NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

INITIATOR DIFFRACTION LIMITS FOR PULSE DETONATION ENGINE OPERATION

by

Steven P. Werner

December 2002

Thesis Advisor:	Christopher M. Brophy
Second Reader:	Jose O. Sinibaldi

Approved for public release; distribution is unlimited.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** December 2002	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE: Initiator Diffraction Limits for Pulse Detonation Engine Operation	**5. FUNDING NUMBERS** **Contract Number: N00014-02-2-0153**
6. AUTHOR(S) Steven P. Werner	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research Ballston Tower One 800 N. Quincy Street Arlington, VA 22217-5660	**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.	**12b. DISTRIBUTION CODE**

13. ABSTRACT *(maximum 200 words)*

Operational characteristics of a valveless pulse detonation engine system are being characterized by both experimental and computational efforts. The detonation diffraction process from a small "initiator" combustor to a larger diameter main combustor in a continuous airflow configuration was evaluated during multi-cycle operation of a pulse detonation engine. The multi-cycle detonation experiments were performed on an axisymetric engine geometry operating on both ethylene and propane fuel/air mixtures. The new design explored the effect of forward relief area on performance and its ability to isolate the detonation products from the incoming air flow during cyclic operation.

The use of a small fuel-oxygen initiator to initiate a fuel/air detonation in a larger main combustor has been achieved and has demonstrated the benefit of generating an overdriven detonation condition near the diffraction plane for enhanced transmission to a larger combustor. Mach reflections have been observed on the outer wall downstream of the diffraction plane for the two-dimensional geometry and appear to be the primary re-initiation mechanisms for the re-established fuel-air detonations for this geometry. Multi-cycle tests have successfully evaluated initiator/main combustor diameter ratios of up to 1.58 and are expected to continue through 2.0.

14. SUBJECT TERMS Pulse Detonation Engine, Detonation, Valveless, Space Propulsion, Hydrocarbon Fuels	**15. NUMBER OF PAGES** 63
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

INITIATOR DIFFRACTION LIMITS FOR PULSE DETONATION ENGINE OPERATION

Steven P. Werner
Lieutenant, United States Navy
B.S., United States Naval Academy, 1996

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ASTRONAUTICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 2002

Author: Steven P. Werner

Approved by: Christopher M. Brophy
Thesis Advisor

Jose O. Sinibaldi
Second Reader

Maximilian Platzer
Chairman,
Department of Aeronautics and Astronautics

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

Operational characteristics of a valveless pulse detonation engine system are being characterized by both experimental and computational efforts. The detonation diffraction process from a small “initiator” combustor to a larger diameter main combustor in a continuous airflow configuration was evaluated during multi-cycle operation of a pulse detonation engine. The multi-cycle detonation experiments were performed on an axisymetric engine geometry operating on both ethylene and propane fuel/air mixtures. The new design explored the effect of forward relief area on performance and its ability to isolate the detonation products from the incoming air flow during cyclic operation.

The use of a small fuel-oxygen initiator to initiate a fuel/air detonation in a larger main combustor has been achieved and has demonstrated the benefit of generating an overdriven detonation condition near the diffraction plane for enhanced transmission to a larger combustor. Mach reflections have been observed on the outer wall downstream of the diffraction plane for the two-dimensional geometry and appear to be the primary re-initiation mechanisms for the re-established fuel-air detonations for this geometry. Multi-cycle tests have successfully evaluated initiator/main combustor diameter ratios of up to 1.58 and are expected to continue through 2.0.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would like to acknowledge the financial support of the Office of Naval Research for enabling the purchase and development of the equipment used in this thesis. This work was performed under ONR Contract N00014-01-2-0153.

I would like to thank Professor Chris Brophy for providing me the opportunity to conduct this research and for his many hours of guidance and instruction leading to the completion of this thesis. I would also like to thank Professor Jose Sinibaldi for his guidance and Mr. Harry Conner for the many hours he spent preparing my test cell for operation. Additional thanks goes to Frank Franzen, Jim Lefler, and Glenn Harrel for the many parts machined and many hours spent in their shops towards the completion of this PDE.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

A. BACKGROUND

This investigation was conducted as part of the Office of Naval Research program for fundamental research into pulse detonation engines (PDEs). The United States Navy has a current interest in developing a low cost, less complex propulsion system which operates on fuels certified for shipboard use, specifically a JP-10/air mixture. The interest in PDEs has increased dramatically in recent years due to their high theoretical performance and wide range of potential applications[Ref. 1].

This study explored ethylene/air and propane/air mixtures due to the detonation sensitivity of ethylene and the combustion similarities of propane to higher order hydrocarbon fuels. Practical operation of these systems requires the use of fuels that have already gained acceptance/approval by the military and/or aviation industry, such as kerosene based Jet-A, JP-5, JP-8 or JP-10. The use of such fuels has inherent difficulties since such fuel/air mixtures are often difficult to detonate [Refs. 2 and 3], especially in a repetitive and reliable manner. Therefore an initiator which consists of a small tube or auxiliary combustor filled with mixtures highly sensitive to detonation is being investigated as the means to initiate a detonation in a larger main combustor containing a less sensitive fuel-air mixture [Ref. 4]. Thus the importance of detonation diffraction or transmission from the small tube into a larger diameter main combustor arises.

Generally, an initiator is significantly smaller than the main combustor and the detonation wave needs to transition from the initiator into the main combustion chamber through a diffraction process. Previous work has been done on the diffraction of a JP-10/Oxygen detonation wave into a larger main combustion chamber with out the use of a transition cone. It was found that the detonation waves were unable to transition into the larger combustion chamber and therefore a transition process would be needed [Ref. 5].

Various initiator concepts exist which operate on fuel-oxygen mixtures while others utilize a blend of oxygen-enriched air as the oxidizer. Although the use of oxygen provides excellent reliability, repeatability, and a very rapid ignition event, the minimization of the oxygen required is of paramount performance since it is treated as "fuel" for specific impulse (I_{sp}) and specific fuel consumption (SFC) calculations and directly reduces the overall system performance. Thus, efficient coupling between an initiator and the larger combustor is of high importance [Ref. 4].

It is believed that with a gradual change in geometry, the detonation wave leaving the initiator will transition successfully from the initiator into the main combustion chamber [Ref. 6]. This study explored a new design where an initiator combustor operating on a highly detonable mixture first diffracts to a larger diameter and then diverges through a conical transition section with a divergence of 10 degrees (total angle) or five degrees (half angle). The initiator, therefore, acts as the detonation ignition source for the primary fuel/air mixture in the main combustor. For an effective transmission to successfully occur, the detonation wave exiting the initiator must overcome the diffraction process and continue to propagate into the less sensitive fuel/air mixture as a detonation wave.

The goal was to determine how aggressive of a transition can be made as the detonation wave leaves the 1.75 inch diameter initiator and expands into the main combustion chamber. A 5 degree ramp that expands from 2.5 inches inner diameter (ID) to 4 inches ID was designed to help determine the critical diameter diffraction ratio. The critical diffraction ratio is defined as the maximum diameter ratio which a detonation wave successfully transitions from the initiator (D_i) into the main combustor (D). In this study, the initiator's exit plane was allowed to traverse axially within the divergent conical section, thus effectively varying the D/D_i ratio. Therefore, this defined the diffraction limits for this specific combination of fuel/air and fuel/oxygen mixtures. This study also explored the ability of the continuous airflow design to isolate the detonation products from the incoming airflow.

B. OPERATIONAL ISSUES

1. PDE Operation

Over the last 15 years, pulse detonation engines have received a considerable amount of interest due to their potential for high performance. These engines produce detonation waves that propagate through a premixed fuel/air mixture and produce large intermittent chamber pressures and corresponding thrusts [Ref. 7]. The concept of using detonations as a means of propulsion is based on the simple concept of using a thrust tube, with the downstream side open, in which detonation waves are produced in a repetitive manner. A fuel/air mixture is injected at the beginning of each cycle, ignited, and the deflagration wave quickly transitions into a detonation wave, producing significant head pressure at the closed end, and ultimately thrust. After the detonation wave exits the combustor, an expansion wave (rarefaction wave) travels from the exit of the combustor to the head wall relieving the high pressure and removing the hot products from the combustor. Further information on pulse detonation engines can be found in various review papers by Eidelman et al. [Ref. 8], Bussing et al. [Ref. 7], and Kailasanath [Ref. 9], and some applied research papers by Brophy et al. [Ref. 10] and Bussing [Ref. 11].

Most current chemical propulsion systems used in the aerospace community are based on a constant pressure combustion process. However, pulse detonation engines are more closely modeled as a constant volume combustion process with the differences being the conditions by which heat is added to the working fluid. When similar fuel/air mixtures at matching original conditions are analyzed, the thermal efficiency is significantly higher in a detonation combustion process than in conventional constant pressure combustion process [Ref. 5].

The current work on utilizing detonations for propulsion has primarily focused on a cyclic detonation process in pulse detonation engines. The experiments were successfully carried out at the United States Naval Postgraduate School in Monterey, California [Ref. 12]. The pulse detonation engine geometry under development at the Naval Postgraduate School is a continuous air flow design, which does not utilize or require valves to supply the air to the main combustion chamber. The absence of a valve on the air flow has permitted a convenient flow path to rapidly fill, detonate, and purge the combustion chamber at rates up to 100 Hz. However, this absence has also introduced difficulties into the initiation process due to lowered confinement conditions when compared to conventional PDE concepts which involve some type of valve on the air supply. The current geometry also utilized the initiator approach as described previously and is depicted in Figure 1.

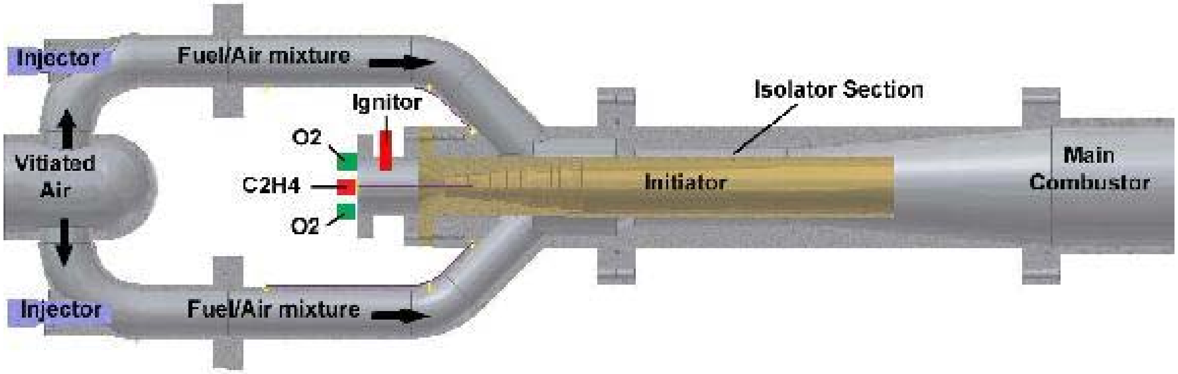

Figure 1. Valveless PDE Configuration

The initiator combustor operated on an oxygen-enriched fuel-air mixture to rapidly and reliably generate a detonation wave, which was then used to initiate the less sensitive fuel/air mixture located in the main combustor. A critical region of interest was at the initiator exit plane where the exiting detonation wave experienced a diffraction process into the main combustion chamber. The concern for this area of the system was the motivation for characterizing the effects of the diffraction condition between an initiator of diameter, D_i, and the main combustor of diameter, D, at the diffraction plane. The effects of diameter ratio (D/D_i), mixture variation (fuel/air gradient), and varying degrees of confinement continue to be evaluated so that a more optimized condition can exist.

2. Detonation Transmission

A large body of research has been performed in the area of detonation diffraction, most of which involved homogeneous mixtures and focused on the concept of a critical diameter d_c. The critical diameter indicates the minimum tube diameter for a successful detonation transmission into an unconfined space for a given fuel/oxidizer mixture. If the detonation wave is traveling in a tube with a diameter d<dc and encounters a sudden expansion into an unconfined space, the detonation diffraction process will cause the detonation to fail [Ref. 6].

For homogeneous mixtures, the well documented critical diameter, d_c, value of 13 times the cell size (λ) of the mixture for transmission of a detonation wave to an unconfined volume has been verified many times to hold true for most mixtures [Ref. 13]. The 13λ value has been shown to be valid for mixtures containing more irregular cell spacing, typically fuel/air mixtures with higher activation energies. Mixtures containing highly regular detonation cell structure, such as argon diluted fuel/oxygen mixtures have been shown to often require a larger critical diameter than the 13λ rule, thus revealing the increased importance of wavefront structure during the diffraction processes in producing gas-dynamic hot spots for spontaneous reignition to occur. The re-initiation process can be a result of a non-uniform energy distribution that exists during the diffraction process which is created by shocks colliding with each other and producing local hot spots where the detonation re-initiation occurs [Ref. 6]. The increased irregularity in the cellular structure for fuel-air mixtures often aids in the adjustment to sudden expansion conditions and can be interpreted as possessing more levels of instability and therefore more modes by which spontaneous reinitiation may occur near a critical diameter value [Ref. 14].

Teodorcyzk [Ref. 15] and Oran [Refs. 16 and 17] have looked at the reinitiation mechanisms of Mach reflections from the propagation of a quasi-detonation in an obstacle-laden channel at a rigid wall and imparting a spherical blast wave on a rigid wall, respectively. Both studies stressed the importance of the rapid reignition sites immediately behind the generated Mach stems at the wall. Murray [Ref. 18] also demonstrated the importance of shock-shock and shock-wall collisions for different exit conditions at the diffraction plane, including tube bundles, annular orifices, and cylindrical diffraction. The reinitiation mechanism associated with the Mach reflections observed in those studies is extremely important for the initiator concept utilized in the current engine. It also becomes increasingly important as the combustor diameter approaches the cell size of the mixture and few transverse waves exist to assist with adjusting to the expansion condition occurring at the diffraction plane. The reinitiation process for such conditions appears to be a very local process and the influence of the wave front structure [Ref. 19] and reflection cannot be ignored during analysis.

Desbordes [Ref. 20] and Lannoy [Ref. 21] have investigated the effects of overdriving a detonation wave during diffraction from a smaller combustion tube to a larger volume. In both studies it was determined that a definitive benefit existed when a detonation wave was allowed to propagate into a less reactive mixture immediately before diffraction occurred, thus creating an overdriven condition in the less reactive mixture. Recently, Murray et al. [Ref. 22] investigated the direct benefit of utilizing a fuel-oxygen driver section, an initiator, and propagating the generated detonation wave into a fuel-air mixture in order to generate the overdriven condition. Overall values of the effectiveness of driver-receptor mixtures and diameter ratios approached 30 for some conditions. This indicates that there is a dramatic reduction in the required critical diameter for the receptor mixture. Thus, a combination of Mach reflections and overdriven conditions are the mechanisms which appear to dominate initiator transmissions on the scale of most PDEs and will likely be responsible for the successful application in such systems [Ref. 4]. This mechanism is employed by the valveless PDE concept investigated in the current study.

Previous studies on homogeneous fuel/air mixtures have shown successful diffraction of detonation waves when uniform throughout both the initiator and the main combustor for diffraction ratios of 1.25 and lower [Ref. 23]. For the purpose of this study, however, the mixture composition changed from an oxygen enriched fuel/air mixture to a fuel/air mixture when transitioning from the initiator to the main combustor at the point of diffraction and explored the benefit of heterogeneous conditions at the diffraction plane. The PDE was operated up to a diffraction ratio of 1.58 for ethylene/air and 1.2 for propane/air mixtures. Continued research will explore diffraction ratios up to 2.25.

3. Continuous Airflow PDE Design

The operational cycle of the valveless PDE is shown below in Figure 2. The cycle begins with air flowing through the engine and purging the previous combustion products (A). Fuel is injected into the incoming air and flows into the main combustor (B). Near the end of the fuel injection event (C), a highly detonable mixture is rapidly injected into the initiator (D). The mixture in the initiator is ignited and a detonation wave forms (E). The detonation wave exits the initiator and initiates the fuel/air mixture residing in the main combustor (G). After the detonation wave exits the main combustor, a series of rarefaction waves reduce the pressure inside of the combustor and the combustion products are purged (H). The process is then repeated.

Immediately after the detonation wave from the initiator diffracts into the main combustor, a combustion-driven shock wave begins propagating upstream into the incoming air stream. This propagation can be eliminated if the total pressure of the incoming air is sufficiently high and results in a choke point somewhere in the isolator, thereby producing a supersonic flow regime immediately downstream of this point. The current test program evaluated subsonic inlet flow conditions and limited the isolator flow Mach number to less than 0.95. Future testing will explore a supersonic isolator mode which may be used to model the forward diffuser section of a mixed compression inlet.

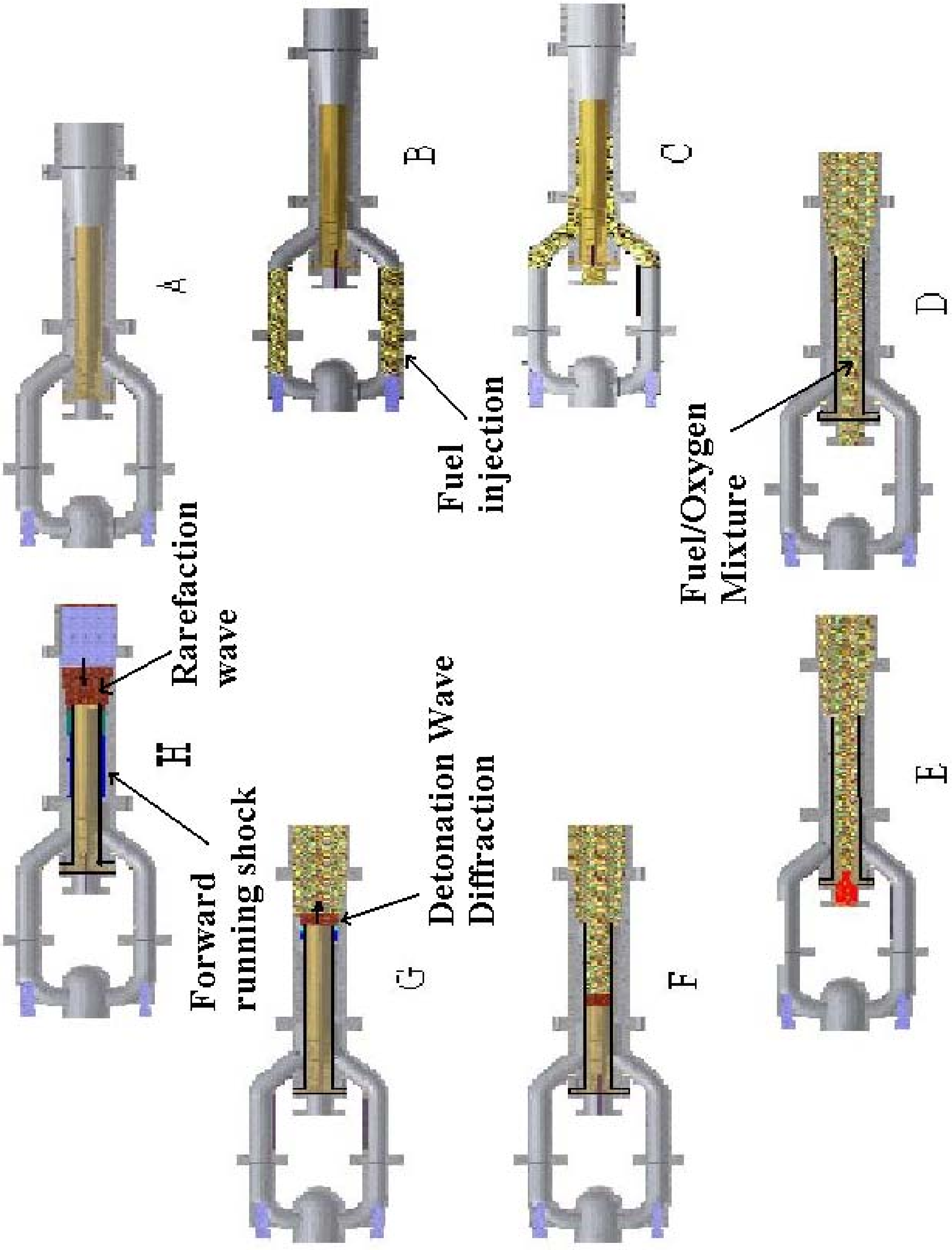

Figure 2. Valveless PDE Cycle

II. EXPERIMENTAL SETUP

A. PULSE DETONATION ENGINE

The valveless PDE consisted of four fuel/air inlet arms discharging into a common inlet manifold. The four fuel/air inlet arms have no particular physical or operational size requirements beyond providing enough length for good mixing and for the fuel to vaporize prior to entering the main combustor. The fuel/air mixture was then allowed to co-flow around the initiator, through the isolator and transition ramp and into the main combustor which was 1 meter in length and had a 4 inch inner diameter. The initiator could be moved to different axial positions along the 5-degree transition ramp to investigate various diffraction ratios between the initiator and the main combustor [Figure 3 and 4].

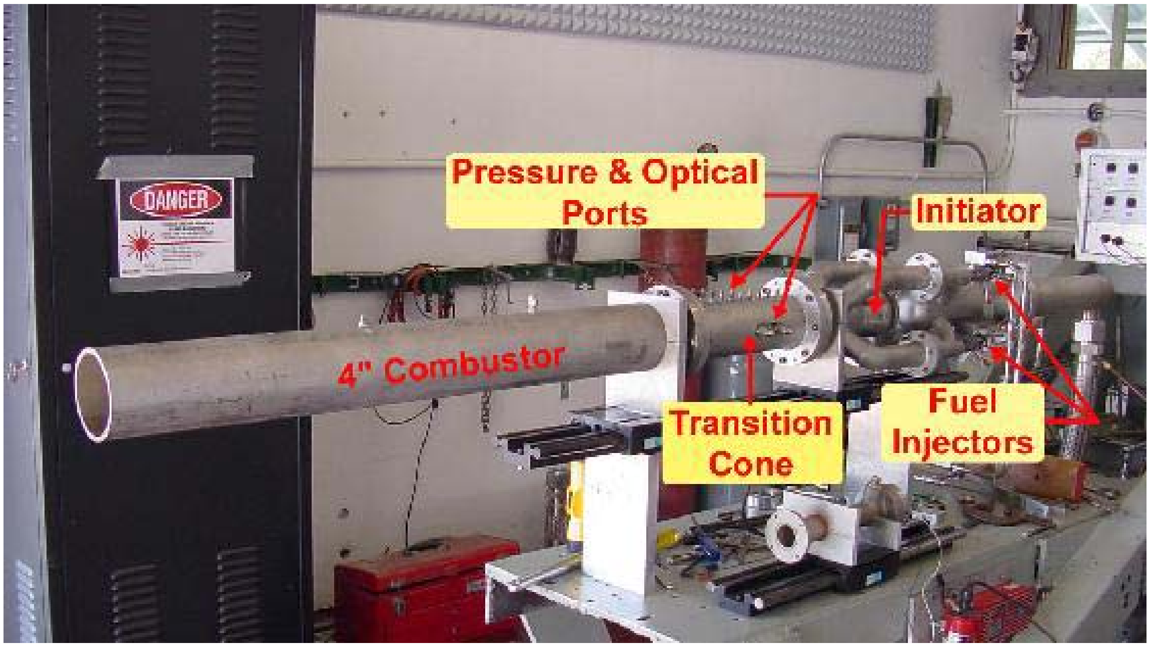

Figure 3. Pulse Detonation Engine Design

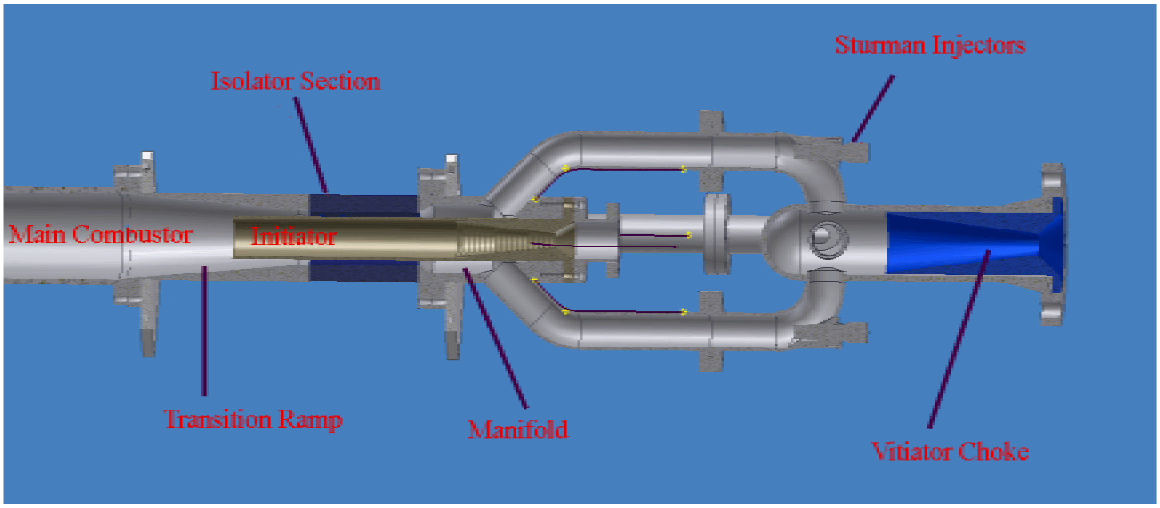

Figure 4. PDE Drawing

The temperature of the inlet air could be adjusted from 50 °F to 300 °F via a hydrogen vitiator with an oxygen replenishing system to keep the oxygen molar ratio at 21%. This air flows through a choke upstream of the PDE in order to isolate the upstream pressure fluctuations and set inlet conditions to the PDE. A 0.57 inch diameter orifice was used to monitor and control the mass flow rate of the air flowing through the PDE. The fuel injection was controlled by either four Sturman Industries diesel prototype liquid fuel injectors [Figure 5] or four conventional solenoid valves for gaseous fuel injection. The Sturman Industries electro-hydraulic injectors were designed for use in diesel and direct-injection engines and have been slightly modified for PDE applications. Each Sturman injector produced a spray with Sauter Mean Diameter (SMD) values ranging from 14 μm to 9 μm for the 1500 psi to 2000 psi common rail pressure range respectively [Figure 6]. Duration of the fuel injection was from 4 ms to 5.5 ms [Ref. 12].

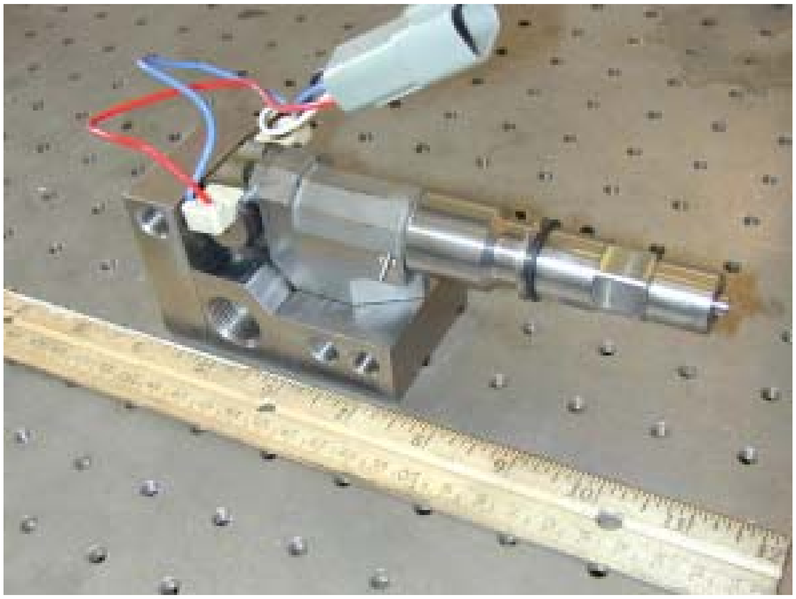

Figure 5. Sturman Industries Fuel Injector

Figure 6. Hydraulic Power Unit

B. INITIATOR

The initiator was a 15.625-inch long stainless steel chamber with an internal diameter of 1.75 inches [Figure 7]. The initiator geometry was previously developed from research performed by LT Dave Forster on initiating detonations [Ref. 24]. The initiator used an ethylene/air/oxygen mixture with a molar ratio of 1/1.02/2.78 respectively to rapidly and reliably form a detonation. Purge air continuously flowed through the initiator during operation and provided about 20% of the oxidizer required for operation of the initiator. Oxygen and ethylene were then injected at appropriate intervals before the initiation of a detonation in the initiator. Oxygen was injected into the initiator through 4 Parker Hannifin (0091600-4) valves [Figure 8]. Ethylene was injected using a Valvetech (15060-2) valve. The initiator design has demonstrated up to 100Hz operation on ethylene, propane, and JP-10 [Ref. 25].

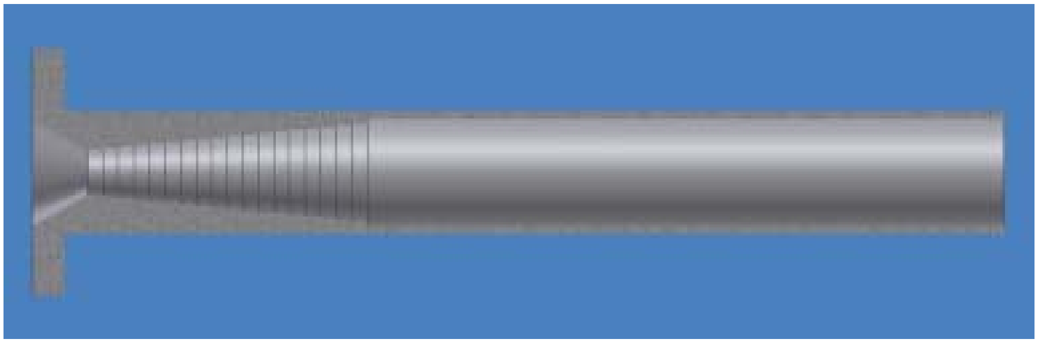

Figure 7. Initiator

Figure 8. Parker Hannifin O_2 Valve

C. DIAGNOSTICS

High frequency Kistler 603B1 pressure transducers and type-K thermocouples were placed along the PDE to monitor detonation/shock wavespeeds and engine inlet conditions. Infrared transmission measurements were made at two locations with a 3.39 μm He-Ne laser [Figure 9] and an infrared diode to determine the proper timing of the fuel delivery and fuel mass fraction. The Kistler pressure transducers were placed at locations 1 and 2 (2 inch spacing) for measuring upstream shock propagation, and at locations 3 and 4 (6 inch spacing) for measuring detonation wave speeds in order to determine successful detonation transition in the main combustor [Figure 10].

Figure 9. Location of 3.39 μm He-Ne Laser Transmission

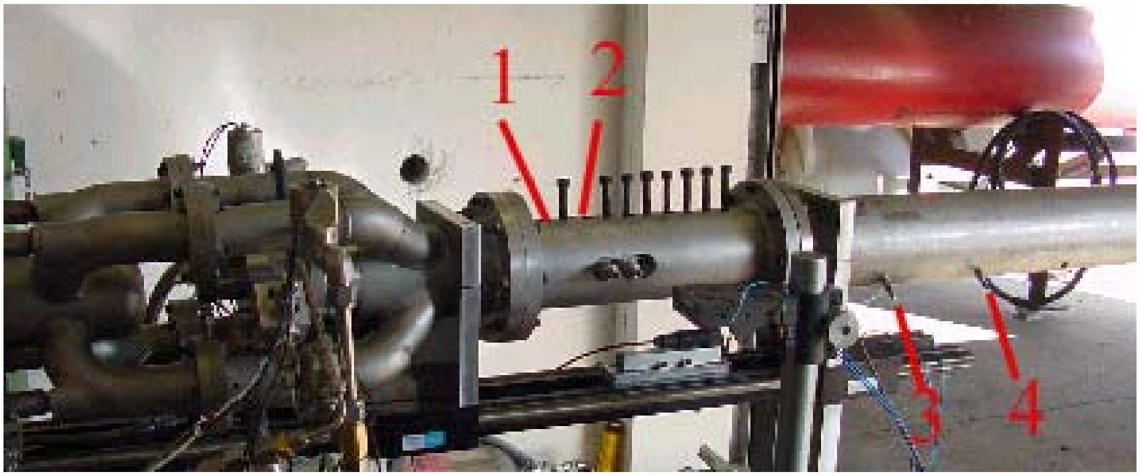

Figure 10. Transducer Locations

Various other pressure transducers and thermocouples were monitored throughout the PDE facility. The Visual Basic GUI used to operate the facility monitored the operation of the PDE and provided the ability to abort runs safely. All operations of the facility were controlled by an approved standard operating procedure supplied in Appendix A.

D. VITIATOR

A hydrogen/oxygen vitiator [Figure 11] was used to raise the inlet air temperature to the PDE when desired. This was done to simulate typical inlet conditions that the PDE would experience under the expected supersonic flight conditions.

Compressed air flowed through the vitiator, where a hydrogen/oxygen igniter was used to light a self-sustaining hydrogen\air combustor and raise the temperature of the inlet air up to 500 ^{o}F. Since the vitiator combusts externally provided hydrogen, additional oxygen is added to the vitiated air at the exit of the vitiator to bring the heated air back to the proper oxygen molar concentration of 21% for use in the PDE.

Figure 11. Vitiator

E. SOFTWARE

Fuel injection and ignition timing were controlled using a PC computer running a Visual Basic 5.0 Graphical Interface [Figure 12] and a BNC 5000 Pulse Generator. The computer was also configured to measure system temperatures and pressures using a low-speed data acquisition board. The signals from the Kistler pressure transducers were sampled by a National Instruments Data Acquisition board at 500 kHz and viewed using a LabVIEW 5.0 user created program to plot the data. The high speed data taken from the Kistler pressure transducers and was used to determine detonation wave speeds and upstream shock propagation in the PDE [Figure 13].

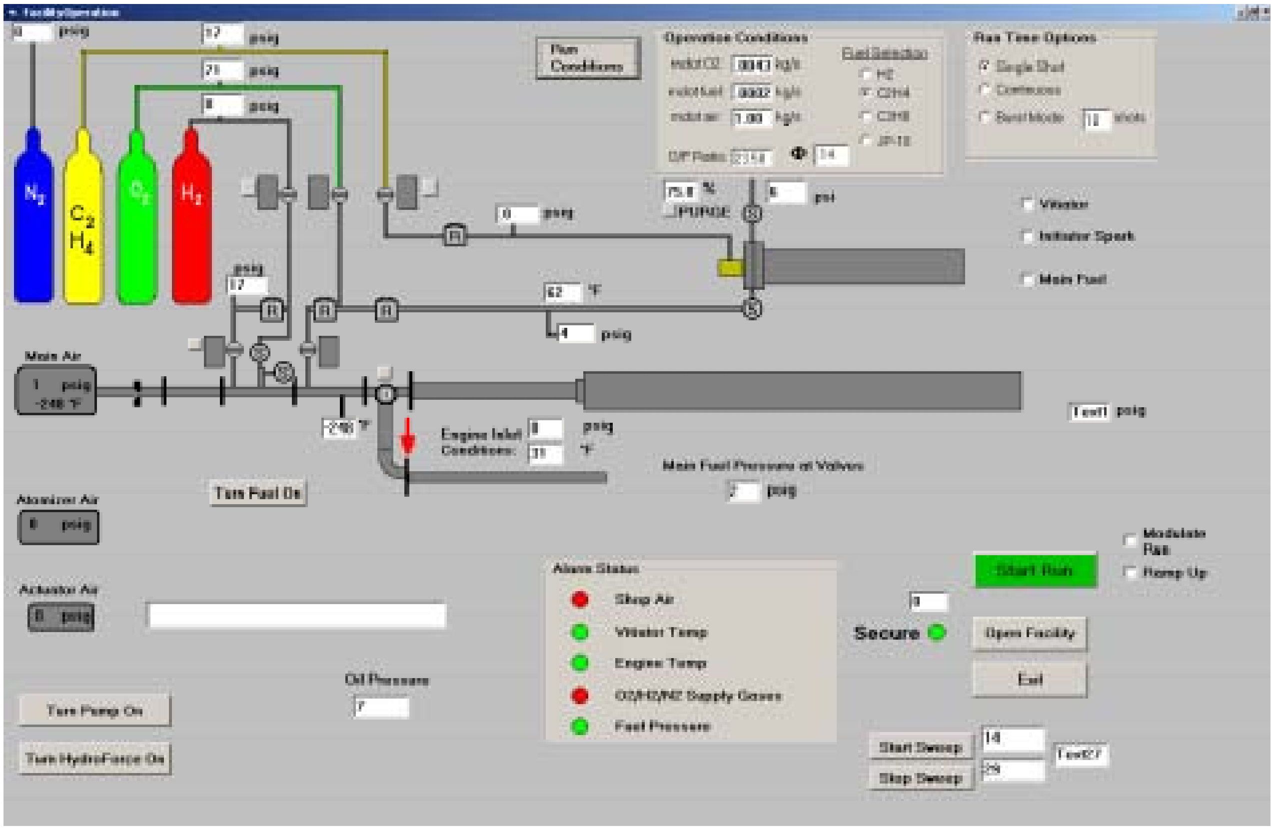

Figure 12. Facility Operations GUI (Visual Basic 5.0)

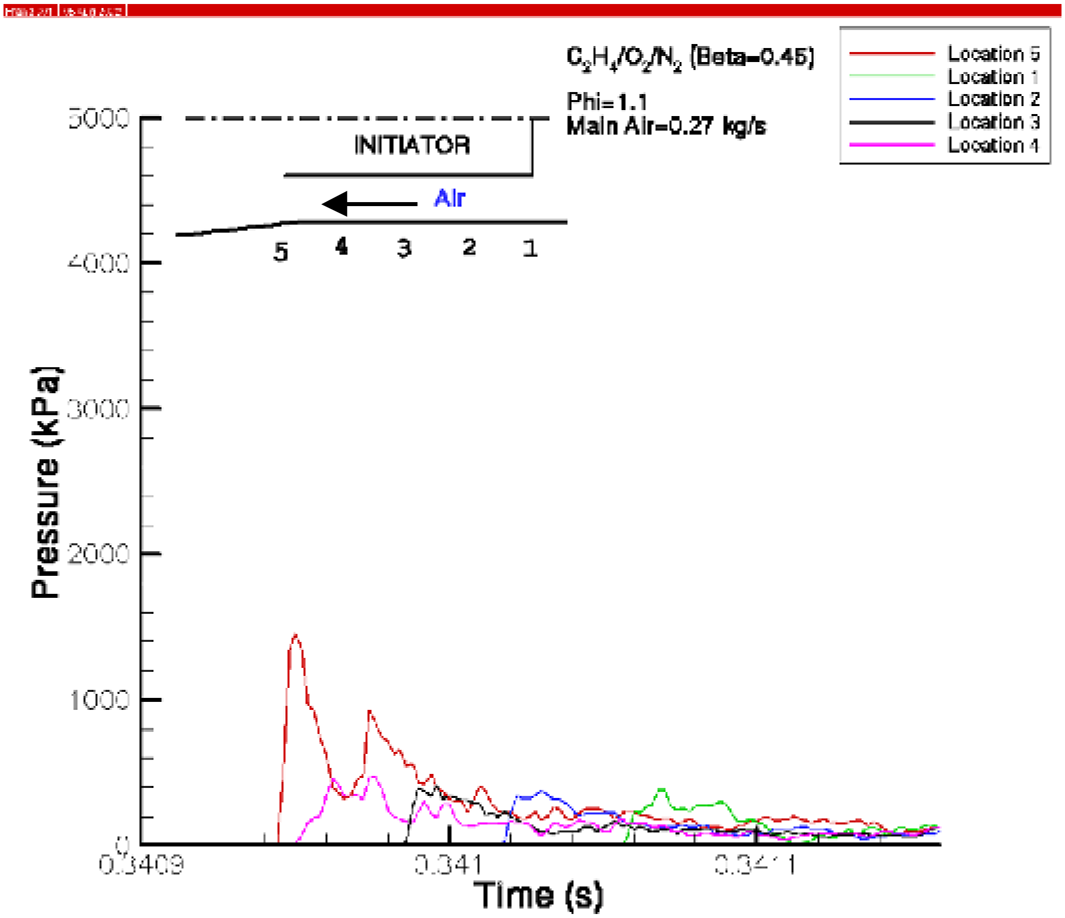

Figure 13. Sample Kistler Pressure Transducer Data

III. RESULTS

A. FUEL INJECTION CHARACTERISTICS

The initial tests on the multi-cycle engine were performed to verify the timing of the fuel delivery and the resulting equivalence ratios. A 3.39 micron He-Ne laser was used since hydrocarbon based fuels easily attenuate the 3.39 micron signal due to the C-H stretch bond. An accurate determination of the fuel/oxygen mixture arrival time at the diffraction plane was needed to accurately fill the initiator and prevent over filling into the main combustor. Similarly, the timing of the main combustor's fuel/air mixturewas also determined to precisely locate the end of the fuel injection charge at the initiator diffraction plane at the moment the initiator detonation wave diffracts into the main combustor. The 3.39 micron transmission measurement was used at both the initiator diffraction plane and the combustor exit to determine fuel arrival and mass fraction. This allowed for the appropriate timing of the injection process and coordinated the operation of the initiator. The tests also verified successful operation of the liquid and gaseous fuel injectors.

The transmission ratios received from the laser diode were used in conjunction with the Beer-Lambert law (Equation 1) to determine the partial pressure and eventually the mass fraction of the fuel present at that time of transmission.

$$T = e^{-p\alpha x} \tag{1}$$

Where T is the transmission ratio obtained from the attenuation measurements, x is the transmission path across where the attenuation occurred, α is the absorption coefficient provided in various references [Refs. 26 and 27] for various fuels, and p is the partial pressure. Given this information, the partial pressure can be calculated and subsequently used to determine temporal fuel/air ratios [Figure 14] in the main combustor as well as the spatial distribution of fuel along the combustor.

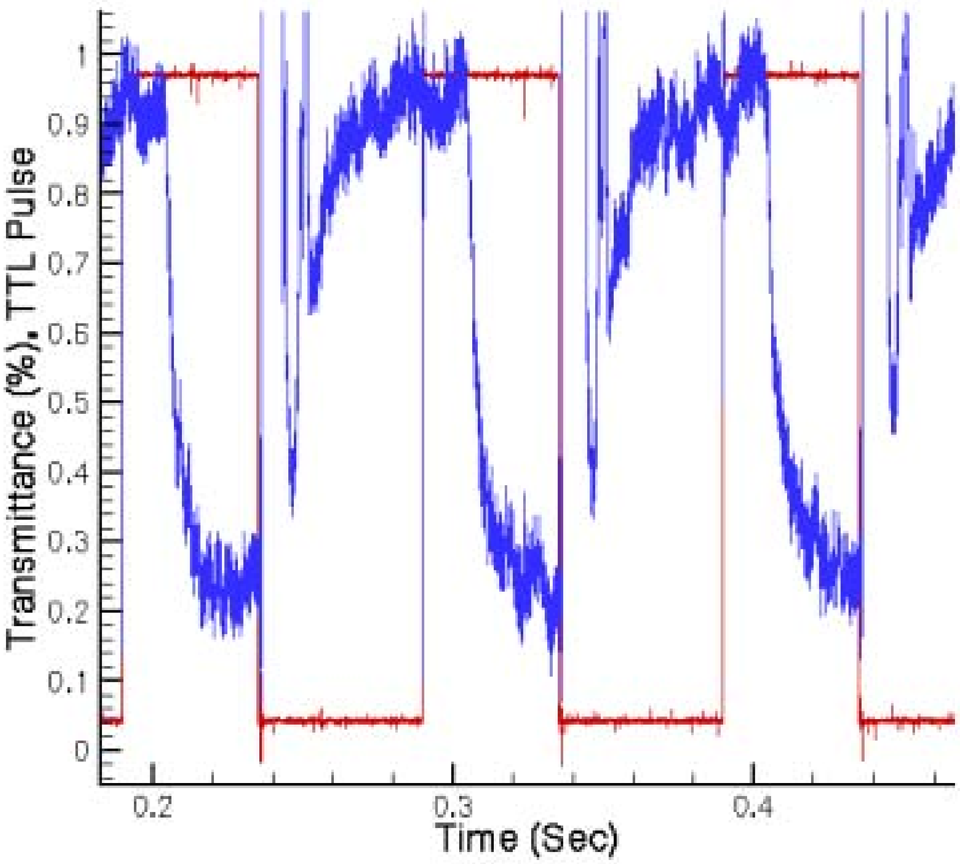

Figure 14. Transmittance of Propane/Air Mixture

The transmittance measurements recorded for different mass flow rates therefore allowed the timing of the injectors and the expected fuel delivery times for the range of test conditions expected [Figure 15]. Figure 15 shows the delay from the time of start of injection to the point where the He-Ne laser diode detects attenuation from the fuel at the diffraction plane. The end of the injection sequence was also determined from the transmittance plots. However, the timing measurements for the end of the injection event are far more inaccurate than the arrival of the injection, so a 30 ms fill time was added to the beginning of the injection event to guarantee its completion.

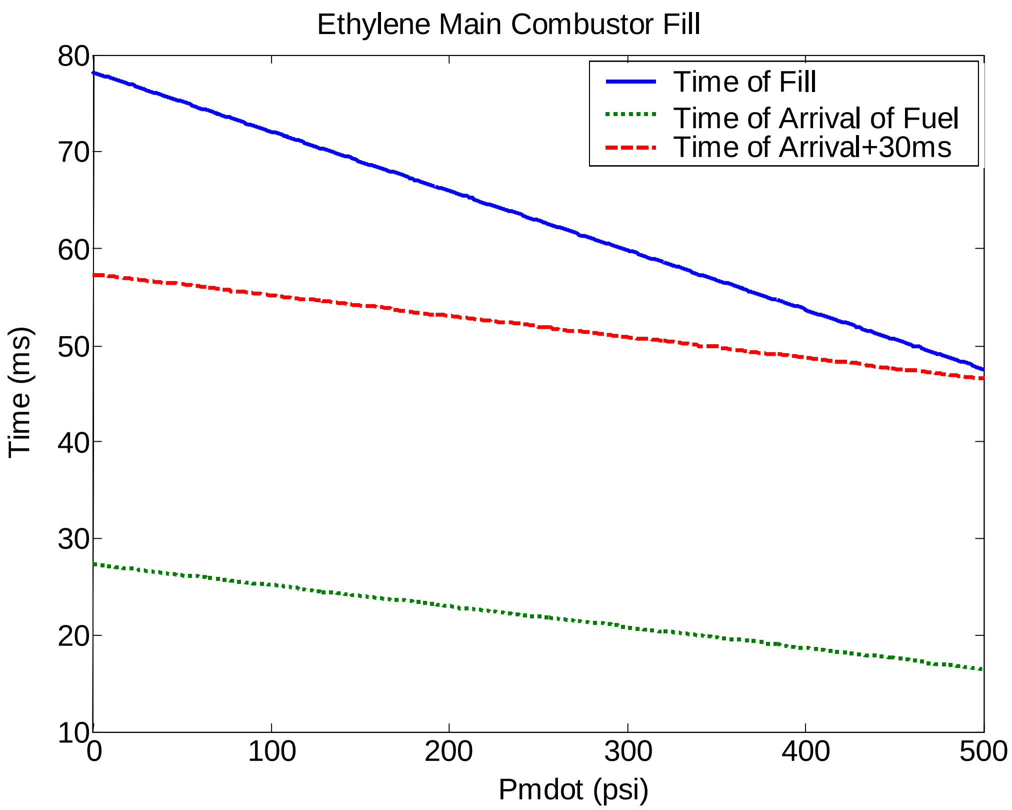

Figure 15. Injector Timing

Typical results for the 10 Hz operation on propane are shown in Figure 16. The square TTL trace represents the injection command for the initiator and the equivalence ratio trace is that for the propane/air mixture as it entered the main combustor. Notice that the equivalence ratio drops to zero as the detonation wave exiting the initiator consumes the fuel present and continues into the main combustor. Another feature to notice in Figure 16 was that the injection of the fuel was not yet completed prior to initiating the detonation as indicated by the equivalence ratio after the detonation passage. This was caused by initiating the detonation prematurely and can be easily corrected by increasing the ignition delay command. The observed variation in the fuel delivery led to a gradient in the equivalence ratio observed in the main combustor and will be evaluated in a future to study its effects on performance.

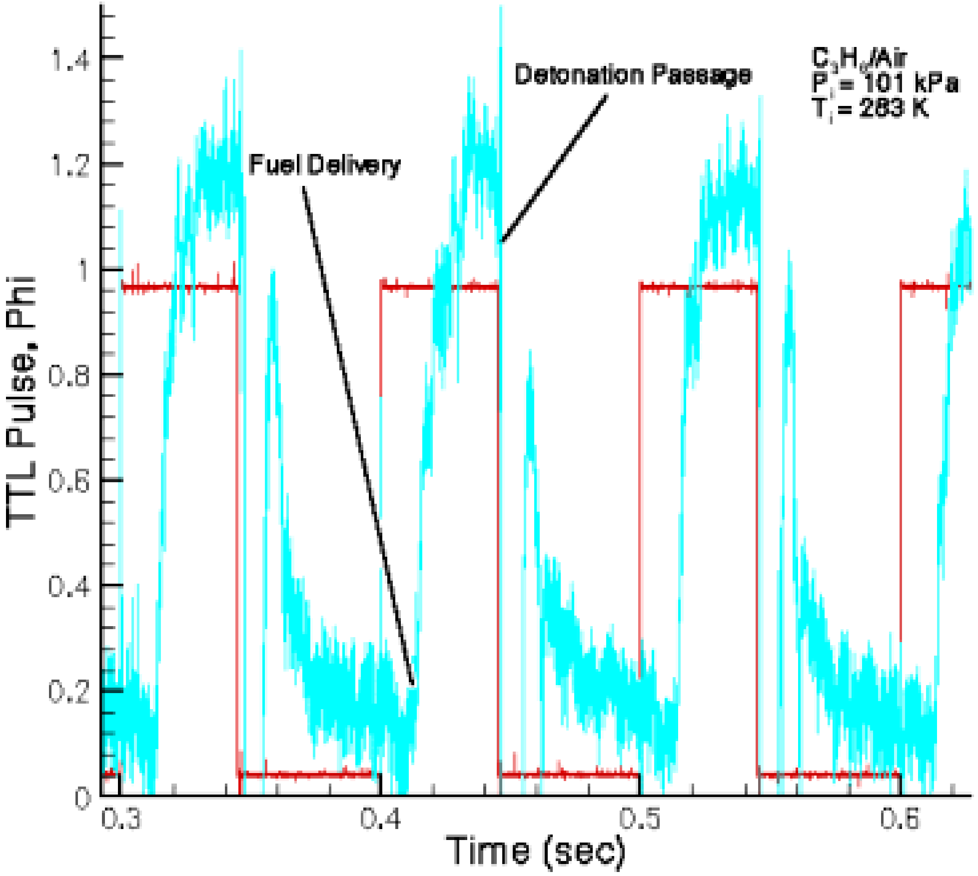

Figure 16. Fuel Injection Timing and Equivalence Ratio vs. Time for Propane/Air Mixture

The fuel injection timing that was found to be most effective during operation of the pulse detonation engine was as follows. The main combustor fuel was injected at the beginning of the cycle (without a delay) for 30 ms. After 14 ms delay in the start of the cycle the fuel/oxygen mixture was then injected into the initiator for 35 ms. This allowed sufficient time for the main fuel air mixture to fill the main combustor prior to initiation and provided 2-3ms of initiator overfill to aid in the detonation diffraction process. At the end of the injection cycle the initiator is then ignited to form the detonation wave. Due to the length of the main combustor and the required fuel injecting timing the operation of the PDE was limited to a maximum of approximately 20 Hz until optimization of the design could be completed. The PDE was operated primarily at 10 Hz in order to ensure the isolation of the detonation events to aid in determining the diffraction ratios.

During the filling of the combustor, the internal flow Mach number changes dramatically through the engine due to the axial area change and is shown in Figure 17. Once a detonation is initiated, a forward and aft propagation of disturbances occurs in the isolator section and the main combustor. Characteristics for the baseline case of D/D_i=1.25 is presented in Figures 17 and 18.

Initially, operation of the PDE was going to use a mass flow rate of approximately 1 kg/s in order to achieve 100 Hz operation. However, it became apparent that the initiator would not operate at mass flow rates over 0.4 kg/s due to local sub-atmospheric pressures at the initiator exit. A pressure transducer was installed in the manifold of the PDE to monitor the pressure of the airflow prior to entering the isolator at various flow rates. It was found that the airflow in the isolator eventually choked and therefore became supersonic in the isolator section at a mass flow rate of approximately 0.3 kg/s.

Since the first portion of this test program was to evaluate the subsonic isolator operation of this engine, the mass flow was therefore limited to prevent the isolator from choking locally and producing a supersonic flow region immediately downstream of that point. The condition depicted in Figure 17 shows the isolator Mach number approaching 0.95 and then decreasing as the cross-sectional area downstream of the isolator increases.

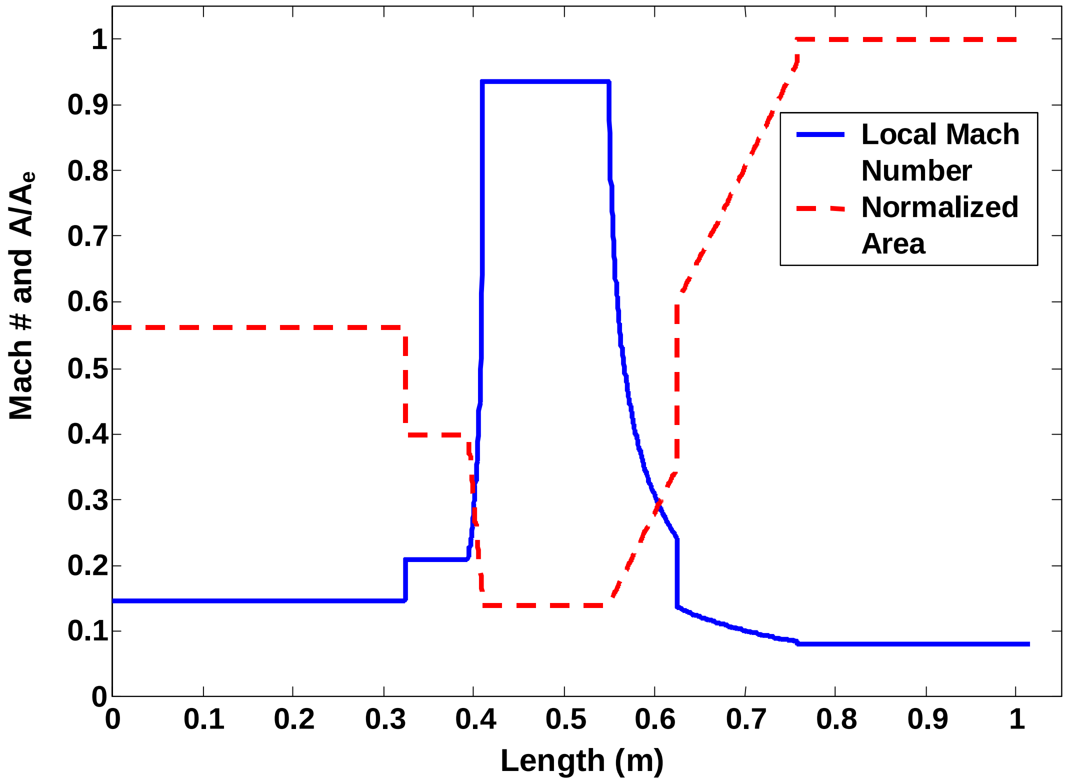

Figure 17. Local Mach Number vs. Cross-sectional Area

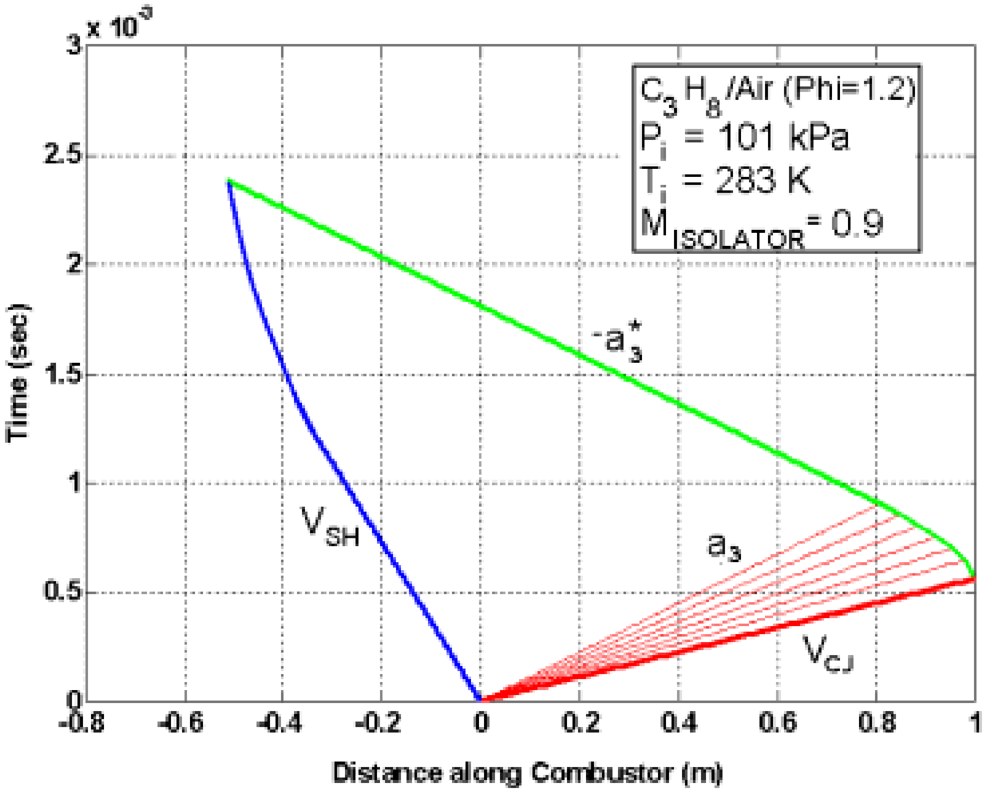

Figure 18. X-T Diagram of Forward and Rearward Propagation of Disturbances

Figure 18 shows the behavior of both the upstream and downstream propagating disturbances for a $M_{ISOLATOR}$=0.95 condition of propane/air at an equivalence ratio of 1.2 with x=0 being defined as the initiator exit. The lower right running trace depicts the propagation of the propane/air detonation towards the tube exit at the detonation velocity, V_{CJ} = 1820 m/s. Immediately behind the detonation front are a series of rarefaction waves which gradually reduce the post-detonation pressure to a lower value. Once the detonation wave exits the tube, a series of rarefaction waves begin to propagate upstream in order to reduce the pressure in the combustor. Only the leading rarefaction wave is depicted in the figure and is shown to propagate at the local speed of sound of the products. This wave will eventually catch up to the upstream running shock wave initially propagating upstream at about V_{SH}=450 m/s in the laboratory reference frame. Once the rarefaction waves catch up to the upstream propagating shock wave and relieve the pressure driving the shock, the detonation cycle is considered complete and the combustor is purged with the incoming air. The process repeats for each detonation cycle. The information in Figure 18 is useful because it depicts where the rarefaction waves intersect with the upstream propagating shock. The distance indicated on the x-axis reveals the necessary isolator length to prevent the upstream propagating shock from extending further upstream in the valveless geometry. It can be seen that the isolator length for a valveless design operating in a subsonic mode and an isolator Mach number of 0.95 would need to be approximately 0.5 meters long for a 1 meter long main combustor. If the isolator section is shorter than this length, the forward propagating disturbance could result in an inlet problem. However, by reducing the length of the main combustor the length required for the isolator would be shortened as well.

B. DIFFRACTION RESULTS

Detonation wave diffraction conditions at the initiator/main combustor interface were characterized on single-shot detonation facility using high-speed Schlieren and CH* chemiluminescence imaging which utilized a 10nm FWHM interference filter centered at 430nm [Ref. 28]. Previous single shot images are shown for this geometry and was representative of the valveless configuration. This also allowed multiple diffraction ratios to be characterized . The experimental setup for those tests and sample CH* images are shown below in Figures 19 and 20.

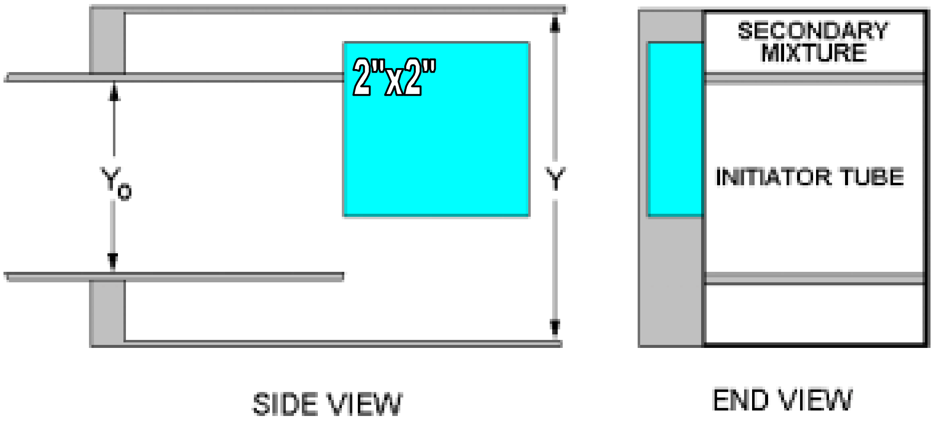

Figure 19. Two-Dimensional Diffraction Geometry (From Ref 28)

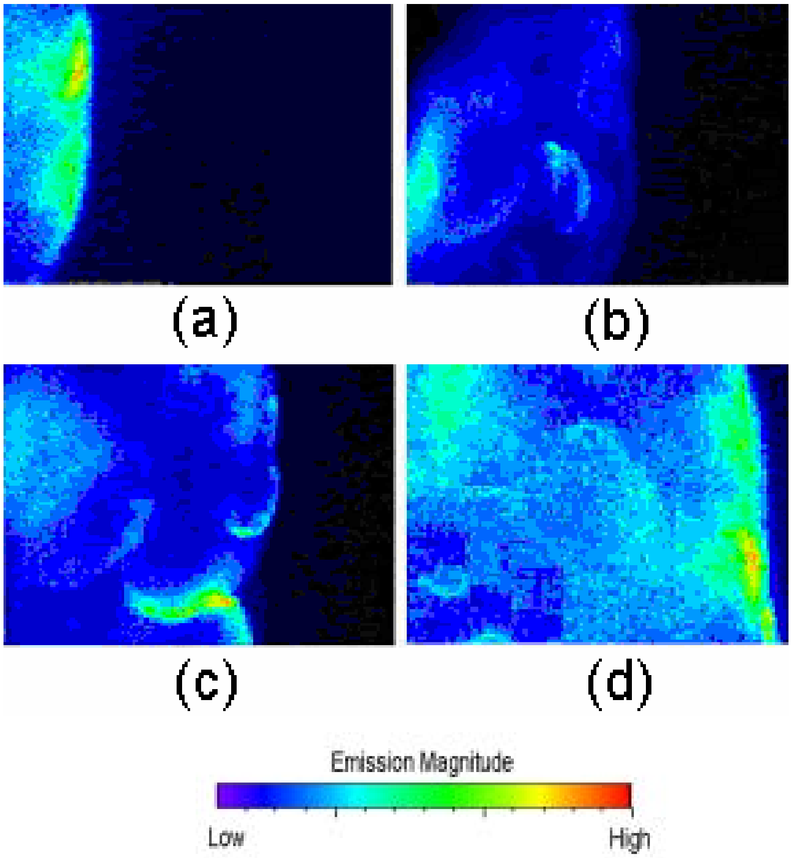

Figure 20. Experimental Setup for Single-Shot CH* Images (left) Sample Images at (a) t=15 µs (b) t=22 µs ,(c) t=29 µs, (d) t=36 µs for a Diameter Ratio of 1.33. (From Ref 28)

The observed detonation wave speeds during tests were very close to Chapman-Jouget values provided by the Thermo-chemical Equilibrium Program and shown in Figure 21. Occasionally, the observed detonation wave speeds were due to an overdriven condition which occurs during the re-initiation of the detonation in the main combustor. This results in a generally higher detonation wave speed than would normally be observed. Sample TEP outputs for an Ethylene equivalence ratio of 1.4 and Propane equivalence ratio of 1.2 are shown in Appendix B.

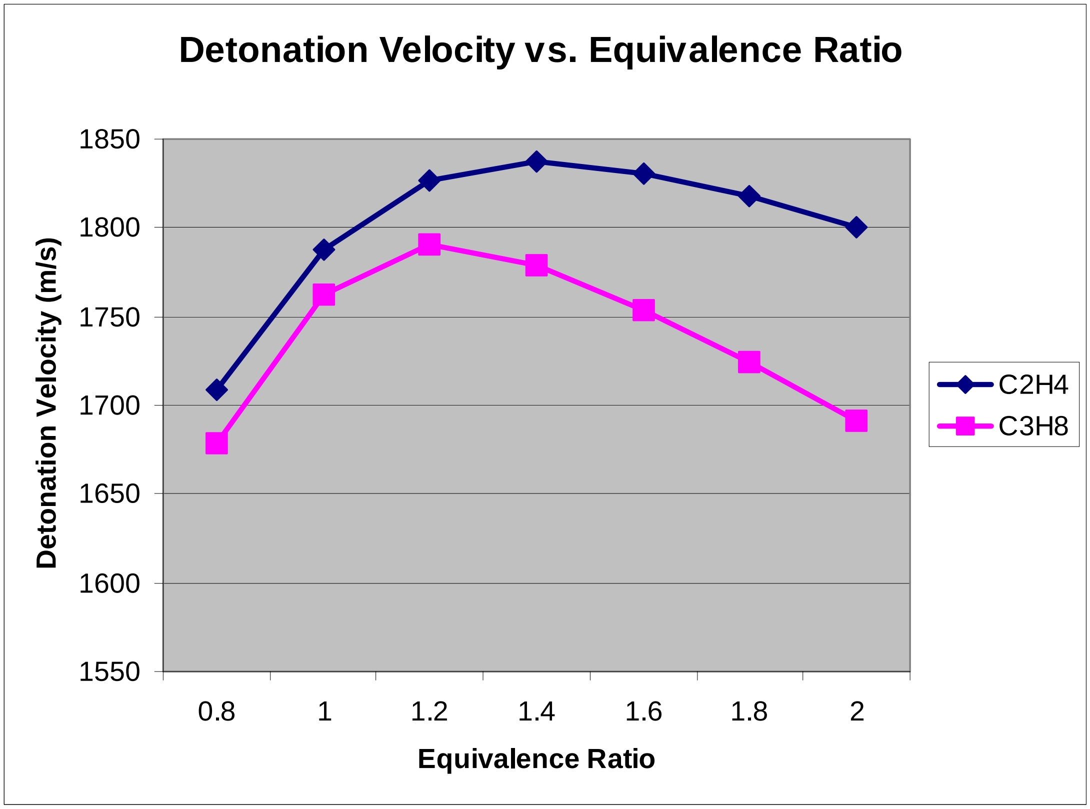

Figure 21. Detonation Velocity vs. Equivalence Ratio

The PDE was designed to evaluate diffraction ratios from 1.42 to 2.28. Two transition ramps were designed for evaluating the operation of the PDE, a 5 degree transition ramp and a 10 degree transition ramp. However, due to the failure of two of the Parker Hannifin oxygen valves, only the 5 degree transition was evaluated and limited the largest diffraction ratio evaluated to 1.58. The engine has been evaluated over diffraction range of 1.25 to 1.58 and operated on both ethylene/air and propane/air from stoichiometric to an equivalence ratio of 1.5. From previous research conducted on single cycle pulse detonation engines, these conditions were expected to produce successful detonation transitions up to diffraction ratios of 2.0. Figure 22 shows results of previous PDE studies where successful and unsuccessful detonations were observed at different diffraction and equivalence ratios when the main combustor is filled with a stoichiometric ethylene/air mixture [Ref. 28].

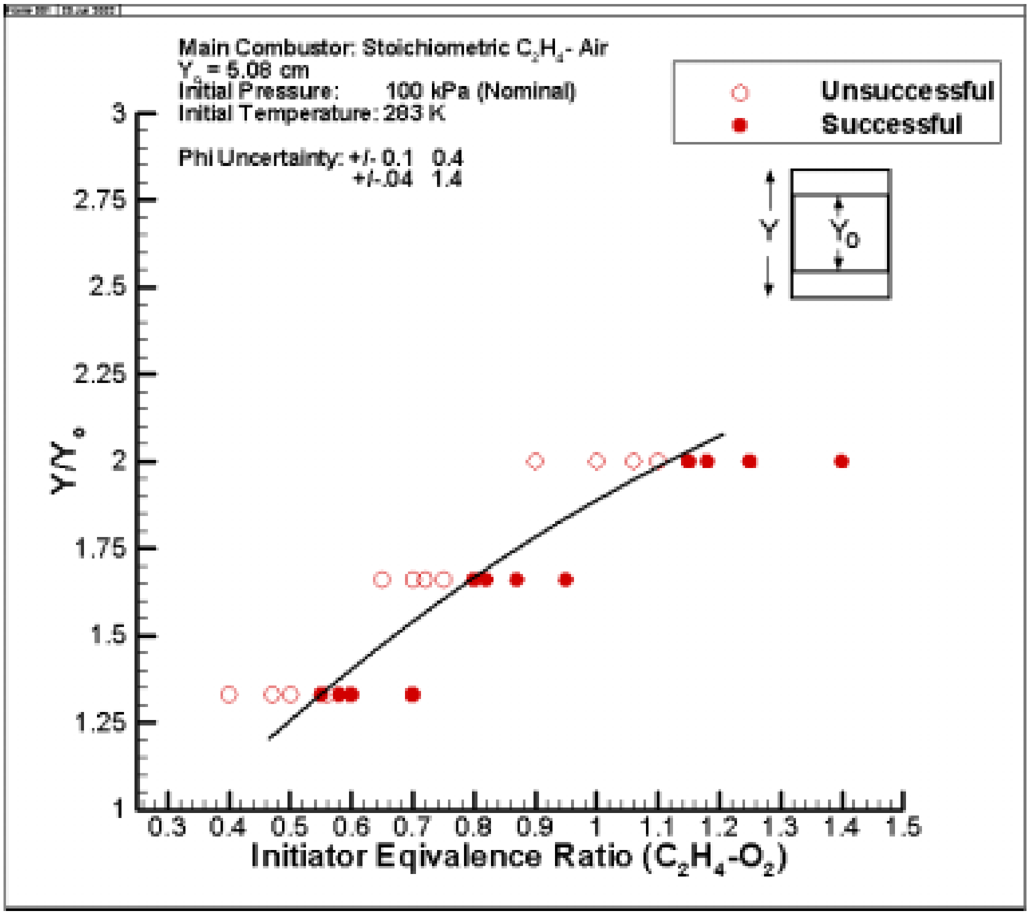

Figure 22. Diffraction Ratio vs. Equivalence Ratio Study

It is expected that the upper limit to be evaluated will be a diameter ratio of 2.28 with the 10 degree transition ramp in follow on research. It can been seen that ethylene/air mixtures at an equivalence ratio of 1.2 have successfully diffracted for all of the diameter ratios tested to date. Propane was evaluated at only two conditions, and will continue to be investigated in the near future. Results to date are shown below in Figure 23. The failure of the Parker Hannifin oxygen valves has delayed investigation on the larger diffraction ratios.

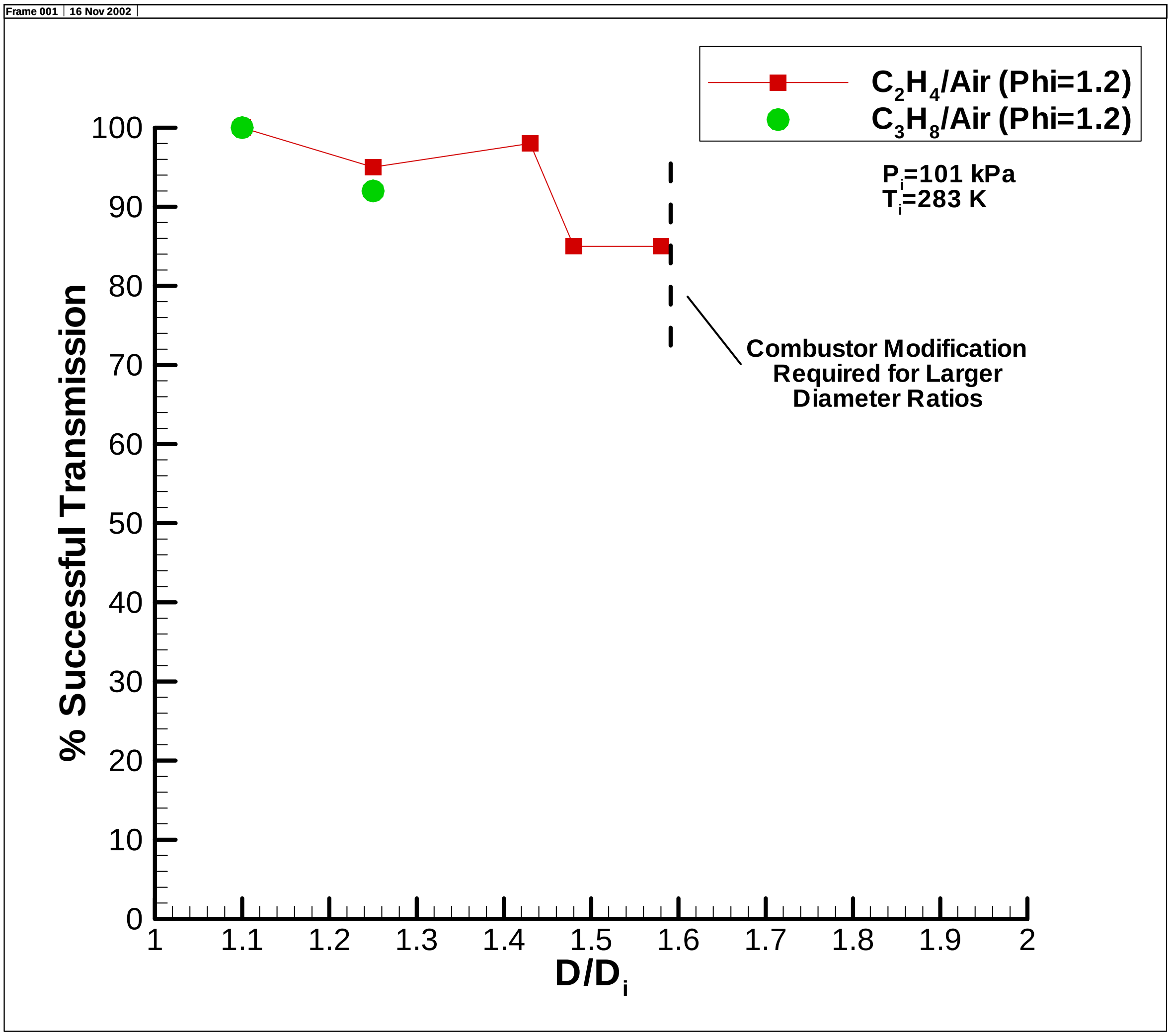

Figure 23. Preliminary Diffraction Results for a Multi-Cycle Valveless PDE

C. PERFORMANCE CALCULATIONS

Thrust measurements were taken and used to calculate the specific impulse of the valveless PDE geometry operating on ethylene. Ethylene was chosen for the comparison due to the large amount of references referring to the specific impulse of ethylene/air detonation tubes. Although a simple tube does not accurately model an engine with dynamic flow, it does provide a reasonable reference point for these calculations. At this time, it does not appear that the specific impulse is noticeably reduced compared to simple tube results. The results at this time contain a +/- 10% error due to noise in the acquired signal and the smoothing of the high frequency/transient load cell measurements. These measurements are being redesigned and will be acquired more accurately with a new six degree of freedom thrust stand to be used in future testing. It will provide two independent measurements of thrust to improve the fidelity of the calculation.

IV. CONCLUSIONS

The generation of strong Mach stem reflections downstream of the diffraction plane of the initiator combustor have been found to be a reliable reinitiation mechanism for the transmission of a detonation wave into a larger combustor over the range of diffraction ratios evaluated to date. So far, diffraction ratios up to 1.58 have been successful with ethylene/air mixtures and propane/air mixtures have been successful diffracting over a 1.43 ratio. The reliable generation of Mach stems along the wall downstream of the diffraction plane for coaxial initiators/combustors should be a valuable mechanism to take advantage during engine design since they do not depend directly on cell size, but on the strength of the exiting shockwave and the physical diffraction condition. The sensitivity of the mixture to reignition can and should be correlated to the detonation cell size of the reactants used.

The ability to isolate the incoming air flow from the detonation products has been shown to rely heavily on the isolator Mach number and combustion chamber length. Because the isolator length was not long enough to isolate the air flow for subsonic operation, the isolator section will need to be lengthened or the main combustor shortened for continued testing in a subsonic mode. The difficulty in transitioning a detonation wave into the main combustor was noticed when higher mass flow rates were used. This was due to local sub-atmospheric pressures at the initiator exit when flow in the isolator became sonic. Future research on a revised PDE design will focus on the supersonic flow of fuel/air mixtures in the PDE. Although only subsonic isolator Mach numbers were evaluated during this portion of the test program, sonic or supersonic values corresponding to total pressure of 100 psi or higher will likely provide total inlet isolation from the post detonation pressure and will be evaluated in the next phase of this research.

THIS PAGE LEFT INTENTIONALLY BLANK

V. FUTURE WORK

Initial performance estimates of the valveless engine geometry appear to be only slightly lower than conventionally valved systems. Thereby revealing a potential design simplicity without incurring unreasonable losses. Although no significant performance loss has been observed, current uncertainties will need to be reduced to improve the fidelity of the calculations and provide more definitive results. Future work will involve improved thrust measurements, higher frequency operation, and the utilization of liquid fuels at frequencies above 40 Hz.

The design of the engine limited testing to air mass flow rates below 0.3 kg/s due to the engine choking at the manifold at higher flow rates. This limit affected the operating frequency of the PDE. By changing, the cross sectional area in these sections, the mass flow rate could be substantially increased without the airflow becoming supersonic in the transition ramp. However the purpose of this thesis was to determine how large of a diffraction area the initiator could withstand before the detonation wave failed. By increasing the cross sectional area of the manifold and the transition ramp, the risk of detonation failure increases and thus, the critical diffraction limit will be determined.

Since the research objectives for this thesis were not completed due to equipment failure, all diffraction ratios were not observed for performance. Additionally, not all the desired fuels were characterized for detonation failure for the different diffraction ratios. Follow-on work should continue to study the diffraction limits and evaluate JP-10 operation as well. Once the diffraction limits are determined the initiator can be redesigned at the optimum diffraction ratio to improve the frequency of operation.

Mapping of the Pressure Volume Time (PVT) curves for a PDE would be very helpful for this engine geometry. Although conventional PV curves are 2 dimensional, the required figures would be 3 dimensional due to the transient flow.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A: FACILITY OPERATIONS

TEST CELL #2

STANDARD OPERATING PROCEDURES FOR ETHYLENE FUEL

Facility Open Procedures:

1) Press RED "Emergency Stop" button in for Test Cell #2
2) Turn on "SCARP" computer
3) Turn on power to Cabinet #2
4) Turn on 24 volt power supply at test cell #1 area. Switch is labeled "POWER TO 24VDC POWER SUPPLY/CELL 1"
5) Turn on 115 volt power supply to Test Cell #1 in same panel as 24 volt power switch
6) Execute "TC2_CONTROL_STEVE" from the icon on desktop ("SCARP")
7) Turn on "LIGHTS" at the video display panel to indicate gases are in use.
8) Open HP air valve at the HP air tanks
9) Turn on power to ER3000 regulator valves inside main control panel inside Test Cell #1
10) Ensure manual purge valve is open. Valve is under optics table in Test Cell #1
11) Set purge air pressure to desired setting (green regulator in Test Cell #1)
12) If using the He-Ne laser for diagnostics, turn on laser and ensure shutter is open

In Cell #2:

13) Open shop air, main air (vitiator), and HP air valves on rear wall
14) Ensure relief valves to O_2, H_2, and C_2H_4 tanks are closed
15) Open O_2 (2), H_2(2), N_2(1), and C_2H_4(1) tank valves on right side wall and verify desired pressure at the bottles
16) Open the C_2H_4 valve at the test stand
17) Open left wall N_2 valves and manually set regulator pressure to desired pressure for C_2H_4 injection
18) Turn on the Kistler amplifiers
    a) Ensure proper gain is set in all amplifiers
    b) Set mode to Operate, Short, and Charge
19) Plug in laser diode amplifier if using the laser for diagnostics

Note: At this time you have full pressure of all gases and liquids at the test stand

In Control Room:

20) Set the main air pressure for ER3000 regulator valve on SADDLER computer.
    a) Select Node 1
    b) Set main air pressure at desired level
21) Enter "RUN CONDITIONS", set desired conditions and exit
22) Enter "FACILITY OPERATIONS" and check the "CONTINUOUS" and "SPARK" boxes.
23) Execute "HighSpeedDAQ.vi" from the desktop ("SCARP")
    a) Set sample ratio to 500,000 Hz
    b) Set device to 2
    c) Set channels to 0:3
    d) Set number of scans to 1,000,000
24) Evacuate all personnel from Test Cell #2
25) In Cabinet #2 arm the MSD Ignition switch
26) Reset "Emergency Stop" button

Run Procedures:

27) Ensure all "Alarm Status" indicators are green in "Facility Operations"
    Note: If an indicators are red the test run will automatically be aborted
28) Ensure area is clear of golfers and all RPCL personnel are in control room
29) Start recording on VCR(s)
30) Turn siren on at video display panel

*********** WARNING ***********

The next step will result in the commencement of a run profile and ignition

31) In "Facility Operations" click "Start Run"
32) Open Main Air Valve switch to the right of the video display panel
33) Once firing has begun click "Play" in the HighSpeedDAQ.vi application
34) Once data acquisition is complete click "Stop Run" in "Facility Operations"
35) Secure the Main air valve from switch to right of video display panel
36) Maintain purge air for 10-20 seconds (manual "Purge" button in "Facility Operations")
37) Secure siren at video display panel
38) Stop recording on VCR(s)
39) Press "emergency Stop" button

Close Facility Procedure for Ethylene Operations:

Control Room:

1) Ensure “Emergency Stop” button is depressed
2) Close HighSpeedDAQ.vi application
3) Exit “Facility Operations”
4) Disarm the MSD Ignition switch
5) Secure power to Cabinet #2
6) Secure 24V power supply (switch labeled “Power to 24VDC Power Supply/Cell #1”)
7) Secure 115V power supply to Test Cell #1
8) Close HP air valve at HP tanks
9) Turn off He-Ne laser and close shutter
10) Reduce Purge Air regulator in Test Cell #1 to 0 psi
11) Turn off power to ER3000 regulator valves inside main control panel inside Test Cell #1

Test Cell #2

12) Unplug laser diode amplifier
13) Close N_2 (1), C_2H_4 (1), O_2 (2), H_2 (2) bottle valves on right wall
14) Open H_2 relief valve to vent H_2 pressure and then close relief valve on right wall
15) Open C_2H_4 relief valve to vent C_2H_4 pressure and then close relief valve on right wall
16) Wait a few minutes then open O_2 relief valve to vent O_2 pressure and then close relief valve on right wall

Note: Steps 5-7 are separated in time so as to allow dissipation of gases prior to venting additional gases

17) Close HP air, main air (vitiator), and shop air valves on rear wall
18) Close N_2 bottle valve on left wall
19) Set N_2 regulator pressure to zero (Regulator valve turned all the way to left)
20) Close C_2H_4 bottle valve at the test stand

Control Room:

21) Secure “Lights” on video display panel

TEST CELL #2

STANDARD OPERATING PROCEDURES FOR PROPANE FUEL

Facility Open Procedures:

1) Press RED “Emergency Stop” button in for Test Cell #2
2) Turn on “SCARP” computer
3) Turn on power to Cabinet #2
4) Turn on 24 volt power supply at test cell #1 area. Switch is labeled “POWER TO 24VDC POWER SUPPLY/CELL 1”
5) Turn on 115 volt power supply to Test Cell #1 in same panel as 24 volt power switch
6) Execute “TC2_CONTROL_STEVE” from the icon on desktop (“SCARP”)
7) Turn on “LIGHTS” at the video display panel to indicate gases are in use.
8) Open HP air valve at the HP air tanks
9) Turn on power to ER3000 regulator valves inside main control panel inside Test Cell #1
10) Ensure manual purge valve is open. Valve is under optics table in Test Cell #1
11) Set purge air pressure to desired setting (green regulator in Test Cell #1)
12) If using the He-Ne laser for diagnostics, turn on laser and ensure shutter is open

In Cell #2:

13) Open shop air, main air (vitiator), and HP air valves on rear wall
14) Ensure relief valves to O_2, H_2, and C_2H_4 tanks are closed
15) Open O_2 (2), H_2(2), N_2(1), and C_2H_4(1) tank valves on right side wall and verify desired pressure at the bottles
16) Open left wall propane valve and set pressure to 125 psi
17) Open the propane ball valve to the test stand, verify pressure is still 125 psi
18) Turn on the Kistler amplifiers
    a. Ensure proper gain is set in all amplifiers
    b. Set mode to Operate, Short, and Charge
19) Plug in laser diode amplifier if using the laser for diagnostics
20) Ensure red LED on hydro-pump breaker is off (not lit) and close the hydro-pump breaker if LED is off.
    Note: If LED is on when closing the breaker, the hydro-pump will turn on

Note: At this time you have full pressure of all gases and liquids at the test stand

In Control Room:

21) Set the main air pressure for ER3000 regulator valve on SADDLER computer.
    a. Select Node 1
    b. Set main air pressure at desired level
22) Enter "RUN CONDITIONS", set desired conditions and exit
23) Enter "FACILITY OPERATIONS" and check the "CONTINUOUS" and "SPARK" boxes.
24) Execute "HighSpeedDAQ.vi" from the desktop ("SCARP")
    a. Set sample ratio to 500,000 Hz
    b. Set device to 2
    c. Set channels to 0:3
    d. Set number of scans to 1,000,000
25) Evacuate all personnel from Test Cell #2
26) In Cabinet #2 arm the MSD Ignition switch
27) Reset "Emergency Stop" button

Run Procedures:

28) Ensure all "Alarm Status" indicators are green in "Facility Operations"
    Note: If an indicators are red the test run will automatically be aborted
29) Ensure area is clear of golfers and all RPCL personnel are in control room
30) Start recording on VCR(s)
31) Turn siren on at video display panel

*********** WARNING ***********

The next step will result in the commencement of a run profile and ignition

32) In "Facility Operations" click "Start Run"
33) Open Main Air Valve switch to the right of the video display panel
34) Once firing has begun click "Play" in the HighSpeedDAQ.vi application
35) Once data acquisition is complete click "Stop Run" in "Facility Operations"
36) Secure the Main air valve from switch to right of video display panel
37) Maintain purge air for 10-20 seconds (manual "Purge" button in "Facility Operations")
38) Secure siren at video display panel
39) Stop recording on VCR(s)
40) Press "emergency Stop" button

Close Facility Procedure for Propane Operations:

Control Room:

1) Ensure "Emergency Stop" button is depressed
2) Close HighSpeedDAQ.vi application
3) Exit "Facility Operations"
4) Disarm the MSD Ignition switch
5) Secure power to Cabinet #2
6) Secure 24V power supply (switch labeled "Power to 24VDC Power Supply/Cell #1")
7) Secure 115V power supply to Test Cell #1
8) Close HP air valve at HP tanks
9) Turn off He-Ne laser and close shutter
10) Reduce Purge Air regulator in Test Cell #1 to 0 psi
11) Turn off power to ER3000 regulator valves inside main control panel inside Test Cell #1

Test Cell #2

12) Unplug laser diode amplifier
13) Close N_2 (1), C_2H_4 (1), O_2 (2), H_2 (2) bottle valves on right wall
14) Open H_2 relief valve to vent H_2 pressure and then close relief valve on right wall
15) Open C_2H_4 relief valve to vent C_2H_4 pressure and then close relief valve on right wall
16) Wait a few minutes then open O_2 relief valve to vent O_2 pressure and then close relief valve on right wall

Note: Steps 5-7 are separated in time so as to allow dissipation of gases prior to venting additional gases

17) Close HP air, main air (vitiator), and shop air valves on rear wall
18) Open hydro-pump breaker
19) Close propane ball valve on test stand
20) Close propane valve at propane tank on left wall

Control Room:

21) Secure "Lights" on video display panel

TEST CELL #2

STANDARD OPERATING PROCEDURES FOR JP-10 FUEL

Facility Open Procedures:

1) Press RED "Emergency Stop" button in for Test Cell #2
2) Turn on "SCARP" computer
3) Turn on power to Cabinet #2
4) Turn on 24 volt power supply at test cell #1 area. Switch is labeled "POWER TO 24VDC POWER SUPPLY/CELL 1"
5) Turn on 115 volt power supply to Test Cell #1 in same panel as 24 volt power switch
6) Execute "TC2_CONTROL_STEVE" from the icon on desktop ("SCARP")
7) Turn on "LIGHTS" at the video display panel to indicate gases are in use.
8) Open HP air valve at the HP air tanks
9) Turn on power to ER3000 regulator valves inside main control panel inside Test Cell #1
10) Ensure manual purge valve is open. Valve is under optics table in Test Cell #1
11) Set purge air pressure to desired setting (green regulator in Test Cell #1)
12) If using the He-Ne laser for diagnostics, turn on laser and ensure shutter is open

In Cell #2:

13) Open shop air, main air (vitiator), and HP air valves on rear wall
14) Ensure relief valves to O_2, H_2, and C_2H_4 tanks are closed
15) Open O_2 (2), H_2(2), N_2(1), and C_2H_4(1) tank valves on right side wall and verify desired pressure at the bottles
16) Check left wall N_2 valves (relief valve and ball valve to JP-10 pressure vessel) to ensure they are closed and the regulator valve is set to zero pressure (turned all the way to the left)
17) Check the JP-10 valve at the pressure vessel to ensure it is closed
18) Open left wall N_2 valve and manually set regulator pressure to 125 psi
19) Open the ball valve to the JP-10 pressure vessel, verify pressure is still 125 psi
20) Open JP-10 valve at the pressure vessel
21) Turn on the Kistler amplifiers
    a. Ensure proper gain is set in all amplifiers
    b. Set mode to Operate, Short, and Charge
22) Plug in laser diode amplifier if using the laser for diagnostics
23) Ensure red LED on hydro-pump breaker is off (not lit) and close the hydro-pump breaker if LED is off.
    Note: If LED is on when closing the breaker, the hydro-pump will turn on

Note: At this time you have full pressure of all gases and liquids at the test stand

In Control Room:

24) Set the main air pressure for ER3000 regulator valve on SADDLER computer.
    a. Select Node 1
    b. Set main air pressure at desired level
25) Enter “RUN CONDITIONS”, set desired conditions and exit
26) Enter “FACILITY OPERATIONS” and check the “CONTINUOUS” and “SPARK” boxes.
27) Execute “HighSpeedDAQ.vi” from the desktop (“SCARP”)
    a. Set sample ratio to 500,000 Hz
    b. Set device to 2
    c. Set channels to 0:3
    d. Set number of scans to 1,000,000
28) Evacuate all personnel from Test Cell #2
29) In Cabinet #2 arm the MSD Ignition switch
30) Reset “Emergency Stop” button

Run Procedures:

31) Ensure all “Alarm Status” indicators are green in “Facility Operations”
    Note: If an indicators are red the test run will automatically be aborted
32) Ensure area is clear of golfers and all RPCL personnel are in control room
33) Start recording on VCR(s)
34) Turn siren on at video display panel

*********** WARNING ***********

The next step will result in the commencement of a run profile and ignition

35) In “Facility Operations” click “Start Run”
36) Open Main Air Valve switch to the right of the video display panel
37) Once firing has begun click “Play” in the HighSpeedDAQ.vi application
38) Once data acquisition is complete click “Stop Run” in “Facility Operations”
39) Secure the Main air valve from switch to right of video display panel
40) Maintain purge air for 10-20 seconds (manual “Purge” button in “Facility Operations”)
41) Secure siren at video display panel
42) Stop recording on VCR(s)
43) Press “emergency Stop” button

Close Facility Procedure for JP-10 Operations:

Control Room:

1) Ensure "Emergency Stop" button is depressed
2) Close HighSpeedDAQ.vi application
3) Exit "Facility Operations"
4) Disarm the MSD Ignition switch
5) Secure power to Cabinet #2
6) Secure 24V power supply (switch labeled "Power to 24VDC Power Supply/Cell #1")
7) Secure 115V power supply to Test Cell #1
8) Close HP air valve at HP tanks
9) Turn off He-Ne laser and close shutter
10) Reduce Purge Air regulator in Test Cell #1 to 0 psi
11) Turn off power to ER3000 regulator valves inside main control panel inside Test Cell #1

Test Cell #2

12) Unplug laser diode amplifier
13) Close N_2 (1), C_2H_4 (1), O_2 (2), H_2 (2) bottle valves on right wall
14) Open H_2 relief valve to vent H_2 pressure and then close relief valve on right wall
15) Open C_2H_4 relief valve to vent C_2H_4 pressure and then close relief valve on right wall
16) Wait a few minutes then open O_2 relief valve to vent O_2 pressure and then close relief valve on right wall

Note: Steps 5-7 are separated in time so as to allow dissipation of gases prior to venting additional gases

17) Close HP air, main air (vitiator), and shop air valves on rear wall
18) Open hydro-pump breaker
19) Close N_2 bottle valve on left wall
20) Set N_2 regulator pressure to zero (Regulator valve turned all the way to left)
21) Open N_2 relief valve to vent N_2 pressure, then close valve
22) Close N_2 ball valve to JP-10 pressure vessel
23) Close JP-10 valve at pressure vessel

Control Room:

24) Secure "Lights" on video display panel

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX B: THERMO-CHEMICAL EQUILIBRIUM PROGRAM (TEP) OUTPUTS FOR ETHYLENE AND PROPANE

ETHYLENE (C_2H_4), EQUIVALENCE RATIO = 1.4

```
DETONATION PROPERTIES OF AN IDEAL REACTING GAS
                                              WT FRACTION  ENTHALPY  STATE   TEMP    DENSITY
       CHEMICAL FORMULA                              (SEE NOTE) JOULES/MOL         DEG K   KG/M3
 OXIDANT N  2.00000                                0.79000       55.023    G    300.00   0.0000
 OXIDANT O  2.00000                                0.21000       54.154    G    300.00   0.0000
 FUEL    C  2.00000   H  4.00000                    1.00000    52339.012    G    300.00 568.8000
0O/F=1.1639E+01     PERCENT   FUEL=7.9121E+00     EQUIVALENCE   RATIO=1.4000E+00      STOIC   MIXTURE
RATIO=1.6294E+01  DENSITY=0.0000E+00
 UNBURNED GAS


 P1,ATM           1.0000
 T1,DEG K         300.00
 H1,CAL/G          35.70
 M1,MOL WT        28.708
 GAMMA1           1.3783
 SON VEL,M/SEC     346.1
0BURNED GAS


 P, N/M2        1.8265 6
 T, DEG K           2825
 H, J/KG        1.3037 6
 S, J/(KG)(K)   9.4670 3
 G, CAL/GRAM     -6080.4
 U, CAL/GRAM       101.5
 DEN, (KG/M3)   2.08

 M, MOL WT        26.702
 (DLV/DLP)T     -1.00291
 (DLV/DLT)P       1.0675
 CP, J/(KG)(K   2.0092 3
 CP GAS(SF)       0.3599
 GAMMA GAS(SF)    1.2605
 GAMMA (S)        1.2100
 SON VEL,M/SEC    1031.7
 MU, POISE      7.84E-04
 K,ERG/S-CM-K   1.78E+04
 PRANDTL NO      0.66443
0DETONATION PARAMETERS


 P/P1             18.027
 T/T1              9.417
 M/M1             0.9301
 RHO/RHO1         1.7806
 MACH NO.         5.3084
 DET VEL,M/SEC    1837.0
 MOL WT(MIX)      26.702
```

PROPANE (C3H8), EQUIVALENCE RATIO = 1.2

```
DETONATION PROPERTIES OF AN IDEAL REACTING GAS
                                           WT FRACTION  ENTHALPY  STATE   TEMP    DENSITY
     CHEMICAL FORMULA                      (SEE NOTE) JOULES/MOL          DEG K   KG/M3
 FUEL    C  3.00000   H  8.00000             1.00000  -103650.477    G    300.00 500.0000
 OXIDANT N  2.00000                          0.79000       55.023    G    300.00   0.0000
 OXIDANT O  2.00000                          0.21000       54.154    G    300.00   0.0000
0O/F=1.4398E+01      PERCENT   FUEL=6.4945E+00      EQUIVALENCE   RATIO=1.2000E+00      STOIC   MIXTURE
RATIO=1.7277E+01  DENSITY=0.0000E+00
 UNBURNED GAS


 P1,ATM           1.0000
 T1,DEG K         300.00
 H1,CAL/G         -36.06
 M1,MOL WT        29.430
 GAMMA1           1.3646
 SON VEL,M/SEC     340.1
0BURNED GAS


 P, N/M2        1.7893 6
 T, DEG K           2730
 H, J/KG        9.4931 5
 S, J/(KG)(K)   9.3385 3
 G, CAL/GRAM     -5867.3
 U, CAL/GRAM        26.9
 DEN, (KG/M3)   2.14

 M, MOL WT        27.112
 (DLV/DLP)T     -1.00309
 (DLV/DLT)P       1.0769
 CP, J/(KG)(K   2.1101 3
 CP GAS(SF)       0.3607
 GAMMA GAS(SF)    1.2548
 GAMMA (S)        1.1981
 SON VEL,M/SEC    1001.6
 MU, POISE      7.68E-04
 K,ERG/S-CM-K   1.70E+04
 PRANDTL NO      0.68327
0DETONATION PARAMETERS


 P/P1             17.659
 T/T1              9.101
 M/M1             0.9212
 RHO/RHO1         1.7874
 MACH NO.         5.2641
 DET VEL,M/SEC    1790.2
 MOL WT(MIX)      27.112
```

LIST OF REFERENCES

1) Kailasanath, K., "Recent Developments in the Research on Pulse Detonation Engines," AIAA Paper No. 2002-0470.

2) Lee, J.H.S., and Guirao, C.M., "Fuel-Air Explosions," Proceedings of the International Conference on Fuel-Air Explosions, November 4-6, 1981, University of Waterloo Press, Waterloo, Ontario, 1982, p. 1005.

3) Beeson, H.D., McClenagan, R.D., Pitz, W.J., Westbrook, C.K., and Lee, J.H.S., "Detonabilty of Hydrocarbon Fuels in Air," Progress in Astronautics and Aeronautics, Vol. 133, American Institute of Aeronautics and Astronautics, New York, NY, 1990, pp. 19-36.

4) Brophy, C.M., Werner, S.P., Sinibaldi, J.O., Netzer, D.W., "Experimental Performance of a Valveless Pulse Detonation Engine," 51st JANNAF Propulsion Conference, Lake Buena Vista, Florida, November 18-21, 2002.

5) Hofstedt, T., "Propagation of a Two-Phase Detonation Across a Geometric Diffraction With compositional Discontinuity," Master's Thesis, Naval Postgraduate School, Monterey, California, June 2000.

6) Sinibaldi, J., Brophy, C., Kailasanath, K., "Initiator Detonation Diffraction Studies In Pulse Detonation Engines," 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Salt Lake City, Utah, July 8-11, 2001, Paper No. AIAA 2001-3466.

7) Bussing, T., Pappas, G., "An Introduction to Pulse Detonation Engines," 33rd AIAA Aerospace Sciences Meeting & Exhibit, Reno, Nevada, January 11-14, 1999, Paper No. AIAA 94-0263.

8) Eidelman, S., Grossmann, W., "Pulsed Detonation Engine: Experimental and Theoretical Review," AIAA Paper 99-1067, 1999.

9) Kailasanath, K., "Applications of Detonation to Propulsion: A Review," AIAA Paper 99-1067, 1999.

10) Brophy, C.M., Netzer, D.W., Sinibaldi, J.O., Johnson, R.G., "Operation of a JP-10/Air Pulse Detonation Engine," 36th AIAA/ASME/ASE Joint Propulsion Conference, Salt Lake City, Utah, July 2000, Paper No. AIAA 2000-3591.

11) Busing, T.R.A., "A Rotary Valve Multiple Pulsed Detonation Engine (RVMPDE)," 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, San Diego, California, July 10-12, 1995, AIAA Paper No. 95-2577.

12) Damphousse, P., “Characterization and Performance of a Liquid Hydrocarbon-Fueled Pulse Detonation Rocket Engine,” Master’s Thesis, Naval Postgraduate School, Monterey, California, December 2001.

13) Knystautas, R., Lee, J.H., and Guirao, C.M., “The Critical Tube Diameter for Detonation Failure in Hydrocarbon-Air Mixtures,” *Combustion and Flame*, Vol. 48, pg. 63, 1982.

14) Moen, I.O., Donato, M., Knystautas, R., and Lee, J.H., “The Influence of Confinement on the Propagation of Detonations Near the Detonability Limit,” 18th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 19811, pp. 1615-1622, 1980.

15) Teodorcczyk, A., Lee, J.H., and Knystautas, R., “Photographic Study of the Structure and Propagration Mechanisms of Quasidetonations in Rough Tubes,” Progress in Astronautics and Aeronautics, Vol. 133, American Institute of Aeronautics and Astronautics, New York, NY, 1990, pp. 223-240.

16) Oran, E.S., and Boris, J.P., “Ignition in a Complex Mach Structure,” Progress in Astronautics and Aeronautics, Vol. 153, American Institute of Aeronautics and Astronautics, New York, NY, 1993, pp. 241-252.

17) Oran, E.S., Jones, D.A., and Sichel, M., “Numerical Simulations of Detonation Transmission,” *Proceedings of the Royal Society A*, Vol. 436, 1992, pp. 267-297.

18) Murray, S.B., Zhang, F., and Gerrard, K.B., “The Influence of Driver Power and Receptor Confinement on Pre-Detonators for Pulse Detonation Engines,” 18th International Colloquium on the Dynamics of Explosions and Reactive Systems, August 10-12, 2001, Seattle, Washington.

19) Edwards, D.H., Thomas, G.O. Thomas, and Nettleton, M.A., “The Diffraction of a Planar Detonation Wave at an Abrupt Area Change,” *Journal of Fluid Mechanics,* Vol. 95, pp. 79-96, 1979.

20) Desbordes, D., “Transmission of Overdriven Plane Detonations: Critical Diameter as a Function of Cell Regularity and Size,” Progress in Astronautics and Aeronautics, Vol. 114, American Institute of Aeronautics and Astronautics, New York, NY, 1990, pp. 170-185, 1988.

21) Desbordes, D., and Lannoy, A., “Effects of a Negative Step of Fuel Concentration on Critical Diameter of Diffraction of a Detonation,” Progress in Astronautics and Aeronautics, Vol. 133, American Institute of Aeronautics and Astronautics, New York, NY, 1990, pp. 170-186.

22) Murray, S.B., Thibault, P.A., Zhang, F., Bjerketvedt, D., Sulmistras, A., Thomas, G.O., Jenssen, A., and Moen, I.O., "The Role of Energy Distribution on the Transmission of Detonation," International Colloquium on Control of Detonation Processes, Moscow, Russia, July 4-7, 2000.

23) Johnson, R.G., "Design, Characterization, and Performance of a Valveless Pulse Detonation Engine," Master's Thesis, Naval Postgraduate School, Monterey, California, June 2000.

24) Forster, D., "Evaluation of a liquid-Fueled Pulse Detonation Engine Combustor," Master's Thesis, Naval Postgraduate School, Monterey, California, December 1998.

25) Brophy, C.M., Sinibaldi, J.O., Damphousse, P., "Initiator Performance for Liquid-Fueled Pulse Detonation Engines," 40th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 14-17, 2002, AIAA Paper No. 2002-0472.

26) Jaynes, D., Beam, B., "Hydrocarbon Gas Absorbtion by a HeNe Laser Beam at a 3.39-m Wavelength," Applied Optics, Volume 8, No. 8, 1969, 1741-1742.

27) Olson, D., Mallard, W., Gardiner, W., "High Temperature Absorbtion of the 3.39 mm He-Ne Laser Line by Small Hydrocarbons," Applied Spectroscopy, Volume 32, No. 5, 1978, 489-493.

28) Brophy, C.M., Sinibaldi, J.O., Netzer, D.W., "Initiator Diffraction Limits in a Pulse Detonation Engine," 15th Office of Naval Research Propulsion Meeting, August 5-7, 2002.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, VA

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, CA

3. Dr. Christopher M. Brophy, Code AA/Br
   Department of Aeronautics and Astronautics
   United States Naval Postgraduate School
   Monterey, CA

4. Dr. Maximilian Platzer
   Chairman, Department of Aeronautics and Astronautics
   United States Naval Postgraduate School
   Monterey, CA

5. Dr. Jose O. Sinibaldi
   Department of Aeronautics and Astronautics
   United States Naval Postgraduate School
   Monterey, CA

6. LT Steven P. Werner
   Norfolk, VA

7. Dr. Gabriel Roy
   Office of Naval Research
   Mechanics Division, Office333
   Arlington, VA

8. Department of Aeronautics and Astronautics
   Code AA
   Naval Postgraduate School
   Monterey, CA