent burns, five were turbulent without N_2O, and six were quiescent.

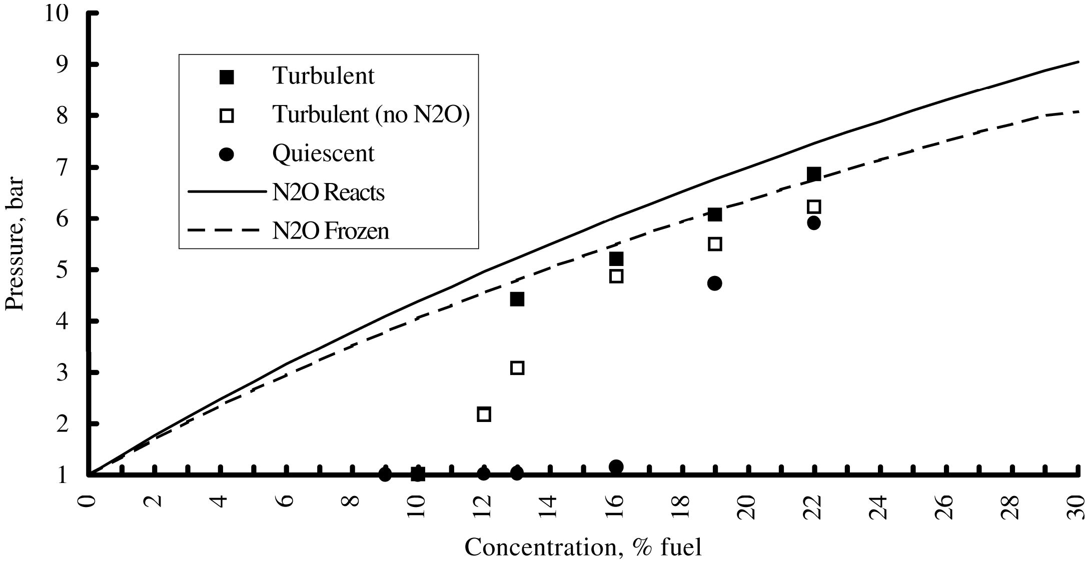


Figure 4.28: Mixture C. Peak pressure vs. composition. Fuel composition: 25% H_2, 25% N_2O, 50% NH_3.

Peak pressure vs. composition results for mixture C are shown in Fig. 4.28. The lean upward propagation limit is 10%, 9% and lower concentrations resulted in no flame detection by the schlieren system. The downward propagation limit is close to 16%. The mixture at which the N_2O participates is 13% fuel in air. This result is also supported by the final pressure vs. concentration graph for mixture C, shown in Fig. 4.29. The flame speed vs. concentration graph is shown in Fig. 4.30. The flame speed at the downward propagation limit for this mixture is about 5 cm/sec.

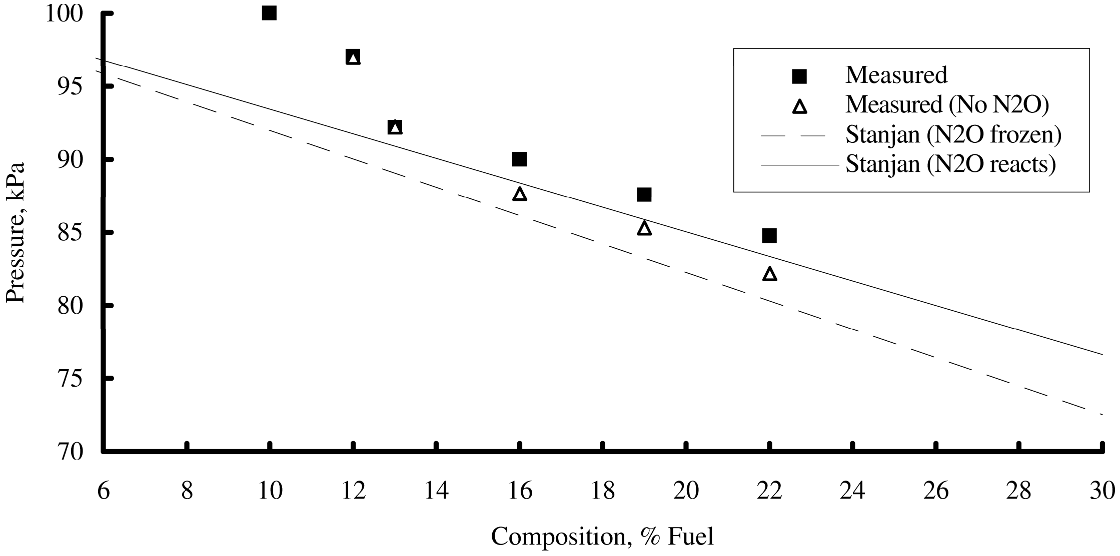


Figure 4.29: Mixture C. Final pressure vs. composition. Fuel composition: 25% H_2, 25% N_2O, 50% NH_3.

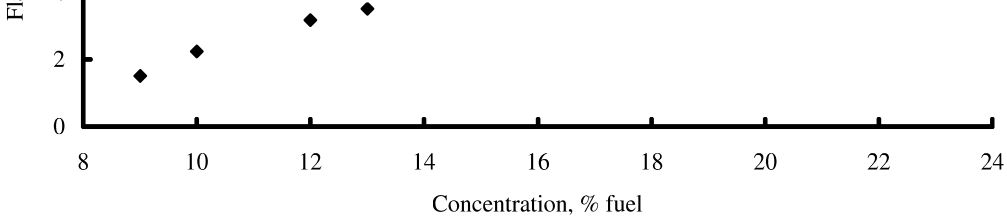


Figure 4.30: Mixture C. Burning velocity vs. composition. Fuel composition: 25% H_2, 25% N_2O, 50% NH_3.

Mixture D The final H_2-N_2O-NH_3 mixture tested was mixture D, composed of 16.7% H_2, 33.3% N_2O, and 50% NH_3. This mixture contains an NH_3/H_2 ratio of 3:1. The peak pressure plot is shown in Fig. 4.31. A total of 18 tests were run for this mixture, four turbulent, eight quiescent, four turbulent with N_2 substituted for the N_2O and two quiescent runs made with humidified air.

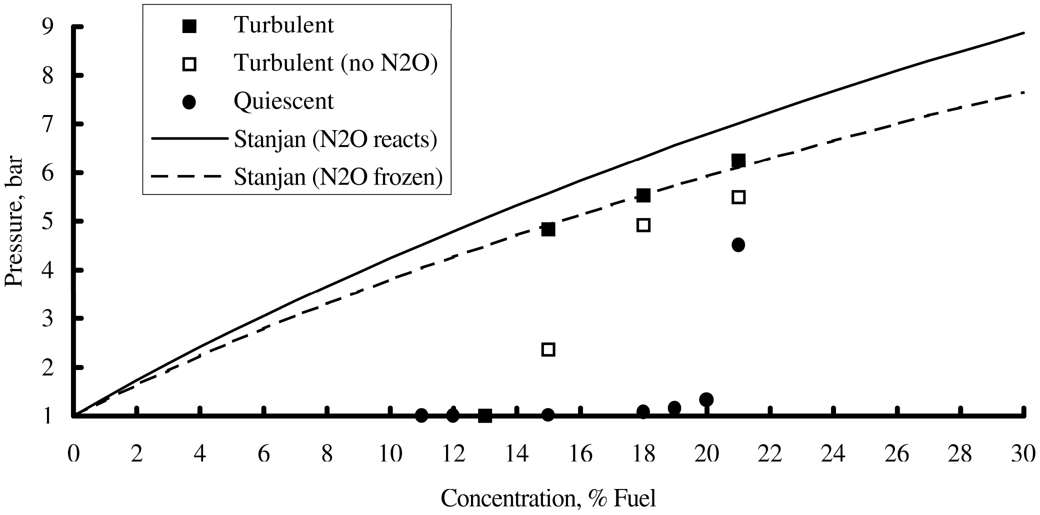


Figure 4.31: Mixture D. Peak pressure vs. composition. Fuel composition: 16.7% H_2, 33.3% N_2O, 50% NH_3.

The peak pressure results indicate a downward propagation limit of 20%. The N_2O participation limit is 15%, indicating that flames close to the upward limit are hot enough to dissociate the N_2O. Inspection of the schlieren photograph indicates that the upward propagation limit is 12%.

The corresponding final pressure vs. concentration graph for mixture D is shown in Fig. 4.32. The burning velocity vs. concentration graph is shown in Fig. 4.33. The downward propagation limit corresponds with a velocity of about 5 cm/sec.

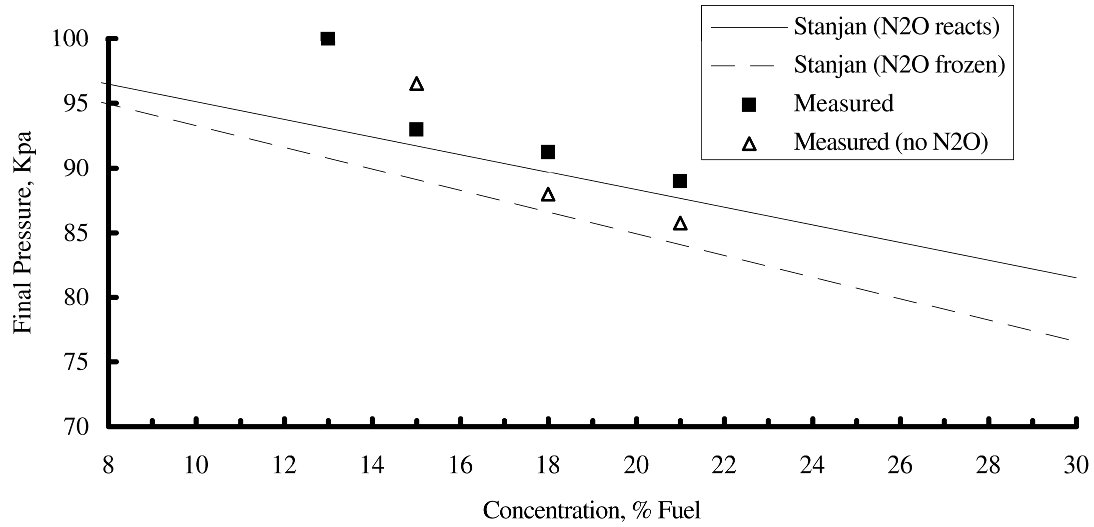


Figure 4.32: Mixture D. Final pressure vs. composition. Fuel composition: 16.7% H_2, 33.3% N_2O, 50% NH_3.

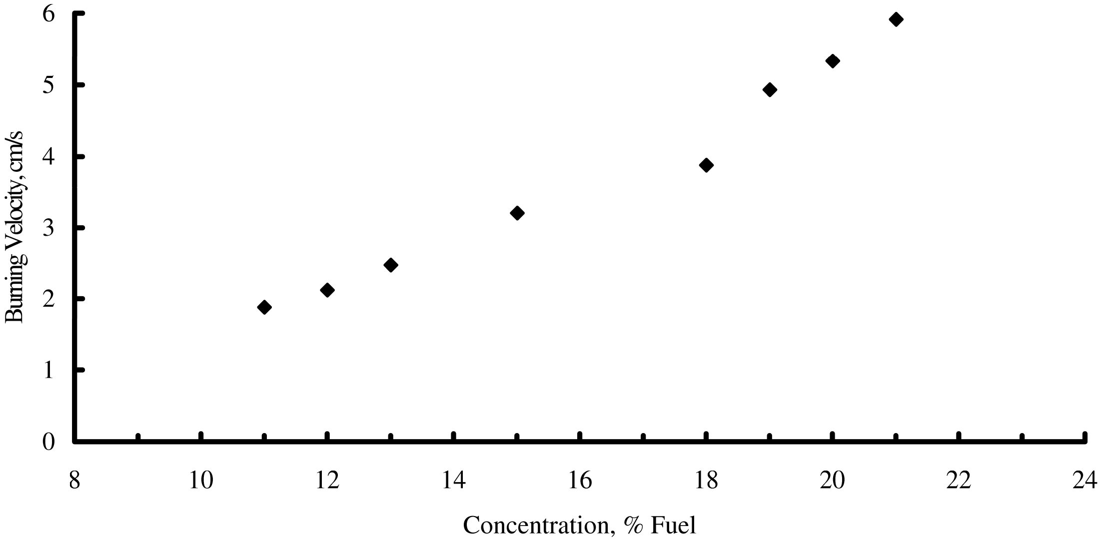


Figure 4.33: Mixture D. Burning velocity vs. composition. Fuel composition: 16.7% H_2, 33.3% N_2O, 50% NH_3.

4.6 N_2O Participation

The study of the combustion characteristics of quaternary mixture of H_2-N_2O-NH_3 and air indicated that the N_2O does not participate in the combustion process for all mixtures. Hydrogen-rich mixtures did not burn N_2O below the downward lean limit, but the N_2O participated in the combustion of NH_3-rich mixtures. Figure 4.34 summarizes these results for both the flammability and the N_2O participation limits based on the present experiments.

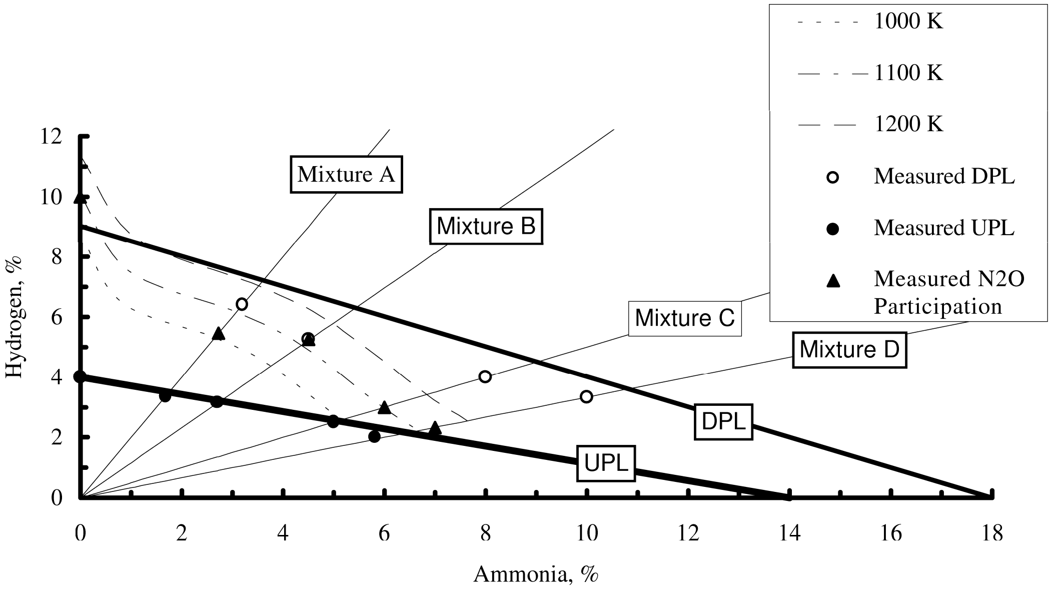


Figure 4.34: N_2O participation and propagation limits for a quaternary mixture of H_2, N_2O, NH_3, and air. The propagation limit lines shown are for the ternary mixtures of H_2-NH_3-air.

The straight lines radiating from the origin are lines of constant H_2/NH_3 ratio associated with the quaternary mixtures studied in this report. The dashed lines are constant pressure isotherms calculated for the temperatures indicated in the legend. These isotherms are calculated using STANJAN with frozen (non-reactive) N_2O. The triangles are observed N_2O participation points interpreted from the data presented in this chapter.

This chart shows a correlation between the adiabatic flame temperature and the N_2O participation points. For mixtures with a constant pressure adiabatic flame temperature higher than 1300 K, the N_2O participates in the combustion process. Mixtures which have an adiabatic flame temperature nearer to 1000 K can be approximated by treating the N_2O as inert in the equilibrium calculation. The existence of a limiting flame temperature is consistent with the observations of Breshears [1996] as discussed in Chapter 2. The upward and downward propagation limits for H_2-NH_3 mixtures are shown, and each of the four quaternary mixtures are also shown. As discussed previously, the predictions of Le Chatelier's rule are in reasonable agreement with the experimental data and the discrepancies can be explained by the participation of N_2O in the combustion process with increasing amounts of NH_3.

4.7 Effect of Humidity

Ten experiments were also conducted to determine the effect of the humidity on the lean combustion properties of these mixtures. Runs 197 - 206 were designed to obtain burning velocities for H_2-air mixtures. Four experiments were run at 45% humidity, 9, 8, 6, and 4% H_2 in air. An additional four experiments were run with the same H_2 concentration, only the air used in the reactants was saturated (100% humidity). The measured burning velocity is shown in Fig. 4.35 and compared with the previous results [Koroll, et al., 1993] obtained with a two-kernel method. Note that there is no observable effect of the humidity on the flame speed and our results are in good agreement with Koroll et al.'s data at 8% and 9% H_2.

Two runs were conducted with the composition of mixture D and saturated air. The saturated case took slightly longer (10%) to reach peak pressure than the 45% R.H. case (see Fig. 4.36).

There were no significant differences in peak pressure or burning velocity for these limited variations in humidity. Experiments by [Koroll, et al., 1993] on H_2-air mixtures indicate that in order to change the burning velocity by a substantial amount, much larger (20 to 30%) amounts of water vapor are needed. Extensive studies [Kumar, et al., 1983] on H_2-air-steam flammability have also shown a very slight effect of steam concentration on the flammability limit up to the inerting concentration

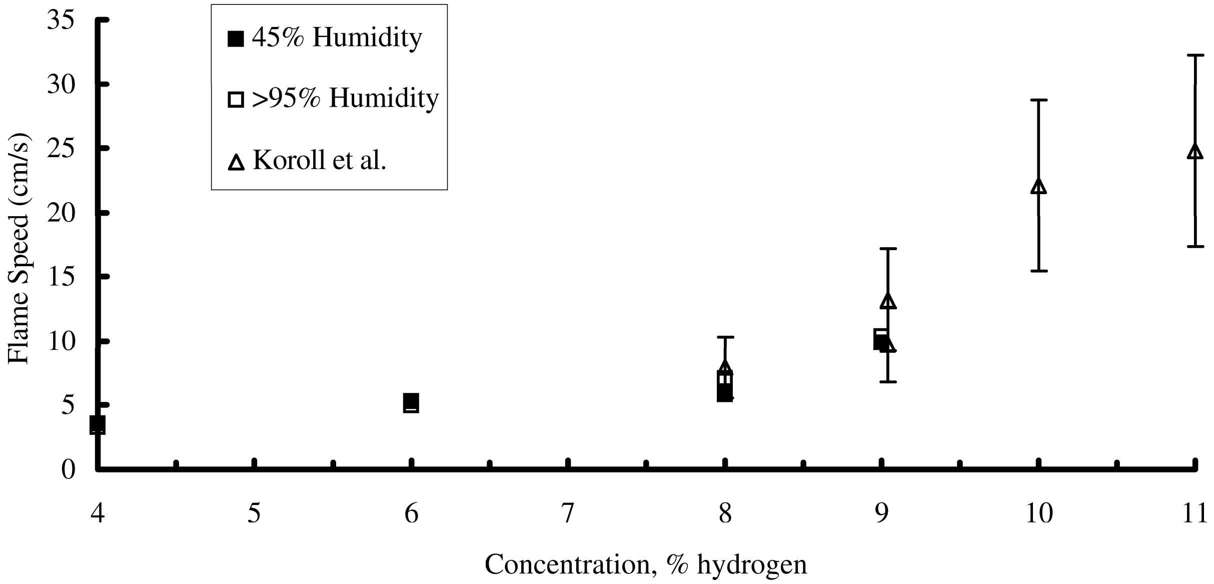


Figure 4.35: Burning velocity vs. H_2 concentration. Humidity has no significant effect on burning velocity at room temperature.

of about 60%.

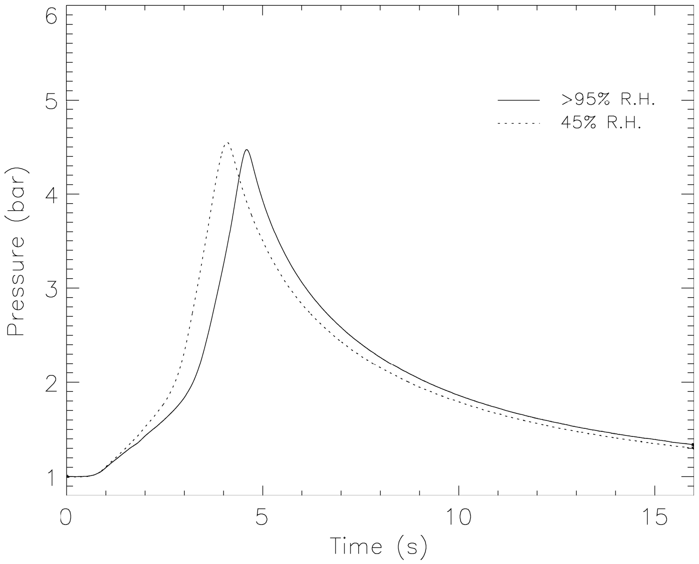


Figure 4.36: Pressure histories for mixture D, 18%, with humidity at two different values.

4.8 Video Observations

The schlieren system output was recorded by a Panasonic 1970 video recording system. Later, after the experiment was over, an Epix video digitizer board was used to grab a series of frames from the tape playback. We have chosen frames that illustrate the range of combustion phenomena observed in these experiments.

A typical laminar flame is shown in Fig. 4.37. This case is 20% NH_3 in air. The flame front is smooth and spherical. A dimple produced by buoyancy is observed at the bottom of the flame in the last two frames. Turbulent motion induced by the mixing fan has the effect of distorting and rapidly convecting the flame away from the ignition point. Figure 4.38 shows a frame sequence for a mixture of 18% NH_3 in air. A highly wrinkled flame front is seen in all frames.

For rich mixtures, the instability of the flame results in a cellular structure visible as bright lines on the flame surface. This is observed in Fig. 4.39 for a quiescent burn of 20% of Mixture B in air. An unusual case is seen in Fig. 4.40, 15.5% mixture A in air, close to the downward propagation limit. The flow produced by the buoyant rise of the flame results in a low-speed wake above the electrodes. The flame can be observed to propagate back down this wake and stabilize just above the electrodes. Therefore, in this case the electrodes are acting as a flame holder. Note that frame e is taken 2 s after frame d.

Figure 4.41 shows a sequence of frames for mixture C at 10%. This flame is slightly above the upward propagation limit and the distorting effects of buoyancy are clearly visible. Figure 4.42 shows a sequence of frames for mixture C at 9%. This flame is just below the upward propagating limit. In comparison with the 10% case, the flame has clearly stopped growing radially after the first three frames. The radial velocity is less than 1 cm/s in the last frame. The boundary between the products and the surroundings becomes indistinct, indicating that combustion has ceased. For comparison, a spark in an inert atmosphere is shown in Figure 4.43. The apparent decrease in size from frame a) to frame b) is an artifact resulting from the camera "blooming" when suddenly over-exposed by the luminosity of the electric discharge.

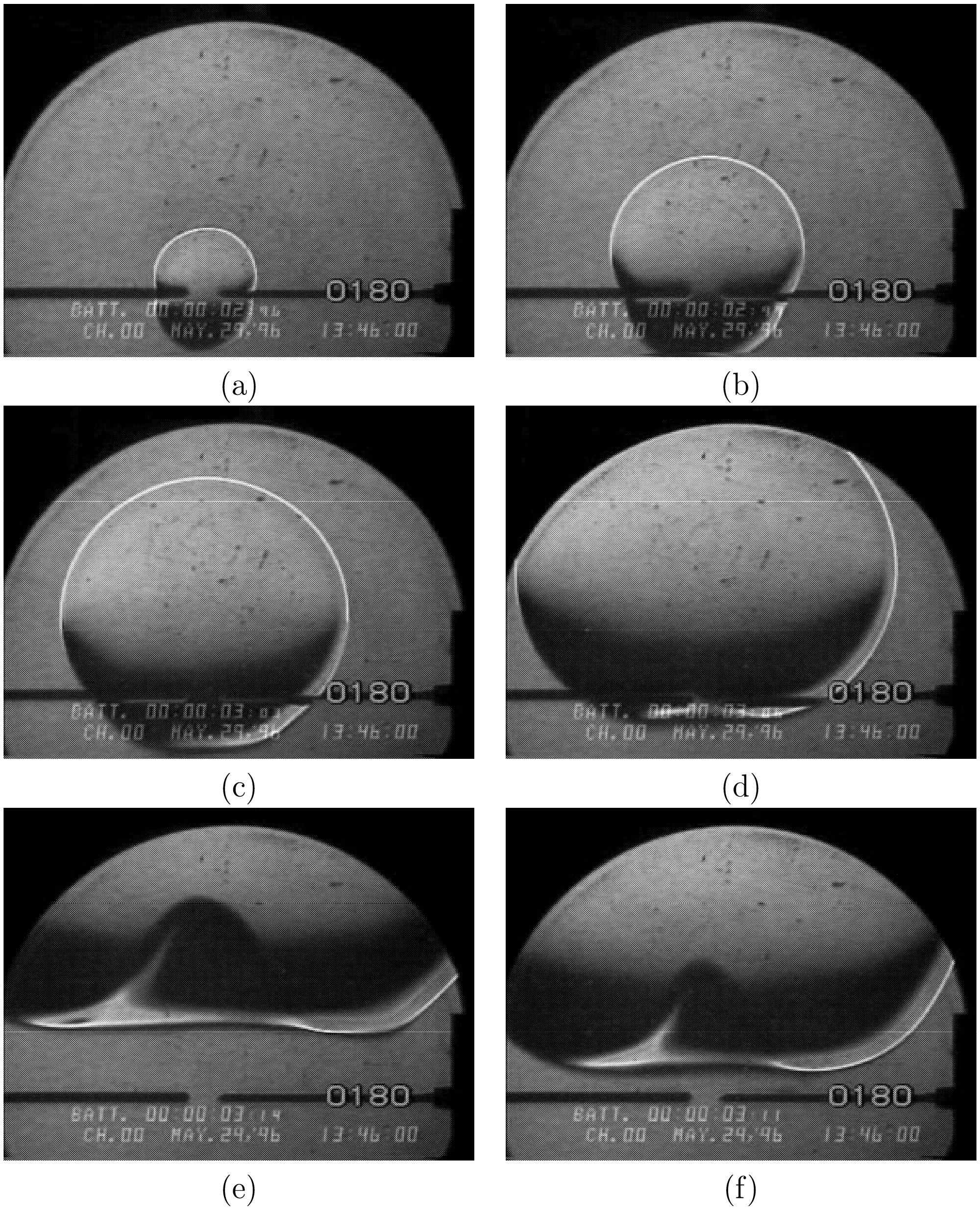
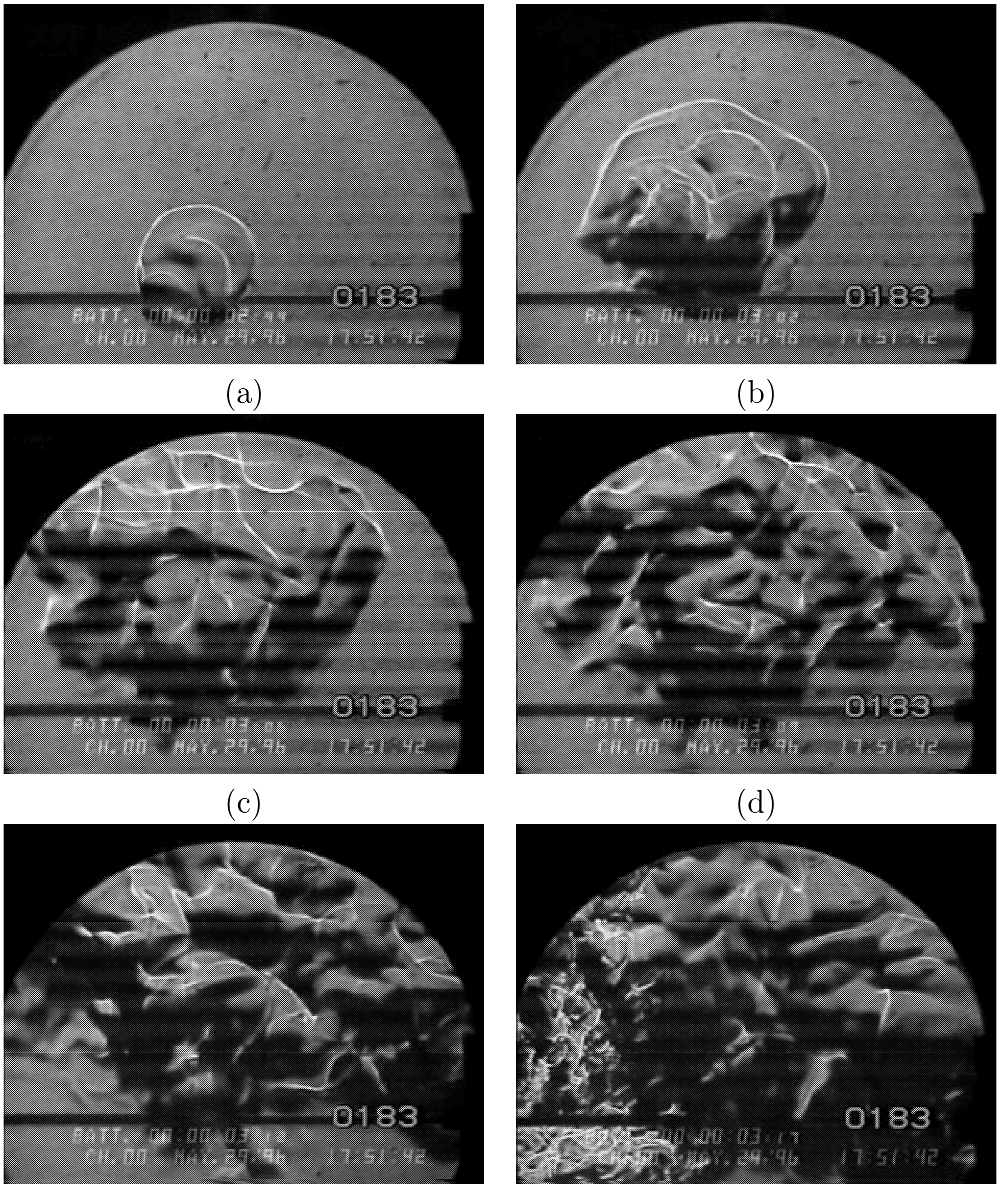


Figure 4.37: Sequence of video frames from experiment 180.

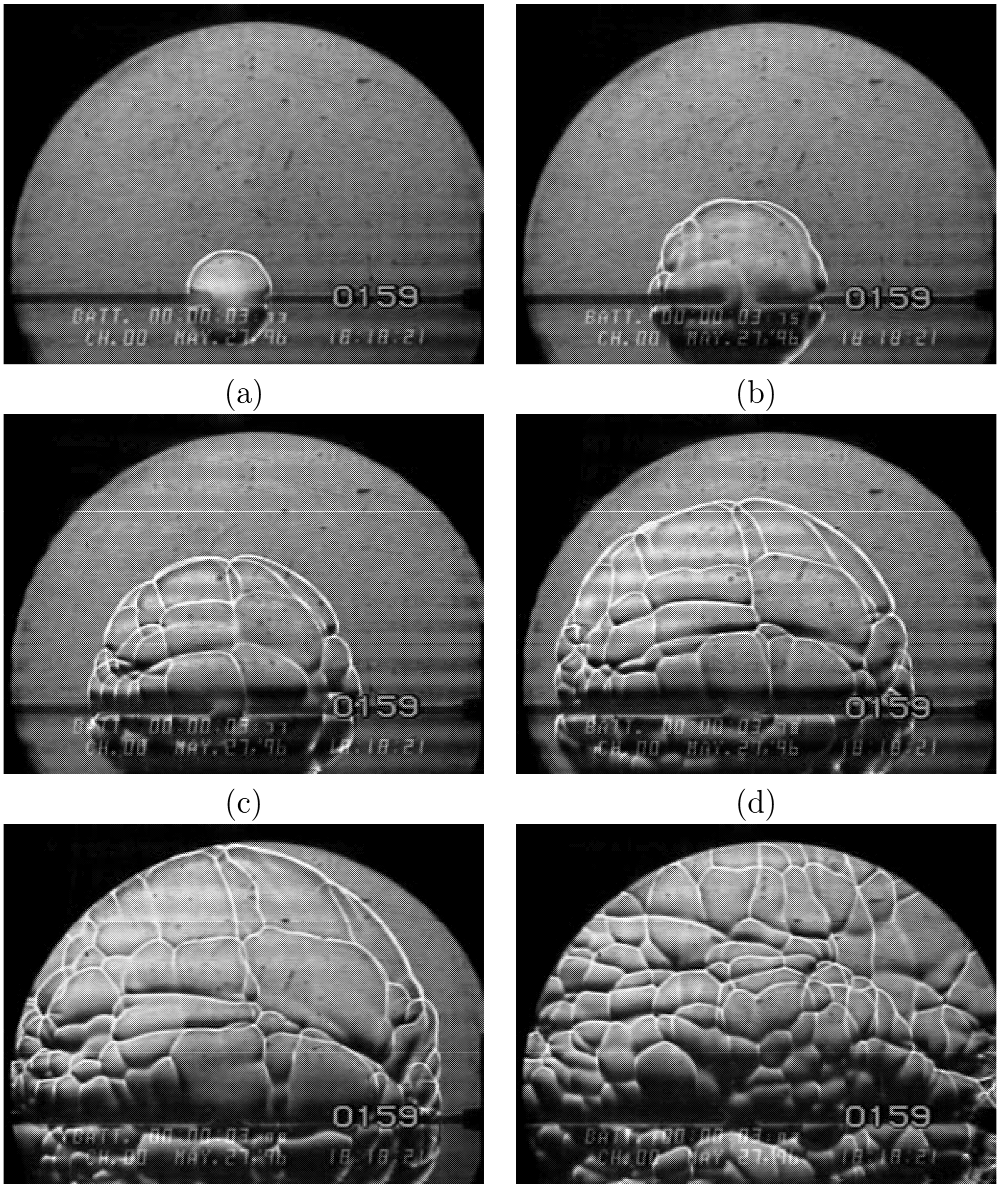


(a) (b)

(c) (d)

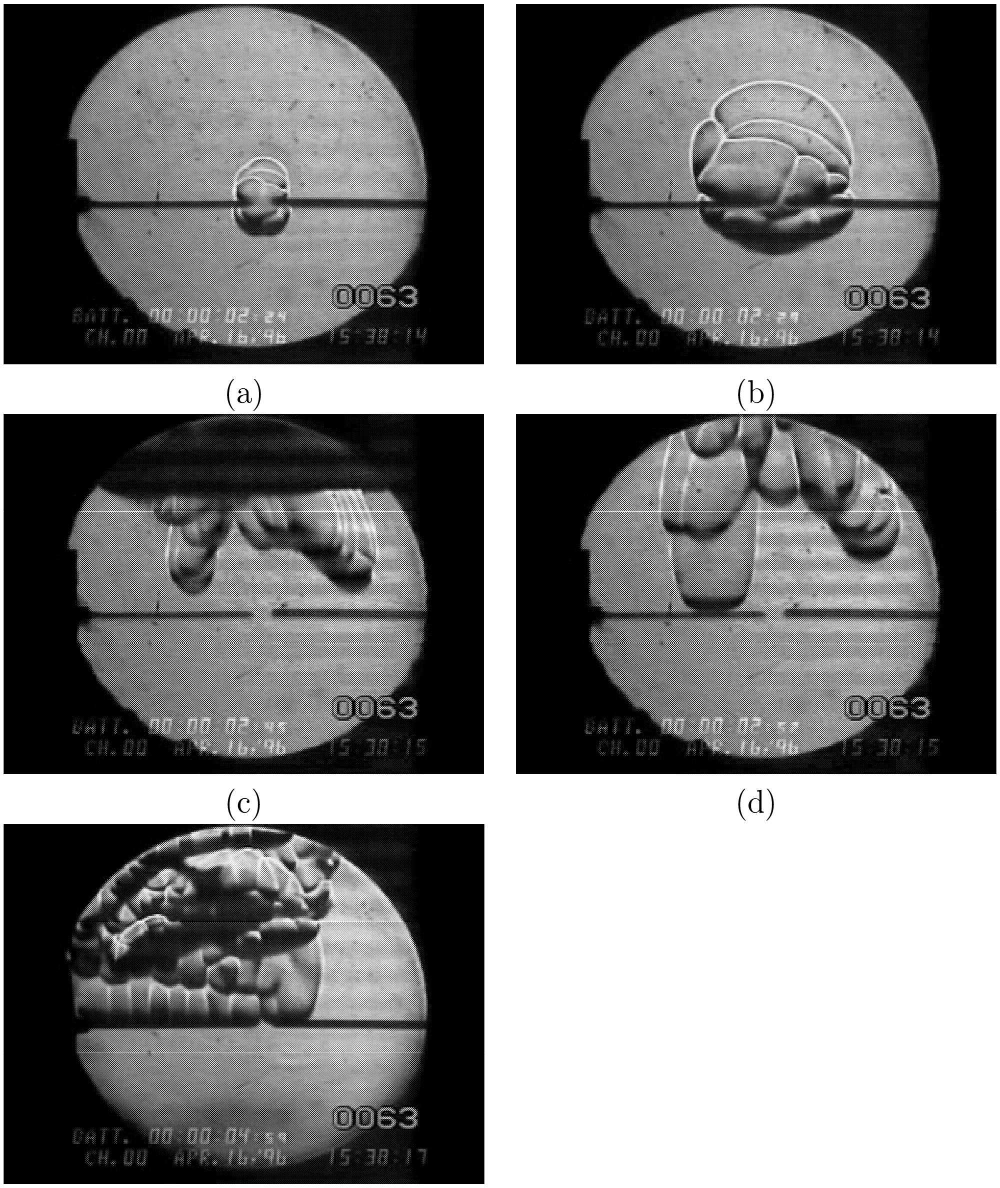
(e) (f)

Figure 4.38: Sequence of video frames from experiment 183.



(a) (b) (c) (d) (e) (f)

Figure 4.39: Sequence of video frames from experiment 159.

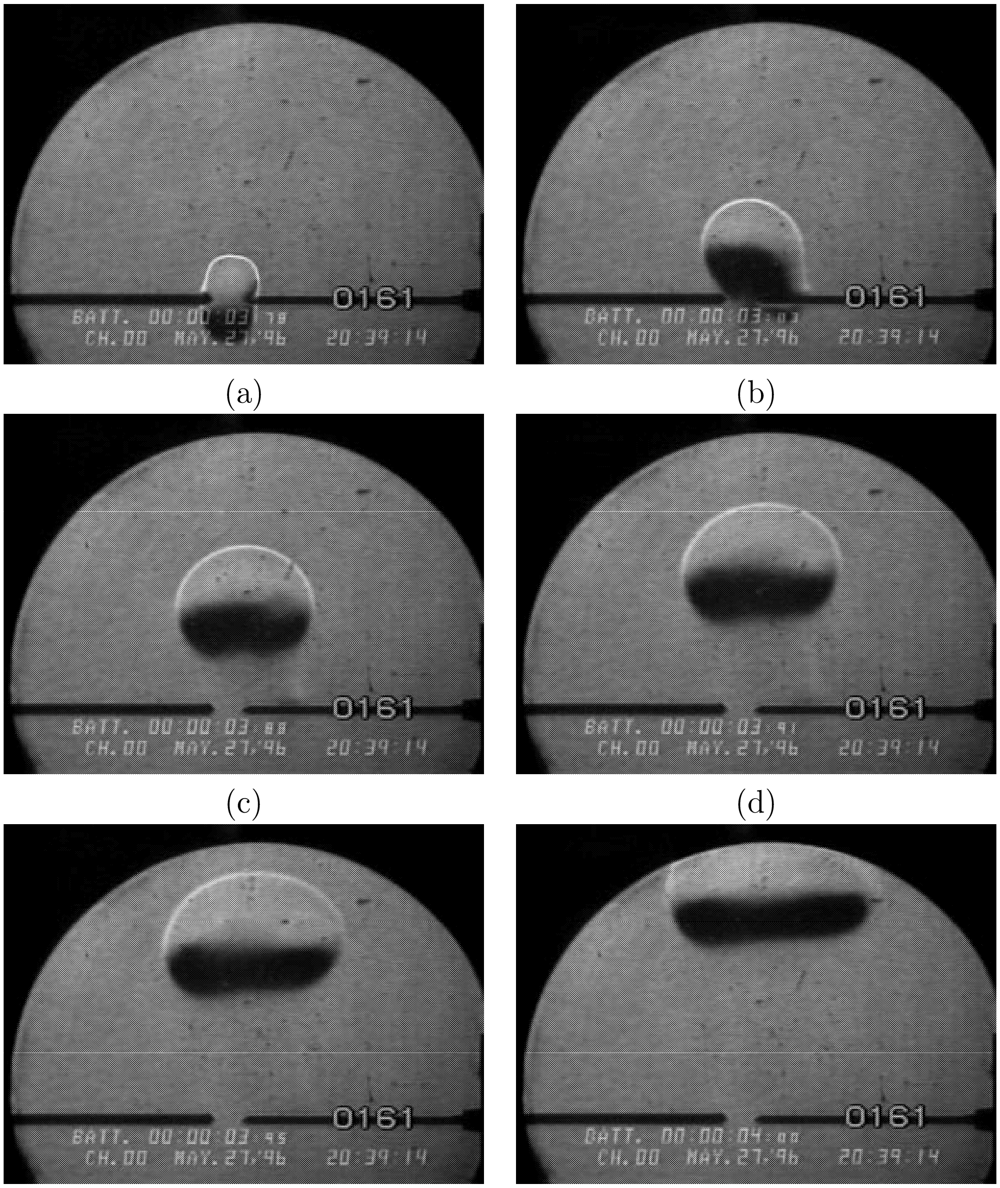


(a) (b)

(c) (d)

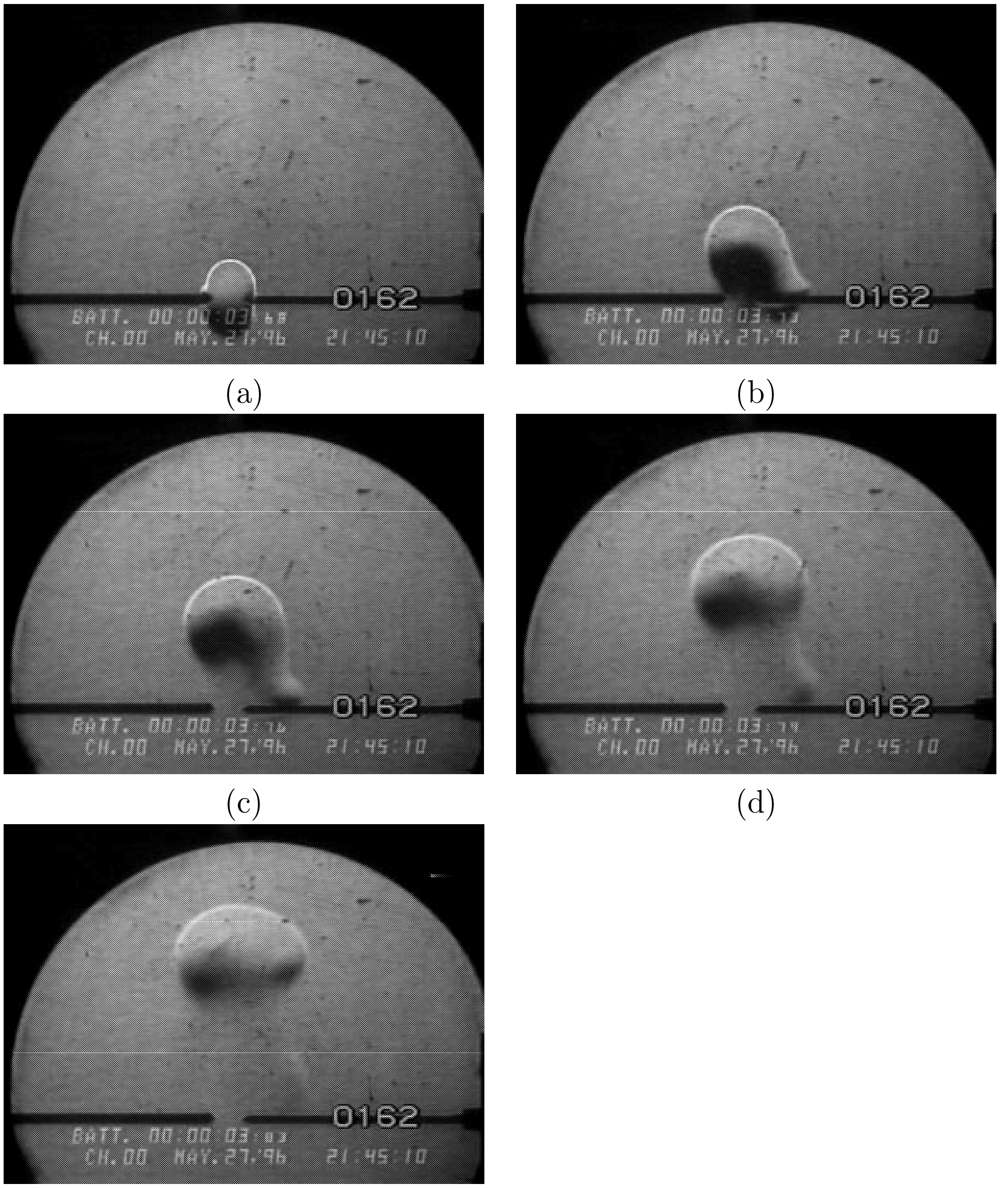
(e)

Figure 4.40: Sequence of video frames from experiment 63.



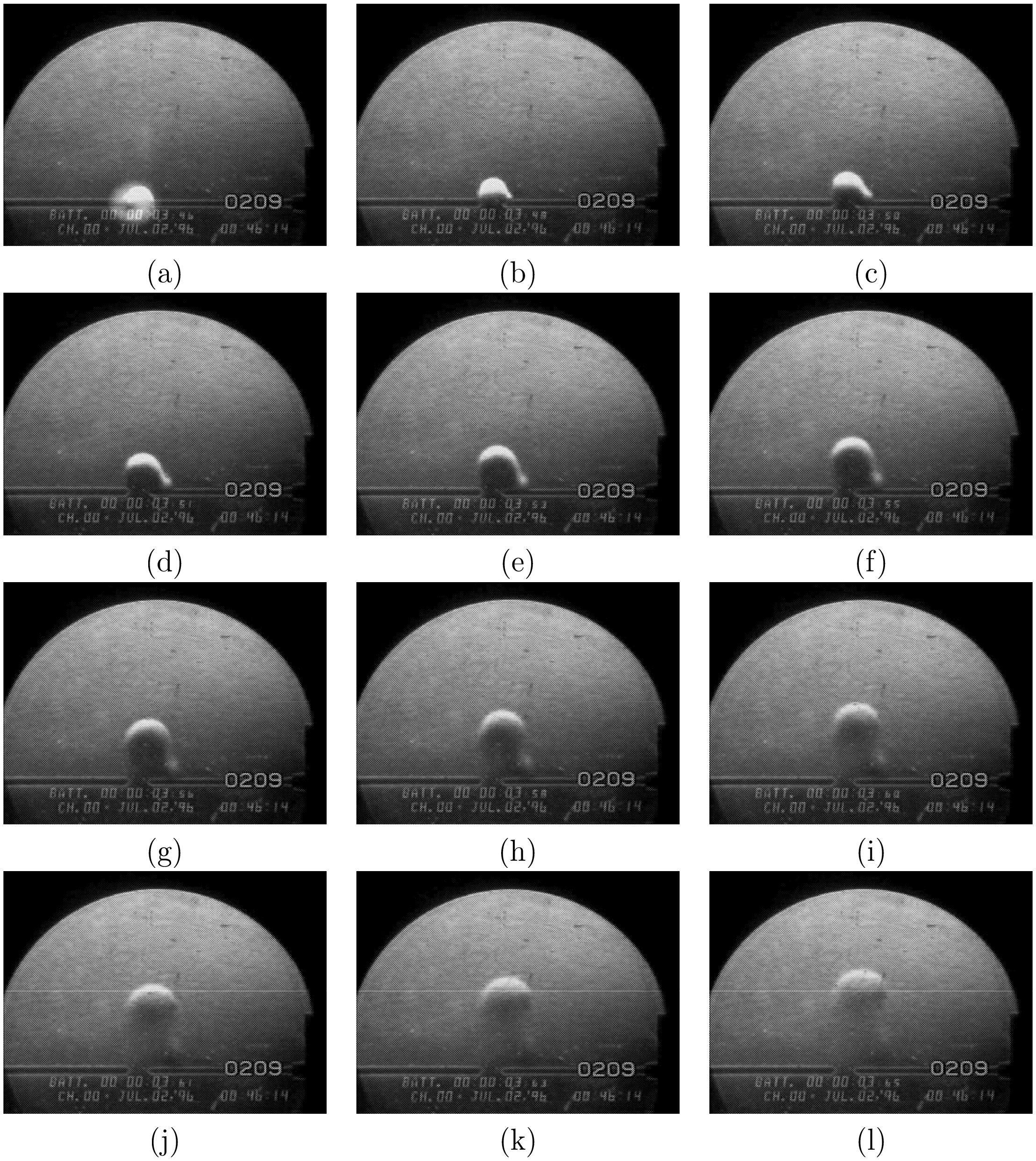
(a) (b) (c) (d) (e) (f)

Figure 4.41: Sequence of video frames from experiment 161.



(a) (b) (c) (d) (e)

Figure 4.42: Sequence of video frames from experiment 162.



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

(j) (k) (l)

Figure 4.43: Sequence of video frames from experiment 209. Inert gas, 10 J spark only.

Chapter 5 Summary and Conclusions

A facility was constructed to study the near-limit combustion characteristics of premixed fuel-oxidizer system in a closed volume. Special precautions were taken with the gas handling system for ammonia and the combustible gases.

A series of experiments were carried out to explore the combustion behavior of hydrogen-ammonia-nitrous oxide mixtures in air. Mixtures of these compositions are of particular interest for safety assessments of operations at the Hanford waste tanks. These gases are the major constituents of release gases observed in some of the waste tanks at that site. Results from this study can be used to evaluate some of the combustion hazards associated with operations in the tanks.

Two hundred eight experiments were carried out for the present report. Studies of hydrogen-air, hydrogen-nitrous oxide, ammonia-air, and ammonia-nitrous oxide were conducted to compare results to previous literature. Pressure histories, final equilibrium pressures, and burning velocities were measured. The present results were in reasonable agreement with previous experiments, taking into consideration the differences in the facilities. We observed that the nitrous oxide does not always participate in the combustion of hydrogen-nitrous oxide-air mixtures, but participates in the combustion of ammonia-nitrous oxide-air mixtures.

A mixture based on the conservative estimate of the gas release from Tank 101-SY was studied to determine lean flammability and combustion characteristics. The upward propagation limit for the mixture is 8% and the downward propagation limit is 15.25%. The burning velocity is determined to vary from 1 cm/sec at the lean limit to 8 cm/sec at 18%.

The peak pressure for a burn of this mixture can be predicted by the constant volume equilibrium pressure for the mixture at values above 15% fuel. The nitrous oxide was found to begin dissociating in the reaction at 13% fuel; below that value the nitrous oxide can be treated as an inert diluent in the combustion process. The final tank pressure could be predicted by equilibrium approximations for greater than 13% fuel.

Three other hydrogen-nitrous oxide-ammonia mixtures were examined to find the effect of the nitrous oxide on mixtures rich in ammonia. The nitrous oxide was found to begin participating in the combustion process when the constant pressure adiabatic flame temperature approached 1100 K. Using the present and previous data, an approximate flammability limit diagram for H_2 - NH_3 - N_2O -air mixtures can be constructed.

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Appendix A Test Conditions

A total of 208 test conditions were studied. The principle features of these tests are summarized here and the details are given in the following tables. Low energy spark ignition (10 mJ) was used for tests 1-48, high energy (10 J) spark ignition was used for tests 49 and later.

Runs	Fuel	Comments
1-13	CH_4, H_2	Shakedown tests.
14-24	H_2	8 and 9 % with N_2O addition.
25-37, 96 - 125	H_2-NH_3	Le Chatelier's rule investigation.
38 - 95	Mixture A	Conservative estimate of 101SY release. Quiescent, turbulent (7 to 30%), and N_2 substituted for N_2O.
126-131, 143-147	Mixture B	Quiescent, turbulent (7 to 30%), and N_2 substituted for N_2O.
132-142	Mixture C	Quiescent, turbulent (7 to 30%), and N_2 substituted for N_2O.
148 - 155	Mixture D	Quiescent, turbulent (7 to 30%), and N_2 substituted for N_2O.
156 - 159	Mixture B	UPL
160 - 166	Mixture C	UPL
167 - 174	Mixture D	UPL
175 - 197	NH_3 , N_2O	N_2O reactivity
198 - 208	H_2, Mix D	Humidity study.

Run No.	Date	H_2	N_2O	NH_3	CH_4	Air	Other		Mix	Fan	Po	T_o	P_{max}	P_{final}	T_{final}	Burn?	dP/dt_{max}	P_{AICC}	Video	Tape
		(kPa)	(kPa)	(kPa)	(kPa)	(kPa)	(gas)	(kPa)	(%)			(C)	(bar)	(kPa)	(C)		(bar/s)	(bar)	Time	timer
1	9/20/95	10.10	0.00	0.00	0.00	89.90			10.1	OFF	1.00	23*	4.10	88.30	N/A	YES	N/A	4.32	N/A	N/A
2	9/28/95	0.00	0.00	0.00	7.00	93.00			7.0	OFF	1.00	23*	6.10	90.70	N/A	YES	N/A	7.66	N/A	N/A
3	9/30/95	0.00	0.00	0.00	6.00	94.00			6.0	OFF	1.00	23*	5.84	92.00	N/A	YES	N/A	6.89	N/A	N/A
4	9/30/95	0.00	0.00	0.00	8.00	92.00			8.0	OFF	1.00	23*	7.17	92.00	N/A	YES	N/A	8.24	N/A	N/A
5	10/1/95	0.00	5.00	0.00	6.50	88.50			11.5	OFF	1.00	23*	6.75	N/A	N/A	YES	N/A	7.73	N/A	N/A
6	10/1/95	0.00	5.00	0.00	6.00	89.00			11.0	OFF	1.00	23*	1.00	N/A	N/A	NO	N/A	7.36	N/A	N/A
6a	10/1/95	0.00	5.00	0.00	6.95	89.00				OFF	1.01	23*	6.43	N/A	N/A	YES	N/A		N/A	N/A
7	10/2/95	0.00	15.00	0.00	6.00	79.00			21.0	OFF	1.00	23*	1.00	N/A	N/A	NO	N/A	8.95	N/A	N/A
7a	10/2/95	0.00	15.00	0.00	6.33	79.00				OFF	1.00	23*	1.00	N/A	N/A	NO	N/A		N/A	N/A
7b	10/2/95	0.00	15.00	0.00	6.98	79.00				OFF	1.00	23*	7.80	N/A	N/A	YES	N/A		N/A	N/A
8	10/2/95	6.40	5.50	0.00	3.00	79.70	N2	5.40	20.3	OFF	1.00	23*	7.20	92.00	N/A	YES	N/A	6.57	N/A	N/A
9	10/2/95	6.40	5.50	0.00	3.00	79.70	N2	5.40	20.3	OFF	1.00	23*	7.20	N/A	N/A	YES	N/A	6.57	N/A	N/A
10	1/11/96	12.00	0.00	0.00	0.00	88.00			12.0	OFF	1.00	23*	3.70	N/A	N/A	YES	N/A	4.80	17:12:17	6:14:17
11	1/11/96	9.00	0.00	0.00	0.00	91.00			9.0	OFF	1.00	23*	3.30	N/A	N/A	YES	1.90	3.47	18:21:07	00:63
12	1/13/96	33.00	0.00	0.00	0.00	0.00	O2	66.00	33.0	OFF	0.50	23*	N/A	N/A	N/A	YES	N/A	4.73	13:17:40	06:30
13	1/13/96	8.00	0.00	0.00	0.00	92.00			8.0	OFF	1.00	23.2	1.10	99.30	22.8	UPF	0.00	3.71	17:08:48	06:86
13a	1/13/96	8.00	0.00	0.00	0.00	92.00				OFF	1.00	N/A	1.00	99.05	23.2	UPF	0.00			04:05
13b	1/13/96	8.00	0.00	0.00	0.00	92.00				ON	1.00	N/A	3.16	91.06	29.5	YES	3.90			03:77
14	1/13/96	9.00	6.00	0.00	0.00	85.00			15.0	OFF	1.00	24.4	3.17	90.38	33.7	YES	1.75	4.67	18:30:14	06:77
15	1/14/96	9.00	9.00	0.00	0.00	82.00			18.0	OFF	1.00	23.4	3.30	90.74	28.7	YES	2.25	4.99	13:54:53	05:17
16	1/14/96	9.00	13.50	0.00	0.00	77.50			22.5	OFF	1.00	22.6	3.21	91.10	30.0	YES	1.75	5.47	14:59:51	06:26
17	1/14/96	9.00	18.00	0.00	0.00	73.00			27.0	OFF	1.00	23.4	3.28	91.33	26.9	YES	1.80	5.94	16:00:42	03:24
18	1/15/96	8.00	8.00	0.00	0.00	84.00			16.0	OFF	1.00	21.4	1.10	99.60	23.2	UPF	0.09	4.61	1:57:26	07:94
18a	1/15/96	8.00	8.00	0.00	0.00	84.00				OFF	1.00	23.2	1.08	99.29	N/A	UPF	0.07			03:24
18b	1/15/96	8.00	8.00	0.00	0.00	84.00				ON	1.00	N/A	3.18	91.57	27.7	YES	5.50			03:56
19	1/15/96	8.00	12.00	0.00	0.00	80.00			20.0	OFF	1.00	22.5	1.08	99.46	24.1	UPF	0.00	5.05	3:04:55	09:30

Run No.	Date	H_2 (kPa)	N_2O (kPa)	NH_3 (kPa)	CH_4 (kPa)	Air (kPa)	Other (gas)	Other (kPa)	Mix (%)	Fan	Po	T_o (C)	P_{max} (bar)	P_{final} (kPa)	T_{final} (C)	Burn?	dP/dt_{max} (bar/s)	P_{AICC} (bar)	Video Time	Tape timer
19a	1/15/96	8.00	12.00	0.00	0.00	80.00				OFF	1.00	24.1	1.05	99.22	24.3	UPF				04:82
19b	1/15/96	8.00	12.00	0.00	0.00	80.00				ON	1.00	24.3	3.12	91.66	27.9	YES	4.25			02:21
20	1/15/96	8.00	16.00	0.00	0.00	76.00			24.0	OFF	1.00	23.1	1.13	99.55	27.8	UPF		5.47	4:22:12	03:72
20a	1/15/96	8.00	16.00	0.00	0.00	76.00				OFF	1.00	27.8	1.08	99.35	25.3	UPF				03:19
20b	1/15/96	8.00	16.00	0.00	0.00	76.00				ON	1.00	25.3	3.15	92.06	30.1	YES	4.60			02:47
21	1/17/96	8.00	24.00	0.00	0.00	68.00			32.0	OFF	1.00	21.2	1.10	N/A	N/A	UPF		6.31	17:02:40	02:39
21a	1/17/96	8.00	24.00	0.00	0.00	68.00				OFF	1.00	N/A	1.10	99.67	23.5	UPF				02:71
21b	1/17/96	8.00	24.00	0.00	0.00	68.00				ON	1.00	23.5	3.17	92.72	28.3	YES	5.00			01:72
22	1/25/96	8.00	32.00	0.00	0.00	60.00			40.0	OFF	1.00	21.3	1.10	99.64	22.8	UPF		7.12	15:11	02:17
22a	1/25/96	8.00	32.00	0.00	0.00	60.00				OFF	1.00		1.05	99.43	22.9	UPF				02:15
22b	1/25/96	8.00	32.00	0.00	0.00	60.00				ON	1.00		3.15	93.20	29.9	YES	5.00			06:88
23	2/13/96	8.00	12.60	0.00	0.00	0.00	N2	79.00	20.6	OFF	1.04	20.4	1.17	103.46	20.3	UPF	0.02	5.17	19:14	N/A
23d	2/13/96	8.00	12.60	0.00	0.00	0.00	N2	79.00		ON	1.03	20.4	3.40	97.50	28.8	YES				06:03
24	3/21/96	8.00	0.00	0.00	0.00	92.00			8.0	OFF	1.00	20.9	1.05	99.71	21.3	UPF	0.09	3.73	16:43	11:84
24A	3/21/96	8.00	0.00	0.00	0.00	92.00				ON	1.00	21.3	3.26	91.20	27.8	YES	5.56			06:52
25	3/22/96	8.00	0.00	8.00	0.00	84.00			16.0	OFF	1.00	20.8	6.10	81.65	26.0	YES	10.41	6.57	N/A	N/A
26	3/26/96	8.00	0.00	2.00	0.00	90.00			10.0	OFF	1.00	20.5	3.49	88.57	23.9	YES	2.00	4.51	15:32:20	10:19
27	3/26/96	8.00	0.00	4.00	0.00	88.00			12.0	OFF	1.00	21.7	4.63	86.74	26.3	YES	10.30	5.24	16:45:02	10:67
28	3/27/96	6.00	0.00	5.00	0.00	89.00			11.0	OFF	1.00	20.4	1.22	98.16	23.6	UPF	0.18	5.07	11:17:23	08:01
28a	3/27/96	6.00	0.00	5.00	0.00	89.00				OFF	98.16	23.6	1.22	98.40	23.4	UPF	0.06			04:28
28b	3/27/96	6.00	0.00	5.00	0.00	89.00				ON	98.40	23.4	3.84	88.36	27.8	YES	6.24			16:35
29	3/27/96	6.00	0.00	6.00	0.00	88.00			12.0	OFF	1.00	20.9	3.96	87.21	27.1	YES	2.33	5.43	16:09:30	5:39
30	3/27/96	6.00	0.00	7.00	0.00	87.00			13.0	OFF	1.00	22.3	4.33	86.15	29.0	YES	3.57	5.77	17:20:40	5:98
31	3/28/96	4.00	0.00	9.00	0.00	87.00			13.0	OFF	1.00	20.7	1.18	99.15	23.7	UPF	0.32	5.96	10:54:35	02:93
31A	3/28/96	4.00	0.00	9.00	0.00	87.00				OFF	99.15	23.7	1.14	98.77	22.4	UPF	0.25			03:01
31B	3/28/96	4.00	0.00	9.00	0.00	87.00				ON	98.77	22.4	4.65	86.42	25.7	YES	9.14			02:71

Run No.	Date	H_2	N_2O	NH_3	CH_4	Air	Other		Mix	Fan	Po	T_o	P_{max}	P_{final}	T_{final}	Burn?	dP/dt_{max}	P_{AICC}	Video	Tape
		(kPa)	(kPa)	(kPa)	(kPa)	(kPa)	(gas)	(kPa)	(%)			(C)	(bar)	(kPa)	(C)		(bar/s)	(bar)	Time	timer
32	3/28/96	4.00	0.00	10.00	0.00	86.00			14.0	OFF	1.00	22.4	1.34	97.15	33.1	UPF	0.26	6.29	11:51:55	04:68
32A	3/28/96	4.00	0.00	10.00	0.00	86.00				OFF	1.00	23.1	1.05	97.59	26.0	UPF	0.11			03:62
32B	3/28/96	4.00	0.00	10.00	0.00	86.00				ON	0.98	26.0	4.56	85.33	26.4	YES	7.60			03:49
33	3/28/96	4.00	0.00	11.00	0.00	85.00			15.0	OFF	1.00	22.4	4.45	84.35	28.8	YES	2.93	6.61	13:39:41	02:95
34	3/29/96	2.00	0.00	12.00	0.00	86.00			14.0	OFF	1.00	20.4	1.00	99.95	20.4	UPF	0.00	6.47	12:33:20	3:20
34A	3/29/96	2.00	0.00	12.00	0.00	86.00				ON	99.95	20.4	5.50	86.05	27.3	YES	13.30			3:06
35	3/29/96	2.00	0.00	14.00	0.00	84.00			16.0	OFF	1.00	22.3	1.00	99.95	22.3	UPF	0.00	7.10	14:04:48	03:90
35d	3/29/96	2.00	0.00	14.00	0.00	84.00				OFF	1.00	22.2	5.98	83.55	27.5	YES	17.30			05:50
36	3/29/96	2.00	0.00	16.00	0.00	82.00			18.0	OFF	1.00	23.8	1.00	99.91	23.8	UPF	0.00	7.70	15:38:19	N/A
36c	3/29/96	2.00	0.00	16.00	0.00	82.00				OFF	1.00	23.6	6.59	81.38	29.9	YES	25.60			09:66
37	3/29/96	2.00	0.00	18.00	0.00	80.00			20.0	OFF	1.00	24.9	1.00	99.90	24.8	UPF	0.17	8.26	16:49:15	02:03
37E	3/29/96	2.00	0.00	18.00	0.00	80.00				OFF	1.00	24.7	1.00	99.76	24.7	UPF	0.00			03:09
37F	3/29/96	3.00	0.00	18.00	0.00	80.00				ON	1.00	24.4	7.76	78.75	31.4	YES	12.99			19:47
38	4/1/96	8.25	13.25	3.50	0.00	75.00			25.0	OFF	1.00	20.4	6.08	92.39	26.3	YES	13.73	6.47	13:57:11	03:96
39	4/1/96	6.60	10.60	2.80	0.00	80.00			20.0	OFF	1.00	22.4	1.10	99.67	24.5	UPF	0.17	5.55	15:14:27	02:43
39A	4/1/96	6.60	10.60	2.80	0.00	80.00				OFF	99.67	24.5	1.10	99.45	24.2	UPF	0.09			02:77
39B	4/1/96	6.60	10.60	2.80	0.00	80.00				ON	99.45	24.2	4.49	94.35	28.3	YES	8.21			02:15
40	4/1/96	7.26	11.66	3.08	0.00	78.00			22.0	OFF	1.00	23.3	4.39	93.77	29.3	YES	3.21	5.92	16:22:43	04:71
41	4/1/96	7.59	12.19	3.22	0.00	77.00			23.0	OFF	1.00	24.4	4.87	93.60	30.1	YES	4.95	6.15	17:15:40	01:88
42	4/2/96	7.92	12.72	3.36	0.00	76.00			24.0	OFF	1.00	20.7	5.38	93.24	29.3	YES	9.98	6.29	9:45:18	01:99
43	4/2/96	6.93	11.13	2.94	0.00	79.00			21.0	OFF	1.00	20.9	1.61	94.78	24.3	YES	0.23	5.74	17:13:48	08:29
44	4/3/96	6.27	10.07	2.66	0.00	81.00			19.0	OFF	1.00	20.4	1.00	99.95	20.4	NO	0.02	5.36	10:17:49	N/A
44E	4/3/96	6.27	10.07	2.66	0.00	81.00				ON	1.01	20.4	5.04	94.46	25.7	YES	14.80			09:02
45	4/3/96	4.00	6.00	10.00	0.00	80.00			20.0	OFF	1.00	22.3	4.72	88.09	29.6	YES	3.36	6.88	11:26:55	02:05
46	4/3/96	3.00	6.00	18.00	0.00	73.00			27.0	OFF	1.00	23.2	7.05	80.55	30.6	YES	16.60	8.94	13:16:54	02:40
47	4/3/96	3.00	4.00	18.00	0.00	75.00			25.0	OFF	1.00	25.4	1.00	100.00	25.4	NO	0.02	8.77	14:44:59	N/A

Run No.	Date	H_2 (kPa)	N_2O (kPa)	NH_3 (kPa)	CH_4 (kPa)	Air (kPa)	Other (gas)	(kPa)	Mix (%)	Fan	Po	T_o (C)	P_{max} (bar)	P_{final} (kPa)	T_{final} (C)	Burn?	dP/dt_{max} (bar/s)	P_{AICC} (bar)	Video Time	Tape timer
47a	4/3/96	3.00	4.00	18.00	0.00	75.00				ON	1.00	25.4	1.00	99.89	25.4	NO	0.00			N/A
47b	4/3/96	3.00	4.00	18.00	0.00	75.00				ON	99.89	25.4	8.04	79.64	32.0	YES	13.80		14:44:59	07:90
48	4/3/96	3.00	5.00	18.00	0.00	74.00			26.0	ON	1.00	26.4	N/A	78.85	33.3	UPF	N/A	8.86	16:22:27	
49	4/12/96	0.00	0.00	0.00	5.50	94.50			5.5	OFF	1.00	20.6	3.95	92.25	27.8	YES	1.25	6.50	13:38:25	07:49
50	4/12/96	0.00	0.00	0.00	5.00	95.00			5.0	OFF	1.00	22.6	1.05	99.86	22.8	UPF	0.10	6.11	14:47:44	03:30
50A	4/12/96	0.00	0.00	0.00	5.00	95.00				ON	99.86	22.8	5.27	93.08	28.8	YES	10.32			03:56
51	4/15/96	7.14	6.12	3.57	0.17	83.00			17.0	OFF	100.00	20.4	4.33	90.75	28.6	YES	3.37	5.78	9:24:06	01:66
52	4/15/96	6.72	5.76	3.36	0.16	84.00			16.0	OFF	100.00	22.2	3.87	91.00	29.0	YES	2.49	5.35	10:25:57	3:01
53	4/15/96	6.30	5.40	3.15	0.15	85.00			15.0	OFF	100.00	23.3	1.10	99.65	24.5	UPF	0.18	5.19	12:20:35	0:91
53a	4/15/96	6.30	5.40	3.15	0.15	85.00				OFF	99.65	24.5	1.10	98.64	32.0	UPF	0.22			02:56
53b	4/15/96	6.30	5.40	3.15	0.15	85.00				ON	98.64	32.0	3.89	90.56	29.7	YES	7.21			01:94
54	4/15/96	5.88	5.04	2.94	0.14	86.00			14.0	OFF	100.00	23.4	1.10	99.17	31.7	UPF	0.12	4.95	13:32:30	02:58
54A	4/15/96	5.88	5.04	2.94	0.14	86.00				ON	99.17	31.7	3.86	91.78	29.6	YES	7.93			02:98
55	4/15/96	5.46	4.68	2.73	0.13	87.00			13.0	OFF	100.00	24.1	1.10	99.64	30.9	UPF	0.13	4.59	14:26:52	01:53
55A	4/15/96	5.46	4.68	2.73	0.13	87.00				ON	99.64	30.9	3.62	91.73	29.0	YES	4.78			01:47
56	4/15/96	5.04	4.32	2.52	0.12	88.00			12.0	OFF	100.00	25.0	1.10	99.66	30.0	UPF	0.12	4.35	5:36:07	02:34
56A	4/15/96	5.04	4.32	2.52	0.12	88.00				ON	99.66	30.0	2.78	94.15	28.8	YES	2.90			02:45
57	4/15/96	4.62	3.96	2.31	0.11	89.00			11.0	OFF	100.00	25.3	1.10	99.80	28.7	UPF	0.09	4.11	16:23:30	02:15
57A	4/15/96	4.62	3.96	2.31	0.11	89.00				ON	99.80	28.7	2.35	96.20	29.4	YES	2.23			01:52
58	4/15/96	4.20	3.60	2.10	0.10	90.00			10.0	OFF	100.00	25.2	1.10	99.91	29.4	UPF	0.13	3.91	17:16:33	01:76
58A	4/15/96	4.20	3.60	2.10	0.10	90.00				ON	99.91	29.4	1.94	97.91	28.5	YES	1.31			01:55
59	4/16/96	3.78	3.24	1.89	0.09	91.00			9.0	OFF	100.00	23.2	1.10	100.02	26.3	UPF	0.08	3.65	10:44:40	01:55
59A	4/16/96	3.78	3.24	1.89	0.09	91.00				ON	100.02	26.3	1.48	99.06	27.0	YES	0.56			02:05
60	4/16/96	3.36	2.88	1.68	0.08	92.00			8.0	OFF	100.00	23.2	1.10	99.98	24.6	UPF	0.08	3.34	11:37:51	02:11
60A	4/16/96	3.36	2.88	1.68	0.08	92.00				ON	99.98	24.6	1.10	99.76	25.1	YES	0.08			11:40
61	4/16/96	2.94	2.52	1.47	0.07	93.00			7.0	OFF	100.00	23.6	1.00	99.99	23.5	NO	0.07	3.07	12:56:57	03:43

Run No.	Date	H_2 (kPa)	N_2O (kPa)	NH_3 (kPa)	CH_4 (kPa)	Air (kPa)	Other (gas)	Other (kPa)	Mix (%)	Fan	Po	T_o (C)	P_{max} (bar)	P_{final} (kPa)	T_{final} (C)	Burn?	dP/dt_{max} (bar/s)	P_{AICC} (bar)	Video Time	Tape timer
61b	4/16/96	3.94	2.52	1.47	0.07	93.00				ON	101.00	23.9	1.53	100.05	28.7	YES	0.09			03:86
62	4/16/96	6.72	5.76	3.36	0.16	84.00			16.0	OFF	100.00	23.8	3.87	91.20	28.8	YES	2.56	5.35	14:36:07	02:17
63	4/16/96	6.51	5.58	3.26	0.16	84.50			15.5	OFF	100.00	25.1	3.52	90.92	29.2	YES	1.96	5.17	15:38:14	02:24
64	4/16/96	6.41	5.49	3.20	0.15	84.75			15.3	OFF	100.00	25.6	1.88	93.70	29.2	YES	0.186	5.11	16:43:54	02:03
65	4/17/96	3.36	2.88	1.68	0.08	92.00			8.0	OFF		23.4	1.00	99.96	23.1	NO	0.09	3.34	10:55:09	03:88
65C	4/17/96	3.36	2.88	1.68	0.08	92.00				ON	99.94	23.8	1.10	99.70	25.1	YES	0.00			02:50
65D	4/17/96	4.36	2.88	1.68	0.08	92.00				ON	100.70	25.1	1.95	98.59	29.6	YES	1.29			02:57
66	4/17/96	3.78	3.24	1.89	0.09	91.00			9.0	OFF	100.00	23.4	1.00	99.98	23.4	UPF	0.14	3.65	11:55:27	05:17
66A	4/17/96	3.78	3.24	1.89	0.09	91.00				OFF	99.98	23.4	1.00	99.82	24.5	UPF	0.10			01:86
66B	4/17/96	3.78	3.24	1.89	0.09	91.00				ON	99.82	24.5	1.55	98.92	25.4	YES	0.47			02:50
67	4/17/96	4.20	3.60	2.10	0.10	90.00			10.0	OFF	100.09	23.3	1.00	99.93	25.7	UPF	0.10	3.96	12:55:26	03:69
67A	4/17/96	4.20	3.60	2.10	0.10	90.00				OFF	99.93	25.7	1.00	99.82	24.1	UPF	0.11			02:21
67B	4/17/96	4.20	3.60	2.10	0.10	90.00				ON	99.82	24.1	1.83	97.98	28.7	YES	1.20			02:41
68	4/24/96	6.30	5.40	3.15	0.15	85.00			15.0	ON	100.00	21.2	4.63	92.05	26.9	YES	11.17	5.18	9:21:25	01:88
69	4/24/96	7.56	6.48	3.78	0.18	82.00			18.0	ON	100.00	23.7	5.39	90.12	29.3	YES	11.46	5.87	10:09:53	02:20
70	4/24/96	8.40	7.20	4.20	0.20	80.00			20.0	ON	100.00	25.5	5.87	88.95	30.8	YES	22.05	6.30	11:23:43	02:09
71	4/24/96	10.08	8.64	5.04	0.24	76.00			24.0	ON	100.00	26.3	6.75	85.94	32.1	YES	27.10	7.11		
72	4/24/96	10.92	9.36	5.46	0.26	74.00			26.0	ON	100.00	27.7	7.04	84.53	33.2	YES	13.77	7.49	13:59:45	01:73
73	4/24/96	11.76	10.08	5.88	0.28	72.00			28.0	ON	100.00	28.4	7.35	83.20	34.0	YES	3.86	7.85	15:01:54	01:56
74	4/24/96	12.60	10.80	6.30	0.30	70.00			30.0	ON	100.00	28.6	8.06	81.99	34.6	YES	9.62	8.19	16:29:32	06:71
75	4/25/96	5.88	5.04	2.94	0.14	86.00			14.0	ON	100.00	23.8	4.26	92.33	29.4	YES	7.75	4.95	11:12:06	02:13
76	4/25/96	6.72	5.76	3.36	0.16	84.00			16.0	ON	100.00	25.2	4.81	91.28	30.3	YES	14.27	5.41	12:04:59	01:09
77	4/25/96	7.14	6.12	3.57	0.17	83.00			17.0	ON	100.00	26.3	5.12	90.71	31.3	YES	14.26	5.78	13:00:30	01:86
78	4/25/96	7.98	6.84	3.99	0.19	81.00			19.0	ON	100.00	26.7	5.64	89.16	30.6	YES	12.02	6.09	14:11:52	02:27
79	4/25/96	9.24	7.92	4.62	0.22	78.00			22.0	ON	100.00	27.5	6.38	87.07	31.6	YES	36.50	6.72	15:50:16	01:63
80	4/30/96	6.30	0.00	3.15	0.15	85.00	N2	5.40	15.0	ON	100.00	23.4	4.13	89.36	27.9	YES	8.45	4.61	10:47:10	01:71

Run No.	Date	H_2 (kPa)	N_2O (kPa)	NH_3 (kPa)	CH_4 (kPa)	Air (kPa)	Other (gas)	Other (kPa)	Mix (%)	Fan	P_o	T_o (C)	P_{max} (bar)	P_{final} (kPa)	T_{final} (C)	Burn?	dP/dt_{max} (bar/s)	P_{AICC} (bar)	Video Time	Tape timer
81	4/30/96	6.30	2.70	3.15	0.15	85.00	N2	2.70	15.0	ON	100.00	24.6	4.34	90.68	30.0	YES	9.97	4.90	12:11:54	04:97
82	4/30/96	6.30	1.35	3.15	0.15	85.00	N2	4.05	15.0	ON	100.00	25.8	4.23	90.01	29.6	YES	9.39	6.15	13:06:06	02:02
83	4/30/96	6.30	4.05	3.15	0.15	85.00	N2	1.35	15.0	ON	100.00	26.2	4.52	91.46	30.0	YES	11.62	5.04	14:18:04	02:62
84	4/30/96	5.88	0.00	2.94	0.14	86.00	N2	5.04	14.0	ON	100.00	25.6	3.96	90.15	29.9	YES	7.09	4.29	16:21:43	03:42
85	5/3/96	5.46	0.00	2.73	0.13	87.00	N2	4.68	13.0	ON	100.00	23.6	3.66	90.73	30.0	YES	6.74		10:28:43	03:38
86	5/3/96	5.04	0.00	2.52	0.12	88.00	N2	4.32	12.0		100.00	24.9	3.48	91.51	29.7	YES	4.13	4.09	11:34:36	02:47
87	5/3/96	4.20	0.00	2.10	0.10	90.00	N2	3.60	10.0	ON	100.00	24.7	2.07	97.43	27.8	YES	1.64	3.48	14:23:41	02:89
88	5/3/96	4.20	3.60	2.10	0.10	90.00			10.0	ON	100.00	24.8	2.04	97.46	28.5	YES	1.40	3.96	15:09:57	06:08
89	5/3/96	6.72	0.00	3.36	0.16	84.00	N2	5.76	16.0	ON	100.00	24.6	4.42	88.34	29.7	YES	12.28	4.66	16:17:13	01:92
90	5/6/96	4.62	3.96	2.31	0.11	89.00			11.0	ON	100.00	23.7	2.37	95.90	29.5	YES	2.56	4.21	11:52:59	03:29
91	5/6/96	5.04	4.32	2.52	0.12	88.00			12.0	ON	100.00	24.6	3.39	92.08	29.7	YES	4.46	4.35	12:49:44	01:30
92	5/6/96	4.62	0.00	2.31	0.11	89.00	N2	3.96	11.0	ON	100.00	25.5	2.41	95.42	27.9	YES	2.40	3.69	13:43:39	02:52
93	5/6/96	3.78	0.00	1.89	0.09	91.00		3.24	9.0	ON	100.00	25.6	1.52	98.95	29.5	YES	0.79	3.27	14:45:30	01:93
94	5/6/96	3.36	0.00	1.68	0.08	92.00	N2	2.88	8.0	ON	100.00	25.4	1.05	99.96	27.3	YES	0.08	3.04	15:45:42	07:95
95	5/6/96	7.14	0.00	3.57	0.17	83.00	N2	6.12	17.0	ON	100.00	25.4	4.50	87.76	30.4	YES	12.57	4.84	16:45:13	02:21
96	5/13/96	5.00	0.00	0.00	0.00	95.00			5.0	OFF	100.00	23.8	1.00	99.90	26.9	UPF	0.03	2.80	11:37:30	02:40
96a	5/13/96	5.00	0.00	0.00	0.00	95.00				ON	100.00	26.9	1.63	98.32	29.6	YES	0.88			02:63
97	5/13/96	4.00	0.00	0.00	0.00	96.00			4.0	OFF	100.00	24.3	1.00	100.00	24.3	UPF	0.03	2.45	14:03:03	02:11
97c	5/13/96	4.54	0.00	0.00	0.00	96.00				ON	100.00	24.3	1.40	99.67	29.1	YES	0.47			02:13
98	5/13/96	3.00	0.00	0.00	0.00	97.00			3.0	OFF	100.00	24.5	1.00	100.00	24.5	NO	0.03	2.12	15:33:07	02:63
98c	5/13/96	4.50	0.00	0.00	0.00	95.50				ON	101.50	24.8	1.33	100.72	27.2	YES	0.32			02:41
99	5/14/96	3.00	0.00	2.00	0.00	95.00			5.0	OFF	100.00	24.2	1.00	99.98	24.2	NO	0.02	3.02	15:22:34	03:77
99c	5/14/96	3.00	0.00	4.00	0.00	95.00				OFF	102.00	26.2	1.14	101.87	27.2	YES	0.07			02:01
100	5/14/96	2.00	0.00	6.00	0.00	92.00			8.0		100.00	24.3	1.00	99.98	24.3	NO	0.04	4.35		02:40
100a	5/14/96	2.00	0.00	10.00	0.00	92.00				ON	104.00	26.6	3.06	97.83	29.9	YES	3.73			02:45
101	5/14/96	2.00	0.00	10.00	0.00	88.00			12.0	OFF	100.00	25.4	1.00	99.85	30.0	NO	0.04	5.81		02:85

Run No.	Date	H_2 (kPa)	N_2O (kPa)	NH_3 (kPa)	CH_4 (kPa)	Air (kPa)	Other (gas)	(kPa)	Mix (%)	Fan	Po	T_o (C)	P_{max} (bar)	P_{final} (kPa)	T_{final} (C)	Burn?	dP/dt_{max} (bar/s)	P_{AICC} (bar)	Video Time	Tape timer
101a	5/14/96	2.00	0.00	10.00	0.00	88.00				ON	99.85	30.0	1.00	88.35	30.7	YES	12.50			02:64
102	5/15/96	2.00	0.00	8.00	0.00	90.00			10.0	ON	100.00	24.0	1.00	99.92	25.6	UPF	0.03	5.10	10:31:55	04:22
102a	5/15/96	2.00	0.00	8.00	0.00	90.00					99.92	25.6	1.60	99.47	27.3	YES	0.02			01:43
103	5/15/96	2.00	0.00	7.00	0.00	91.00			9.0		100.00	N/A	N/A	N/A	N/A	N/A	N/A	4.79	N/A	N/A
104	5/16/96	2.00	0.00	7.00	0.00	91.00			9.0		100.00	N/A	N/A	N/A	N/A	N/A	N/A	4.79	N/A	N/A
105	5/16/96	2.00	0.00	7.00	0.00	91.00			9.0	OFF	100.00	24.2	1.00	99.97	24.2	NO	N/A	4.79	9:30:32	03:08
105a	5/16/96	2.00	0.00	7.50	0.00	91.00				OFF	100.50	24.2	1.01	100.45	26.0	UPF	N/A			02:91
105b	5/16/96	2.00	0.00	7.50	0.00	91.00				ON	100.45	26.0	1.00	100.36	25.7	NO	N/A			02:43
105c	5/16/96	4.00	0.00	7.50	0.00	91.00				ON	102.50	25.7	4.71	90.51	30.2	YES	N/A			04:09
106	5/16/96	2.00	0.00	7.00	0.00	91.00			9.0	OFF	100.00	25.8	1.00	99.95	27.0	UPF	N/A	4.74	10:57:32	02:05
106a	5/16/96	2.00	0.00	7.00	0.00	91.00				ON	99.94	27.0	1.00	99.94	26.2	NO	N/A			02:07
106b	5/16/96	4.50	0.00	7.00	0.00	91.00				ON	102.50	26.2	4.70	90.45	30.4	YES	N/A			06:02
107	5/16/96	0.00	0.00	15.00	0.00	85.00			15.0	OFF	100.00	29.0	1.00	99.98	29.0	UPF	N/A	7.06	12:00:40	02:31
107a	5/16/96	0.00	0.00	15.00	0.00	85.00				ON	100.00	29.0	1.00	99.90	27.2	NO	N/A			02:93
107b	5/16/96	2.00	0.00	15.00	0.00	85.00				ON	100.00	27.2	N/A	84.61	32.6	YES	N/A			03:14
108	5/16/96	0.00	0.00	14.00	0.00	86.00			14.0	OFF	100.00	28.6	1.00	99.90	28.6	UPF	N/A	6.66	13:11:53	03:13
108a	5/16/96	2.00	0.00	14.00	0.00	86.00				ON	102.00	28.6	6.10	86.02	33.8	YES	N/A			02:40
109	5/16/96	0.00	0.00	13.00	0.00	87.00			13.0	OFF	100.00	29.7	1.00	99.30	29.6	UPF	N/A	6.33	14:17:04	02:10
109a	5/16/96	2.00	0.00	13.00	0.00	87.00				ON	102.00	29.6	5.80	87.20	34.0	YES	N/A			02:03
110	5/16/96	0.00	0.00	12.00	0.00	88.00			12.0	OFF	100.00	30.1	1.00	99.90	29.9	NO	N/A	6.00	15:18:18	02:24
110a	5/16/96	2.00	0.00	12.00	0.00	88.00				ON	102.00	29.9	5.40	88.42	34.3	YES	N/A			03:13
111	5/16/96	1.00	0.00	12.00	0.00	87.00			13.0	OFF	100.00	30.0	1.00	99.92	31.4	UPF	N/A	6.24	16:27:54	04:30
111a	5/16/96	1.00	0.00	12.00	0.00	87.00				ON	99.92	34.9	5.06	88.04	34.9	YES	N/A			01:91
112	5/16/96	1.00	0.00	11.00	0.00	88.00			12.0	OFF	100.00	29.9	1.00	99.96	32.4	UPF	N/A	5.90	17:34:01	02:47
112a	5/16/96	1.00	0.00	11.00	0.00	88.00				ON	99.96	32.4	1.00	99.86	30.0	NO	N/A			02:17
112b	5/16/96	3.00	0.00	11.00	0.00	88.00				ON	99.86	30.0	5.46	87.99	34.2	YES	N/A			02:98

Run No.	Date	H_2	N_2O	NH_3	CH_4	Air	Other		Mix	Fan	Po	T_o	P_{max}	P_{final}	T_{final}	Burn?	dP/dt $_{max}$	P_{AICC}	Video	Tape
		(kPa)	(kPa)	(kPa)	(kPa)	(kPa)	(gas)	(kPa)	(%)			(C)	(bar)	(kPa)	(C)		(bar/s)	(bar)	Time	timer
113	5/18/96	1.00	0.00	10.00	0.00	89.00			11.0	OFF	100.05	24.1	1.00	100.00	24.1	UPF	N/A	2.03	14:05:27	02:86
114	5/18/96	1.00	0.00	9.00	0.00	90.00			10.0	OFF	100.00	24.1	1.00	99.98	24.1	NO	N/A	2.58	16:53:19	02:52
114a	5/18/96	3.00	0.00	9.00	0.00	90.00				ON	102.00	24.1	5.00	90.00	30.0	YES	N/A			02:55
115	5/18/96	0.00	0.00	16.00	0.00	84.00			16.0	OFF	100.00	26.1	1.01	99.90	40.6	UPF	N/A	7.28	17:58:27	05:04
115a	5/18/96	0.00	0.00	16.00	0.00	84.00				ON	100.00	40.6	5.55	84.39	30.8	YES	N/A			07:39
116	5/19/96	0.00	0.00	17.00	0.00	83.00			17.0	OFF	100.00	23.8	1.12	99.08	30.8	UPF	N/A	7.58	13:47:44	02:49
116a	5/19/96	0.00	0.00	17.00	0.00	83.00				ON	99.08	30.8	1.00	99.02	24.3	NO	N/A			N/A
116b	5/19/96	0.00	0.00	17.00	0.00	83.00				ON	99.02	24.3	1.00	98.82	24.8	NO	N/A			N/A
116c	5/19/96	2.00	0.00	17.00	0.00	83.00				ON	100.80	24.8	6.65	82.62	32.5	YES	N/A			03:42
117	5/19/96	0.00	0.00	18.00	0.00	82.00			18.0	OFF	100.00	26.3	1.67	95.09	32.4	YES	N/A	7.87	15:30:52	02:33
117a	5/19/96	2.00	0.00	18.00	0.00	82.00				ON	97.00	32.4	5.41	82.17	32.7	YES	N/A			02:71
118	5/19/96	2.00	0.00	15.00	0.00	83.00			17.0	OFF	100.00	28.3	4.39	82.81	34.0	YES	N/A	7.40	16:42:57	02:90
119	5/19/96	2.00	0.00	14.00	0.00	84.00			16.0	OFF	100.00	28.2	1.63	95.11	34.6	YES	N/A	7.10	17:58:25	03:42
119a	5/19/96	5.00	0.00	14.00	0.00	84.00				ON	98.10	34.6	5.14	83.35	35.0	YES	N/A			02:47
120	5/20/96	0.00	0.00	16.00	0.00	84.00			16.0	OFF	100.00	24.1	1.05	99.78	32.2	UPF	0.06	7.28	16:25:48	03:75
120a	5/20/96	0.00	0.00	16.00	0.00	84.00				ON	99.78	32.2	1.00	99.60	26.4	NO	0.00			02:70
120b	5/20/96	2.00	0.00	16.00	0.00	84.00				ON	101.60	26.4	6.49	83.75	33.5	YES	23.47			03:42
121	5/20/96	0.00	0.00	18.00	0.00	82.00			18.0	OFF	100.00	26.7	3.18	83.43	33.0	YES	0.49	7.10	17:42:16	03:16
122	5/19/96	2.00	0.00	15.00	0.00	83.00			17.0	OFF	100.00	28.1	4.36	82.94	34.0	YES	1.87	7.04	18:53:44	02:37
123	5/21/96	2.00	0.00	14.00	0.00	84.00			16.0	OFF	100.00	24.1	1.48	97.28	30.0	YES	0.36	7.10	10:56:40	02:35
123a	5/21/96	4.00	0.00	14.00	0.00	84.00				ON	97.28	30.0	5.67	83.35	32.7	YES	18.75			02:57
124	5/21/96	2.00	0.00	13.00	0.00	85.00			15.0	OFF	100.05	26.7	1.20	99.02	34.5	UPF	0.35	6.79	12:11:35	02:84
124a	5/21/96	4.00	0.00	13.00	0.00	85.00				ON	101.02	34.5	5.94	84.26	32.0	YES	20.00			02:63
125	5/21/96	2.00	0.00	12.00	0.00	86.00			14.0	OFF	100.00	28.1	1.10	99.70	30.7	UPF	0.16	6.47	13:22:51	03:09
125a	5/21/96	2.00	0.00	12.00	0.00	86.00			14.0	ON	99.70	30.7	5.32	86.31	32.3	YES	12.83			02:04
126	5/21/96	4.20	4.20	3.60	0.00	88.00			12.0	OFF	100.00	28.0	1.01	100.07	33.0	UPF	0.03	4.51	14:55:12	04:13

Run No.	Date	H_2	N_2O	NH_3	CH_4	Air	Other		Mix	Fan	Po	T_o	P_{max}	P_{final}	T_{final}	Burn?	dP/dt_{max}	P_{AICC}	Video	Tape
		(kPa)	(kPa)	(kPa)	(kPa)	(kPa)	(gas)	(kPa)	(%)			(C)	(bar)	(kPa)	(C)		(bar/s)	(bar)	Time	timer
126a	5/21/96	4.20	4.20	3.60	0.00	88.00				ON	100.07	33.0	2.32	96.11	30.3	YES	2.12			02:60
127	5/21/96	5.25	5.25	4.50	0.00	85.00			15.0	OFF	100.00	27.5	1.45	99.52	34.2	UPF	0.12	5.22	15:50:00	02:85
127a	5/21/96	5.25	5.25	4.50	0.00	85.00				ON	99.52	34.2	4.28	92.33	31.7	YES	4.28			02:86
128	5/21/96	5.95	5.95	5.10	0.00	83.00			17.0	OFF	100.00	28.1	3.53	91.01	33.0	YES	1.57	5.71	16:53:25	02:64
129	5/22/96	5.95	5.95	5.10	0.00	83.00			17.0	ON	100.00	24.2	5.07	91.12	29.9	YES	16.03	5.71	11:12:44	02:54
130	5/22/96	5.25	5.25	4.50	0.00	85.00			15.0	ON	100.00	26.4	4.56	92.25	30.1	YES	8.59	5.24	12:00:44	03:25
131	5/22/96	4.20	4.20	3.60	0.00	88.00			12.0	ON	100.00	26.7	2.48	95.83	30.0	YES	2.63	4.51	13:21:26	02:51
132	5/22/96	4.00	4.00	8.00	0.00	84.00			16.0	ON	100.00	26.6	5.20	89.98	31.7	YES	15.40	6.10	14:26:55	03:90
133	5/22/96	3.25	3.25	6.50	0.00	87.00			13.0	ON	100.00	27.7	4.43	92.16	31.8	YES	5.88	5.23	15:22:13	02:70
134	5/22/96	4.75	4.75	9.50	0.00	81.00			19.0	ON	100.00	28.2	6.07	87.58	33.4	YES	16.84	6.77	16:15:27	02:99
135	5/22/96	4.75	0.00	9.50	0.00	81.00	N2	4.75	19.0	ON	100.00	28.8	5.49	85.32	33.5	YES	16.30	6.15	17:24:31	02:46
136	5/23/96	4.00	0.00	8.00	0.00	84.00	N2	4.00	13.0	ON	100.00	24.3	4.87	87.64	29.6	YES	11.40	4.80	11:03:45	03:59
137	5/23/96	3.25	0.00	6.50	0.00	87.00	N2	3.25	13.0	ON	100.00	25.9	3.08	92.24	30.2	YES	3.86	4.80		03:45
138	5/23/96	2.50	2.50	5.00	0.00	90.00			10.0	ON	100.00	26.0	1.05	100.00	28.5	NO	0.03	4.39	13:34:30	08:18
138a	5/23/96	2.50	2.50	5.00	0.00	90.00				ON	100.00	28.5	1.00	99.85	26.6	NO	0.02			03:53
138b	5/23/96	4.50	2.50	5.00	0.00	90.00				ON	101.85	26.6	4.20	93.37	31.0	YES	7.80			02:36
139	5/23/96	3.00	3.00	6.00	0.00	88.00			12.0	ON	100.00	26.9	2.19	97.06	29.8	YES	2.23	4.96	14:32:28	03:36
140	5/23/96	3.00	0.00	6.00	0.00	88.00	N2	3.00	12.0	ON	100.00	26.6	2.16	97.00	30.0	YES	2.09	4.56	15:29:41	04:69
141	5/23/96	5.50	5.50	11.00	0.00	78.00			22.0	ON	100.00	27.5	6.86	84.73	32.0	YES	26.84	7.46	16:23:19	03:10
142	5/23/96	5.50	0.00	11.00	0.00	78.00	N2	5.50	22.0	ON	100.00	28.8	6.23	82.18	33.2	YES	18.00	6.75	17:21:42	04:47
143	5/23/96	5.25	0.00	4.50	0.00	85.00	N2	5.25	15.0	ON	100.00	26.3	4.07	89.80	30.1	YES	8.06	4.55	21:56:11	03:27
144	5/23/96	5.95	0.00	5.10	0.00	83.00	N2	5.95	17.0	ON	100.08	26.9	4.45	88.20	32.0	YES	11.92	4.93	23:04:39	02:68
145	5/23/96	4.20	0.00	3.60	0.00	88.00	N2	4.20	12.0	ON	100.00	27.5	2.42	95.56	29.7	YES	2.43	3.96	23:58:04	03:08
146	5/24/96	7.00	7.00	6.00	0.00	80.00			20.0	ON	100.00	25.5	5.76	89.06	30.3	YES	13.71	6.37	12:02:55	02:70
147	5/24/96	7.00	0.00	6.00	0.00	80.00	N2	7.00	20.0	ON	100.00	26.7	5.09	85.68	30.8	YES	11.59	5.46	13:13:13	03:61
148	5/24/96	3.00	6.00	9.00	0.00	82.00			18.0	ON	100.00	27.1	5.52	91.20	31.4	YES	13.05	6.32	14:41:19	03:65

Run No.	Date	H_2	N_2O	NH_3	CH_4	Air	Other		Mix	Fan	Po	T_o	P_{max}	P_{final}	T_{final}	Burn?	dP/dt_{max}	P_{AICC}	Video	Tape
		(kPa)	(kPa)	(kPa)	(kPa)	(kPa)	(gas)	(kPa)	(%)			(C)	(bar)	(kPa)	(C)		(bar/s)	(bar)	Time	timer
149	5/24/96	2.50	5.00	7.50	0.00	85.00			15.0	ON	100.10	28.4	4.83	92.98	31.7	YES	12.68	5.57	15:41:13	08:35
150	5/24/96	2.17	4.33	6.50	0.00	87.00			13.0	ON	100.00	28.7	1.00	99.95	28.6	NO	0.00	5.06	16:40:40	07:24
150a	5/24/96	2.17	4.33	6.50	0.00	87.00				OFF	100.00	28.6	1.00	99.88	29.7	UPF	0.02			03:94
150b	5/24/96	4.17	4.33	6.50	0.00	87.00				ON	101.98	29.7	4.88	93.11	31.3	YES	9.88			03:01
151	5/24/96	2.50	0.00	7.50	0.00	85.00	N2	5.00	15.0	ON	100.00	28.3	2.36	96.50	29.9	YES	2.56	4.92	18:03:06	02:69
152	5/26/96	3.00	0.00	9.00	0.00	82.00	N2	6.00	18.0	ON	100.00	24.8	4.91	87.95	29.8	YES	11.57	5.53	15:32:22	02:86
153	5/26/96	3.50	7.00	10.50	0.00	79.00			21.0	ON	100.00	26.1	6.24	88.93	31.0	YES	25.40	7.01	16:52:55	05:47
154	5/26/96	3.50	0.00	10.50	0.00	79.00	N2	7.00	21.0	ON	100.00	25.7	5.48	85.72	30.3	YES	16.22	6.11	20:32:20	06:70
155	5/26/96	3.50	3.50	3.00	0.00	90.00			10.0	OFF	100.00	26.6	1.00	100.00	28.1	UPF	0.03	4.25	22:15:11	03:22
155a	5/26/96	7.50	3.50	3.00	0.00	90.00				ON	104.00	28.1	4.40	94.08	32.1	YES	11.68			02:09
156	5/26/96	3.15	3.15	2.70	0.00	91.00			9.0	OFF	100.00	27.5	1.00	99.90	27.4	UPF	0.02	3.73	23:15:46	04:89
156a	5/26/96	3.15	3.15	2.70	0.00	91.00				ON	99.90	27.4	1.01	100.25	29.5	UPF	0.04	3.73		02:67
156b	5/26/96	6.15	3.15	2.70	0.00	91.00				ON	100.25	29.5	3.78	93.83	31.1	YES	6.39			03:05
157	5/27/96	2.80	2.80	2.40	0.00	92.00			8.0	OFF	100.00	27.6	1.00	100.00	27.9	NO	0.02	3.46	0:26:51	05:32
157a	5/27/96	6.80	2.80	2.40	0.00	92.00				ON	104.00	27.9	3.98	94.32	29.9	YES	7.78			02:42
158	5/27/96	4.90	4.90	4.20	0.00	86.00			14.0	OFF	100.00	25.2	1.05	99.80	31.3	UPF	0.10	5.01	17:22:08	03:44
158a	5/27/96	4.90	4.90	4.20	0.00	86.00				ON	99.80	31.3	3.83	91.70	30.4	YES	5.63			02:83
159	5/27/96	7.00	7.00	6.00	0.00	80.00			20.0	OFF	100.00	26.3	5.36	89.61	32.2	YES	10.82	6.37	18:18:21	03:73
160	5/27/96	3.00	3.00	6.00	0.00	88.00			12.0	OFF	100.00	27.1	1.01	100.00	30.0	UPF	0.08	4.96	19:50:56	03:15
160a	5/27/96	3.00	3.00	6.00	0.00	88.00				ON	100.00	30.0	1.97	97.52	28.7	YES	1.53			03:23
161	5/27/96	2.50	2.50	5.00	0.00	90.00			10.0	OFF	100.00	27.5	1.00	99.97	27.5	UPF	0.06	4.39	20:39:14	03:78
161a	5/27/96	2.50	2.50	5.00	0.00	90.00				ON	99.97	27.5	1.00	99.90	26.7	NO	0.03			03:11
161b	5/27/96	5.00	2.50	5.00	0.00	90.00				ON	102.40	26.7	4.47	93.13	30.1	YES	8.14			02:91
162	5/27/96	2.25	2.25	4.50	0.00	91.00			9.0	OFF	100.00	27.6	1.00	99.95	27.6	NO	N/A	4.10	21:45:10	03:68
162a	5/27/96	5.25	2.25	4.50	0.00	91.00				ON	102.95	27.6	4.19	93.55	30.1	YES	8.61			02:58
163	5/27/96	3.25	3.25	6.50	0.00	87.00			13.0	OFF	100.10	27.9	1.02	99.93	33.2	UPF	0.05	5.23	22:45:57	03:23

Run No.	Date	H_2 (kPa)	N_2O (kPa)	NH_3 (kPa)	CH_4 (kPa)	Air (kPa)	Other (gas)	Other (kPa)	Mix (%)	Fan	Po	T_o (C)	P_{max} (bar)	P_{final} (kPa)	T_{final} (C)	Burn?	dP/dt_{max} (bar/s)	P_{AICC} (bar)	Video Time	Tape timer
163a	5/27/96	3.25	3.25	6.50	0.00	87.00				ON	99.93	33.2	4.06	91.76	31.5	YES	4.71			02:62
164	5/27/96	4.00	4.00	8.00	0.00	84.00			16.0	OFF	100.00	28.6	1.14	99.42	37.8	UPF	0.15	6.03	23:41:24	02:45
164a	5/27/96	4.00	4.00	8.00	0.00	84.00				ON	99.42	37.8	4.97	89.81	32.3	YES	10.46			03:08
165	5/28/96	4.75	4.75	9.50	0.00	81.00			19.0	OFF	100.00	28.8	4.72	87.28	33.3	YES	3.75	6.77	0:49:11	04:46
166	5/28/96	5.50	5.50	11.00	0.00	78.00			22.0	OFF	100.00	29.3	5.90	84.91	34.5	YES	14.87	7.46	1:56:52	03:06
167	5/28/96	2.50	5.00	7.50	0.00	85.00			15.0	OFF	100.00	29.9	1.01	99.97	32.5	UPF	0.03	5.57	3:03:37	03:81
167a	5/28/96	2.50	5.00	7.50	0.00	85.00			15.0	ON	99.97	32.5	2.66	95.71	32.1	YES	3.41			03:19
168	5/28/96	2.17	4.33	6.50	0.00	87.00			13.0	OFF	100.16	25.6	1.00	100.13	27.4	UPF	0.02	5.06	11:35:48	03:75
168a	5/28/96	5.17	4.33	6.50	0.00	87.00				ON	100.13	27.4	5.18	92.92	32.6	YES	14.76			03:79
169	5/28/96	2.00	4.00	6.00	0.00	88.00			12.0	OFF	100.00	26.8	1.00	100.00	27.2	UPF?	0.02	4.79	12:32:29	03:42
169a	5/28/96	5.00	4.00	6.00	0.00	88.00				ON	103.00	27.2	4.93	93.40	31.0	YES	11.80			03:62
170	5/28/96	1.83	3.67	5.50	0.00	89.00			11.0	OFF	100.00	28.2	1.00	99.92	27.8	NO	0.03	4.52	13:30:02	04:53
170a	5/28/96	4.83	3.67	5.50	0.00	89.00				ON	102.92	27.8	4.60	94.08	31.9	YES	9.86			02:38
171	5/28/96	3.00	6.00	9.00	0.00	82.00			18.0	OFF	100.00	28.2	1.08	99.72	31.5	UPF	0.14	6.32	14:30:15	06:46
171a	5/28/96	3.00	6.00	9.00	0.00	82.00				ON	99.72	31.5	5.22	91.11	32.3	YES	13.49			03:12
172	5/28/96	3.50	7.00	10.50	0.00	79.00			21.0	OFF	100.00	28.8	4.50	89.42	34.8	YES	2.53	7.01	15:36:04	04:28
173	5/28/96	3.17	6.33	9.50	0.00	81.00			19.0	OFF	100.00	28.6	1.15	99.44	37.7	UPF	0.22	6.56	17:31:57	05:15
173a	5/28/96	3.17	6.33	9.50	0.00	81.00				ON	99.68	28.6	5.36	90.80	33.7	YES	10.63			03:54
174	5/28/96	3.33	6.67	10.00	0.00	80.00			20.0	OFF	100.00	28.6	1.32	99.07	31.4	UPF	0.26	6.79	18:44:04	04:05
174a	5/28/96	3.33	6.67	10.00	0.00	80.00				ON	99.07	31.4	N/A	90.17	33.4	YES	N/A			03:42
175	5/28/96	0.00	4.00	14.00	0.00	82.00			18.0	OFF	100.00	29.4	1.00	99.97	35.0	UPF	0.03	7.14	19:45:07	05:02
175a	5/28/96	0.00	4.00	14.00	0.00	82.00				ON	99.97	35.0	1.00	99.83	29.3	NO	0.03			02:40
175b	5/28/96	2.00	4.00	14.00	0.00	82.00				ON	101.93	29.3	6.53	87.89	34.6	YES	24.76			03:08
176	5/28/96	0.00	4.00	18.00	0.00	78.00			22.0	OFF	100.00	26.9	5.10	84.10	32.8	YES	3.61	8.23	23:10:01	04:07
177	5/29/96	0.00	4.00	17.00	0.00	79.00			21.0	OFF	100.00	28.4	4.56	85.54	34.9	YES	1.95	7.95	0:32:03	04:70
178	5/29/96	0.00	5.00	15.00	0.00	80.00			20.0	OFF	100.00	29.4	1.10	99.66	31.8	UPF	0.17	7.50	1:50:04	02:87

Run No.	Date	H_2 (kPa)	N_2O (kPa)	NH_3 (kPa)	CH_4 (kPa)	Air (kPa)	Other (gas)	Other (kPa)	Mix (%)	Fan	Po	T_o (C)	P_{max} (bar)	P_{final} (kPa)	T_{final} (C)	Burn?	dP/dt_{max} (bar/s)	P_{AICC} (bar)	Video Time	Tape timer
178a	5/29/96	0.00	5.00	15.00	0.00	80.00				ON	99.66	31.8	1.10	99.53	30.2	NO	0.13			04:40
178b	5/29/96	2.00	5.00	15.00	0.00	80.00				ON	101.53	30.2	6.71	87.41	35.6	YES	27.31			05:09
179	5/29/96	0.00	4.00	16.00	0.00	80.00			20.0	OFF	100.00	25.6	1.45	98.45	30.8	YES	0.33	7.28	12:06:08	03:25
179a	5/29/96	0.00	4.00	16.00	0.00	80.00				ON	98.45	30.8	1.00	98.72	25.8	NO	0.00			02:56
179b	5/29/96	2.00	4.00	16.00	0.00	80.00				ON	101.72	25.8	6.59	85.24	32.7	YES	24.95			02:42
180	5/29/96	0.00	0.00	20.00	0.00	80.00			20.0	OFF	100.00	26.9	5.05	80.14	34.2	YES	2.86	8.43	13:46:00	02:96
181	5/29/96	0.00	0.00	22.00	0.00	78.00			22.0	OFF	100.00	28.4	5.40	79.69	35.0	YES	3.61	8.86	14:54:33	03:30
182	5/29/96	0.00	0.00	24.00	0.00	76.00			24.0	OFF	100.00	29.8	5.31	82.61	35.6	YES	3.81	8.88	15:56:31	06:26
183	5/29/96	0.00	0.00	18.00	0.00	82.00			18.0	ON	100.00	28.3	6.67	82.52	34.1	YES	17.15	7.87	17:51:42	02:99
184	5/30/96	0.00	0.00	16.00	0.00	84.00			16.0	ON	100.00	24.7	6.16	84.21	29.8	YES	18.91	7.28	0:13:29	02:44
185	5/30/96	0.00	0.00	20.00	0.00	80.00			20.0	ON	100.00	26.3	7.28	80.01	32.6	YES	28.84	8.43	1:54:41	02:48
186	5/30/96	0.00	8.00	14.00	0.00	78.00			22.0	OFF	100.00	25.1	1.05	99.97	32.8	UPF	0.11	7.42	22:06:45	02:63
186a	5/30/96	0.00	8.00	14.00	0.00	78.00				ON	99.97	32.8	1.00	99.81	25.2	NO	0.00			02:78
186b	5/30/96	2.00	8.00	14.00	0.00	78.00				ON	101.81	25.2	6.96	90.12	33.5	YES	29.56			04:30
187	5/30/96	1.00	0.00	12.00	0.00	87.00			13.0	OFF	100.00	26.8	1.01	99.93	30.4	UPF	0.03	6.24	23:35:24	03:09
187a	5/30/96	1.00	0.00	12.00	0.00	87.00				ON	99.83	30.4	5.08	87.76	31.5	YES	17.59			04:91
188	5/31/96	1.00	4.00	12.00	0.00	83.00			17.0	OFF	100.00	27.1	1.02	99.94	28.7	UPF	0.04	6.64	0:40:57	03:31
188a	5/31/96	1.00	4.00	12.00	0.00	83.00			17.0	ON	101.94	28.7	5.65	89.71	32.7	YES	13.78			02:75
189	5/31/96	1.00	8.00	10.00	0.00	81.00			19.0	OFF	100.00	28.3	1.00	99.98	29.0	UPF	0.04	6.37	1:43:39	04:15
189a	5/31/96	1.00	8.00	10.00	0.00	81.00				ON	99.98	29.0	1.00	99.94	28.3	NO	0.00			03:49
189b	5/31/96	3.00	8.00	10.00	0.00	81.00				OFF	101.94	28.3	6.08	93.03	33.5	YES	22.03			03:31
190	5/31/96	0.00	8.00	16.00	0.00	76.00			24.0	OFF	100.00	28.9	4.88	88.14	33.5	YES	2.52	8.02	2:59:16	03:26
191	5/31/96	0.00	8.00	15.00	0.00	77.00			23.0	OFF	100.00	25.6	2.00	94.83	29.0	YES	0.35	7.73	12:01:11	03:63
192	5/31/96	0.00	8.00	13.00	0.00	79.00			21.0	OFF	100.00	26.3	1.00	99.90	28.3	UPF	0.09	7.12	13:01:22	03:70
192a	5/31/96	2.00	8.00	13.00	0.00	79.00				ON	101.90	28.3	6.82	91.00	32.8	YES	14.28			02:92
193	5/31/96	0.00	4.00	15.00	0.00	81.00			19.0	OFF	100.00	27.9	1.02	99.74	30.0	UPF	0.09	7.36	14:11:34	03:86

Run No.	Date	H_2 (kPa)	N_2O (kPa)	NH_3 (kPa)	CH_4 (kPa)	Air (kPa)	Other (gas)	Other (kPa)	Mix (%)	Fan	P_o	T_o (C)	P_{max} (bar)	P_{final} (kPa)	T_{final} (C)	Burn?	dP/dt_{max} (bar/s)	P_{AICC} (bar)	Video Time	Tape timer
193a	5/31/96	0.00	4.00	15.00	0.00	81.00				ON	99.74	30.0	5.98	87.83	33.6	YES	14.20			04:28
194	5/31/96	0.00	4.00	13.00	0.00	83.00			17.0	OFF	100.00	28.6	1.00	99.88	28.6	NO	0.09	6.73	15:24:33	05:65
194a	5/31/96	2.00	4.00	13.00	0.00	83.00				ON	101.88	28.6	6.33	89.11	33.9	YES	22.02			04:41
195	5/31/96	0.00	8.00	17.00	0.00	75.00			25.0	OFF	100.00	29.0	5.40	87.30	35.0	YES	4.88	8.31	16:34:28	02:79
196	5/31/96	0.00	8.00	18.00	0.00	74.00			26.0	OFF	100.00	30.3	5.54	85.68	34.7	YES	4.31	8.60	17:38	04:29
197	5/31/96	0.00	8.00	12.00	0.00	80.00			20.0	OFF	100.00	25.2	1.00	99.98	25.2	UPF	22.99	6.80	0:02:40	02:85
197a	5/31/96	2.10	8.00	12.00	0.00	80.00				ON	102.88	25.2	6.46	92.14	30.9	YES	1.84			02:81
198	6/11/96	9.00	0.00	0.00	0.00	91.00			9.0	OFF	100.15	23.6	3.29	88.93	29.2	YES	2.16	4.02	10:40:02	03:57
199	6/11/96	9.00	0.00	0.00	0.00	91.00	H2O	SAT	9.0	OFF	100.00	25.2	3.31	87.99	29.7	YES	0.12	4.02	11:28:29	03:11
200	6/11/96	8.00	0.00	0.00	0.00	92.00	H2O	SAT	8.0	OFF	100.00	25.9	1.10	98.45	36.9	UPF	4.63	3.73	12:18:54	04:89
200a	6/11/96	8.00	0.00	0.00	0.00	92.00	H2O	SAT		ON	98.45	36.9	3.13	89.58	30.0	YES	0.12			04:14
201	6/11/96	8.00	0.00	0.00	0.00	92.00			8.0	OFF	100.00	26.5	1.09	99.01	32.7	YES	0.11	3.73	13:08:12	03:47
201a	6/11/96	8.00	0.00	0.00	0.00	92.00				ON	99.01	26.5	3.13	90.23	29.3	YES	4.82			03:46
202	6/11/96	6.00	0.00	0.00	0.00	94.00			6.0	OFF	100.00	26.4	1.02	99.93	30.9	UPF	0.08	3.12	14:33:39	02:70
202a	6/11/96	6.00	0.00	0.00	0.00	94.00				ON	99.93	30.9	2.21	95.81	29.4	YES	2.19			02:95
203	6/11/96	6.00	0.00	0.00	0.00	94.00	H2O	SAT	6.0	OFF	100.00	26.8	1.02	99.73	28.2	UPF	0.03	3.12	15:19:12	03:55
203a	6/11/96	6.00	0.00	0.00	0.00	94.00	H2O	SAT		ON	99.73	28.2	2.18	94.84	29.8	YES	2.02			03:92
204	6/11/96	6.00	0.00	0.00	0.00	94.00	H2O	SAT	6.0	OFF	100.00	27.0	1.07	99.75	28.3	UPF	0.02	3.12	16:05:14	05:89
204a	6/11/96	6.00	0.00	0.00	0.00	94.00	H2O	SAT		ON	99.75	28.3	2.19	94.84	29.4	YES	2.08			03:33
205	6/11/96	4.00	0.00	0.00	0.00	96.00	H2O	SAT	4.0	OFF	100.00	26.5	1.00	100.00	28.0	UPF	0.17	2.46	16:54:54	00:15
205a	6/11/96	7.00	0.00	0.00	0.00	96.00	H2O	SAT		ON	103.00	28.0	2.83	94.91	28.1	YES	3.57			04:13
206	6/11/96	4.00	0.00	0.00	0.00	96.00			4.0	OFF	100.00	26.5	1.00	99.96	26.9	UPF	0.17	2.46	17:51:43	03:46
206a	6/11/96	7.00	0.00	0.00	0.00	96.00				ON	102.96	26.9	2.94	95.50	29.7	YES	4.38			03:58
207	6/12/96	3.50	7.00	10.50	0.00	79.00	H2O	SAT	21.0	OFF	100.00	25.1	4.56	88.05	31.3	YES	2.47	7.01	11:38:54	02:97
208	6/12/96	3.17	6.33	9.50	0.00	81.00	H2O	SAT	19.0	OFF	100.00	26.4	1.19	29.00	29.0	UPF	0.25	6.52	13:18:02	03:45
208a	6/12/96	3.17	6.33	9.50	0.00	81.00	H2O	SAT		ON	99.03	29.0	5.36	89.74	32.9	YES	10.62			02:42

Appendix B Burning Velocity

The measured radial flame velocity dr/dt (cm/s), density ratio ρ_b/ρ_u, and laminar burning velocity S_u (cm/s) are given here in tabular form.

Table B.1: Hydrogen-Air. Laminar burning velocity.

% Mix	4	6	8	9
dr/dt	7.43	13.61	17.90	32.17
ρ_b/ρ_u	.482	.388	.326	.308
S_u	3.58	5.28	5.84	9.89

Table B.2: Ammonia–Air. Laminar burning velocity.

% Mix	12	13	14	15	16	17	18	20	22	24
dr/dt	4.27	3.64	4.42	11.21	17.37	19.71	24.62	37.16	45.8	48.7
ρ_b/ρ_u	.204	.193	.183	.174	.167	.160	.154	.143	.134	.136
S_u	.871	.702	.809	1.96	2.89	3.15	3.77	5.30	6.10	6.64

Table B.3: Ammonia–Air–4% N_2O. Laminar burning velocity.

% Mix	13	14	15	16	17	18
dr/dt	5.10	11.62	16.56	22.6	27.75	36.75
ρ_b/ρ_u	.181	.164	.157	.150	.145	.140
S_u	.923	1.90	2.60	3.41	4.03	5.16

Table B.4: Ammonia - Air - 8% N_2O. Laminar burning velocity.

% Mix	12	13	14	15	16	17	18
dr/dt	6.98	11.54	14.38	22.7	29.5	38.8	44.7
ρ_b/ρ_u	.179	.171	.164	.157	.151	.145	.140
S_u	1.25	1.97	2.35	3.57	4.44	5.64	6.27

Table B.5: Mixture A. Laminar burning velocity.

% Mix	7	8	9	10	11	12	13	14	15	16	17
dr/dt	4.38	7.78	9.84	12.92	15.31	15.82	17.43	18.62	25.50	29.56	37.30
ρ_b/ρ_u	.38	.35	.33	.31	.301	.274	.260	.248	.236	.226	.217
S_u	1.68	2.76	3.25	3.98	4.62	4.34	4.54	4.61	6.03	6.70	8.10

Table B.6: Mixture B. Laminar burning velocity.

% Mix	8	9	10	12	14	15	17	20
dr/dt	4.96	8.24	10.02	13.45	18.36	20.64	31.09	62.38
ρ_b/ρ_u	.352	.327	.3061	.267	.245	.233	.215	.192
S_u	1.75	2.69	3.07	3.60	4.50	4.82	6.67	11.99

Table B.7: Mixture C. Laminar burning velocity.

% Mix	9	10	12	13	16	19	22
dr/dt	6.12	8.0	12.84	14.48	26.55	45.12	67.8
ρ_b/ρ_u	.299	.279	.247	.243	0.205	.180	.162
S_u	1.83	2.23	3.17	3.51	5.43	8.12	11.01

Table B.8: Mixture D. Laminar burning velocity.

% Mix	11	12	13	15	18	19	20	21
dr/dt	6.94	8.28	10.21	14.55	20.02	26.45	29.78	34.09
ρ_b/ρ_u	0.271	0.256	0.243	0.220	0.193	0.186	0.179	0.174
S_u	1.88	2.12	2.48	3.19	3.87	4.92	5.33	5.92

Appendix C Checklists

A series of checklists were used to carry out the operations needed to startup, run and shut down the experiment. These checklists implemented the safety procedures that were developed in the course of contructing the experiment and carrying out a safety assessment.

There are five checklists:

1. Bottle installation/change
2. Start of day/end of day
3. Burns with ammonia
4. Failed burn (NOGO) procedure
5. Burns without ammonia

C.1 Bottle Installation/Change

Ammonia Storage/Dispensing System - Checklist

Bottle change/New bottle installation

1. Check exhaust, sparger *Guggenheim basement*
    (a) _____Check that all valves in system are closed (use list)

    (b) _____Verify exhaust vent operation

    Read the Magnehelic gauges in room 14

        i. _____EF3, high-velocity vent: ($\sim$ 0.4-in. H_2O)

        ii. _____EF1, emergency purge, Rm 14: ($\sim$ 0.4-in. H_2)

        actuate Manual purge to test.

    (c) _____Lock out/Tag Main Vacuum valve (B1)

    (d) _____Check sparger

        i. _____Water level (2-3-in. below line)

        ii. _____Ph less than 9

        If Ph is too high, drain tank (SV10) and refill. Run H_2O into floor drain while draining tank.

    Skip e) and f) if no bottle is present

    (e) Suit up with appropriate equipment

        i. _____ Chemical goggles and faceshield

        ii. _____ Rubber gloves

        iii. _____ Respirator available

    (f) _____ Through access port, check bottle valve is tightly closed.

    (g) Purge Ammonia supply line if needed (see “end of day” procedure)

        i. Check that all valves in system are closed, see list.

        ii. _____ Open Ammonia Vacuum valve (SV8)

(h) Evacuate Ammonia Line *Control Room*

   i. _____ Switch selector to "NH3" on front panel
   ii. _____ Open NH3 vacuum valve (C1)
   iii. _____ Open the "key switch" valve (KS1)
   iv. _____ Open Ammonia valve on control panel (SV1)
   v. _____ Open the needle valve (NV1)
   vi. _____ Press the red NH3 button.
   vii. _____ Release the button when vacuum drops below 5 kPa
   viii. _____ Close Ammonia feed valve (SV1)

(i) Purge pump exhaust line *Experiment Room*

   i. _____ Close Ammonia Vacuum valve (SV8)
   ii. _____ Open Bleed up valve (SV7), bleed system up to 1 bar, close bleed up valve.
   iii. _____ Open Purge Valve (SV9)

(j) Using Nitrogen to Purge pump exhaust line *Control Room*

   i. _____ Open nitrogen valve on diluent rack
   ii. _____ Open Diluent valve (SV5)
   iii. _____ Allow system to purge for 30 sec.
   iv. _____ Close Diluent Valve (SV5)
   v. _____ Close the "key switch" valve (KS1)
   vi. _____ Return to bottle farm

Bottle Change Procedure *Two operators in bottle farm*

(k) Remove Old Bottle (if needed)

   i. _____ Operator 1 suits up with chemical goggles, faceshield, Apron, and respirator is available. Operator 2 at eyewash.
   ii. _____ Open cabinet
   iii. _____ Unthread the yoke securing nut

   iv. _____ Remove yoke from bottle, air will leak into hose
   v. _____ Secure a cap on the bottle
   vi. _____ Release the securing strap
   vii. _____ Remove the empty bottle

(l) Regulator adjustment *if required*

   i. _____ Open pump bypass circuit (SV1, NV1, KS1, C1, SV9)
   ii. _____ N_2 purge bottle open, regulator set to 150 kPa
   iii. _____ Manually actuate FV2 (N2 Purge)
   iv. _____ Adjust regulator to 20 psi (150 kPa)
   v. _____ Close SV1, NV1, KS1, C1, SV9
   vi. _____ Close SV8
   vii. _____ Evacuate Ammonia Line if needed *Control Room* Repeat steps g) to j)

(m) Install New Bottle

   i. _____ Place the new bottle in the cabinet, secure the strap
   ii. _____ Remove the cap from the bottle.
   iii. _____ Remove the plastic insert from the bottle nozzle
   iv. _____ Place a new rubber gasket on the sealing surface of the yoke
   v. _____ Place the yoke over the bottle, secure the sealing surface in place.
   vi. _____ Tighten the yoke.
   vii. _____ Open the valve on the bottle.

2. The system state is:

air in ammonia bottle hookup line
ammonnia line under vacuum
vacuum lines filled with N_2, 1 bar

Line from SV to KS1 filled with N_2, 1 bar

tank - unchanged

C.2 Start/End of Day

Ammonia Storage-Dispensing System - Start of Day

Last Modified: April 21, 1999

1. **Sparger, Exhaust Operation** *Gugg basement*
   - (a) ___ close all valves on gas supply, mimic panels, set room purge to "manual"
   - (b) ___ Verify Kinney Vacuum valve (B1) is locked out
   - (c) ___ SV7 & SV9 closed, SV8 open, check and start NH_3 vacuum pump
   - (d) ___ Test exhaust vent EF3: ________ ($\sim$ 0.42-in. H_2O), EF1 ________ ($\sim$ 0.42-in. H_2)
   - (e) ___ Set NH_3 selector valve on 14 Gugg.
   - (f) ___ Fill sparger, check pH
   - (g) ___ Reset room purge to "auto"
   - (h) ___ Evacuate NH_3 line up to N_2 purge regulator (bottle farm) (C1, KS1, SV1 open)
   - (i) ___ Close SV1, KS1, C1
2. **Opening ammonia bottle** *bottle farm*

   One operator is required with equipment bag, keys.
   - (a) ___ Open N_2 purge bottle, regulator at 20-40 psi, supply pressure ________ (psi)
   - (b) ___ Suit up with appropriate equipment (faceshield, rubber gloves, respirator available)
   - (c) ___ Open access door on cabinet
   - (d) ___ Open NH_3 bottle valve (3/8-square drive socket, $\sim$ 2 turns)
   - (e) ___ Close and lock access door
   - (f) ___ Open other gas bottles as needed
   - (g) ___ Lock bottle farm

3. **Charging the Ammonia system** *Control room*
    (a) ___ Switch selector on panel to “NH_3” (FV1)
    (b) ___ Press “NH_3” button (PB1) on gas panel to fill line
    (c) ___ NH_3 line pressurized to ________ (psig) (PG1)
    Adjust NH_3 regulator pressure to 15 psig if needed *bottle farm*
    (d) ___ Hang ”Warning: Line Loaded with Ammonia” placard over Ammonia feed valve handle
4. **System is ready for use** Ammonia bottle open, line at 15 psig

End of Day (Shutdown) Operations

1. **Turn off ammonia bottle** *Bottle farm*
   (a) __ Suit up with gloves, faceshield
   (b) __ Open access door
   (c) __ Close Ammonia bottle valve
   (d) __ Close and lock access door
2. **Purging the Ammonia Line** *control room*
   (a) __ Fill tank with air (90 kPa) or use products from the last shot
   (b) __ Mixer on
   (c) __ Close NH_3 vacuum line (C1)
   (d) __ Open tank isolation valve (A1)
   (e) __ Open ammonia feed valve (SV1)
   (f) __ Switch KS1 on, Open needle valve (NV1)
   (g) __ Select "Purge" valve (FV2), purge (PB2) for 20 s
3. **Dispose of tank contents and evacuate line**
   (a) __ Open NH_3 vacuum line (C1)
   (b) __ Wait (!) for pressure to approach 0.1 kPa

   (c) __ Close NH_3 line valve (SV1)
   (d) __ Close KS1
   (e) __ Close tank isolation valve (A1)
   (f) __ Close NH_3 vacuum valve (C1)
   (g) __ Change NH_3 line placard to "System Safe: Line Under Vacuum"
4. **Final Purge** (In control room)
   (a) __ Turn off vacuum pump
   (b) __ Crack open valve SV7 and bleed pump up to atmospheric pressure

   (c) ___ Close valve SV7 and SV8
   (d) ___ Open SV9
   (e) ___ Open N_2 diluent line, SV6, NV1, KS1, C1, purge for 20 s
   (f) ___ Close N_2 diluent line, SV6, NV1, KS1, C1
   (g) ___ Close SV9

5. ___ Shut down video and instruments (see list)
6. ___ Mimic panel power off
7. ___ Check Ph of Sparger and dump (SV10)

Final state of system

   (a) Tank: under vacuum
   (b) Ammonia line: Under vacuum
   (c) Gas handling line: N_2 from SV1 to C1
   (d) Ammonia Vacuum line: N_2 from C1 to SV9 to Sparger,
   Air from SV8 to vacuum pump

Valve List

1. Mimic Panels *control room*
    - (a) A-1, tank isolation
    - (b) B-1, house vacuum line (NO NH_3!)
    - (c) C-1, NH_3 vacuum line
    - (d) KS1, key switch authority valve
    - (e) NV1, needle vavle for gas supply manifold
    - (f) SV1-6 gas supply feed valves
    - (g) Diluent supply valves (Air, N_2 Ar)
    - (h) NH_3 control system (purge or NH_3)
        - i. FV1 NH_3 bottle farm block valve (PB)
        - ii. FV2 N_2 purge bottle farm block valve (PB)
    - (i) FV3 CH_4 bottle farm block valve (PB)
    - (j) H_2 bottle farm block valve (PB)
2. Manual valves *Experiment room*
    - (a) SV7, air bleed-up for vacuum lines
    - (b) SV8, NH_3 vacuum pump isolation valve
    - (c) SV9, NH_3 vacuum pump bypass valve
    - (d) SV10, sparger drain valve
3. Bottle farm (not included in valve shut down list)
    - (a) NH_3 bottle valve
    - (b) NH_3 regulator outlet valve (Leave open at all times)
    - (c) N_2 purge bottle valve
    - (d) N_2 purge regulator outlet valve (Leave open at all times)
    - (e) Air supply for air-operated valves (Leave open at all times)
    - (f) CH_4 bottle (leave regulator exit valve open at all times)

(g) N_2O bottle (leave regulator exit valve open at all times)

(h) Other bottles in farm (N_2, O_2, H_2, Ar)

Instrumentation

1. ___ Light source & fan (north side of vessel, power strip and switches)
2. ___ Video Camera, small monitor (on top of CONVOL)
3. ___ VCR, load CONVOL tape and cue up (Under Hyjet control panel)
4. ___ Timer (set switch on minibox to CONVOL)
5. ___ Monitor, Computer (Brookside)
6. ___ Trigtek amplifier (Blue rack panel)
7. ___ Dynamics amplifier (Blue rack panel)
8. ___ TM11 (under convol table, check switch, controlled from mimic panel)
9. ___ Hipotronics power supply (grey rack panel, check switch, controlled from mimic panel)

C.3 Burns with NH_3

CONVOL Shot Checklist (NH_3Operation) Last Modified: April 21, 1999

Shot: ________ Date: ________ Time: ________ Operator(s): ____________________

Preparation and pump down

1. ___ “NH_3 Start of Day” checklist complete
2. ___ Complete “Incomplete burn procedure” checklist item 1
3. ___ If 1st shot of day: Turn on instruments, close SV7, SV9
4. ___ Evacuate tank. Open: ________ SV8, ________ C1, ________ A1, P (mbar) ________
5. ___ Balance dynamic amplifiers for Kulite transducers *set filter on 1 Hz*
6. ___ Leak check for 5-10 min, close C1. Delta P (mbar) ________
7. ___ Close and lock door to room 14, turn on warning lights

Gas Fill Room 14 Off Limits

Fill to desired pressure using key switch (KS1) external block valves, gas supply valves (SV1-6), and NV1. (H_2 block valve switch on wall)

Gas	Target Fraction	Target Partial Pressure	Target Final Pressure	Final Pressure
		kPa	kPa	kPa
		kPa	kPa	kPa
		kPa	kPa	kPa
		kPa	kPa	kPa
		kPa	kPa	kPa

8. ___ Close SV1-6, KS1, A1
9. ___ Run mixer for 2 minutes
10. ___ Turn off mixer, wait 1 minute

11. Pressure: ________ kPa Temperature: ________ °C
12. ___ Initial gas sample, if required. GC file ________ , FTIR file ________
13. ___ Dynamics amplifiers *set filter on 300 Hz*

Firing Room 14 Off Limits

14. ___ Turn on ignition power, arm
15. ___ Arm DAS
16. ___ Cue tape, reset video timer
17. ___ Press **FIRE** button, Time: ________
18. ___ Check DAS results, video for burn.
19. If complete burn, run mixer until T less than 27 °C

    Final pressure: ________ kPa Final Temperature: ________ °C
20. ___ Final gas sample, if required. Backfill with N_2 to 100 kPa GC file ________ , FTIR file ________
21. If misfire/incomplete/no burn, follow "Incomplete Burn" checklist

Tank Venting Room 14 safe

22. ___ Open (SV8) *if closed*, C1, A1
23. ___ Evacuate vessel P (kPa) ________
24. ___ Close A1
25. ___ Open KS1, SV5, dispense air for ten seconds
26. ___ Close KS1, SV5, C1
27. ___ Turn off warning lights
28. If last shot of day, see "End of Day Procedure"

C.4 Failed Combustion

Incomplete Burn Procedure - Checklist

1. Prior to running experiment
   (a) _____ Calculate lean limit estimate of mixture
   (b) _____ Determine corrective action for spark failing to ignite mixture
2. During Experiment
   (a) Spark fails to ignite mixture
      i. _____ Reset video tape
      ii. _____ Type in Information in DAS, label Run ()a
      iii. _____ Arm DAS
      iv. _____ Start video, timer
      v. _____ Arm and fire
      vi. _____ Disarm spark
      vii. _____ Determine if spark ignited mixture
      viii. _____ Open tank isolation valve (ISO 1) and record pressure
      ix. _____ Close isolation valve (ISO 1)
      x. _____ Turn mixer fan on
      xi. _____ Type in information in DAS, label Run ()b
      xii. _____ Arm DAS
      xiii. _____ Start video, timer
      xiv. _____ Arm and fire
      xv. _____ Disarm spark
      xvi. _____ Determine if spark ignited mixture
      xvii. _____ Open tank isolation valve (ISO 1) and record pressure
      xviii. _____ If mixture did not ignite

    - A. ______ Open key switch valve (KS1)
    - B. ______ Add necessary hydrogen to ignite mixture
    - C. ______ Close Valves (SV2, KS1, ISO 1)
    - D. ______ Turn on Mixer for 5 min.
    - E. ______ Arm and fire
    - F. ______ Disarm spark
  - xix. ______ If mixture ignited, dispose of products according to main checklist

(b) Spark failure and test abort

  - i. ______ If glow plug is available
    - A. ______ turn on glow plug power and arm
    - B. ______ Turn on ignition switch
    - C. ______ Observe system for combustion via video
  - ii. ______ If glow plug is not available, mixture must be inerted and disposed of
    - A. ______ Add diluent to tank to reduce fuel concentration according to calculations from above
    - B. ______ Open diluent valve (SV5)
    - C. ______ Open Nitrogen valve on diluent rack
    - D. ______ Open key switch valve (KS1)
    - E. ______ Allow pressure to reach predetermined value (less than 250 kPa) and turn off diluent valve (SV5)
    - F. ______ Close key switch valve
    - G. ______ Close isolation valve (ISO-1)
    - H. ______ Allow mixer to run for 5 minutes
    - I. ______ If P exceeds 100 kPa, bleed excess through sparger
    - J. ______ Open pump bypass valve (SV9)

K. _____ Open Vacuum system valve (C1), allow pressure to bleed through sparger.

L. _____ Close pump bypass valve (SV9), open ammonia vacuum pump valve (SV8)

M. _____ Allow system to evacuate to less than 0.1 kPa

System is safe, return to main checklist

C.5 Burns without NH_3

CONVOL Checklist (no NH3)

Last Modified: April 21, 1999

1. ___ Complete Start of Day Checklist if necessary
2. ___ Determine corrective action for mixture in the case it does not burn.
3. ___ Turn on
    (a) ___ HYJET power strip
    (b) ___ Mimic panel main power switch
    (c) ___ T/C manifold vacuum gage
    (d) ___ Valve actuators air supply valve
4. ___ Close valves to vacuum lines (VAC-1 thru VAC-6)
5. ___ Turn on Kinney pump (see Kinney Pump Operating Instructions)
6. ___ Open
    (a) ___ Vacuum valve (VAC-1)
    (b) ___ Tank isolation valve 1 (ISO-1)
    (c) ___ Valve to Kinney pump (VAC-2)
7. ___ Evacuate until vacuum $\sim$ 75 mTorr
8. ___ Record evacuated pressure
9. ___ Close Vacuum valve (VAC-1)
10. ___ Turn off T/C vacuum gage
11. ___ Wait 15 minutes, while waiting
12. ___ Turn on
    (a) ___ Camera
    (b) ___ Light source and Fan
    (c) ___ VCR

   (d) ___ Timer (set on line 2)
   (e) ___ Monitor
   (f) ___ DAS, enter data
   (g) ___ Trigtek amplifier
   (h) ___ Dynamics amplifier and balance
   (i) ___ Glow plug power supply, if necessary

13. ___ If pressure in vessel exceeds 0.1 kPa, abort test
14. ___ If desirable, bleed up air to near required pressure by opening the ammonia vacuum system (ISO-2) and opening the bleed up valve (SV7)
15. ___ Close door to room 14
16. ___ Turn on warning light

Room 14 to be isolated beyond this point

17. Open key switch valve (KS1)
18. Add gases to vessel by partial pressures. Use mixer to expedite gas settling, use needle valve (NV1) to meter gases.
   (a) ___ Air/Diluent
   (b) ___ Hydrogen
   (c) ___ Methane
   (d) ___ Nitrous Oxide
   (e) ___ Oxygen
19. ___ Gas feed valves (SV1-6) closed
20. ___ Close key switch valve (KS1)
21. ___ Close tank isolation valve (ISO-1)
22. ___ Run mixer for 10 minutes
23. ___ Record temperature
24. ___ Turn on ignition power
25. ___ Arm DAS

26. ___ Start video ”record”
27. ___ Start timer
28. ___ Arm and fire
29. ___ Check DAS and video for burn
30. ___ If complete burn:
    (a) ___ ________ Turn on mixer
    (b) ___ ________ Open tank isolation (ISO-1) when T ∼ 30 C.
    (c) ___ ________ Record temperature and pressure
    (d) ___ ________ Turn off mixer
31. ___ If incomplete/no burn, follow “Incomplete burn” checklist

Room 14 safe to enter beyond this point

32. ___ Turn off warning lights
33. ___ Unlock and open doors
34. ___ Open main vacuum valve (VAC1)
35. ___ Open Liquid Ring vacuum valve (VAC3)
36. ___ Start liquid ring pump
37. ___ Wait until pressure is below 10 kPa
38. ___ Stop liquid ring pump
39. ___ Close liquid ring vacuum valve (VAC3)
40. ___ Open Kinney vacuum pump valve (VAC2)
41. ___ Evacuate vessel to evacuated state
42. ___ Close all valves (VAC-1,3,5; ISO-1, C1)
43. ___ If last shot of day, turn off:
    (a) ___ Instruments
    (b) ___ Camera, cover mirrors, lens
    (c) ___ Electronic Heise Gauge

(d) ___ Light source, let fan run for 15 min.

(e) ___ Monitor, VCR

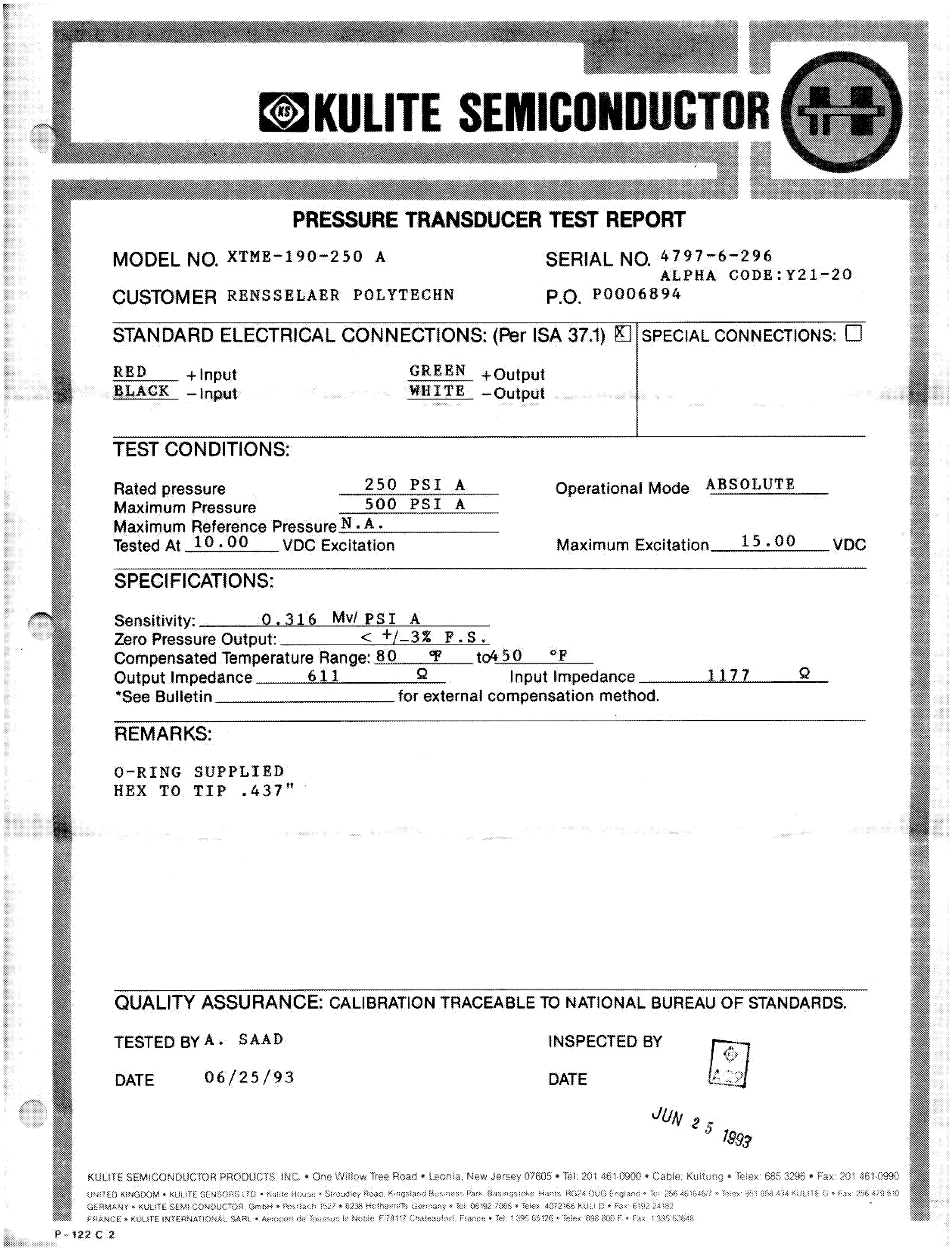
(f) ___ Main Power switch on Mimic Panel

(g) ___ Kinney pump (see procedure)

(h) ___ Necessary bottles in bottle farm, lock farm

Appendix D Instrument Data

In this appendix, we reproduce the data sheets and calibrations for the two pressure instruments.



KULITE SEMICONDUCTOR

PRESSURE TRANSDUCER TEST REPORT

MODEL NO. XTME-190-250 A
SERIAL NO. 4797-6-296
ALPHA CODE:Y21-20
CUSTOMER RENSSELAER POLYTECHN
P.O. P0006894

STANDARD ELECTRICAL CONNECTIONS: (Per ISA 37.1) ☒
SPECIAL CONNECTIONS: ☐

RED +Input
BLACK −Input
GREEN +Output
WHITE −Output

TEST CONDITIONS:

Rated pressure 250 PSI A
Maximum Pressure 500 PSI A
Maximum Reference Pressure N.A.
Tested At 10.00 VDC Excitation
Operational Mode ABSOLUTE
Maximum Excitation 15.00 VDC

SPECIFICATIONS:

Sensitivity: 0.316 Mv/ PSI A
Zero Pressure Output: < +/−3% F.S.
Compensated Temperature Range: 80 °F to 450 °F
Output Impedance 611 Ω
Input Impedance 1177 Ω
*See Bulletin ______ for external compensation method.

REMARKS:

O-RING SUPPLIED
HEX TO TIP .437"

QUALITY ASSURANCE: CALIBRATION TRACEABLE TO NATIONAL BUREAU OF STANDARDS.

TESTED BY A. SAAD
DATE 06/25/93
INSPECTED BY A 22
DATE JUN 25 1993

KULITE SEMICONDUCTOR PRODUCTS, INC. • One Willow Tree Road • Leonia, New Jersey 07605 • Tel: 201 461-0900 • Cable: Kultung • Telex: 685 3296 • Fax: 201 461-0990
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GERMANY • KULITE SEMI CONDUCTOR, GmbH • Postfach 1527 • 6238 Hofheim/Ts Germany • Tel: 06192 7065 • Telex: 4072166 KULI D • Fax: 6192 24182
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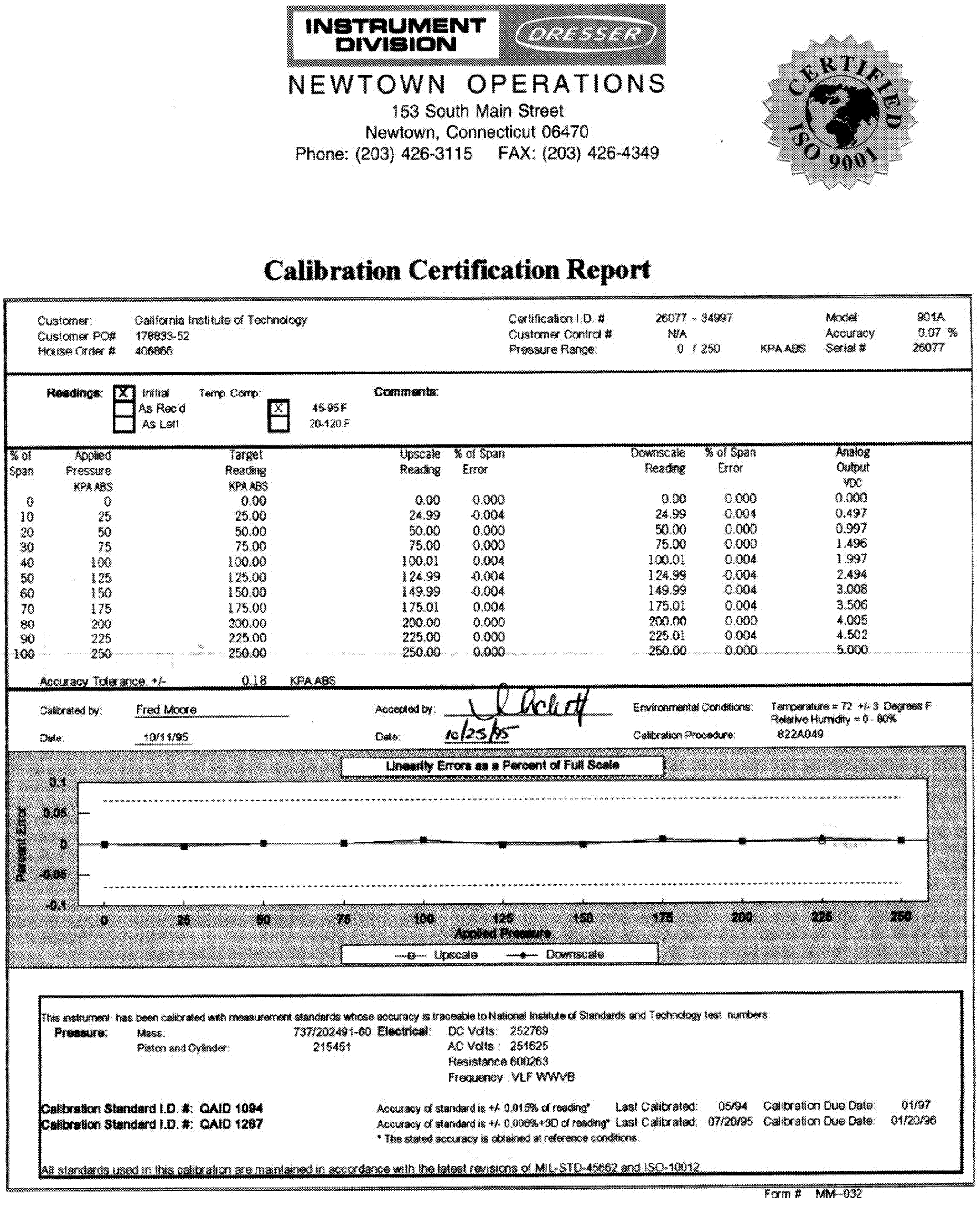
P-122 C 2



INSTRUMENT DIVISION
DRESSER

NEWTOWN OPERATIONS
153 South Main Street
Newtown, Connecticut 06470
Phone: (203) 426-3115 FAX: (203) 426-4349

CERTIFIED ISO 9001

Calibration Certification Report

Customer: California Institute of Technology
Customer PO# 178833-52
House Order # 406866

Certification I.D. # 26077 - 34997
Customer Control # N/A
Pressure Range: 0 / 250 KPA ABS

Model: 901A
Accuracy 0.07 %
Serial # 26077

Readings: ☒ Initial ☐ As Rec'd ☐ As Left

Temp. Comp: ☒ 45-95 F ☐ 20-120 F

Comments:

% of Span	Applied Pressure KPA ABS	Target Reading KPA ABS	Upscale Reading	% of Span Error	Downscale Reading	% of Span Error	Analog Output VDC
0	0	0.00	0.00	0.000	0.00	0.000	0.000
10	25	25.00	24.99	-0.004	24.99	-0.004	0.497
20	50	50.00	50.00	0.000	50.00	0.000	0.997
30	75	75.00	75.00	0.000	75.00	0.000	1.496
40	100	100.00	100.01	0.004	100.01	0.004	1.997
50	125	125.00	124.99	-0.004	124.99	-0.004	2.494
60	150	150.00	149.99	-0.004	149.99	-0.004	3.008
70	175	175.00	175.01	0.004	175.01	0.004	3.506
80	200	200.00	200.00	0.000	200.00	0.000	4.005
90	225	225.00	225.00	0.000	225.01	0.004	4.502
100	250	250.00	250.00	0.000	250.00	0.000	5.000

Accuracy Tolerance: +/- 0.18 KPA ABS

Calibrated by: Fred Moore
Date: 10/11/95

Accepted by:
Date: 10/25/95

Environmental Conditions: Temperature = 72 +/- 3 Degrees F
Relative Humidity = 0 - 80%
Calibration Procedure: 822A049

This instrument has been calibrated with measurement standards whose accuracy is traceable to National Institute of Standards and Technology test numbers:

Pressure: Mass: 737/202491-60
Piston and Cylinder: 215451

Electrical: DC Volts: 252769
AC Volts : 251625
Resistance 600263
Frequency : VLF WWVB

Calibration Standard I.D. #: QAID 1094 Accuracy of standard is +/- 0.015% of reading* Last Calibrated: 05/94 Calibration Due Date: 01/97
Calibration Standard I.D. #: QAID 1287 Accuracy of standard is +/- 0.006%+3D of reading* Last Calibrated: 07/20/95 Calibration Due Date: 01/20/96

* The stated accuracy is obtained at reference conditions.

All standards used in this calibration are maintained in accordance with the latest revisions of MIL-STD-45662 and ISO-10012.

Form # MM--032