# Critical Orifice Diameter Measurements for NH3-N2O at Elevated Pressure

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## Introduction

Experiments are in progress to determine the minimum inner diameter of a tube ($d_t$) in which a Chapman-Jouguet (CJ) detonation wave can propagate in NH3-N2O mixtures at pressures in the range of 0.1-5.0 MPa, to provide a data base which will facilitate the design of potential micro-spacecraft propulsion systems. The immediate goal is to determine the detonation cell width ($\lambda$) as a function of equivalence ratio and fill pressure. Estimates for the minimum diameter for a tube in which a stable CJ wave can propagate would then be made with the relationship $d_t = \lambda/\pi$. Direct detonation cell width measurements via soot foils are feasible at relatively low pressures; however, once the pressure exceeds ~1 MPa it is anticipated that the characteristic dimensions of the detonation cells will become too small for the use of soot-foils to be practical. Thus, another means to link the measurable detonation properties of the CJ wave at elevated pressure with the cell size is needed.

It has long been recognized that the critical tube diameter ($d_c$) for detonation wave transmission through a circular opening is nominally 13$\lambda$ for a wide variety of reactive mixtures (Lee 1998). Under critical conditions, the combustion process along the centerline of the transmitted detonation is decoupled from the lead shock wave, temporarily at least. Prior studies have also shown that the reflection of the CJ wave from the upstream side of an orifice plate does not influence the $d_c$ for detonation transmission into an open vessel; i.e., the quenching process of the CJ wave is due to just the phenomena in the immediate vicinity of the orifice (Liu et al. 1984). Thus, it is likely that constant diameter tubes can be used to determine the $d_c$ of a detonable mixture with a sub-caliber orifice plate if quenching of the combustion behind the transmitted detonation can be diagnosed. High-speed flow visualization techniques would be preferred for observing the corresponding transmitted waves. To attain data at elevated pressures (i.e., up to 5 MPa), however, the potential of using flush mounted sensors on the tube wall downstream of the orifice plate is being investigated here; even though Schultz and Shepard (1999) warn that such efforts "should be approached with extreme caution."

## Experimental Apparatus

The 38-mm-bore high-pressure tubes and gas handling system of the ram accelerator facility at the University of Washington are being used to determine of the detonation properties of NH3-N2O mixtures. The configuration of the ram accelerator test section, shown in Fig. 1, has the following primary components: igniter insert, detonation driver section, test mixture detonation stabilizing section, orifice plate and instrumented insert, and secondary tube for propellant detonation property measurements (i.e., velocity, pressure, and cell size via soot-foils). These hardened steel components (102 mm outer diameter) can safely handle reflected detonations from reactive mixtures at fill pressures up to at least 7.5 MPa.

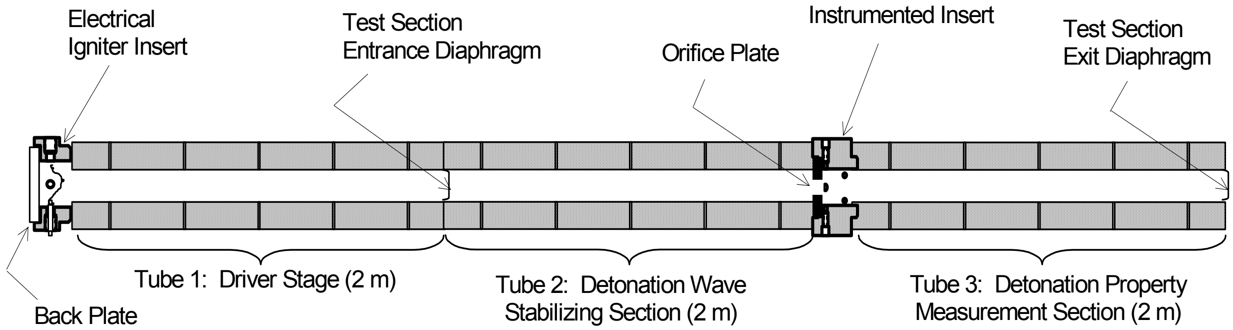



**Figure 1.** Test section configuration for NH3-N2O detonation studies (38-mm-bore).

Separate mass flow controllers route CH4 and N2O through a common plumbing line to the driver section to deliver a stoichiometric mixture at fill pressures up to 5 MPa. Preliminary experiments were carried out by partial pressure filling the NH3 and N2O in the 4-m-long section supporting the orifice plate and instrumented insert, henceforth referred to as the "test section." For stoichiometric mixtures at pressures up to 0.5 MPa, the NH3 is first loaded into the evacuated test section (via fill lines on both sides of the orifice plate) to an absolute pressure of 0.2 MPa, and then N2O is added until the absolute pressure is 0.5 MPa. The mixture is allowed to sit for at least an hour to allow for diffusive mixing. After this waiting period, the fill pressure in the test section is adjusted by venting until the desired pressure is reached.

The electrical igniter insert has a 6.4-mm-thick aluminum plate that isolates the upstream portion of the ram accelerator facility from the test section. After firing the igniter, a planar detonation wave is readily established within the driver section in the stoichiometric CH4-N2O mixture. Upon entering the test section, this CJ wave transmits a shock wave that subsequently initiates detonation of stoichiometric N2O-NH3 within one meter of the entrance diaphragm. The velocity measurements for both of these detonation waves (2200 and 2270 m/s, respectively) are in very good agreement with the CJ speeds calculated by the NASA CEA computer code.

Piezoelectric pressure transducers, fiber optic luminosity probes, and ionization gages have been installed in the sensor ports before and after the orifice plate (3.2 mm thick stainless steel) and the instrumented insert, as indicated in Fig 2. The data from these sensors are digitized at a sampling rate of 1 MHz. The arrival times of the pressure, luminosity, and ionization signals at the various instrument stations are correlated to determine if the combustion zone is moving steadily with the lead shock wave. If the wave speed is close to the predicted CJ speed, one can infer that the signals are from a CJ wave.

The ability for the CJ wave to be transmitted through a tube-occluding orifice plate is diagnosed by the differences in the arrival times of signals from tube-wall mounted pressure transducers, luminosity probes, and ionization gages located immediately downstream of the orifice. Data from the station before the orifice plate (20 cm separation distance) are used as a baseline to compare with measurements from the sensors in the instrumented insert. If the combustion is decoupled from the shock wave after it has passed through the orifice, then both the luminosity and ionization signals are expected to fall farther back from the leading shock wave. Thus, these conditions are the main criteria for establishing whether the detonation was transmitted or not.

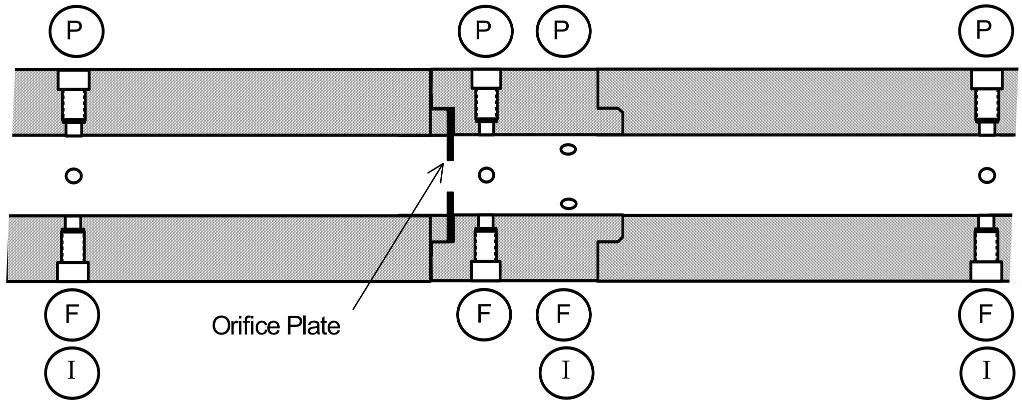
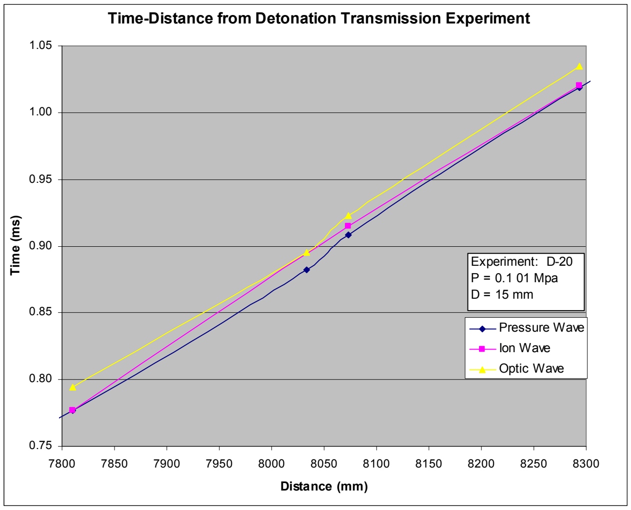



**Figure 2.** Orifice plate and instrumented insert configuration for detonation studies. (Legend: P = pressure transducer, F = fiber-optic probe, I = ionization gage.)

**Experimental Results and Discussion**

The luminous region for a CJ wave in stoichiometric NH3-N2O was typically found to be 12-16 μsec behind the lead pressure rise, which corresponds to a separation distance of ~30 mm. The ionization signal, however, coincides with the lead shock wave, which confirms that the induction zone is closely coupled with the detonation front. Representative time-distance data from two experiments using a 15 mm diameter orifice plate in stoichiometric NH3-N2O at 0.10 and 0.15 MPa are shown in Figs. 3a and 3b, respectively. In the lower pressure experiment (Fig. 3a), the ionization signal was ~7 μsec behind the lead shock wave at the second instrument station in the insert, located 52 mm behind the orifice plate, indicating that the combustion was decoupled even though the diffracted shock wave had reflected off the wall at least once. In the 0.15 MPa experiment (Fig. 3b), the ionization data from the same instrument station coincided exactly with the lead shock wave, which implied that if the detonation had been quenched, it was subsequently reinitiated before this sensor station. The fiber-optic data from both of these experiments did not show any significant difference in the luminous region. It should be noted that in all experiments with stoichiometric NH3-N2O, the CJ wave was reinitiated within 25 cm after passing through the orifice.

The potential for determining whether a CJ wave was temporarily quenched after passing through an orifice with tube-wall mounted ionization gages and pressure transducers looks promising, based on these preliminary experiments; however, there are some concerns. For example, assuming that the 13λ criteria is valid for NH3-N2O mixtures (at this point in time, the authors are not aware of any previous work that corroborates this assumption), the limiting detonation cell width that can be determined with a 15 mm orifice is ~1.2 mm. Based on the detonation cell width datum point ($\lambda = 11$ mm) for stoichiometric NH3-N2O at 0.055 MPa provided by Akbar et al. (1997), the CJ wave passing through the 15 mm orifice should be quenched at fill pressures up to ~0.5 MPa. Thus, the experimental results in Fig. 3b indicate that either the CJ wave had quenched and then been re-established before the instrument station located 52 mm after the orifice, or else the 13λ criteria is not valid for the reactive mixture under consideration. Another factor for this discrepancy may be that the diffusive mixing process has not sufficiently homogenized the test mixture within the one to two hour waiting time before the experiment. (Preliminary tests indicate that there are mixture composition variations of up to 10% along the length of the test section one hour after loading the reactants.)



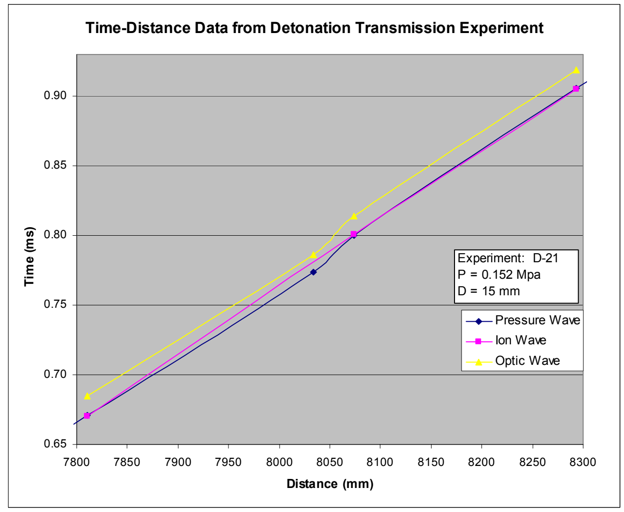




**Figure 3.** Time-distance data using 2NH3+3N2O at different pressures.
a) 0.101 MPa b) 0.152 MPa

## Future Work

In the course of the ongoing research program, the above mentioned concerns will be addressed in the following ways. Multiple ionization probes will be placed within 14 mm of the orifice plate (the closest instrument station) to determine if the diffracted shock wave is still a detonation upon its first impact with the tube wall. Soot foils will be used to correlate detonation cell width with critical orifice estimates to evaluate the validity of the 13λ assumption in NH3-N2O mixtures. A NH3 mass flow controller will be brought on-line in order to premix the NH3-N2O flows in the plumbing lines which route the mixture to the test section. The results of this investigation will facilitate the evaluation of the efficacy of using tube-wall mounted sensors for determining the critical orifice diameter in a constant diameter tube.

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