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NAVAL POSTGRADUATE SCHOOL
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THESIS

PRELIMINARY ASSESSMENT OF A ROTARY
DETONATION ENGINE CONCEPT

by

Stephen A. Monks

September 1983

Thesis Advisor: Raymond P. Shreeve

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values of torque produced by the rotor model. Modifications of the instrumentation and torque measurement system are recommended to allow the transient process and resulting torque to be measured in greater detail, a comparison to be made with the results of numerical modeling, and a definitive assessment of the potential of the concept to be concluded.

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Preliminary Assessment of a Rotary Detonation Engine Concept

by

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Captain, United States Army
B.S., United States Military Academy, 1974

Submitted in partial fulfillment of the requirements for the degree of

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from the

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September 1983

ABSTRACT

Results of a preliminary, experimental assessment of a rotary detonation engine concept are reported. Measurements were taken of the torque produced by a stationary rotor model as a result of a single detonation process initiated within the rotor under known premixed gas conditions. Mixtures of ethylene and oxygen and ethylene and oxygen with three moles of nitrogen ballast were utilized. The results represent the lower bound to values of torque produced by the rotor model. Modifications of the instrumentation and torque measurement system are recommended to allow the transient process and resulting torque to be measured in greater detail, a comparison to be made with the results of numerical modeling, and a definitive assessment of the potential of the concept to be concluded.

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I. INTRODUCTION

Detonation as a form of combustion for propulsive devices has been studied for more than twenty-five years. Due to the high propagation velocities of detonation waves, combustion through detonation can be considered to be a constant volume process. In an engine cycle a larger thermal efficiency is obtained with a constant volume than with a constant pressure combustion process. The latter is used in the Brayton Cycle, which is the basis of all present day gas turbine engines. [Ref. 1] Such has not always been the case. In early gas turbines, before efficient mechanical compression methods were developed, alternatives were sought.. One example was Hans Holzwarth's constant volume cycle gas turbine, which remained in production from 1908 to 1928. [Ref. 2]

As advances were made in compressors (both axial and centrifugal), it was possible to develop gas turbine engines based on the Brayton cycle rather than the constant volume cycle. However, the continuing need to improve turbine engine performance has required an increase in the mechanically induced cycle pressure ratio. In the case of the axial flow compressor, as stages are added to increase the pressure, the blades become progressively smaller, and stage losses become large. One alternative to mechanical compression is to supply the compression thermally by detonative combustion. [Ref. 1]

If the pressure rise produced in this manner is sufficient for the engine cycle, no compressor and associated drive turbine are required and a simpler more efficient engine might result. The challenge lies in finding a practical mechanical arrangement for such an engine.

The characteristics of detonataive combustion are advantageous in several ways. Multiple diffusion processes within and around flame fronts govern the rate of combustion of gas mixtures in deflagrative combustion. These processes, associated flame speeds and propagation rates are relatively slow. "Detonation waves are shock waves which are sustained by the energy of the chemical reaction that is initiated by the shock compression," [Ref. 3]. Reducing the combustion time significantly increases the potential thrust production of propulsion devices. Fast combustion also causes less heating of the containing walls per unit of fuel. Thus for a given wall material more fuel per unit time can be burned by detonation than by normal combustion. This leads to the possibility that the power-to-weight ratio might be improved using detonative combustion, [Ref. 4].

Studies over the past two decades have considered the use of detonation waves in several propulsion engines; in a pulse jet; in a hypersonic ramjet; as a steady state process in the divergent part of the exhaust nozzle of a conventional rocket engine; and in the "RDWE" - rotating detonation wave engine, [Ref. 5]. These different configurations were not

successful for different reasons. For example, in the steady state process, the problem of establishing repeatable and efficient fuel mixing was encountered. The rotating detonation wave engine required the maintenance of a detonation wave continuously traversing circumferentially around an annular combustion chamber with the exhaust through an axial nozzle. In attempts thus far there were found to be problems in controlling the direction and number of waves initiated and in maintaining them continuously. Early investigators [Ref. 6] envisioned a device in which detonation occurred in a number of long tubular combustion chambers placed parallel to one another and valved such that fuel could be introduced sequentially. This particular configuration is not well suited to the transmission of axial to rotary motion, nor could the output power be smoothly continuous. The rate of introduction of the new fuel mixture would have to be comparable to the burn rate, requiring extremely high energy and thus reducing the possible efficiency of the device, [Ref. 4].

Recently, a mechanically simple arrangement for an engine which incorporates detonative combustion was proposed by Eidelman, [Ref. 4]. The arrangement combines the advantage of fast detonative combustion, with its high temperatures and pressures, in a rotary configuration, which can generate shaft power without an auxilliary mechanical transmission system. In order that the operation be smooth, a number of

rotor elements were proposed in which filling and firing occurred sequentially, as in a reciprocating internal combustion engine. The present study was undertaken in order to obtain a preliminary assessment of the potential of the concept proposed in Ref. 4. The objective was to measure the torque produced in a stationary rotor model as a result of a single detonation process initiated under known premixed gas conditions. The measurements would serve to determine what level of thrust could be obtained optimally from an engine cycle based on the proposed concept, and whether the transient process could be calculated adequately.

During the study it was found that detonation could not be generated in ethylene and air mixtures. Further testing thus proceeded with ethylene and oxygen mixtures and ethylene and oxygen mixtures with three moles of nitrogen ballast. The model was first operated with straight radial passages and was shown to fire symmetrically. Then, with passages bent to exit peripherally at the rotor rim, in close to 150 firings, torques of thirty-five to two hundred and one foot pounds were developed. However, the measurement system was unable to respond to the time-varying impulse generated in the rotor and therefore comparison with theory was not possible.

Following a brief synopsis of the concept in the next section are descriptions of both the test model and the test system. Included is a summary of the calibration

performed for the torque measurement. A description of straight tube tests and the torque measurements are preceded by an examination of the detonation limits observed for various mixtures of ethylene, oxygen and nitrogen. An analysis of the torque data taken follows in the discussion section. Conclusions are then presented.

II. DESCRIPTION OF THE EXPERIMENT

A. CONCEPT

The key element in Reference 4 was to burn the combustible mixture in a detonation wave propagating from the hub outwards through passages in a rotor, into which the fuel and air had been previously introduced. A torque on the rotor would be generated as a reaction to the nearly tangential expulsion of gases from the rim. A schematic of the detonation rotor concept is shown in Figure 1.

In an engine based on the use of this arrangement, several rotors (10 or more) would be required on a single shaft. The supply of air and fuel would be valved and the detonations fired sequentially to produce a continuous output torque characteristic. The model used in the experiments here was designed to simulate the geometry of one such rotor disc. However, the model was used stationarily, attached to a cylindrical column instrumented for the measurement of torque.

B. TEST MODEL

The test model is shown in Figure 2. Design drawings, showing details of the construction are given in Appendix F. The detonation chamber, centered in the "hub" of the configuration is formed from the junction of the holes drilled to match to internal diameters of the attached exhaust tubes. An opening was provided on one side of the hub for the

introduction of fuel. The fuel opening is shown in Figure 3a capped by a heavy duty gas valve. On the other side of the hub, a second opening accepted the ignition device, a Champion brand FS-89 igniter used in some current production gas turbines. The igniter had a rated spark energy of .84 Joules. Other views of components of the model are given in Figures 3b and 3c.

The model was tested initially with straight exhaust tubes to investigate the degree of symmetry of the firing. Fueling the model constituted filling both the detonation chamber and the exhaust passages. This had a volume of approximately 56 cubic inches. The inside diameter of the exhaust tube diverged in its last one inch of travel toward the exit.

C. TEST SYSTEM

1. General Arrangement

For reasons of safety, the model was tested in an empty turbojet test cell. (Building 216 at NPS; See Figure 4a.) The model could be seen from the test cell control room to which data were transmitted on coaxial cables. Only the data recording devices were placed in the control room. All other instrumentation, including signal conditioning and amplification, vacuum and fuel system controls, were positioned adjacent to the model. A view of the test set-up in the cell is shown in Figure 4b.

2. Fueling System

The fueling process consisted of three steps:

a. Evacuating the entire system

b. Mixing the fuel in the mixing chamber

c. Transferring the fuel to the model and disconnecting the fueling system.

The fueling system delivered one charge of premixed fuel from a mobile dolly unit (See Figure 5a) which was removed from the area prior to firing. Any combination of ethylene, oxygen and nitrogen could be introduced and metered using partial pressures. The vacuum pump used to evacuate the system prior to fueling also rode on the dolly.

Figure 5b shows a close-up view of the fueling system. There are several features to be noted. Mixture components entered separately from the right via valves 1, 2, and 3, entering the horizontally mounted cylindrical mixing chamber through valve 5. Two pressure gages were provided. The one on the left in Fig. 5b indicated the model chamber pressure. Mixing chamber pressure was indicated on the right. Both gages indicated in terms of absolute pressures with a range of zero to thirty psia. The mixed fuel charge exited to the model via valve six and the nylon tubing shown at the top left of the photograph. Evacuation or purging was accomplished either simultaneously or separately on the mixing chamber side and/or the model side of the system. Valve number eight isolated the vacuum pump from the

system. Details of the fueling procedure can be found at Appendix C. The regulators used with both the oxygen and ethylene had second stage regulation in the low pressure range suited to this study (i.e., 0-30 psia). On the model there were two fuel system components. Figure 6 shows the heavy duty valve on the model which isolated the detonation chamber from the low pressure fuel system components. The valve connected with the dolly unit via the nylon tubing. Figure 7 shows the method used to seal the ends of the rotor passages (tubes) prior to evacuating the system. The metal clamp holding the rubber seals in place was fastened to the exhaust tube with an elastic band. Once the system was evacuated, the clamps were moved aside to allow unobstructed ejection of the seal upon firing.

Prior to testing, the fuel system was checked for leaks by evacuating and watching the rise in pressure over a period of time. It was considered ready for use when negligible loss was seen over a twenty-four hour period.

3. Ignition System

A schematic of the ignition system is shown in Figure 8. When both switches were closed, the igniter fired after the exciter became fully charged. Series switches were provided in the test cell and in the control room. A view of the igniter is given in Figure 3b. Figure 9 shows the components of the ignition system.

4. Torque Measurement

A schematic of the torque and bending measurement system is shown in Figure 10. The system was designed to measure two in-plane components of bending, and the torque. Each of the measurements corresponded to a single channel processed through the signal conditioning unit. Since only one amplifier with sufficient frequency response was available, the three channels could not be recorded concurrently.

Strain gages were mounted on the torque tube as shown in Figures 11a and 11b. Torque was measured by the angled gages of the rosettes and each component of bending was measured by combinations of the opposing pairs of gages mounted nearest the base. The design of the torque tube is described at Appendix D. The gages were incorporated into wheatstone bridges using the signal conditioning unit shown in the middle of Figure 12. On the left in Figure 12 is shown the D.C. voltage source used for the excitation of the bridges. On the right is the amplifier and associated power supply used to provide a signal gain of X1000. At this level of gain the rated frequency response was 40000Hz. Figures 13 and 14 show the oscilloscope, waveform recorder and X-Y plotter used in the testing. The oscilloscope was used mainly as a diagnostic tool while the recorder and plotter were used for data collection.

5. Torque Calibration

The apparatus used to calibrate the torque tube is shown at Figure 15. The two baskets that extended from the torque arm were loaded with known weights producing a symmetric torque loading of the torque tube. The output in volts was recorded on a digital voltmeter. This was done for a range of torque of 0 to 351 ft-lbf. A curve fit to this data produced the equation of the line y = 1.5442 + 19.9862x where x is the voltage reading and y is the corresponding torque in foot pounds.

Subsequent to the mechanical calibration, the X-Y plotter was calibrated with respect to the incoming signal. Sine waves of various known amplitudes were transmitted to the X-Y plotter. One centimeter vertical excursion on the plotter corresponded to .9571 volts.

A one millisecond and a ten millisecond calibration signal were plotted on the X-Y plotter indicating a time of 3.363 milliseconds per centimeter in the single channel record mode. Recording two channels halved the time scale to 1.681 milliseconds per centimeter.

III. EXPERIMENTAL PROGRAM AND RESULTS

A. EXAMINATION OF DETONATION LIMITS

1. Detonation Confirmation

Several firings, at various ethylene/oxygen mixture ratios, were conducted as shown below, to prove that detonation rather than combustion was occurring.

Run No.	Mole Fraction of Ethylene	Model Pressure (psi)
10	.2732	12.5
11	.3279	12.0
12	.5556	12.0
13	.4444	12.0
14	.5000	12.0
15	.5556	12.0
16	.5000	12.0

Both runs number 12 and 15 exhibited combustion rather than detonation. Certain observations helped confirm the occurrence of detonation. For example, rubber stoppers were used to seal the ends of the exhaust tubes while evacuating the model. They became firmly implanted under the effect of the vacuum. After filling and firing, when combustion rather than detonation occurred, some of the stoppers would remain in place. Also, the appearance of the flame was observed to change as the mixture was made richer. At stoichiometric, and some slightly richer mixtures, white, sharp and distinct flames were seen to leave the exhaust tubes. Those seen when combustion occurred were orange in color and much less sharp or distinct. Most obviously

however, the noise of the detonation process clearly contrasted with that generated by the combustion process. The former was extremely loud and sharp while the latter sounded almost muffled and distinctly not "sharp."

According to Lee [Ref. 7], the upper limit for detonation in terms of mole fraction of ethylene is .48. The experiment showed detonation to occur at a mole fraction of .5 but no higher. It should be noted however that in fueling the model it was generally possible to evacuate only to .6 psi. Hence the fuel mixtures introduced and fired were actually slightly leaner than the quoted values, which were calculated assuming an initial perfect vacuum. This might explain the slightly higher limit reached.

2. Lead Foil Impression Test

Schelkin and Troshin [Ref. 8] showed that the distinguishing feature of a detonation could be "recorded" by allowing the wave to run to the end of a tube whose end wall was covered with lead foil. The lead foil was found to deform to show the different characteristics of the wave front. Specifically, the foil showed that the detonation front was not perfectly flat, but rather had a three-dimensional cellular structure, where the elementary component of the wave was a triple wave intersection. When the complex wave front struck the foil, the deformation of the foil was larger at the triple points of the detonation front, and the trace of the wave front was recorded on the foil.

Following Ref. 8, lead foil of approximately .001 of an inch in thickness was placed at the end of one tube of the rotor model in an attempt to force a display on the foil of the features of the detonation wave front. Several mounting methods were used as shown in Figures 16a, b, c and d. First, the foil was placed on the exhaust tube side of a rubber stopper. This was then varied by sandwiching a small amount of putty between the foil and the stopper to allow more deformation of the foil. Then the foil was placed on an aluminum slug again trying with and without a putty cushion. In this case the aluminum slug served to seal the tube. Differing model pressures (8.0-13.5 psi) were used, but none of the attempts yielded a deformed foil.

Two factors may have influenced the results. The lead foil was used shortly after having been flattened using a steel roller. At that point the lead may have been work hardened to the point where the force of the detonation wave would not significantly affect it. Had enough time elapsed between the flattening and the use, the foil could have had a chance to recover to the point where it again could be easily deformed. Secondly, in all cases the foil was ejected along with the stopper. Had the foil and stopper been held firmly in place, an impression may have been obtained. In two cases this was attempted by taping the aluminum slugs to the exhaust tubes with long strips of heavy duty fabric backed tape. This arrangement failed in both cases and the slug sheared through the tape.

3. Detonation of Ethylene and Air

Several attempts were made to initiate detonation with an ethylene air mixture and all were unsuccessful. A schedule of these tests is shown below. Model pressure was fourteen psi.

Run No.	Mole Fraction of Ethylene	Result
29	.0654	Weak combustion
30	.0732	No ignition
31	.0732	Weak combustion
32	.0832	No ignition
33	.0832	Weak combustion
34	.0832	No ignition
35	.1332	No ignition
36	.1332	No ignition
37	.0654	Weak combustion

The "air" used was mixed from the bottled supplies of oxygen and nitrogen. Fuel mixtures attempted ranged from stoichiometric to just under the rich detonation limit according to Borisov and Loban, [Ref. 9]. Those tests fueled to stoichiometric or just slightly richer resulted in either a very weak combustion or no ignition at all. Some consideration was given to the possibility of incomplete mixing and/or the proper mixture not reaching the model due to the mixing chamber and fuel system piping geometries. The order of partial pressure mixing was therefore changed. Initial mixings were performed in the order oxygen, nitrogen and then ethylene. Subsequent to the change, an ethylene, oxygen, nitrogen order was adopted. The change of order did not affect the results. Neither did allowing more time for mixing to occur affect the results. Subsequently, the

order of fuel mixing was kept as ethylene, oxygen, and nitrogen and the model pressure used was always 14 psi.

It was concluded that in order to produce detonations with an ethylene-air mixture either a higher model pressure or a stronger initiating spark, or both, would be required. It should be noted that the rotor passage inside diameter was close to the critical diameter below which detonation could not be initiated. [Ref. 10]

4. Detonation of Ethylene, Oxygen and Nitrogen

The ethylene-air mixture would of course be the most practical combination for an engine. However, the equipment available did not allow further study with that mixture. Instead, a series of tests were conducted to examine the limits of detonation using a stoichiometric ethylene oxygen mixture with nitrogen ballast. Firings were made using ballasts of three, four, and finally six moles of nitrogen. The former two were clearly detonations but the test at six moles of nitrogen ballast showed borderline results. It was at best a weak detonation and most probably a strong combustion in most of seven tests made with six moles of nitrogen ballast.

B. STRAIGHT TUBE TESTS

It was necessary to fire the model prior to the exhaust tubes being bent, to verify the absence of asymmetric firing. This would ensure that any abnormalities indicated

subsequently in the recording of torque were not the result of asymmetric firing.

The bending measurement system was designed so that two channels would measure two respective components of whatever bending force was present, giving, through calibration, both the direction and the magnitude of the resultant force. Since only one amplifier of sufficient response was available, only one component of bending could be measured at a time. Examination of asymmetric bending was thus attacked using a controlled experimental approach. First, one exhaust tube, which was approximately aligned with the set of strain gages constituting one bending channel, was removed. This was to force a known asymmetric firing and establish a measurement reference. Second, a reference was established similarly for the other bending channel. Third, an exhaust tube mounted perpendicular to the plane in which the gages would indicate bending was removed. Several firings were conducted in each of these three configurations. Then several more firings were conducted with all ten exhaust tubes in place, recording both bending channels, but at separate times. The bending measurements with all ten tubes were then compared with the data obtained with the three asymmetric configurations.

A representative example of the data taken from the first bending channel with one tube removed is shown in Figure 17. Of interest in Figure 17 is the first excursion

of the gage output from the steady state initial portion of the curve. (The slight oscillation seen in this steady state portion was found to be a residual sixty cycle noise signal from the power supply.) On the average, the excursion extended .93 cm on the ordinate, corresponding to a bending force of 5.8 pounds. In comparison, as seen in Figure 18, when the first channel was recorded with all ten exhaust tubes in place, only negligible excursions occurred. Two samples were measured by the first bending channel in the configuration and the results were consistent with one another.

Five samples were taken of the response of the second bending channel to the removal of an exhaust tube aligned with the second channel gages. Again, the results were consistent from test to test. A sample of the data is shown in Figure 19. Here, the average excursion was .85 cm, corresponding to a bending force of 5.3 pounds. The slight difference between the two channels was attributed to the fact that the exhaust tubes which were removed were not exactly aligned with the sets of gages. The Biomation Waveform Recorder used to record and store the signal from the gages offered the capability of playing back the stored signal to the X-Y plotter at various speeds. This feature was used to obtain the data traces seen in Figure 19. Note that there are two traces of the same recorded event here. One was made at the playback speed used in Figures 17 and

18. The other, superimposed, was made at the slowest possible playback speed, and shows more detailed resolution of the signal. The added resolution did assist in fixing precisely when the signal began to rise. However, the slight aberrations of the signal waveform shown by the greater resolution were thought to represent the excited higher frequency harmonics of the tube and hence provided no further information on the magnitude of the bending force. With all ten exhaust tubes in place, negligible bending force was measured consistently in five recordings. A sample is shown in Figure 20. This test confirmed the results shown with the first bending channel.

After removing an exhaust tube perpendicular to the alignment of the strain gage bending system, it was expected that negligible signal would be produced, similar to the tests with all ten tubes. For eight out of nine trials the signal was verified to be initially negligible as seen in the two samples shown in Figure 21. It was noted that in most cases with this configuration, although negligible bending was indicated initially in the time trace, the signal eventually increased. Hence when bending was present about some axis, even if not initially oriented with the gages being recorded, it eventually generated a bending signal, probably as a result of an asymmetric mode of oscillation caused by the removal of the tube. The one exception to full consistency in the last series of nine

tests is shown in Figure 22. In this anomalous case, an initial excursion was recorded which was less than half the magnitude of that shown in the case where the gages and the removed exhaust tube were aligned.

The sum of all observations led to the conclusion that the firing was symmetric in the model.

C. TORQUE MEASUREMENT

Torque measurements were first made with ethylene and oxygen mixtures. One hundred firings were made with mixtures varying from just below the lean detonation limit to just above the rich detonation limit. Combustion was observed on either side of these limits. For all firings the model pressure was 14 psi. The maximum value of torque measured by the torque tube during these tests is shown in Figure 23.

Subsequently, twenty-three firings were made with an ethylene, oxygen and nitrogen mixture. Three moles of nitrogen served as a ballast gas and the amounts of ethylene and oxygen were varied between the lean and rich limits of detonation. The torques produced in these firings are shown plotted in Figure 24.

IV. DISCUSSION

A. INTERPRETATION OF TORQUE MEASUREMENTS

A sample of the data taken in measuring the torque is shown in Figure 25. The recording device was set to trigger on the torque signal and capture the signal for a preset amount of time before and after the trigger point. In this figure the initial steady state signal is shown with some slight disturbances that were determined to be a sixty cycle signal from the voltage source used with the instrumentation. The first large negative spike indicates the spark of the igniter. Following this is a length of time until the torque signal is displayed. This time interval varied with the fuel mixture as shown in Figures 26 and 27. In all of the data taken the rest of the graph had the same characteristics. Three distinct peaks were displayed that repeated in an oscillating manner between positive and negative values. The natural frequency of the torque tube and detonation engine system was checked by unloading it rapidly and recording the signal of the resulting harmonic oscillation, [Ref. 11]. It had the same period as the fundamental frequency of the curves of the data taken. A record of several firing events was made using a longer recording time, showing clearly that this system acted as an undamped harmonic oscillator. An example is shown in

Figure 28. The three peaks per half wave in Figure 25 show that several different frequencies of vibration were excited in the engine and torque tube system by the impulse loading of the detonation event. In this case the first three harmonics appear. The longer and thinner torque tube demonstrated a similar harmonic oscillation (see Figure 29), but here the first four harmonics were excited. Tests at lower model pressures yielded the same charactristic curves.

To better understand the sequence of events during the time interval between the igniter spark and the rise of the torque curve, two other tests were conducted. A strand of thin wire carrying an input signal to the recording device was placed over an exhaust tube end so as to be broken when the rubber seal was ejected during the detonation. This showed the break to occur at various locations on the time axis between the igniter spark and the torque curve depending on the fuel mixture used. Also, piezoelectric transducer was mounted on one of the exhaust tubes close to the end with the sensor portion flush with the inside wall. This was done to confirm the previous time measurement and to get an idea of the time that the impulse occurred. The transducer indication came earlier than the wire break as shown in Figure 30. This could be explained by the fact that the transducer was three inches from the end of the tube, and the dynamics of the breaking wire were unknown.

The amount of stretch the wire experienced prior to breaking would have affected the time plot. Further tests were made with the transducer. Samples are shown in Figures 31a, b, and c. Sufficient data was not taken to reach a definitive conclusion but the general trend was clear. As the time between the igniter spike and the rise of the torque curve increased, so did the time between the igniter spike and the transducer spike. This is seen by comparing Figures 31a and b. Physically the time interval from the igniter spark to the transducer indication accounts for the combustion initiation, the transformation from deflagration to detonation and the traverse time of the detonation wave through the tube. It would be expected that the torque production would start as the wave and gases moving along the tube begin to turn tangentially. Identification of the exact impulse time using the transducer trace was not possible because of inconsistencies in the data. The initial peak would always occur signaling the passage of the detonation wave, as shown in Figure 31a. But, at times, two peaks or a more gradual reduction of signal would be present. See Figures 31b and 31c. Theoretical calculations (see Appendix A) based on the assumption of maximum mass flow rate would indicate an impulse time of .82 milliseconds for a stoichiometric mixture of ethylene and oxygen. This closely coincided with the time seen in Figure 31a between the first transducer indication and the signal from the torque tube

transducer. Similar calculations for a stoichiometric mixture of ethylene, oxygen and nitrogen gave an impulse time of .91 milliseconds. Again, that time closely coincided with that shown in Figure 31c. However, the coincidence shown in the theoretical and experimental times shown here should not be taken as prima facie evidence that what was observed was the impulse time. If it was assumed that the flow was choked, then the impulse time would increase, extending perhaps past the point where the torque signal first appeared. The time past the first transducer indication to the torque signal rise includes at least some portion of the time of the impulse and the time it takes the torque measurement system to respond. It appears that from mixture to mixture this time varied very little whereas the time of the combustion initiation, the formation of the detonation and the wave traverse time are very much influenced by the mixture. Hence, probably the time was governed by the response of the system. It can be shown that "impacts as long as ¼ cycle can be treated as sudden impacts with as little as 10% error." [Ref. 12] This further supports the premise that the time from the first transducer indication to the torque curve rise, merely represents the time of response of the system to a rapidly applied load of unknown duration.

From this analysis, it was concluded that the recorded signal of torque was actually the harmonic response of the

torque tube and rotor model system to a rapidly applied (impulse) load. Since the measurement system was unable to respond in time to the impulse generated in the rotor, and since the system appeared virtually undamped far past the time interval of interest, the peak of the recorded signal was taken to indicate the lower bound of the maximum value of the torque produced. This interpretation acknowledged that some portion of the converted energy was lost in exciting the system into the vibratory motion which was seen to include a fundamental and higher harmonics. For the purposes of evaluating the effect of mixture, the peak value was used, and is referred to in the following paragraph as simply "the torque."

B. EFFECT OF MIXTURE ON TORQUE RESULTS

For the ethylene and oxygen mixtures, (See Figure 23), as the mixture was enriched from the lean limit the torque increased smoothly. However, as the mixture was enriched past a point of peak torque production, torque measurements repeated for particular mixtures were not as consistent. The resulting torque was very sensitive to the mixture introduced into the model. Slight variations in mixing the fuel, in reading the gages, or in allowing different times for the fuel components to mix, significantly affected the output torque. Therefore, several firings were made at each fuel mixture in this range to obtain a valid average value of torque.

From the lean end of the spectrum of mixtures, the torque increased quickly to a level of about 155 foot pounds with only slight increases in the amount of ethylene in the mixture. From that point the torque increased gradually with increasing ethylene content to the peak measured value. Past that point the torque dropped quickly with only slight enrichment of the mixture.

The detonation limit on the lean side was somewhat lower than that proposed by Lee for an ethylene/oxygen mixture. Whereas Lee suggested a lower limit with 15% ethylene, detonation was observed with as little as 10% ethylene in the present experiments. This could have been due to the influence of a slight amount of nitrogen in the mixture and the use of a different ignition system.

Figure 24 shows the torque measured for ethylene, oxygen and nitrogen mixtures. Noticeably different in comparison with Figure 23, is the much narrower range of fuel mixtures over which detonation was possible. As the fuel mixture was enriched from the lean side, the torque magnitude increased relatively rapidly with small increases in fuel. It dropped at a similar rate past the peak value of torque. It was noted that with these mixtures, enrichment past the point corresponding to the maximum torque did not bring with it inconsistent readings as before. There was not the sensitivity experienced with the ethylene and oxygen mixtures. With both the ethylene and oxygen, and the ethylene, oxygen

and nitrogen mixtures, the peak torque was reached with a rich mixture close to the rich limit for detonation, as expected. [Ref. 13]

The time between the ignition spark and the initial rise in the torque signal showed an interesting correlation with the change in torque magnitude as the fuel mixture was varied. In the case of the ethylene and oxygen mixtures, (See Figures 23 and 26), it decreased from the lean side to a plateau and then increased with fuel enrichment as the rich limit was approached. The plateau is seen to be centered on the rich side of stoichiometric mixture.

In general as the time between igniter and torque rise decreased, the torque increased. But, as noted, a plateau of nearly constant minimum time was reached. Further, this general trend did not follow near the rich limit where the times increased as the torque increased until the torque peak was reached. Maximum detonation velocities are expected close to the rich limit because of the product molecular weight. [Ref. 13] The time curve appears to be representing the inverse of the burn velocity in the combustion prior to the detonation since the center of the plateau of minimum time is seen to occur just on the rich side of the stoichiometric mixture.

In the case of the ethylene, oxygen and nitrogen mixtures, (see Figures 24 and 27), the minimum time between the igniter spark and the torque signal is seen to coincide with

the mixture for maximum torque, somewhat farther to the rich side of stoichiometric than expected. It is suspected that the nitrogen ballast was actually impeding the combustion process in this case, causing the shift of the plateau to the rich side.

C. COMPARISON WITH THEORY

Approximate theoretical calculations of the torque were made for three fuel mixtures to compare with the measured values. The stoichiometric mixtures of both the ethylene, oxygen and nitrogen combinations were evaluated as well as one lean mixture of ethylene, oxygen and nitrogen. A sample calculation is shown in Appendix A. The results were as follows:

Torque (foot pounds)

	Measured	Theoretical
C_2H_4 and O_2 stoichiometric	161.68	1477.5
C_2H_4, O_2, and N_2 stoichiometric	81.67	1181.97
C_2H_4, O_2, and N_2 Lean mixture ($X_{C_2H_4} = .1229$)	42.45	1073.54

The reasons for the large differences between the measured and approximate theoretical values were twofold. First, the mathematical model used was highly simplified, and did

not account for all the chemical kinetic and fluid dynamic characteristics of the process. If it was assumed in the calculations that the maximum flow rate was not achieved due to choking, to losses, and other interactions, and that concurrently the velocity of the product gases was lower than the sonic velocity, the theoretical torque magnitude would drop radically. For example, taking three quarters of the maximum mass flow rate and of the sonic velocity, the torque calculated for the ethylene and oxygen stoichiometric mixture was only one hundred ninety-nine foot pounds, significantly closer to the measured value.

The second reason was the particular measurement of torque, which was, in fact, the maximum value recorded by a measurement system unable to respond to the applied torque in real time. The maximum recorded torque would inevitably be less than the peak transient torque by an unknown dissipation within the mechanical system.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Based on the results of the preliminary assessment of the potential of the concept proposed in reference 4, the following conclusions were drawn:

1. The present configuration would not support detonation in ethylene and air. This was due to the relatively low spark energy available and the fact that the exhaust tube diameters were close to the critical diameter reported to be needed for detonation.

2. Detonation was achieved successfully with ethylene and oxygen mixtures, and ethylene oxygen mixtures with up to three moles of nitrogen ballast. The detonation limits observed compared favorably with other reported results.

3. Firing occurred symmetrically in the model.

4. The torque measured ranged from thirty-five to two hundred and one foot pounds.

5. The measurement of the torque was based on the recording of the harmonic response of the torque tube transducer and model system to an impulsive load. An undetermined amount of energy was transmitted into the vibration of the system. Neither the impulse time nor the time of response of the measurement system was determined. The magnitudes of torque quoted represent lower bounds to the maximum torque produced during the event.

6. Comparison with theory was limited to the use of a simplified mathematical model. A detailed comparison was not possible because the impulse time, system response time and the energy of the torque tube vibrations were not determined.

7. The potential of the detonation rotor concept could not be concluded from the data taken to date.

B. RECOMMENDATIONS

1. Further steps should be taken to establish the potential of the concept.

2. A different torque measurement system should be designed to overcome the limitations inherent in the mechanical measurement system used here.

3. Measurement of the pressures at various locations in the rotor passage would give a better understanding of the detonation process and allow comparison with more accurate mathematical modelling. This could be accomplished by placing Kulite transducers along the length of a rotor passage.

4. A higher energy ignition source should be used to investigate the more practical application of ethylene and air mixtures.

5. Thought should be given to the mechanics of introducing fuel (valving), and repetitive ignition in a practical rotor since these two items will be key to a

successful engine development once the torque production is verified.

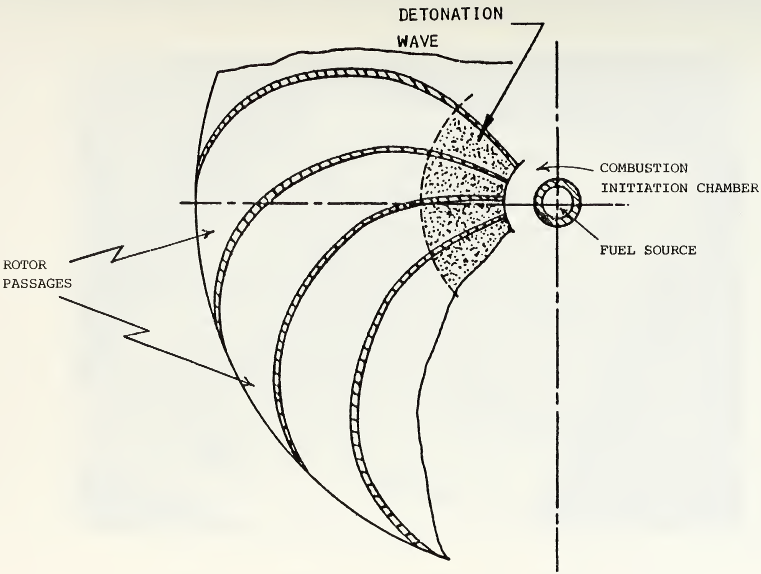


Figure 1. Schematic of Detonation Rotor Concept. A section cutaway of a portion of the rotor is shown.

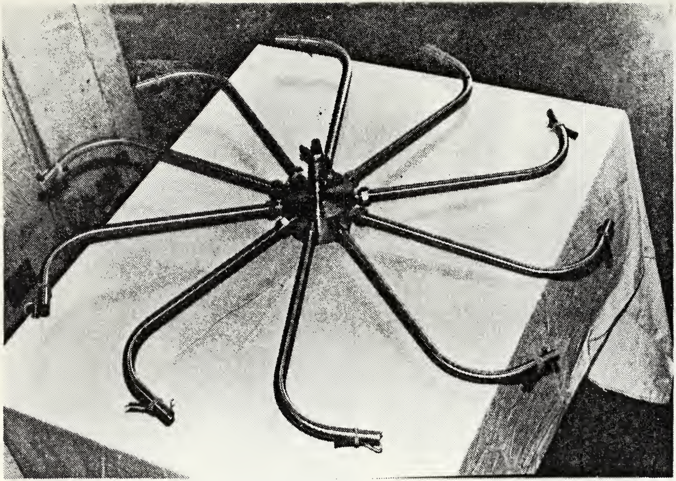


Figure 2. Detonation Engine Rotor Model

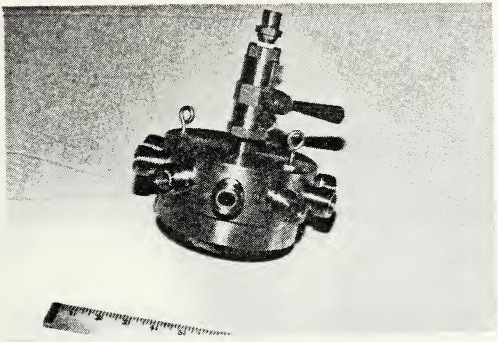


Figure 3a. Rotor Hub with Fuel Valve

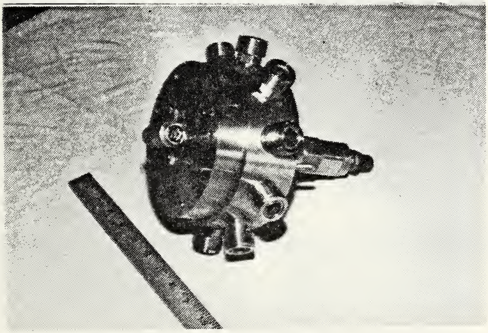


Figure 3b. Igniter Placement on Rotor Hub

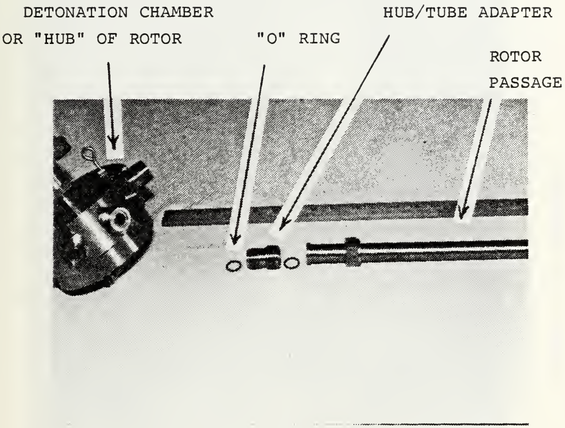


Figure 3c. Hub, Adapter, and Exhaust Tube Interface

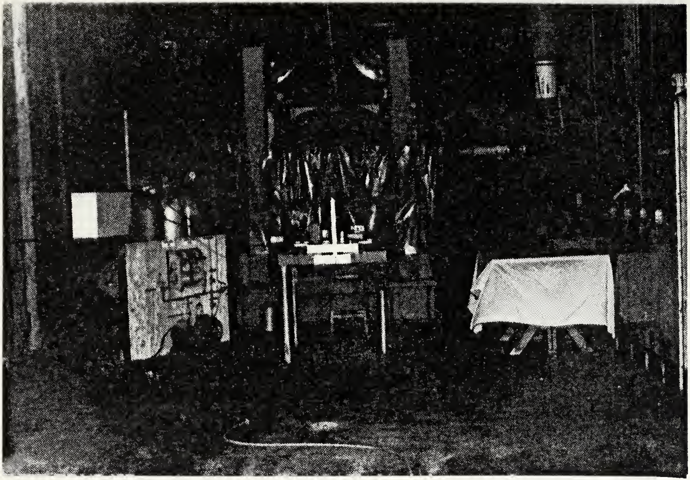


Figure 4a. Test Cell

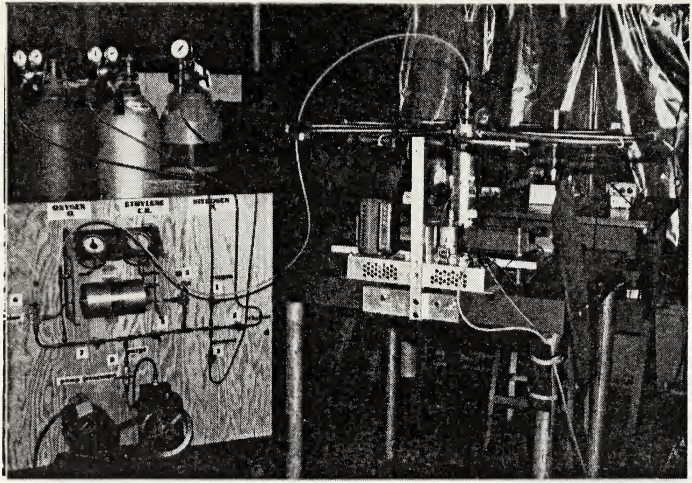


Figure 4b. Test Cell Set-Up

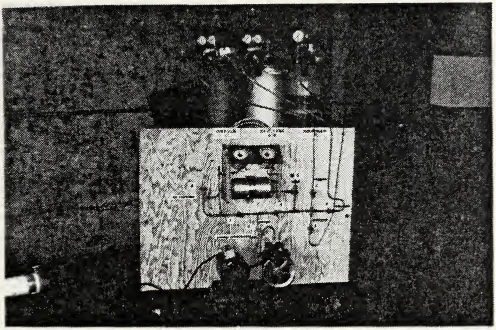


Figure 5a. Fuel Dolly

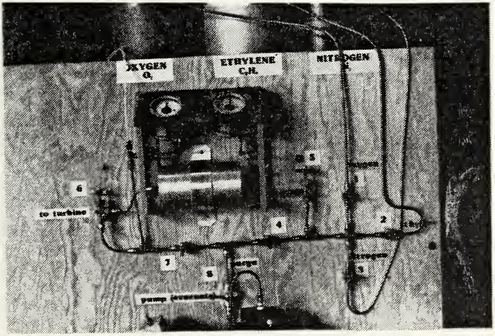


Figure 5b. Fuel Mixing Apparatus

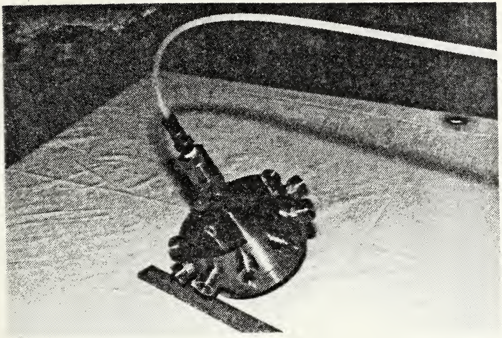


Figure 6. Fuel Connection to Model

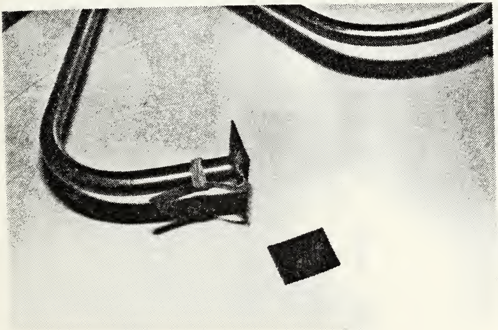


Figure 7. Rotor Passage Seal

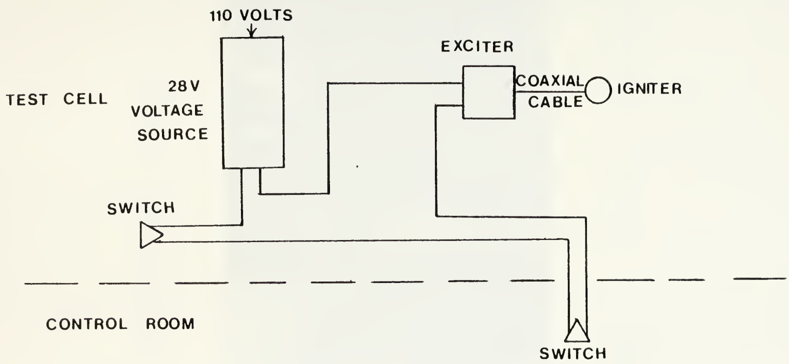


Figure 8. Schematic of Ignition System

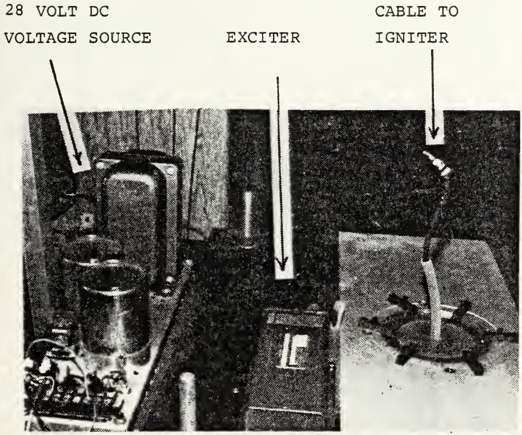


Figure 9. Ignition System

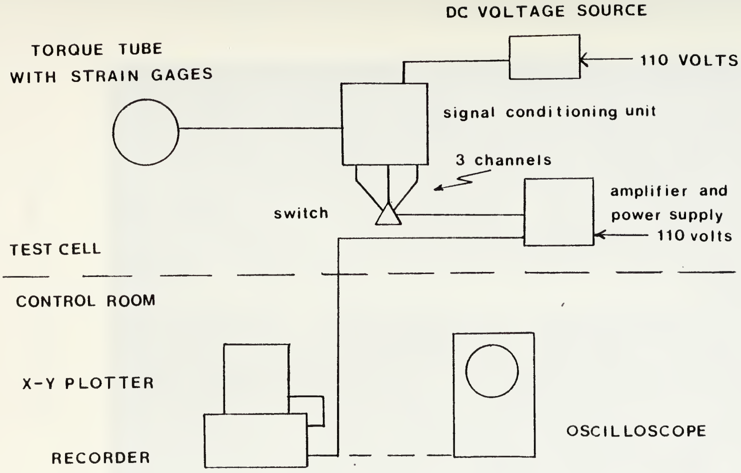


Figure 10. Schematic of Measurement System

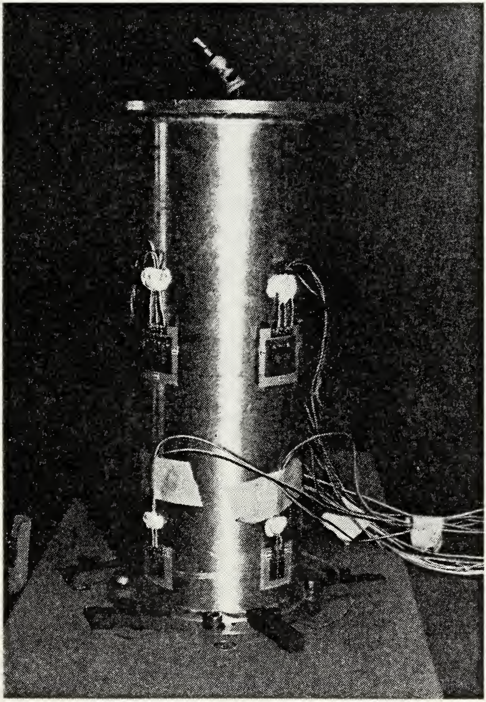


Figure 11a. Torque Tube

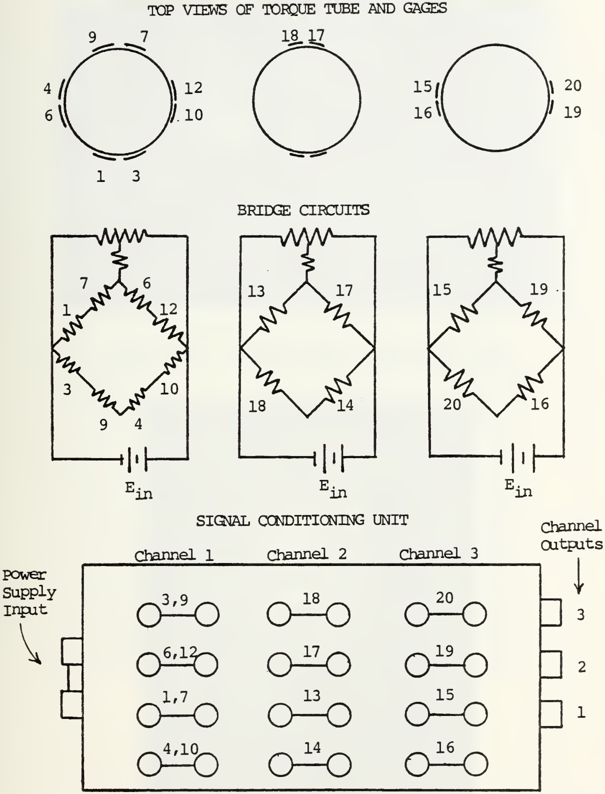


Figure 11b. Gage Placement and Bridge Circuits

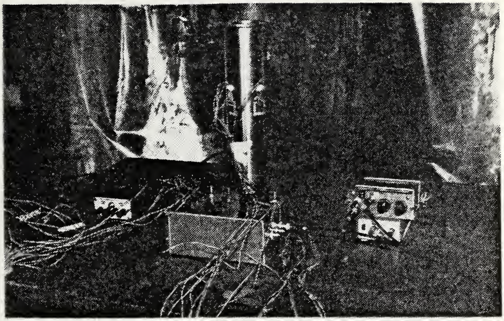


Figure 12. Strain Gage Instrumentation

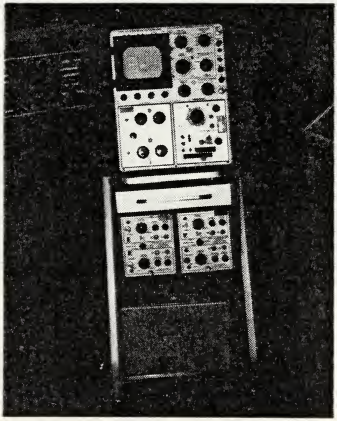


Figure 13. Oscilloscope

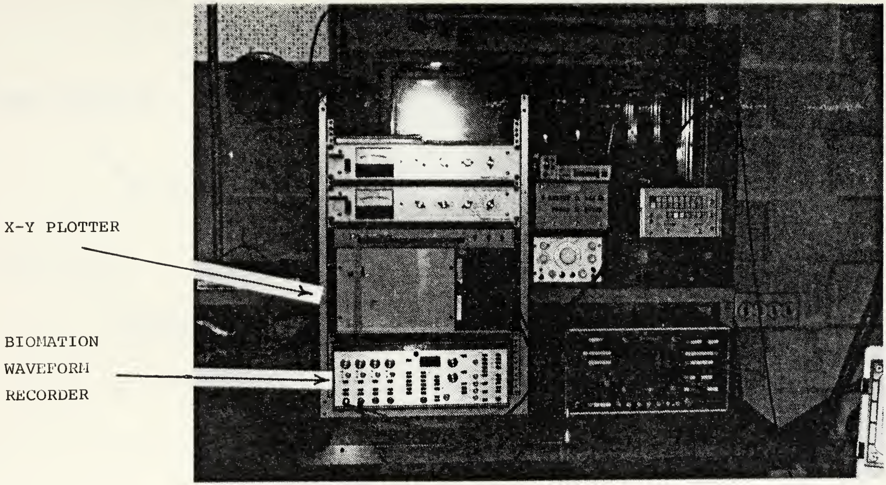


Figure 14. Biomation Waveform Recorder and X-Y Plotter

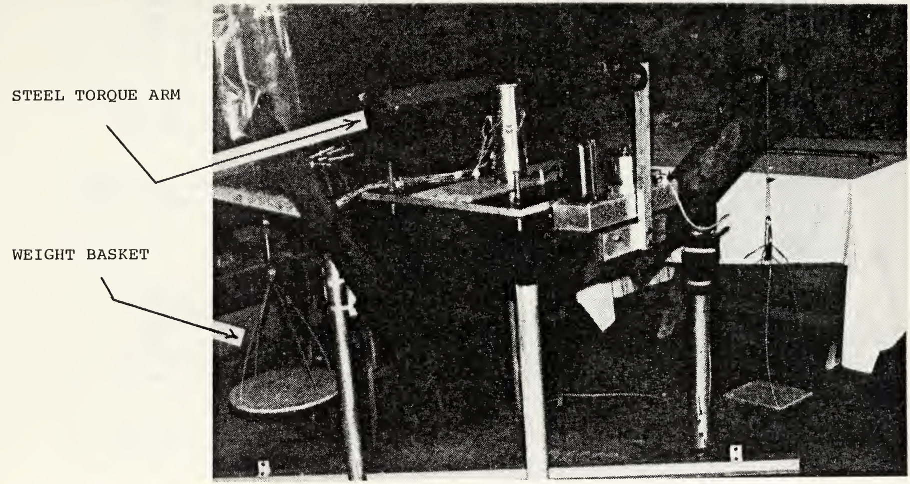


Figure 15. Torque Calibration Apparatus

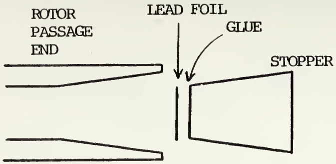


Figure 16a. Lead Foil Placement on Rubber Stopper

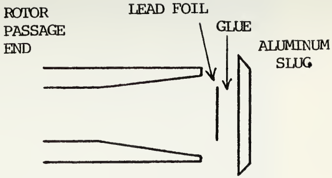


Figure 16c. Lead Foil Placement on Aluminum Disc

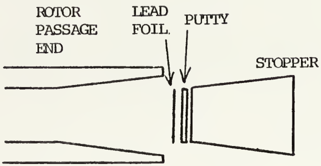


Figure 16b. Lead Foil Placement on Rubber Stopper with Putty

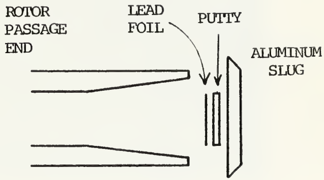


Figure 16d. Lead Foil Placement on Aluminum Disc with Putty

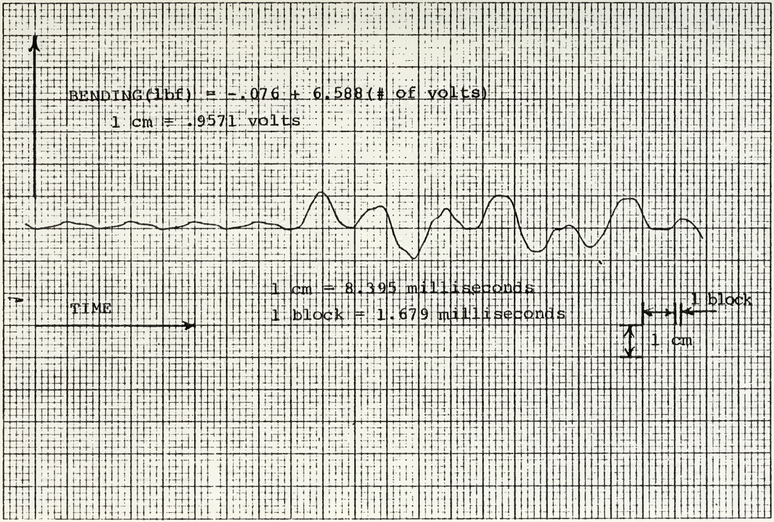


Figure 17. Bending Force Indication; Channel 1, One Rotor Passage Removed

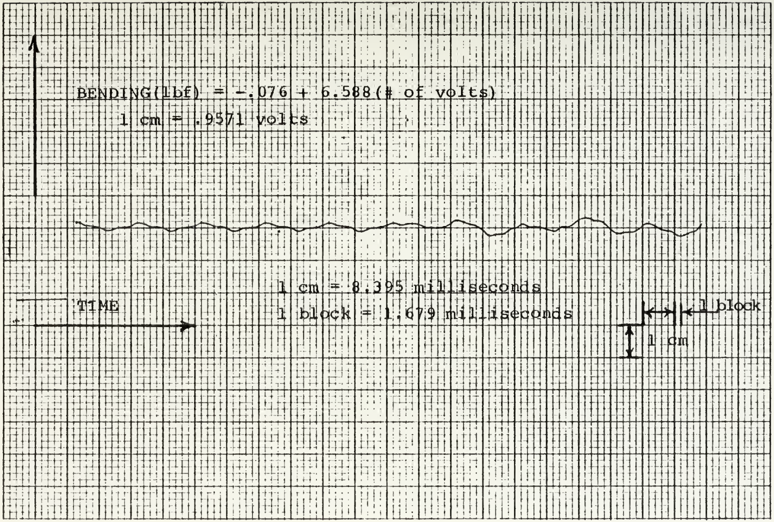


Figure 18. Bending Force Indication; Channel 1, All Passages in Place

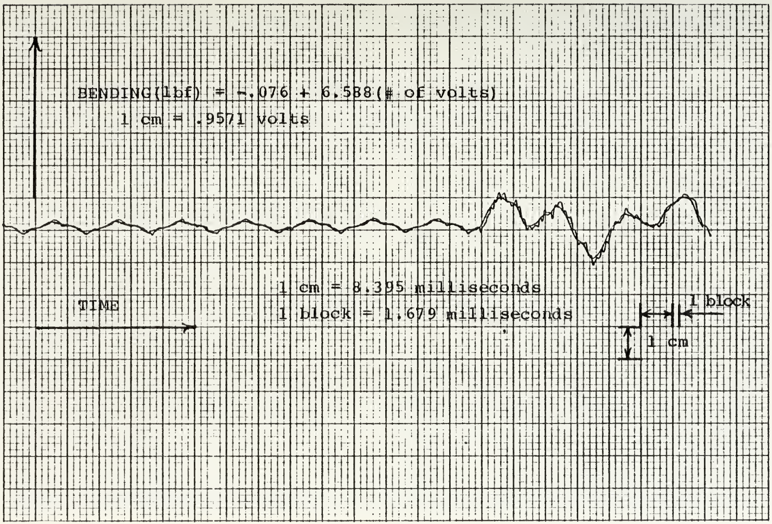


Figure 19. Bending Force Indication; Channel 2, One Rotor Passage Removed

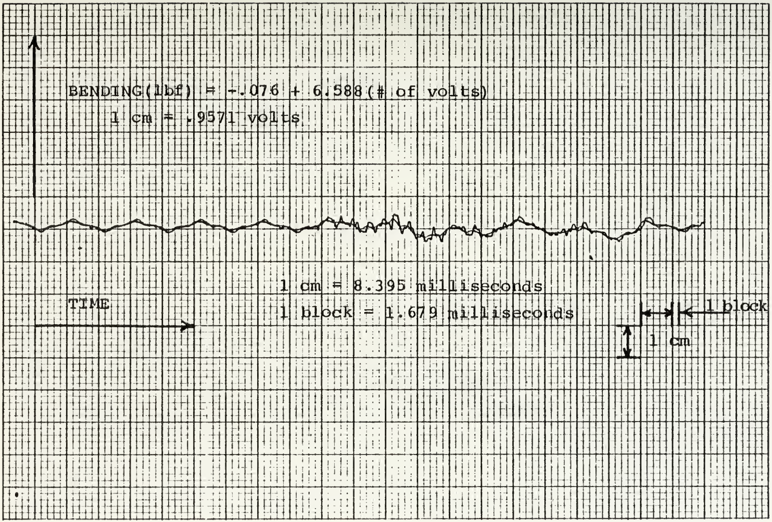


Figure 20. Bending Force Indication; Channel 2, All Passages in Place

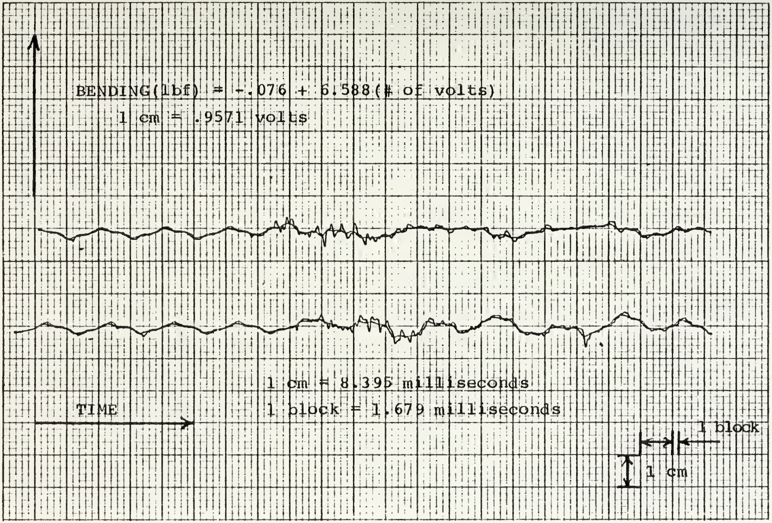


Figure 21. Bending Force Indication; Channel 2, One Rotor Passage Removed Perpendicular to Gage Alignment

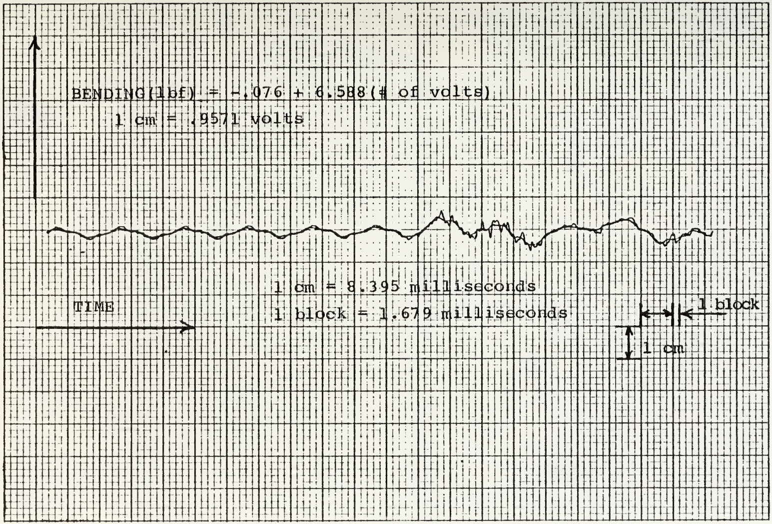


Figure 22. Bending Force Indication; Channel 2, One Rotor Passage Removed Perpendicular to Gage Alignment: Largest Reading

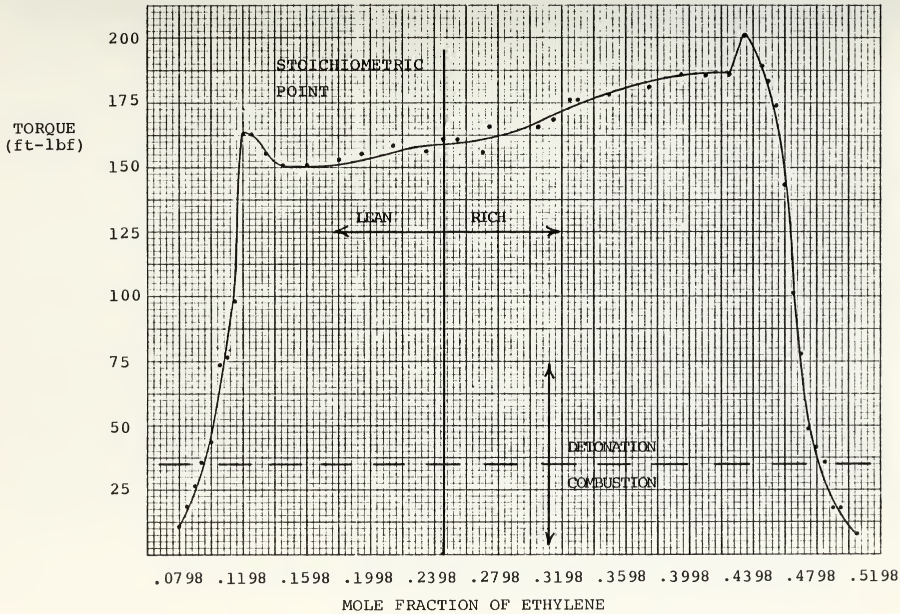


Figure 23. Torque vs. Mole Fraction; Ethylene and Oxygen Mixtures

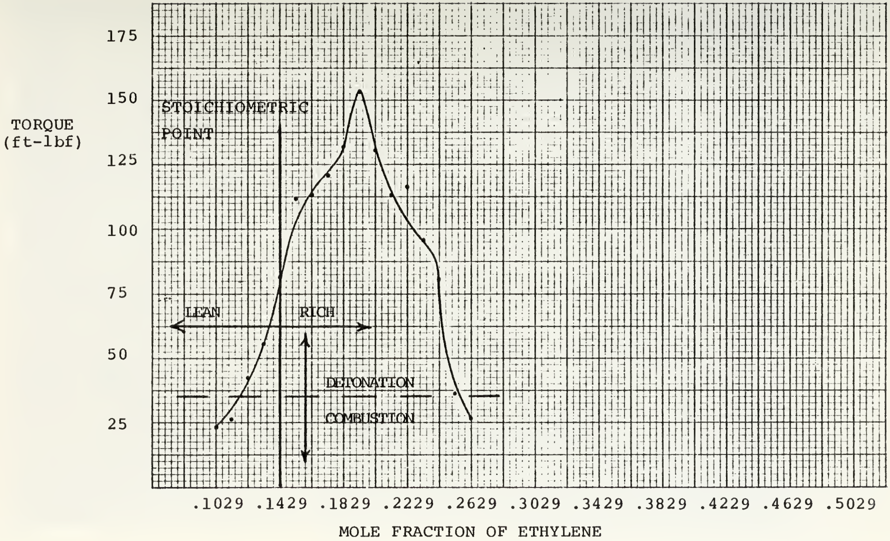


Figure 24. Torque vs. Mole Fraction; Ethylene, Oxygen and Nitrogen Mixtures

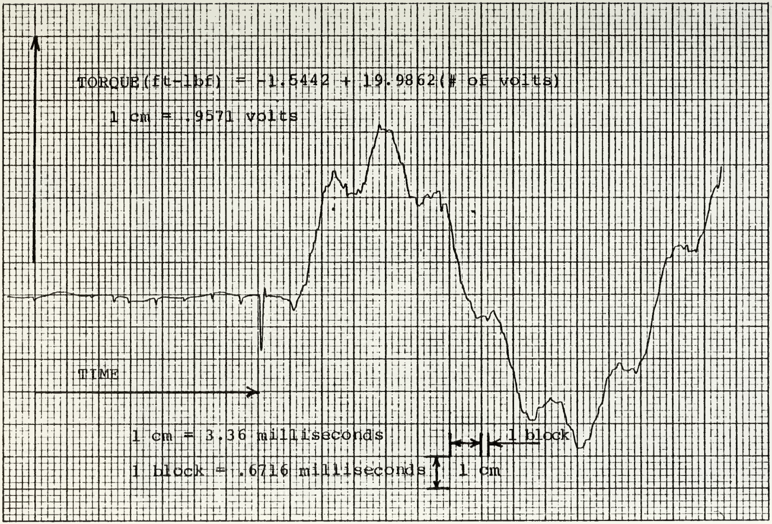


Figure 25. Torque Data Sample

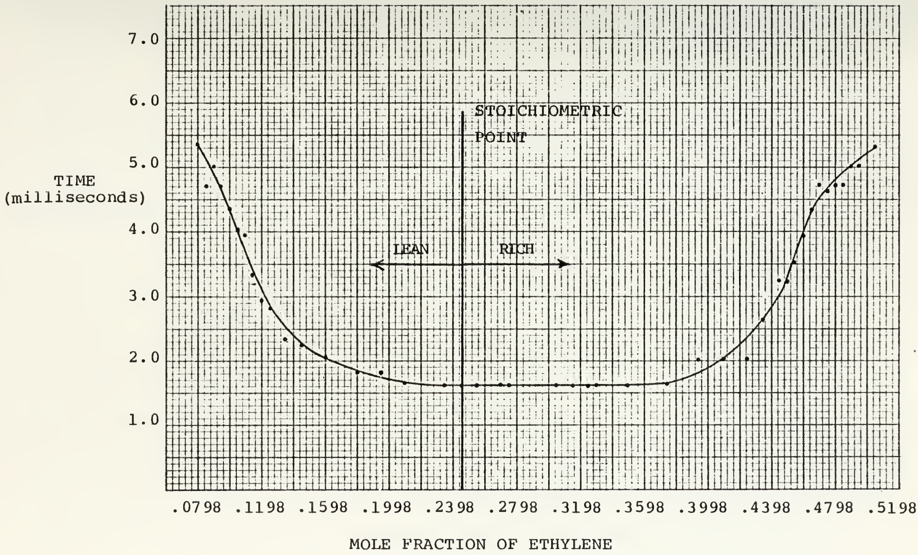


Figure 26. Time of Event Through Rotor Passage;
Ethylene and Oxygen Mixtures

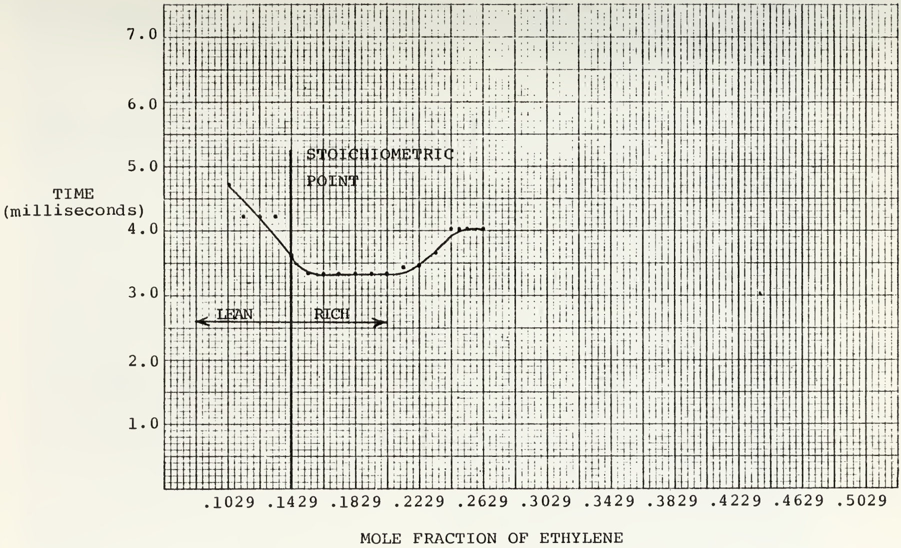


Figure 27. Time of Event Through Rotor Passage; Ethylene, Oxygen and Nitrogen Mixtures

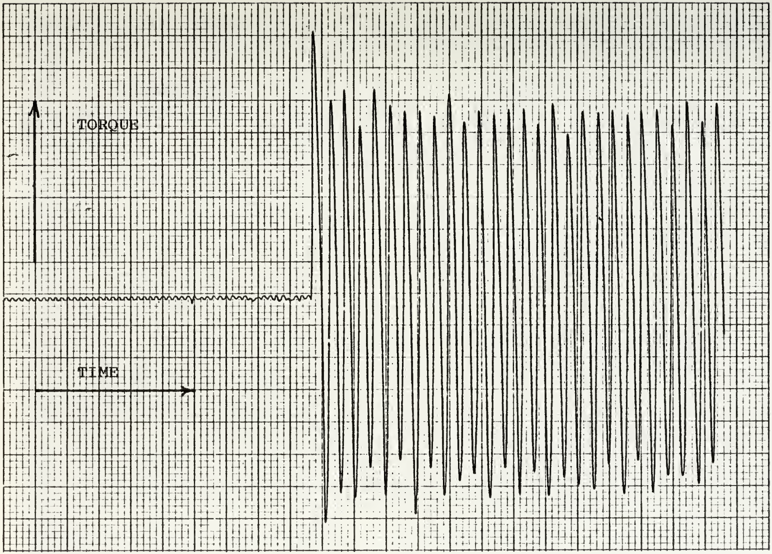


Figure 28. Harmonic Response of the Torque Measurement System

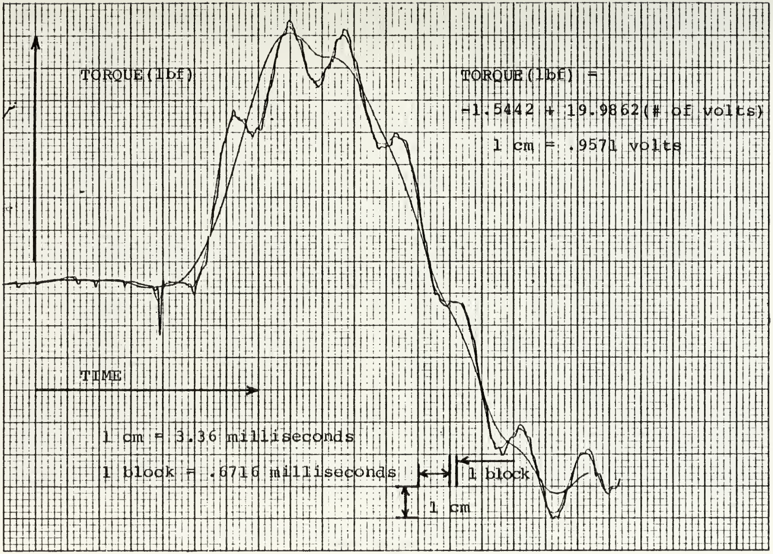


Figure 29. Harmonic Characteristics of Long Torque Tube

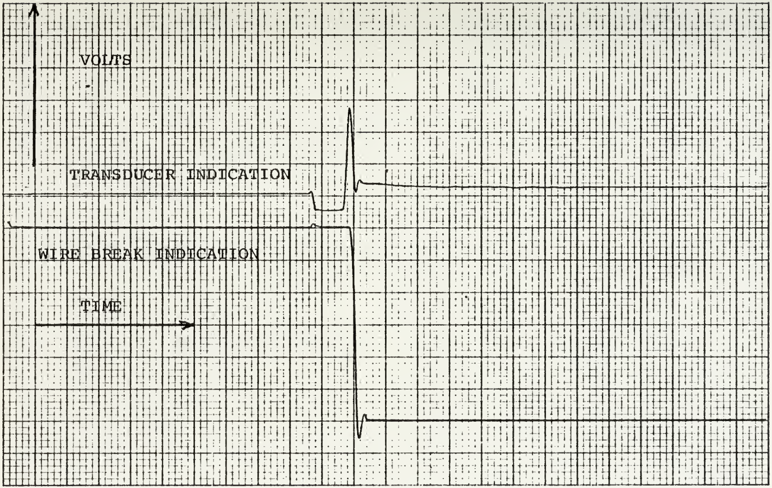


Figure 30. Comparison of Time Measurement Methods

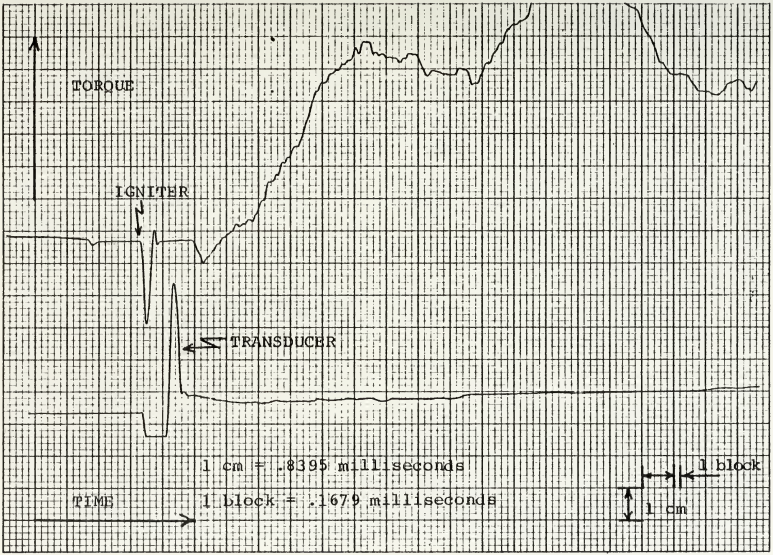


Figure 31a. Piezoelectric Transducer and Torque Signals; Ethylene and Oxygen Stoichiometric Mixture

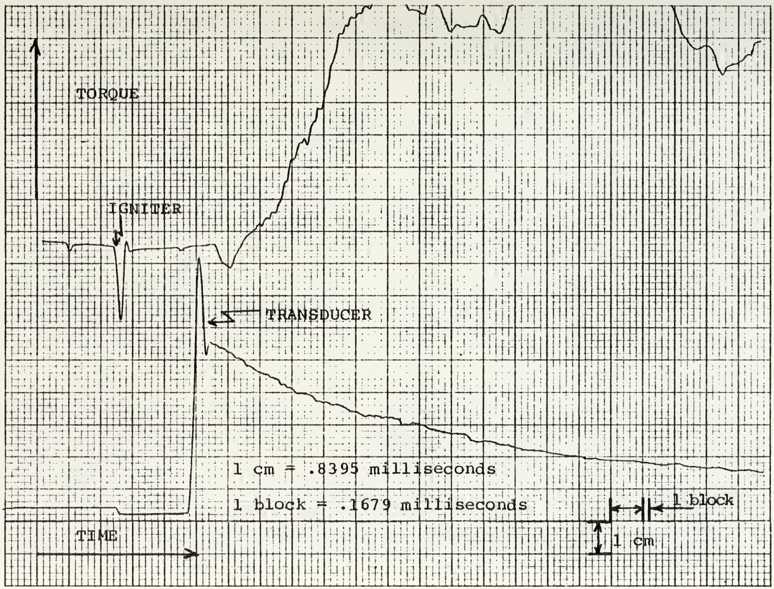


Figure 31b. Piezoelectric Transducer and Torque Signals; Ethylene and Oxygen Rich Mixture

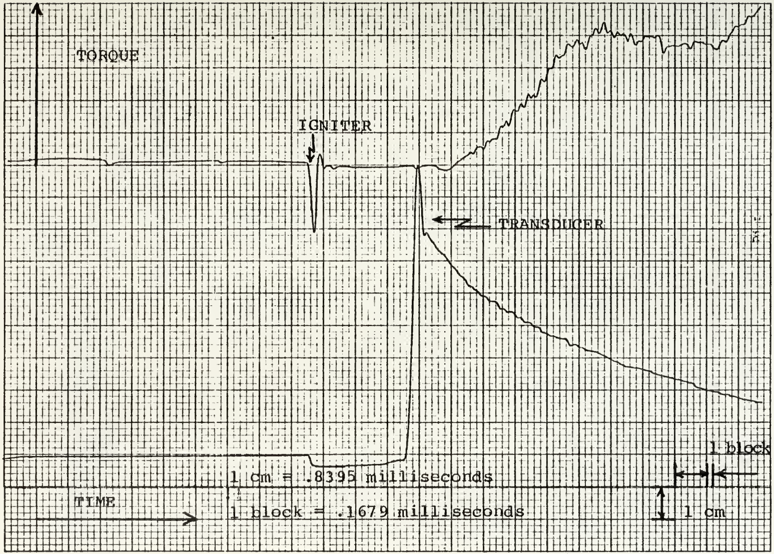


Figure 31c. Piezoelectric Transducer and Torque Signals; Ethylene, Oxygen and Nitrogen Stoichiometric Mixture

APPENDIX A

THEORETICAL CALCULATIONS

The following is a sample calculation [Ref. 17] to determine the torque based on a stoichiometric mixture of ethylene and oxygen. It is assumed that the product gases act as perfect gases and that no dissociation of the product gases occur. The chemical equation taken for the reaction is:

$$C_2H_4 + 3O_2 + .0843N_2 = 2CO_2 + 2H_2O + .0843N_2$$

The mole fractions of components are:

a) Reactants

$$X_{C_2H_4} = .2448$$

$$X_{O_2} = .7345$$

$$X_{N_2} = .0206$$

b) Products

$$X_{CO_2} = .4897$$

$$X_{H_2O} = .4897$$

$$X_{N_2} = .0206$$

The molecular weights are:

a) Reactants

$$\bar{m}_1 = X_{C_2H_4}\bar{m}_{C_2H_4} + X_{O_2}\bar{m}_{O_2} + X_{N_2}\bar{m}_{N_2}$$

$$\bar{m}_1 = (.2448)(28.052) + (.7345)(32) + (.0206)(28.016)$$

$$\bar{m}_1 = 30.95$$

b) Products
$$\bar{m}_2 = X_{CO_2}\bar{m}_{CO_2} + X_{H_2O}\bar{m}_{H_2O} + X_{N_2}\bar{m}_{N_2}$$
$$\bar{m}_2 = (.4897)(44.01) + (.4897)(18.016) + (.0206)(28.016)$$
$$\bar{m}_2 = 30.95$$

The absolute enthalpy is given by:

$$H = N_i\ [(H°-H°_{298}) + H_{f,298}]$$

a) Reactants
$$H_R = (1)[0 + 52467.36/1000] + 0 + 0 = 52.47 \text{ KJ}$$

b) Products
$$H_p = (2)\ [0 - 393522/1000] + (2)[0 - 241827/1000] + 0 = -1270.7 \text{ KJ}$$

The energy of combustion is given by:

$$Q = H_R - H_P = 1323.17 \text{ KJ}$$

and, on a molar basis:

$$\bar{Q} = Q/N_p = 1323.17/4.083 = 323.965 \text{ KJ/mole}$$

The specific heats are given by:

a) Reactants
$$\overline{C_{P_1}} = X_{C_2H_4}\bar{C}_{P_{C_2H_4}} + X_{O_2}\bar{C}_{P_{O_2}} + X_{N_2}\bar{C}_{P_{N_2}}$$
$$\overline{C_{P_1}} = (.2448)(42.89) + (.7345)(29.354) + (.0206)(37.066)$$
$$\overline{C_{P_1}} = 32.66 \text{ J/mole - °K}$$
$$\overline{C_{V_1}} = \overline{C_{P_1}} - \bar{R}$$
$$\overline{C_{V_1}} = 32.66 - 8.314 = 24.346 \text{ J/mole - °K}$$

b) Products (assume T_2 = 3000 K)
$$\overline{C_{P_2}} = X_{CO_2}\bar{C}_{PCO_2} + X_{H_2O}\bar{C}_{P_{H_2O}} + X_{N_2}\bar{C}_{P_{N_2}}$$
$$\overline{C_{P_2}} = (.4897)(62.229 + (.4897)(55.711) + (.0206)(37.066)$$
$$\overline{C_{P_2}} = 58.52 \text{ J/mole - °K}$$
$$\overline{C_{V_2}} = \overline{C_{P_2}} - \bar{R}$$

$$\overline{C_{V_2}} = 58.52 - 8.314 = 50.206 \text{ J/mole - °K}$$

Then, $$\gamma_2 = \overline{C_{P_2}}/\overline{C_{V_2}} = 58.52/50.206 = 1.1656$$

so that, using conservation of energy,

$$T_2 \doteq (2\gamma_2/\gamma_2 + 1)\left\{\frac{(\overline{C_{V_1}}/\bar{m}_1)}{(\overline{C_{V_2}}/\bar{m}_2)} T_1 + Q/\overline{C_{V_2}}\right\}$$

$$T_2 = 7101.78 \text{ °K}$$

Iterations are now made on T_2 to convergence. In this case $T_2 = 6520\text{°K}$

Hence:

$$a_2 = \left\{\gamma_2 R_2 T_2\right\}^{1/2} \quad \text{where } R_2 = \bar{R}/\bar{m}_2 = 8314.3/30.95$$

$$a_2 = 1421.13 \text{ m/s} \qquad R_2 = 268.64 \text{ J/kg - °k}$$

$$P_2 = a^2\rho_2/\gamma_2 \quad \text{where } \rho_2 = (\rho_2/\rho_1)\rho_1 = \frac{(\gamma_2 + 1)\rho_1}{\gamma_2}$$

$$P_2 = 3971940 \text{ N/m}^2$$

The maximum isentropic mass flow rate can now be calculated:

$$\dot{M} = \Gamma PA^*/a$$

Here $$\Gamma = \gamma[2/(\gamma + 1)]^{\gamma-1/2(\gamma - 1)}$$

$$= 1.15311$$

and $$A = .00013 \text{ m}^2$$

and therefore,

$$\dot{M} = .24942 \text{ kg/s}$$

The expected flow time from the tube can then be calculated thus:

$$M = PV/RT = (3971940)(.693)(.00013)/(268.626)(6520)$$

$$= .0002 \text{ kg}$$

The average time is then given by:

$$t = M/\dot{M} = .0002/.24942$$

$$= .00082 \text{ sec}$$

The torque can be calculated as follows:

The thrust for each tube $= \dot{M}u = (.24942)(1421.13)$

$= 354.46$ N

For ten tubes the thrust $= 3544.6$ N

Hence the torque $=$ (Force)(Moment Arm)

$= (3544.6)(.56515)$

$= 1477.5$ ft-lbf

APPENDIX B

LISTING OF FIRINGS

The following table gives a listing of the firings conducted during the study.

RUN #	OBJECTIVE	REMARKS
1-4	Familiarization	Stoichiometric
5-9	Record bending force; Familiarization with oscilloscope/event interaction	Three tubes removed to force bending Stoichiometric
10-16	Confirm detonation vs. combustion	Fuel mix varied past detonation limit. Combustion observed
17-19	Confirm no ignition of either fuel component separately	
20-23	Record torque; continue familiarization with oscilloscope/event interaction	Somewhat rich mixture
24-28	Lead foil test	Varying mixtures
29-37	Ethylene/Air mixture experiments-range of detonation	
38-43	Ethylene/O_2/N_2 mixture experiments-range of detonation w/N_2 ballast	
44-51	Observe response of newly installed amplifier	Stoichiometric
52-54	Familiarization with oscilloscope/event interaction	Stoichiometric

RUN #	OBJECTIVE	REMARKS
55-60	Record two channels of bending simultaneously on oscilloscope	Stoichiometric Unamplified
61-122	Collect data to show negligible asymmetry in firing	Stoichiometric
122-245	Record torque data	Varying mixtures
245-280	Torque data analysis with rotor passage transducer	

APPENDIX C

FUELING PROCEDURES

C.1 PROCEDURE

A. Determine Desired Fueling

1. Choose mixture (i.e., ethylene and air, ethylene and oxygen, or ethylene, oxygen and nitrogen), fuel/oxidizer ratio and desired model pressure. (See Appendix C-3)

2. Calculate partial pressures required (See Appendix C-3).

B. Purge Fuel System (See Figure 5b)

1. Connect nylon tubing from dolly unit to model inlet. (See Figure 6)

2. Open model inlet valve and ensure no exhaust tube seals are in place.

3. Open all valves on fuel dolly except 1, 2, 3 and 8.

4. Place pump valve in the pump position and turn pump on. Allow at least a minute for complete air purging.

C. Evacuate Fuel System

1. Affix seals to exhaust tube ends as shown in Figure 7. System will evacuate to .6 psi if the seals are good. If it does not, check for leaks. Remove seal clamps to one side once evacuation is complete.

2. Ensure regulator master valves and secondary metering valves are opened such that the latter read about 50 psi.

3. Close valves 4 and 6. This stops evacuation of the mixing chamber but continues evacuation of the model.

4. Open valves 1, 2, and 3 as required to meet the desired partial pressures previously calculated.

5. Close valve 7, turn pump off and open valve 6 to transfer fuel mix to the model. When desired model pressure is reached, close the model inlet valve.

6. Remove nylon tubing from the model and withdraw it to the dolly.

7. Open valve 7, turn pump on, and move dolly unit to a safe distance. The model is now ready to fire.

C.2 DETERMINATION OF MIXING CHAMBER/MODEL VOLUME RATIOS

An experiment was conducted to accurately determine the volume ratio between the total fueling system and mixing chamber side of the system. In so doing, a desired model pressure could be consistently attained with precisely calculated partial pressures introduced into the mixing chamber.

Following the procedure described in Appendix C-1, the total system was evacuated, the mixing chamber was filled to a specified pressure with nitrogen, and then transfer was made to fill the whole system, and reach a new equilibrium pressure. These two pressures specified the pressure

ratio and hence the volume ratio in accordance with the equation $V_T/V_{MC} = P_{MC}/P_T$ where PV = constant and where the variables are defined as follows:

P_T = Pressure of the total system or "model pressure"

P_{MC} = Mixing chamber pressure

V_T = Volume of the total system

V_{MC} = Mixing chamber volume

This process was repeated for several different mixing chamber pressures and for two configurations of exhaust tube sealing geometry as shown here:

Case 1: Rubber stopper used as sealer

P_{MC} (psi)	P_T (psi)	P_T/P_{MC}
9	5.8	.6444
12	7.6	.6333
15	9.3	.6200
18	11.1	.6167
22	13.5	.6136
23	14.1	.6130
25	15.2	.6080
	Average =	.6213

Hence V_T/V_{MC} = 1.6095

Case 2: Exhaust tubes extended with plastic 45° elbows sealed with rubber stoppers

P_{MC} (psi)	P_T (psi)	P_T/P_{MC}
9	5.6	.6222
12	7.35	.6125
15	9	.6000
18	10.8	.6000
22	13	.5909
23	13.6	.5913
25	14.7	.5880
27	15.8	.5852
	Average =	.5988

Hence $V_T/V_{MC} = 1.67$

Most of the firings conducted subsequent to this experiment utilized a flat piece of rubber to seal the exhaust tubes. For this purpose, an average of these two volume ratios was used, or $V_T/V_{MC} = 1.64$. Once this ratio was known and a desired model pressure was selected, the mixing chamber pressure could be calculated with the equation; $P_{MC} = P_T\left\{V_T/V_{MC}\right\}$. The specifics of calculating the corresponding partial pressures for a selected mole fraction of fuel are shown in the next section.

C.3 FUEL CALCULATIONS

<u>Ethylene and Oxygen Mixtures</u>

The following is a sample calculation [Ref. 14] to determine the proper partial pressures of mixture components for a specified model pressure and number of moles of fuel. It takes into account the air remaining in the system due to incomplete evacuation.

In general, the chemical equation is:

$$C_2H_4 + 3O_2 + AN_2 \quad 2CO_2 + 2H_2O + AN_2$$

where A is a coefficient to be determined based on the constraint that evacuation leaves some nitrogen in the system, and that no nitrogen is to be added while mixing the fuel.

Total number of moles = 1 + 3 + A = 4 + A

$$P_{C_2H_4} = P_{MC}[1/(4+A)]$$

$$P_{O_2} = P_{MC}[3/(4+A)] - (.6)\ (.21)$$

$$P_{N_2} = P_{MC}[A/(4+A)] - (.6)\ (.79)$$

The amounts subtracted from the last two equations account for the pressure of the oxygen and nitrogen already supplied by the air remaining after evacuation of the system. Setting the last equation equal to zero will allow calculation of the coefficient A under the constraint that no nitrogen will be added. The partial pressure can then be calculated.

Example Problem:

Desired model pressure, $P_T = 14.0$ psi

Volume ratio $V_T/V_{MC} = 1.64$

Number of moles of fuel = 1

The chemical equation is then:

$$C_2H_4 + 3O_2 + AN_2 \qquad 2CO_2 + 2H_2O + AN_2$$

$$P_{MC}[A/(4+A)] - (.6)\ (.79) = 0$$

$$A = .0843 \text{ moles}$$

Hence

$$C_2H_4 + 3O_2 + .0843N_2 \qquad 2CO_2 + 2H_2) + .0843N_2$$

$$P_{MC} = (14.0)\ (1.64) = 22.96 \text{ psi}$$

$$C_2H_4 = (.2448)\ (22.96) = 5.62 \text{ psi}$$

The pressure remaining to be supplied by the oxygen and nitrogen is:

$$P_{(O_2 + N_2)} = 22.96 - 5.62 = 17.34 \text{ psi}$$

Using the mole fractions of the constituents of the oxygen/ nitrogen mixture, the partial pressures can be found. Again, those amounts already fulfilled by the air remaining after evacuation are taken into account.

$$P_{O_2} = (3/3.0843)\ (17.34)-(.6)(.21) = 16.74$$

$$P_{N_2} = (.0843/3.0843)\ (17.34)-(.6)(.79) = 0$$

These calculated values indicate the amount of pressure to be added to the residual .6 psi of air. Hence the gate pressures to which the ethylene and oxygen should be added are:

$$P_{C_2H_4} = 5.62 + .6 = 6.22 \text{ psi}$$

$$P_{O_2} = 6.22 + 16.74 = 22.96 \text{ psi}$$

A calculator problem, written for use with the HP-41CV calculator and periphial printer was used to calculate the partial pressures for the different fuel mixtures used. It prompts the user for the desired model pressure, the volume ratio used and the number of moles of fuel considered. The program runs in a loop manner continuing to add an increment to the number of moles of fuel considered. A sample output is shown here, followed by the program listing on the next page.

Sample Output:

P_{MC}	22.96ØØ	***
P_T	14.ØØØØ	***

V_T/V_{MC}	1.64ØØ	***
No. of moles of ethylene	1.ØØØØ	***
Mole fractions of ethylene	Ø.2448	***
$P_{C_2H_4}$	6.2215	***
P_{O_2}	22.96ØØ	***

The increment size can be varied by changing the amount in program step number thirteen.

Ethylene, Oxygen and Nitrogen Mixtures

1. Stoichiometric mixtures; varying nitrogen ballast.

The following is a sample calculation to determine the proper partial pressures to mix for a specified model pressure and number of moles of nitrogen ballast for a stoichiometric ethylene/oxygen mixture. It takes into account the air remaining in the system due to incomplete evacuation.

Example problem:

Desired model pressure, P_T = 14.0 psi

Volume ratio V_T/V_{MC} = 1.64

Number of moles of nitrogen = 3

Program Listing for Ethylene/Oxygen
Partial Pressure Calculation

```
♦LBL "E+OMOD2"
"PT=?"
PROMPT
STO 01
"YT/YMc=?"
PROMPT
STO 02
"MOLES FUEL=?"
PROMPT
STO 25
♦LBL 06
RCL 25
.0025
+
STO 25
RCL 01
RCL 02
*
STO 03
RCL 25
3
+
.474
ENTER↑
RCL 03
/
STO 26
*
RCL 26
1
-
CHS
/
STO 27
3
+
RCL 25
+
RCL 25
/
1/X
STO 23
RCL 27
3
+
STO 28
3
/
1/X
STO 29
RCL 27
RCL 28
/
STO 30
RCL 23
RCL 03
*
STO 04
RCL 03
-
CHS
STO 24
RCL 29
*
.12605
-
STO 05
RCL 24
RCL 30
*
.47395
-
STO 06
RCL 03
PRX
RCL 01
PRX
RCL 02
PRX
ADV
RCL 25
PRX
RCL 23
PRX
ADV
RCL 04
.6
+
PRX
RCL 05
+
PRX
RCL 06
+
ADV
ADV
GTO 06
.END.
```

The chemical equation is then:

$$C_2H_4 + 3(O_2 + N_2) \quad 2CO_2 + 2H_2O + 3N_2$$

$$P_{MC} = (14.0)(1.64) = 22.96 \text{ psi}$$

$$P_{C_2H_4} = (22.96)(1/7) = 3.23 \text{ psi}$$

$$P_{O_2} = (22.96)(3/7) - (.6)(.21) = 9.56 \text{ psi}$$

$$P_{N_2} = (22.96)(3/7) - (.6)(.79) = 9.2 \text{ psi}$$

These calculated values indicate the amount of pressure to be added to the air remaining in the system after evacuation. Hence the gage pressures to which the ethylene and oxygen should be added are:

$$P_{C_2H_4} = 3.23 + .6 = 3.83 \text{ psi}$$

$$P_{O_2} = 3.83 + 9.56 = 13.39 \text{ psi}$$

$$P_{N_2} = 13.39 + 9.2 = 22.59 \text{ psi}$$

A calculator program, written for use with the HP-41CV calculator and peripheral preinter was used to calculate the partial pressures for the different fuel mixtures considered. It prompts the user for the desired model pressure, the volume ratio used, and the number of moles of nitrogen ballast considered. The program runs in a loop manner continuing to add an increment to the number of moles of nitrogen ballast considered. A sample output is shown here, followed by the program listing on the next page.

Sample Output

P_{MC}	22.96ØØ	***
P_T	14.ØØØØ	***
V_T/V_{MC}	1.64ØØ	***
No. of Moles of Nitrogen	3.ØØØØ	***
$P_{C_2H_4}$	3.88ØØ	***
P_{O_2}	13.5948	***
P_{N_2}	22.9681	***

The increment size can be varied by changing the amount in program step number thirteen.

Program Listing for Partial Pressure Calculation of Stoichiometric Mixtures of Ethylene and Oxygen with Nitrogen Ballast

```
01♦LBL "E+ON"
02 "PT=?"
03 PROMPT
04 STO 01
05 "VT/VMc=?"
06 PROMPT
07 STO 02
08 "MOLES N2=?"
09 PROMPT
10 STO 07
11♦LBL 06
12 RCL 07
13 .5
14 +
15 STO 07
16 4
17 +
18 STO 08
19 RCL 01
20 RCL 02
21 *
22 STO 03
23 RCL 08
24 1/X
25 *
26 STO 24
27 RCL 03
28 RCL 08
29 3
30 /
31 1/X
32 *
33 .12605
34 -
35 STO 05
36 RCL 03
37 RCL 07
38 *
39 RCL 08
40 /
41 .4739
42 -
43 STO 06
44 RCL 03
45 PRX
46 RCL 01
47 PRX
48 RCL 02
49 PRX
50 ADV
51 RCL 07
52 PRX
53 ADV
54 RCL 24
55 .6
56 +
57 PRX
58 RCL 05
59 +
60 PRX
61 RCL 06
62 +
63 PRX
64 ADV
65 ADV
66 GTO 06
67 .END.
```

2. Fixed Nitrogen ballast; varying amount of fuel

The following is a sample calculation to determine the proper partial pressures to mix for a specified model pressure and number of moles of nitrogen ballast with varying amounts of fuel. It takes into account the air remaining in the system due to incomplete evacuation.

Example problem:

Desired model pressure, $P_T = 14.0$ psi

Volume ratio $V_T/V_{MC} = 1.64$

Number of moles of nitrogen = 3

Number of moles of fuel = 1

The chemical equation is then

$$C_2H_4 + 3(O_2 + N_2) \longrightarrow 2\ CO_2 + 2H_2O + 3N_2$$

$$P_{MC} = (14.0)(1.64) = 22.96 \text{ psi}$$

$$P_{C_2H_4} = (22.96)\left(\frac{1}{7}\right) = 3.23 \text{ psi}$$

The pressure remaining to be supplied by the oxygen and nitrogen is:

$$P_{(O_2+N_2)} = 22.96 - 3.23 = 19.73 \text{ psi}$$

Using the mole fractions of the constituents of the oxygen/nitrogen mixture, the partial pressures can be found.

$$P_{O_2} = \left(\frac{3}{6}\right)(19.73) - (.6)(.21) = 9.74$$

$$P_{N_2} = \left(\frac{3}{6}\right)(19.73) - (.6)(.79) = 9.4$$

The gage pressures to which the three gases should be added are:

$$P_{C_2H_4} = 3.23 + .6 = 3.83 \text{ psi}$$

$$P_{O_2} = 3.83 + 9.74 = 13.57 \text{ psi}$$

$$P_{N_2} = 13.57 + 9.4 = 22.97$$

A calculator program, written for use with the HP-41CV calculator and peripherial printer was used to calculate the partial pressures for the different fuel mixtures used. It prompts the user for the desired model pressure, the volume ratio used, the number of moles of nitrogen ballast, and the mole fraction of fuel considered. The program runs in a loop manner continuing to add an increment to the mole fraction considered. A sample output is shown here, followed by the program listing

Sample Output

P_{MC}	22.96ØØ	***
P_T	14.ØØØØ	***
$\frac{V_T}{V_{MC}}$	1.64ØØ	***
Mole Fraction of Ethylene	Ø.1229	***
$P_{C_2H_4}$	3.4218	***
P_{O_2}	13.3648	***
P_{N_2}	22.96ØØ	***

The increment size can be varied by changing the amount in program step number sixteen on the following page.

Program Listing for Partial Pressure Calculation of Varying Mixture of Ethylene and Oxygen with a Fixed Nitrogen Ballast

```
01♦LBL "E+OMODF"
02 "PT=?"
03 PROMPT
04 STO 01
05 "VT/VMc=?"
06 PROMPT
07 STO 02
08 "FUELAMOUNT=?"
09 PROMPT
10 STO 23
11 "MOLES N2=?"
12 PROMPT
13 STO 15
14♦LBL 06
15 RCL 23
16 .01
17 +
18 STO 23
19 RCL 01
20 RCL 02
21 *
22 STO 03
23 RCL 23
24 *
25 STO 04
26 RCL 03
27 -
28 CHS
29 STO 24
30 RCL 15
31 3
32 +
33 STO 16
34 3
35 /
36 1/X
37 STO 17
38 RCL 16
39 3
40 -
41 RCL 16
42 /
43 STO 18
44 RCL 17
45 RCL 24
46 *
47 .12605
48 -
49 STO 05
50 RCL 24
51 RCL 18
52 *
53 .47395
54 -
55 STO 06
56 RCL 03
57 PRX
58 RCL 01
59 PRX
60 RCL 02
61 PRX
62 ADV
63 RCL 23
64 PRX
65 ADV
66 RCL 04
67 .6
68 +
69 PRX
70 RCL 05
71 +
72 PRX
73 RCL 06
74 +
75 PRX
76 ADV
77 ADV
78 GTO 06
79 .END.
```

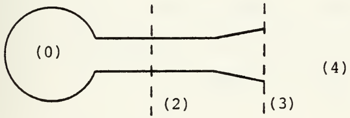
APPENDIX D

DESIGN OF THE TORQUE TUBE

D.1 ESTIMATE OF EXPECTED TORQUE

The design of the torque tube involved two basic considerations. It had to be strong enough to accept the loads without plasticly deforming and yet be elastic enough in the range of expected torque to be sensitive to those loads. [Ref. 15] To estimate the expected torque the exhaust tube exit velocity was calculated. [Ref. 16]

Assumptions:



STATION	CORRESPONDS TO
(0)	Reservoir supply
(2)	Throat of rotor passage
(3)	Exit plane of rotor passage
(4)	Ambient conditions

Steady, one dimensional, adiabatic flow
Perfect gas, inviscid flow
Constant supply pressure of twenty atmospheres producing the flow. This magnitude corresponds to the plateau pressure expected in a typical detonation.

ρ_o	=	(1.5) (1.3) kg/m^3	ρ_4	=	1.3 kg/m^3
γ	=	1.2	P_4	=	1 atmosphere
P_{t_o}	=	P_o = 20 atmospheres	u_4	=	0.0 m/s
T_{t_o}	=	T_o = 1950°K	R	=	287 N-m/kg-°K

P_4/P_{t_o} = .05 ⟶ Isentropic tables give M = 2.5

$A_2/A_1 = 2.25 \longrightarrow$ Isentropic tables give $M = 2.33$

and $P/P_t = .47944$
$T/T_t = .07631$

To operate at the design condition we need:

$$P_4 = P_3 = (.47944)\ (20) = 9.5888 \text{ atmospheres}$$

Hence the nozzle is underexpanded and will operate internally as if it were at the design condition. Assuming then that the nozzle is operating at the design condition:

at $M = 2.6$ isentropic tables give $P_3/P_{t_3} = .05$

$T_3/T_{t_3} = .4252$

$$T_3 = (T_3/T_{t_3})T_{t_3} \quad \text{where } T_{t_3} = T_{t_o}$$

$$T_3 = (.4252)\ (1950\ K) = 829.14°K = 1033°F$$

$$u_3 = M_3 a_3 = (2.6) \left\{ (1.2)\ R\ (829.14) \right\}^{1/2}$$

where $R = (R_{H_2O} + R_{CO_2})/2 = (461 + 189)/2$

$$u_3 = 1478.5 \text{ m/s}$$

$= 325$ J/kg-°K

With the throat choked, $M = 1.0$ and

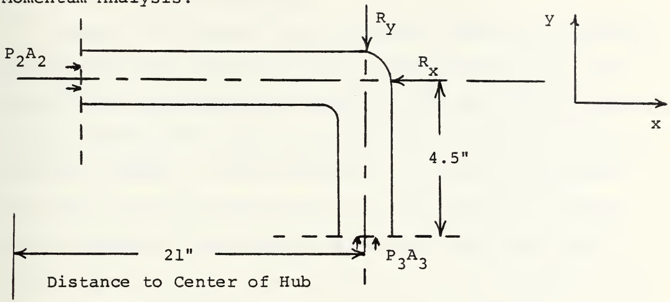
$$u_2 = M_2 a_2 = 1.0 \left\{ (1.2)\ (325)\ (829.14) \right\}^{1/2}$$

$$u_2 = 568.65 \text{ m/s}$$

$$P_2/P_{t_2} = .5283 \rightarrow P_2 = (.5283)\ P_{t_o} = (.5283)\ (20)$$

$= 10.566$ atmospheres
$= 1070599.95\ N/m^2$

Momentum Analysis:



Only the y component as shown here contributes to the resultant torque

$$\Sigma \bar{F} = \dot{M} \, (\bar{u}_{out} - \bar{u}_{in})$$

$$P_3A_3 - R_y = \dot{M} \, (\bar{u}_{out} - 0)$$

$$R_y = P_3A_3 - \rho_3 A_3 u_3^2$$

$$R_y = -205.4\text{N}$$

Where $P_3 = 101325 \text{ N/m}^2$

$\rho_3 = P_3/RT_3 = 101325/(325)(829.14)$

$\rho_3 = .376 \text{ kg/m}^3$

Hence the torque can be calculated:

Torque = (Force) (Moment Arm)

= (205.4 N) (.5715 m)

= 117.4 N-m

= 86.6 ft-lbf.

For ten exhaust tubes the total torque is 866 ft-lbf.

D.2 DESIGN OF TUBE GEOMETRY

Besides the expected level of torque, there were several other things that constrained the geometry of the tube. So as to allow unencumberenced access to the fuel inlet valve, it was decided that the torque tube would connect to the detonation chamber on the side where the igniter was mounted. As such, the tube would have to be large enough in diameter to not interfere with the igniter or its cable, and still small enough to allow proper connection with a flange to the bottom surface of the chamber. This restricted the outside diameter to about four and a half inches and the inside diameter would need to be greater than about 3.75 inches. Based on this, some preliminary calculations were made.

Assumed:

Max torque load = 1000 ft-lbf

Outside diameter = 4.5"

Inside diameter = 4.0"

Material: Steel 1025 MIL-T-5066

F_{ty} = 70000 psi

$F_{sy} \approx \frac{1}{2}F_{ty}$ = 35000 psi

In order to stay away from any nonlinear properties of the material near the elastic limit, the design maximum chosen was half of the yield strength.

$\frac{1}{2}F_{sy}$ = 17500 psi

$$\tau = Tr/J \text{ where } J = (\pi/32)(D_o^4 - D_i^4)$$

$$\tau = (1000)(2.25)(12)/(\pi/32)(4.5^4 - 4^4) = 1785 \text{ psi}$$

This was too far from the design to be considered sensitive.

Similar calculations, varying the diameters and thickness showed that the real key to sensitivity was the thickness variable.

Based on these initial calculations, two different tube materials were procured with which to continue the design.

Material 1 Al 6061 T6

Outside diameter = 4.0"

Thickness - .035"

F_{ty} = 36 ksi

F_{sy} = 18 ksi

$\frac{1}{2}F_{sy}$ = 9 ksi

Material 2 Al 2024 T3

Outside diameter = 4.0"

Thickness = .125"

F_{ty} = 42 ksi

F_{sy} = 21 ksi

$\frac{1}{2}F_{sy}$ = 10.5 ksi

Further iterations of the calculations shown previously were made with the following results:

Material	1 (t = .035")	2 (t = .125")	2 (t = .0625")
Design shear stress	9 ksi	10.5 ksi	10.5 ksi
Shear stress at 1000 ft-lbf	14 ksi	14.2 ksi	8 ksi
Shear stress at 700 ft-lbf	9.8 ksi	2.94 ksi	5.6 ksi

Based on these calculations it was decided that two tubes would be made; one with each of the tube materials available. Material 2 would have its thickness reduced to .0625". As the study progressed and the resolution of bending forces became more important, the tube of material 2 was further reduced to a thickness of .022". The lengths of the tubes were made so that with strain gages mounted midway, any disymmetry of torque transfer at the ends would not be a factor to be considered.

D.3 CHOICE AND PLACEMENT OF STRAIN GATES (See Figures 11a and 11b)

For the measurement of torque, four strain gage rosettes were mounted at equally spaced intervals around the center of the tube. Their orientation was such that the 45° legs of the gages would be sensitive to the maximum shear strains produced under torque loads. These separate legs were connected in a bridge circuit to maximize their possible excitation voltage and hence their output. The possible arrangement also compensated for variations in signal due to tem-

perature effects. Again, for maximum sensitivity, of the gages available at the time, those with the largest gage length and highest resistance (120 ohms) were chosen.

For the measurement of bending, eight rectangular gages of higher resistance (350 ohms) were obtained. They were placed at the base of the tube where the largest bending loads would be imposed. Four pairs were equally spaced around the tube. In order to measure two components of bending in a plane, each set of gages that were alligned (those on opposite sides of the tube) were connected in a bridge circuit so as to indicate one component of any bending force present. This arrangement also compensated for temperature variations.

D.4 BRIDGE CIRCUITS AND SIGNAL CONDITIONING UNIT DESIGN

Figure 11b shows the arrangement of and correspondence between the gage placement on the tube, the bridge circuits and the layout of the signal conditioning box.

D.5 DISTINCTION OF MEASURED SIGNAL

It was imperative in the testing that the torque and bending measurements be separate and distinct and that neither would affect the reading of the other. This was accomplished through the configuration of the respective bridge circuits. For example, in the case of the torque measurement, if a bending force were present, gages on opposite sides of the

tube would experience strains of equal magnitude but of different sign, cancelling the effect.

A simple experiment was conducted with static loads, confirming that the torque gages would read only torque and that the bending gages would likewise read only bending forces. Aberrations noted were small enough to be negligible (less than 1%).

D.6 CALCULATION OF THE CRITICAL EXCITATION VOLTAGE

The maximum excitation of the bridge circuits so as to produce the largest signal without damaging the gages is calculated here:

Assumed: Gages will accept a maximum of .030 amperes of current

Torque: $E_c = I(480) = (.03)(480)$

$E_c = 14.4V$

Bending: $E_c = I(700) = (.03)(700)$

$E_c = 21.0V$

Based on these calculations the excitation voltage was set at 14.0 volts.

APPENDIX E

EQUIPMENT LISTING

1. Sola Constant Voltage D.C. Power Supply
   Catalog no. 281024.1

2. Bendix Ignition Unit
   Type TCN-2003; Stock no. 10-80250-3

3. Endevco Corporation Amplifier
   Model no. 2614M2

4. Endevco Corporation Pressure Pickup
   Model no. 2501-500

5. Datel Systems Inc., Instrumentation Amplifier
   Model no. AM201C

6. Intronics Power Supply
   Model no. PS-100

7. Maxron Inc., SRC Division Power Supply
   Model no. 3564

8. Endevco Corporation Power Supply
   Model no. 2622

9. Biomation Waveform Recorder
   Model 1015

10. Hewlett-Packard X-Y Recorder
    Model 7035B

11. Tektronix, Inc Dual Beam Oscilloscope
    Type 551

12. Tektronix, Inc Plug-in Unit
    Type 53/54D

13. Tektronix Time Mark Generator-Marker Selector
    Type 184

14. General Radio Company Unit Pulse Generator and Power
    Supply
    Type 1217-C

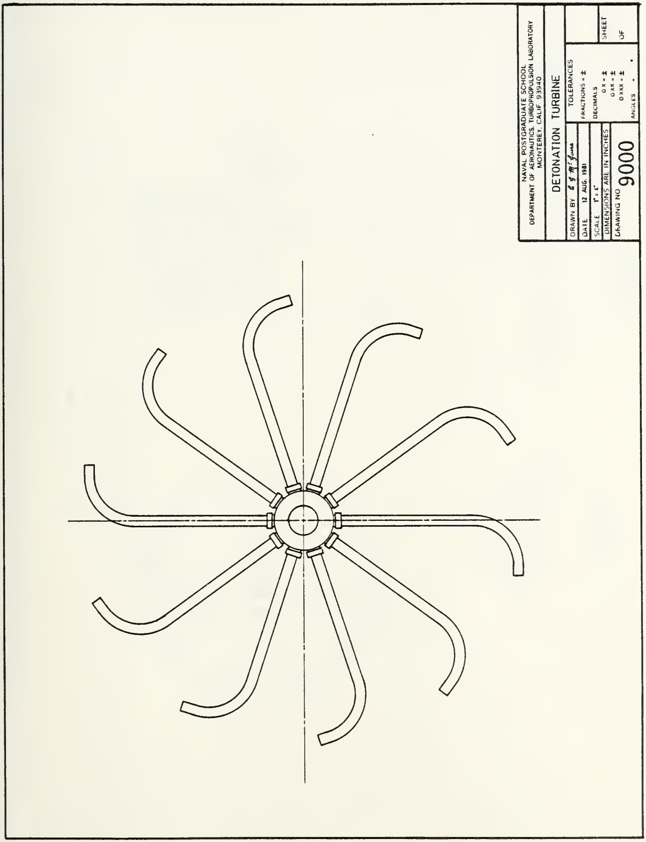
15. Fluke Digital Multimeter
    Model 8810A

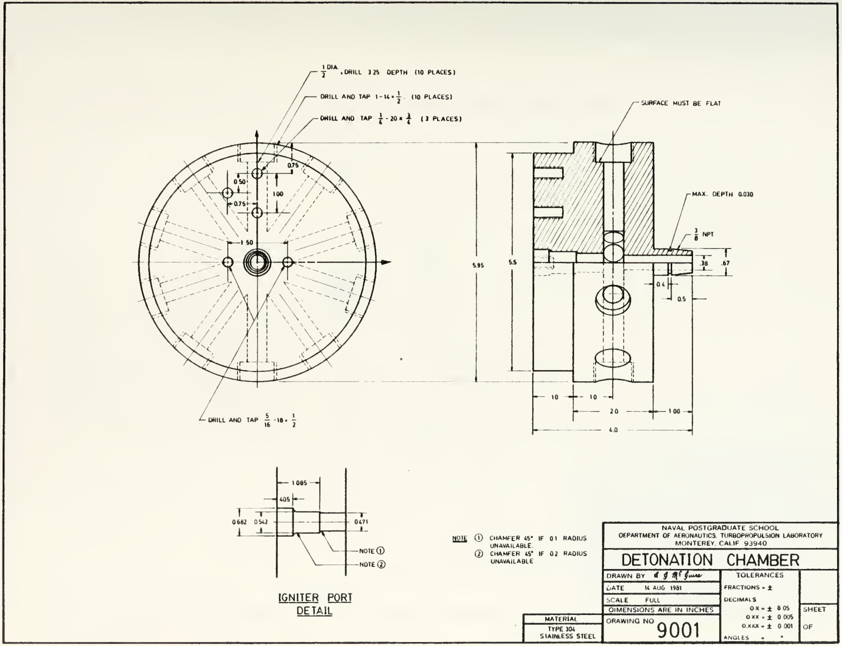
16. Hewlett-Packard Pulse Generator
    Type 8011A

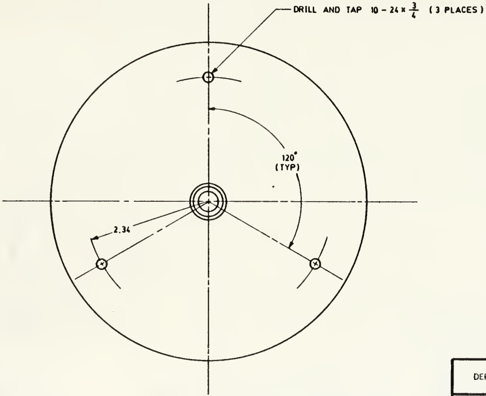
17. Wavetek Multipurpose VCG
    Model 116

APPENDIX F

DESIGN DRAWINGS FOR ROTARY DETONATION TURBINE MODEL
(by A.G. McGuire)



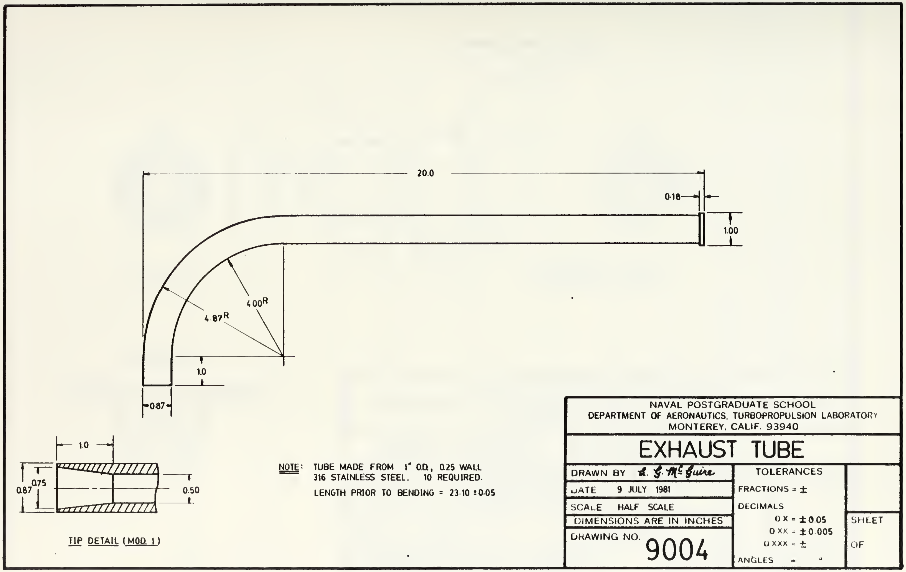

1/2 DIA., DRILL 3.25 DEPTH (10 PLACES)
DRILL AND TAP 1-14 × 1/2. (10 PLACES)
DRILL AND TAP 1/4 - 20 × 3/4 (3 PLACES)
DRILL AND TAP 5/16 -18 × 1/2
SURFACE MUST BE FLAT
MAX. DEPTH 0.030
3/8 NPT
IGNITER PORT DETAIL
NOTE ① CHAMFER 45° IF 0.1 RADIUS UNAVAILABLE.
② CHAMFER 45° IF 0.2 RADIUS UNAVAILABLE
NOTE ①
NOTE ②
NAVAL POSTGRADUATE SCHOOL
DEPARTMENT OF AERONAUTICS, TURBOPROPULSION LABORATORY
MONTEREY, CALIF 93940
DETONATION CHAMBER
DRAWN BY
DATE 14 AUG 1981
SCALE FULL
DIMENSIONS ARE IN INCHES
DRAWING NO 9001
TOLERANCES
FRACTIONS = ±
DECIMALS
0.X = ± 0.05
0.XX = ± 0.005
0.XXX = ± 0.001
ANGLES
SHEET
OF
MATERIAL
TYPE 304 STAINLESS STEEL

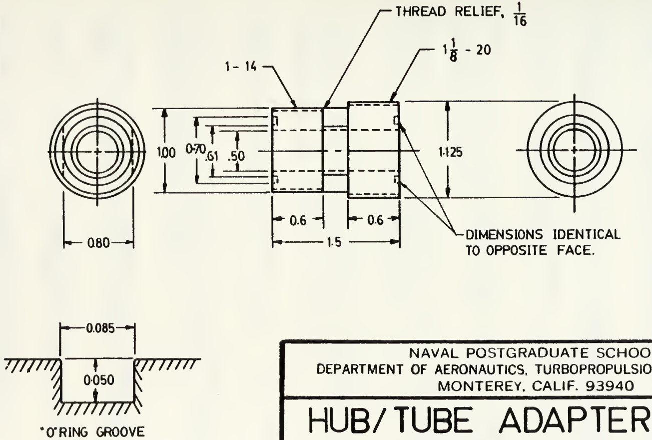


NAVAL POSTGRADUATE SCHOOL
DEPARTMENT OF AERONAUTICS, TURBOPROPULSION LABORATORY
MONTEREY, CALIF 93940

DETONATION CHAMBER (BACK VIEW)

DRAWN BY A. G. McGuire	TOLERANCES		
DATE 10 MAY 1982	FRACTIONS ±		
SCALE FULL	DECIMALS		
DIMENSIONS ARE IN INCHES	0.X = ± 0.05	SHEET	
DRAWING NO. 9002	0.XX = ± 0.01	OF	
	0.XXX = ±		
	ANGLES = °		


20.0
0.18
1.00
4.00R
4.87R
1.0
0.87
1.0
0.75
0.87
0.50
TIP DETAIL (MOD. 1)
NOTE: TUBE MADE FROM 1" O.D., 0.25 WALL
316 STAINLESS STEEL. 10 REQUIRED.
LENGTH PRIOR TO BENDING = 23.10 ±0.05
NAVAL POSTGRADUATE SCHOOL
DEPARTMENT OF AERONAUTICS, TURBOPROPULSION LABORATORY
MONTEREY, CALIF. 93940
EXHAUST TUBE
DRAWN BY L. G. McGuire
DATE 9 JULY 1981
SCALE HALF SCALE
DIMENSIONS ARE IN INCHES
DRAWING NO. 9004
TOLERANCES
FRACTIONS = ±
DECIMALS
0.X = ±0.05
0.XX = ±0.005
0.XXX = ±
ANGLES = °
SHEET
OF



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MONTEREY, CALIF. 93940

HUB/TUBE ADAPTER

DRAWN BY A. G. McGuire

DATE 8 JULY 1981

SCALE FULL

DIMENSIONS ARE IN INCHES

DRAWING NO. 9003

TOLERANCES

FRACTIONS = ±

DECIMALS

0.X = ± 0.05

0.XX = ± 0.005

0.XXX = ± 0.002

ANGLES = °

SHEET

OF

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Thesis
M677 Monks
c.1 Preliminary assessment of a rotary detonation engine concept.