Small Scale Detonation Studies

Direct impulse measurements for detonations and deflagrations

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Introduction

This report is an account of research carried out from January to June 2000 on the feasibility of detonation initiation and impulse generation for small-scale pulse detonation engines. The initial work was focussed on the direct measurement of impulse using the ballistic pendulum technique for single detonations initiated in a tube with one end open to the atmosphere through a thin diaphragm. Three tubes were used: (1) 38-mm diameter by 1.5 m long. (2) 75-mm diameter by 0.6 m long. (3) 75-mm diameter by 1 m long. At the closed end of the tube, combustion was initiated by a low energy, less than 50 mJ, capacitor discharge system. A fast flame or detonation was created by transition to detonation. The effect of spirals and orifice plates was examined on propane- and ethylene-oxygen-nitrogen mixtures with varying initial pressure, equivalence ratio, and dilution amounts. A simple model for the impulse in prompt detonations was developed and calibrated. The results of our experiments were compared with this model.

Experimental Setup

Direct measurements were made of the impulse delivered by a DDT-initiated detonation or a fast flame. The impulse was determined by measuring the displacement of a ballistic pendulum in which a tube was suspended from the ceiling by steel wires (Fig. 1). The combustible mixture, initially contained in the tube by a thin diaphragm, was ignited by a spark at the thrust wall. Combustion products were free to expand out from the tube into an unconfined volume. Pressure histories were recorded, including the pressure at the thrust wall which was then integrated for comparison with the ballistically-determined impulse (Fig. 2). Ionization gauges were used to determine the time-of-arrival of the wave. A calibration experiment was performed in which a detonation was directly initiated in stoichiometric acetylene-oxygen with no obstacles present in the tube. The ballistically-measured impulse was within 3.5% of the value obtained by integrating the thrust-wall pressure trace.

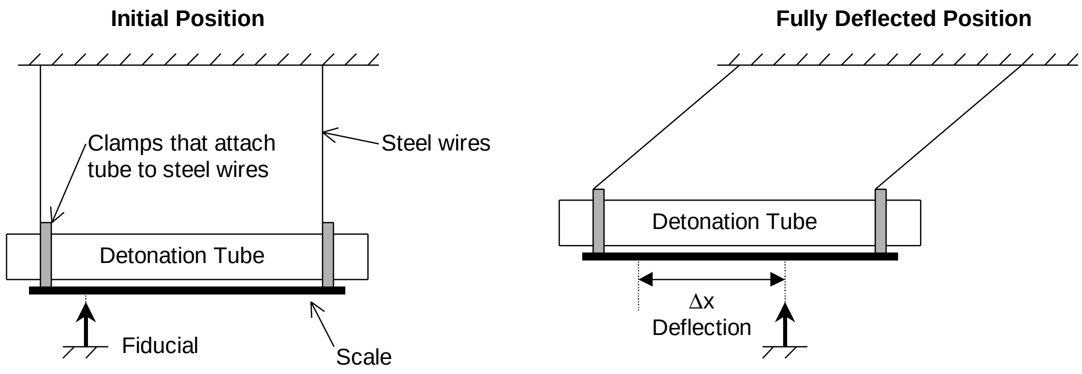


Figure 1. Impulse measurement by a ballistic pendulum.

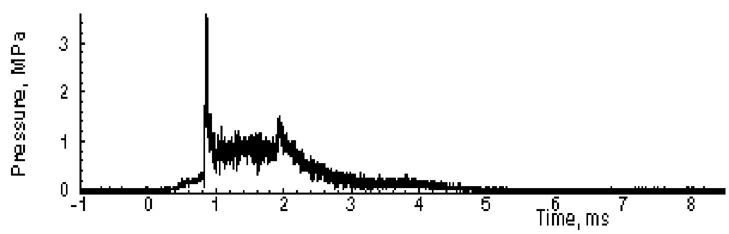


Figure 2. Sample pressure trace recorded at thrust wall.

Analytical Model

Experimental impulse measurements for detonations were compared with analytical predictions. The analytical model approximates the pressure history by two regions: an approximately constant pressure region which begins with the passage of the Taylor wave and ends with the arrival of the first characteristic of the reflected wave (usually an expansion) at the thrust wall, and a second region which models the pressure decrease through the remaining reflected wave. The two regions are described by two parameters, α and β (Fig. 3). A similarity solution can be used to determine α and comparison with experimental pressure histories shows excellent agreement. β is determined by integrating the appropriate region of experimental and numerical pressure traces. Both experimental and numerical results indicate that the flow may be overexpanded by the reflected rarefaction. If this occurs, the impulse decreases from the peak value and care must be taken in determining the impulse from the integrated pressure trace.

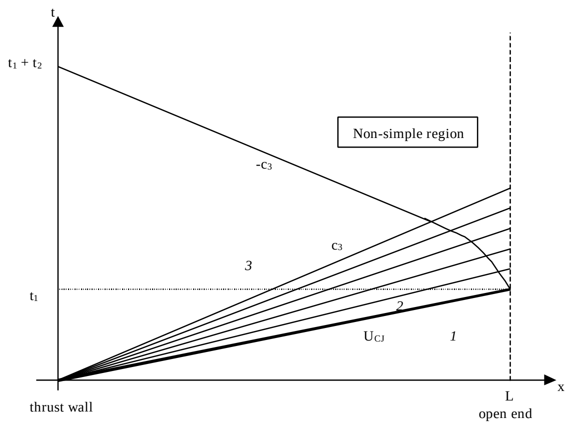
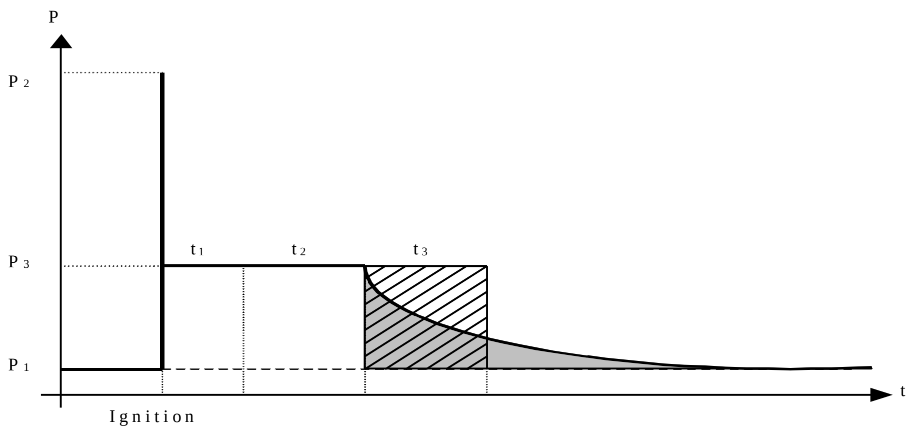


Figure 3. Gas dynamic processes inside the detonation tube.



$$t_1 = \frac{L}{U_{CJ}} \qquad t_2 = \frac{aL}{c_3} \qquad t_3 = \frac{bL}{c_3} = \frac{1}{\Delta P_3}\int_{t_2}^{\infty} \Delta P(t)dt$$

Figure 4. Idealized pressure trace used in the analytical model and parameter definitions.

The values of α and β will depend on the fuel concentration, initial pressure, and amount of dilution. The value of α was evaluated using the single-γ ideal detonation model and found to be $1 < \alpha < 1.1$, weakly dependent on the detonation Mach number and ratio of specific heats γ. An approximate value of 1.1 can be used for quick estimates of the impulse. The values of β determined to be about 0.53 from numerical integration of pressure traces. The impulse is

$$I = \frac{AL\Delta P_3}{U_{CJ}}\left(1 + \frac{U_{CJ}}{c_3}(a + b)\right)$$

where C_3 is the sound speed at the end of Taylor wave. The ratio U_{CJ}/C_3 is approximately 2 for fuel-oxygen-nitrogen mixtures, therefore the impulse is approximately

$$I = 4.3\frac{\Delta P_3}{U_{CJ}}V$$

where V is the tube volume, V = AL.

Results

The impulse was directly measured for three tubes with length to internal diameter (L/d) ratios of 40, 13 and 8. Various obstacle configurations were investigated, including spirals of varying pitch, blockage plates and orifice plates.

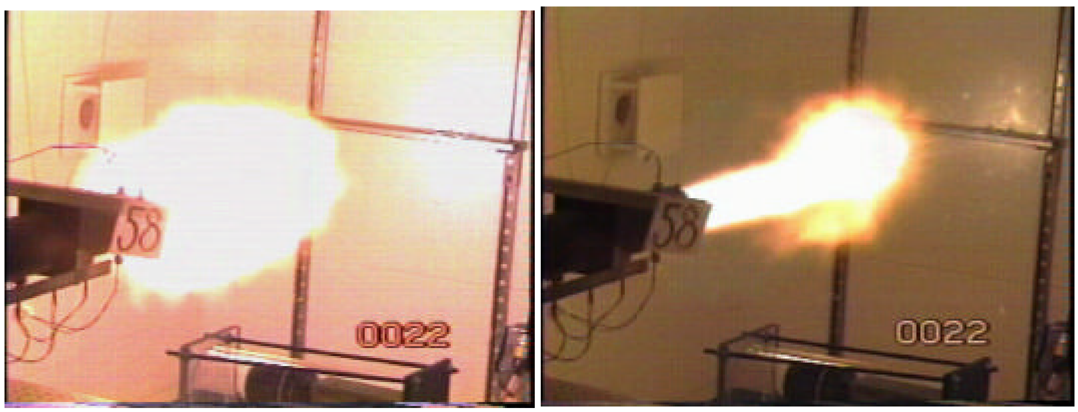


Figure 5. Combustion products expanding out from a detonation tube. The initial mixture was $2C_2H_4+6O_2+2N_2$ at 100kPa.

The tube with L/d ratio of 8 had an internal diameter tube of 75 mm (3 in). 4 ionization gauges and 4 PCB pressure transducers, including one positioned on the thrust wall, were mounted along the tube. Two spirals of different pitch (28 and 50mm) were used to induce DDT in ethylene and propane in oxygen with increasing nitrogen dilution up to air. The blockage ratio was held constant at 0.43. Initial pressures ranged from 50-100 kPa. . Different regimes of detonation, DDT and fast and slow flames were observed with varying nitrogen dilution and some examples of pressure histories are given in Appendix A.

Direct impulse measurements are shown in Fig. 7 for the two spiral configurations. There is little difference in the impulse obtained for the two configurations and both agree quite well with the theoretical predictions in mixtures where a detonation was recorded. In cases with higher nitrogen dilution, only a flame was observed. The impulse obtained was significantly reduced in these cases.

The tube with L/d ratio of 13 also has a 75 mm (3 in) internal diameter. 10 ionization gauges and 4 pressure transducers, including one positioned in the thrust wall, were mounted along the tube. Measurements were carried out in stoichiometric ethylene-oxygen mixtures with nitrogen dilution in a tube free of obstacles and with three different

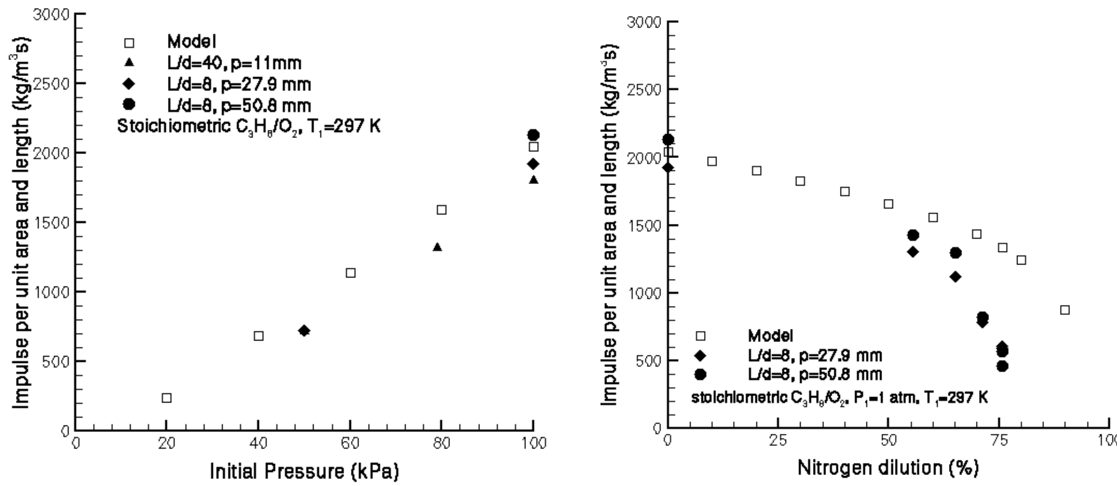


Figure 6. Impulse measurements for stoichiometric C_3H_8-O_2 mixtures with varying N_2 dilution and initial pressure for two spiral configurations. Impulse determined from the ballistic pendulum is compared to values calculated from the theoretical model.

obstacle configurations: blockage plates spaced at one tube diameter were suspended along the centerline of the entire tube by a single threaded rod, orifice plates were spaced at one tube diameter both along the entire length of the tube and along half the length of the tube in the upstream portion. Each obstacle configuration had a blockage ratio of 0.43. The inclusion of obstacles dramatically reduced the DDT times and distances (Fig. 7). At 30kPa initial pressure, the obstacles reduced the DDT time and distance by 88.5%. The obstacles allowed DDT to occur in mixture composed of up to 60% nitrogen. With no obstacles present, DDT was not achieved in mixtures with more than 30% nitrogen. Only a fast flame could be initiated in ethylene-air.

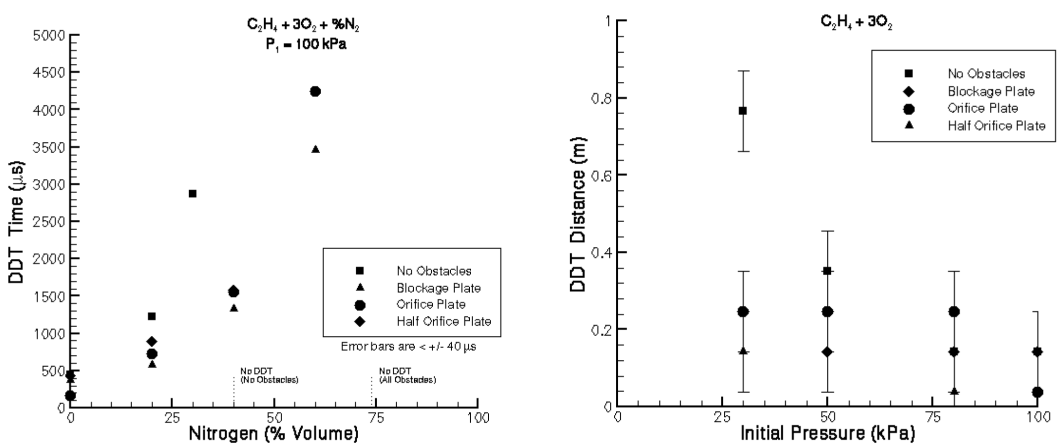


Figure 7. Measured DDT time for stoichiometric C_2H_4-O_2 mixtures with varying N_2 dilution and initial pressure for three obstacle configurations.

The impulse increased by a factor of 2 over a fast flame when a highly diluted mixture could be made to transition to detonation by the presence of obstacles (Fig. 8). In mixtures in which DDT occurred in the absence of obstacles, the inclusion of obstacles reduced the impulse measured by about 25%. It is important to note that in these cases, the impulse derived from the thrust-wall pressure trace overpredicts the impulse measured by the ballistic pendulum by a factor of two since the pressure integration neglects the momentum lost to drag over the obstacles.

The volume of the L/D = 13 tube is about twice that of the shorter tube discussed above and with blockage or orifice plates of the same blockage ratio as the spirals, the measured impulse is around twice that measured for the shorter tube for the same mixture.

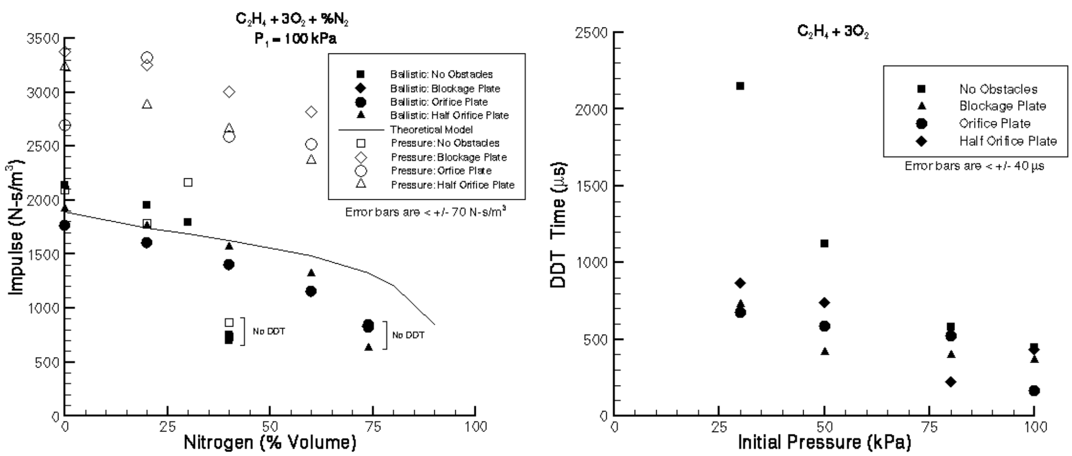


Figure 8. Impulse measurements for stoichiometric C_2H_4-O_2 mixtures with varying N_2 dilution and initial pressure for three obstacle configurations. Impulse determined from the ballistic pendulum is compared to values obtained by integrating the thrust wall pressure history and to values calculated from the theoretical model.

Summary

Including obstacles decreased the time needed for transition to detonation and enabled transition in stoichiometric ethylene-oxygen and propane-oxygen mixtures with up to 60% N2 in 75-mm diameter tubes. Without obstacles, detonation could only be initiated in mixtures with up to 30% nitrogen in the 1-m long tube. Detonation could not be initiated in either fuel in stoichiometric mixtures with air. The impulse obtained using obstacles to produce a fast flame in fuel-air mixtures was about 1/2 of the theoretical impulse predicted for prompt detonation.

The obstacles used were two spirals, repeated orifice plates and repeated central blockage plates. In all cases, the blockage ratio (obstructed area divided by total cross sectional area) was 0.43. No significant differences were observed between the effectiveness of the different types of obstacles. Including the obstacles reduced the measured impulse by about 25% in cases where detonation could be initiated promptly without obstacles.

A simple model was developed to predict the impulse from a prompt initiation of detonation. This model agrees well with cases in which prompt detonation occurs and provides an upper bound for the impulse obtained in our testing.

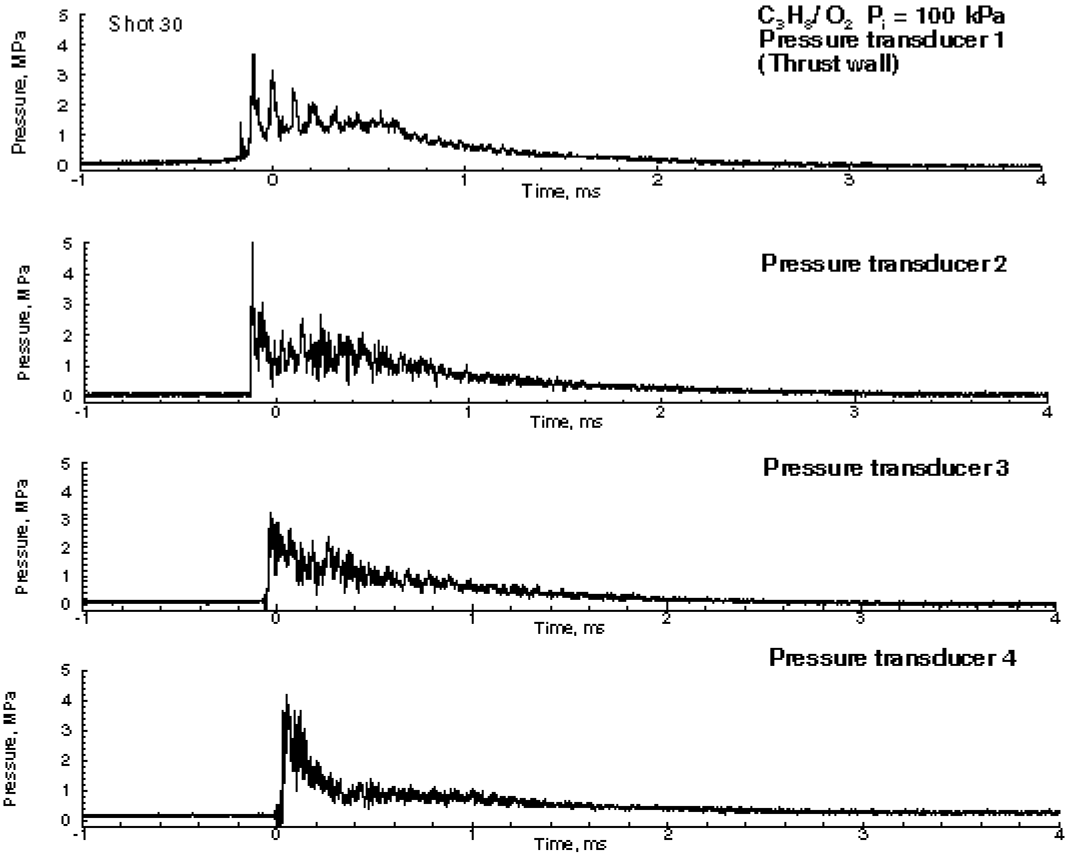
Future Work

To conclude the first phase of this contract, additional tests are in progress to measure the effect of exit end conditions on the ballistic impulse. A flange, a straight extension, and a cone will be placed at the end of the 75 mm diam, 1 m long tube to determine how these influence the ballistic impulse for cases that have been examined previously in this study.

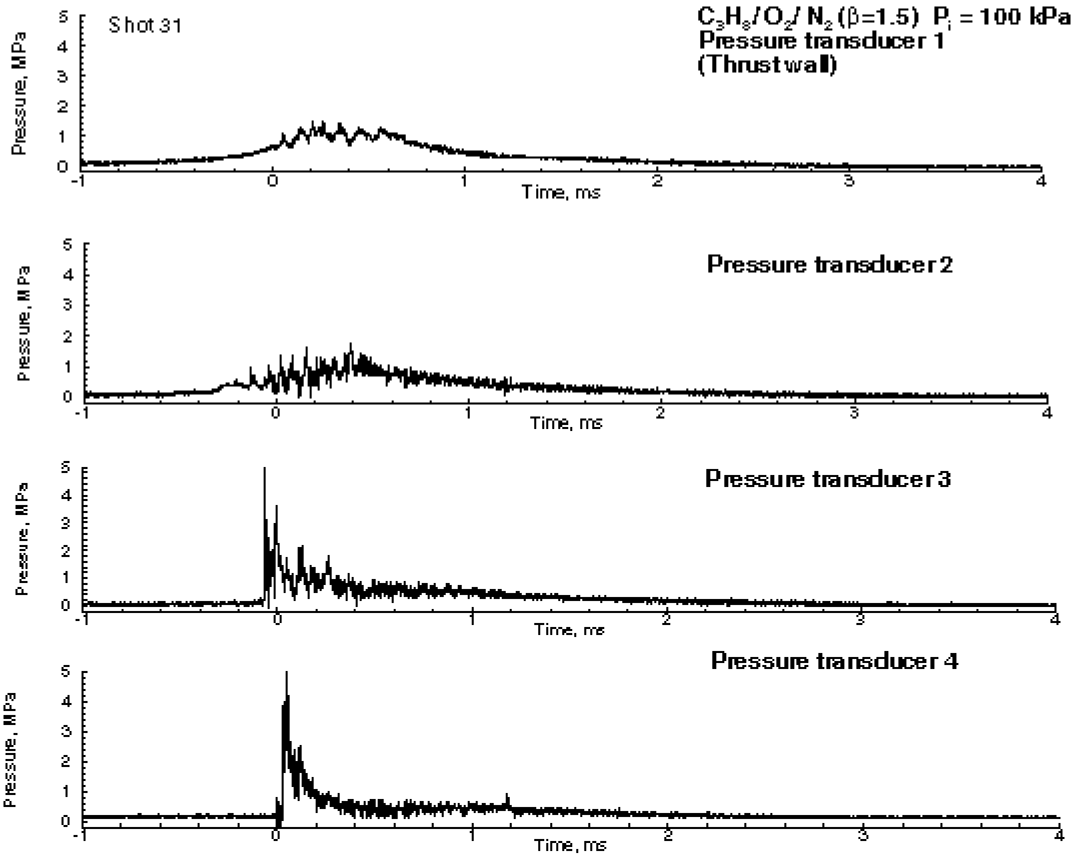
The next phase of the contract will involve development methods to reliably initiate detonation in fuel-air mixtures. This work will proceed by constructing a proof of concept device, implementing this as prototype initiator system on the 75-mm diameter tube, measuring DDT times and impulses for fuel-air mixtures. Initially the fuel will be propane but a heated tube is also under development that will enable working with aviation fuels such as Jet A and JP-10.

Appendix A. Pressure histories recorded in C_3H_8-O_2 mixtures with varying ß at 100kPa, where ß is the ratio of N_2 to O_2 concentration in the initial mixture. The tube has a L/d ratio of 8.

Shot30: detonation

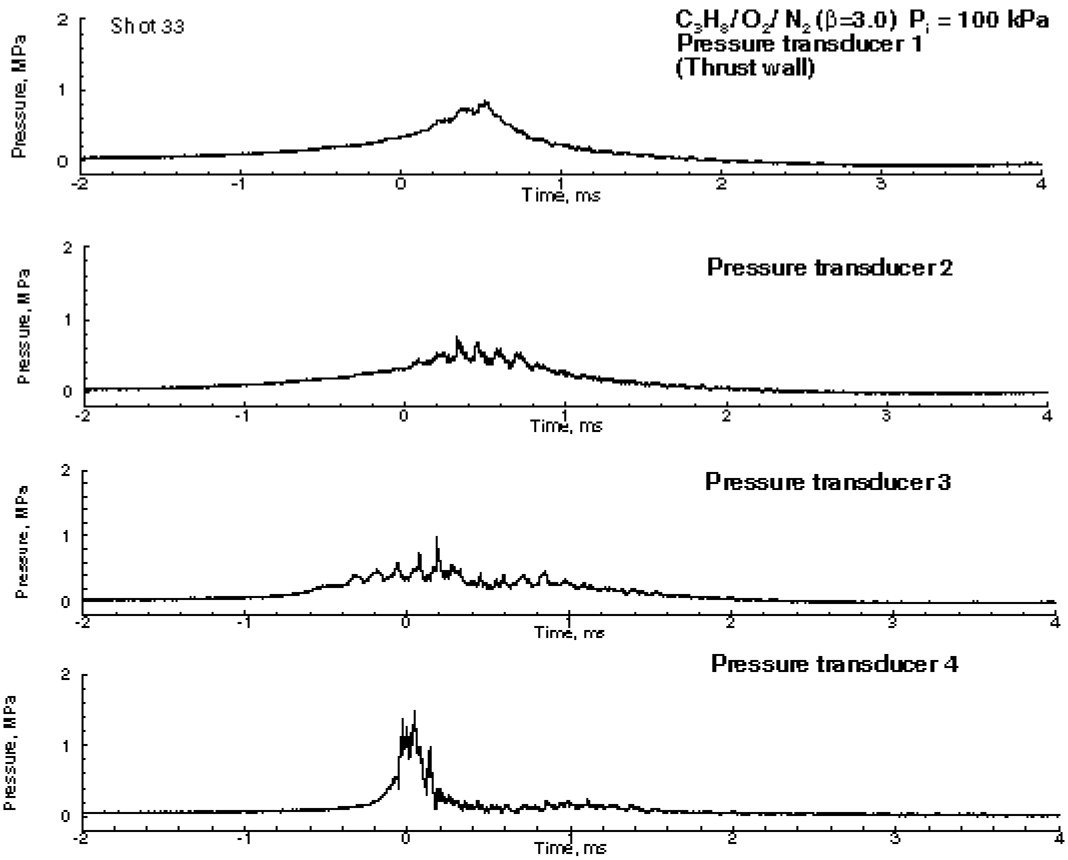


Shot31: DDT



Shot 31
$C_3H_8/O_2/N_2$ (β=1.5) P_i = 100 kPa
Pressure transducer 1
(Thrust wall)
Pressure transducer 2
Pressure transducer 3
Pressure transducer 4
Pressure, MPa
Time, ms

Shot33: Fast flame



Shot35: Slow flame