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13 ABSTRACT

The subject of this report is the ignition of a liquid monopropellant by acoustic cavitation.

An experimental result of this study was the successful preliminary ignition of the monopropellant by an acoustic horn-transducer assembley. Upon examination of these ignition results, it was postulated that the reaction initiated by the acoustic device would definitely result in cumbustion of the monopropellant under proper pressure conditions. The proceedings of the experiment is described.

The writer concluded:

1. The ignition of liquid monopropellant is possible using acoustic techniques under proper conditions;

2. A value for the minimum energy density necessary to initiate the combustion sequence of the liquid monopropellant has been obtained;

3. The acoustic cavitation ignition technique is a precise, simply, and efficient method, however writer suggests more experiment for further development.

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"The Ignition of Liquid Monopropellants By Acoustic Cavitation"

A Trident Scholar Project Report

by

Midshipman Mark S. Campagne, 1975

U.S. Naval Academy

Annapolis, Maryland

Lawrence A. Crum

Advisor: Assoc. Prof. Lawrence A. Crum
Physics Department

Accepted for Trident Scholar Committee

Chairman

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Date

ABSTRACT

This report concerns an investigation into the possibility of implementing an ignition scheme, which utilizes acoustic cavitation, into the technology of liquid propellant gun systems. The feasibility of such an ignition technique, demonstrated by this research, has laid the foundation for further development and future implementation of this type of ultrasonic, low-energy, highly efficient method. Due to the fundamental nature of this research (this was the first attempt to utilize ultrasonics as an ignition scheme), there was a general lack of ballistic and acoustic hardware necessary for an extensive experimental study. Accordingly, this research has intended merely to demonstrate that ultrasonic ignition can occur, to specify the thresholds for its occurrance, and to develop theoretical projections for its implementation. This investigation resulted in an experimental determination of the minimum value of the energy density necessary to initiate a chemical reaction which would cause ignition under proper conditions. The value of the threshold energy density obtained was 2.5 joules/cm^3/sec. Finally, a suggested means of implementation of an acoustic cavitation ignition scheme is given whereby cavitation is developed in a precombustion chamber by an acoustic transducer exterior to the chamber.

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I. HISTORICAL BACKGROUND

A. Liquid Propellant Ballistic Systems

Liquid propellant ballistic systems have been in existence since the Germans experimented with their use during World War II.[1] The United States has been studying the subject with varying intensity since the early 1950's. At this time, the use of hypergolic bipropellants was dominant, and hydrazine/hydrogen pexoxide was the most popular of this type. Interest in bipropellants was on the rise, and study grew to embrace the entire C-H-O-N spectrum. The Naval Ammunition and Net Depot, Seal Beach, was the first to propose the use of hydrazine as a liquid monopropellant[2] for guns.

At this time, thermodynamic studies of various monopropellants and also some bipropellants were conducted, in which hydrazine was examined with nitric acid, hydrogen peroxide, and nitrogen tetroxide. Liquid hydrogen with liquid oxygen was examined, as was aniline and nitric acid.

Of all these systems, liquid hydrogen and liquid oxygen were found to give the best performance.

Until the early 1960's, no significant government supported developmental program was undertaken. However, during the 1950's chemical analysis of the characteristics of existing propellants was performed. Sensitivity, impetus, and thermal stability were the primary characteristics measured and defined. During the early 1960's extensive chemical research was concentrated in the liquid propellant field on the development of a more reliable, safe, and economical liquid propellant. During this period, with interest in caseless preloaded propellants growing, and the interest in hypergolic bipropellants waning, several new ignition concepts were developed. These concepts, which were applicable primarily to liquid monopropellants, included improved pyrotechnic systems, spark ignition, chemical ignition, and compression ignition.

In 1968-69, Naval Air Systems Command revitalized that type of concentrated effort in the liquid propellant ballistic system which would hopefully lead to the development of a workable gun that would be adaptable to the extensive requirements set forth by the U.S. Navy concerning safety, reliability, accuracy, consistancy, and cost.

It became apparent that liquid propellants offered several potential, projected, and/or actual advantages over solid propellant guns. These advantages included:

- Higher impetus propellants.
- Higher muzzle velocities through "Traveling Charge" effect.
- Higher loading densities.
- Elimination of cartridge cases.
- Higher rates of fire.
- Reduced size and weight.
- Reduced storage requirements.
- Reduced or eliminated flash and smoke.
- Reduced gun wear.
- Reduced manpower requirements.
- Lower Cost.

With the experimental work done on Otto fuel in 1971, the current effort began. The Otto fuel was being used as a means of propelling torpedoes at that time, and was used as the propellant in the firing of a gun experimentally in the early 70's. In fiscal year 1974, an extensive effort was begun to develop a potentially fleet-wide gun, using liquid monopropellants. Among those developed were the N.O.S. series[3], currently being used in the primary research effort at the Naval Ordnance Station, Indian Head, Maryland. These propellants are constantly being modified as certain appropriate parameters are redefined, formulated, or discovered.

The primary problems which existed at the outset of this current effort, and prevented the implementation of a liquid propellant ballistic gun system into practical fleet wide use were interior ballistics, fluid handling, and gun sealing. Of these three problems, only that of interior ballistics, which encompasses both ignition and combustion, remains unsolved to a significant degree. Thus, this acoustic cavitation approach is an attempt to progress toward a solution to the ignition problem.

B. Cavitation

Cavitation is broadly defined as the effect due to presence of cavities or bubbles within a liquid which is subjected to a varying pressure. This pressure may be applied acoustically, statically, or by fluid flow.[4]

In 1895 Robert Froude introduced the word cavitation to describe the cavities observed to form in the water near the surface of ship propellers. Rayleigh[5] undertook the first theoretical treatment of the problem when he studied the collapse of a vapor-filled cavity under steady external pressure. His conclusion was that cavities which form on the low-pressure side of a propeller collapse with a violence such that the resulting pressure shock wave created in the water erodes the surface of the propeller.

Blake[6] observed three different phenomena in a focused sound field. At a rather low acoustic pressure amplitude, effervescence of comparatively large bubbles occurred at higher negative acoustic pressures, streamers of long-lived stable bubbles were observed which were called "gaseous" cavities by Blake. At a still lower negative acoustic pressure, he observed a critical pressure, below which occurred the rapid formation and collapse of short-lived so called "vaporous" cavities. Thus, cavitation is generally classified as gaseous or stable when the cavitation intensity is low and vaporous or transient when the intensity is high.

1. Existing Models of Cavitation.

Several models of cavitation bubbles have been proposed by researchers in acoustic cavitation. The simplest of all is the Rayleigh cavity, in which the pressure within the cavity is less than the ambient pressure, and the cavity's pressure remains constant as it collapses, immediately upon its generation in a liquid.[7] This description is valid for a cavity containing only vapor.

Flynn[8] represents the motion of gas-vapor bubbles initially at rest in a liquid by describing two theoretical models. A bubble which oscillates non-linearly about its equilibrium radius is a stable cavity. A contracting cavity whose initial motion approximates that of a Rayleigh cavity until its inward motion is arrested by a rapid rise of internal pressure is a transient cavity. This transient cavity could be either a vaporous transient cavity in which the amounts of vapor and gas may change during a pulsation or a gaseous transient cavity in which the amounts of vapor and gas remain fixed during a pulsation. The cavity pressure is maintained at its equilibrium value by condensation and evaporation of the vapor in the vaporous cavitation.

2. Interest in Cavitation.

Present day research in cavitation is founded in the significant potential that lies in the versatility and useful application of the phenomenon to many situations and processes in the scientific and technological community.

The existence of acoustic cavitation on the face of sonar transducers has long been recognized as a significant limiting factor to the acoustic power that the transducer is capable of radiating into the water.

In 1958, Campbell proposed an apparatus to aid in soldering aluminum and other metals that form surface oxide layers.[9] Also, irradiation of molten metals with high energy sound waves has been shown to reduce the gas content in a solidified metal and also improve the grain structure.[10] Cavitation has been demonstrated as an effective means for promoting dispersion and emulsification of solids and liquids.[11]

Nyborg, Gould, Adams, and Jackson[12] have observed the effect of cavitation on chemical reactions. They have shown that, in several chemical reactions, the rate can be increased, even by "weak cavitation", in which small bubbles form in the region of the transducer. The aforementioned authors related the increased reaction rates to the intense rates of shear in the area of the oscillating bubbles. Cavitation can also be used to promote chemical reactions which would not occur in the absence of an external energy source.

Along with the above catalytic properties, cavitation has been shown to have altered the molecular structure of matter. For example, it has been demonstrated[13] that cavitation has broken up water molecules in a study involving hydrogen peroxide formation in water in the following manner:

$$H_2O \rightarrow H^o + OH^o;\ OH^o + OH^o \rightarrow H_2O_2^*$$

Finally, it has been suggested that cavitation could have been an energy source in the formation of amino acids from the several simple chemical compounds existing in our primeval history and thus indirectly contributed to the evolution of life on the earth.[14]

C. Note on Confidential Nature of the Liquid Propellant Field

Due to the confidentiality of many facts and figures related to liquid propellant development technology, general, inexplicit statements are often used throughout this report when necessary to avoid a security violation.

*The absence of valence signs will be discussed in Section V.

II. INTRODUCTION

This project is concerned with an investigation of acoustic cavitation as a possible source of ignition of liquid monopropellants. It is postulated that this type of ignition would result in a low energy, efficient and safe method.

The previous work accomplished in this area consisted of several exploratory tests conducted in early 1974 by Dr. Lawrence Crum of the U.S. Naval Academy, who suggested this project and served as project advisor. Crum succeeded in causing a partial ignition of the propellant using a ceramic cylindrical transducer which operated at a frequency of 38.6 kHZ.[15] The cavitation produced by this device was concentrated along the axis of the cylinder.

The overall purpose of this report is to present a theoretical and experimental foundation for future development of a practical ignition device for liquid propellant guns which utilizes acoustic cavitation as its energy source. The investigation involved consideration of several alternative means of introducing the ultrasonic energy into the monopropellant. Eventually, a decision was made to utilize an acoustic horn. Several exponential and catenoidal horns were designed, machined from aluminum, and outfitted with ceramic piezoelectric transducers which drove them at various frequencies in the region of 25-35 kHZ. Due to the inability of the above systems to introduce sufficient acoustic energy into the propellant, it was decided to utilize a more sophisticated commercially manufactured catenoidal horn. In this system, a ceramic transducer was driven by a 350 watt ultrasonic generator and the entire system was engineered to operate at 20 kHZ. This system was used to introduce the acoustic cavitation into the liquid monopropellant during the primary measurements of the effects of an acoustic ignition apparatus on the liquid monopropellant. It was found that acoustic cavitation induced a chemical reaction within the monopropellant which, under proper confinement conditions, would have resulted in an ignition of the propellant. An approximate value for the minimum energy density in Joules per unit volume per second necessary to initiate this reaction was determined. It is believed that by a refinement of this data, along with an increased understanding of the inherent characteristics of the propellant by chemists, a feasible acoustic ignition scheme can be developed.

III. EXPERIMENTAL OBSERVATIONS AND RESULTS

A. Present Ignition Techniques

There are presently two ignition techniques being used in the main thrust of liquid monopropellant testing activities. These are pyrotechnic ignition and spark ignition.

Pyrotechnic ignition involves a method which is similar to that used in solid propellant guns.[16] Several high temperature igniters were made based on metal/metal oxide or metal/metal nitrate mixtures initially to achieve favorable ignition consistency. At the present time, lead stiffnate igniters which utilize several grains of bullseye[17] are used to give a reasonably predictable pressure-time curve in most instances. This pressure-time curve is often close to that which is characteristic of ideal propellant burning.[18]

Discharge of a high voltage capacitor bank through the propellant was proposed as an alternative to pyrotechnic ignition as early as 1952.[19] This technique is analogous to the ignition of the gasoline/air mixture in an internal combustion engine. This type of ignition had been consistant, but the decision has been made to suspend active primary testing activities at the present time (April 1975) in favor of the pyrotechnic method.

A final note concerning the laser technique should be mentioned at this time. Tests have been conducted at the U.S. Naval Weapons laboratory at Dahlgren, Virginia, in which a neodynium laser was used to ignite a small quantity of propellant.[20] The focused laser beam ignited the propellant only in the presense of a certain dye of various concentrations which was utilized to increase the light absorption characteristics of the propellant. The results of this work, carried out in the early 1970's, were that the laser could be used successfully to ignite the propellant, but that laser ignition should not be considered as a primary ignition source at this time. It should, however, be considered for future use when knowledge of the composition and characteristics of the monopropellant become better known.

B. Early Acoustic Ignition Schemes

The earliest acoustic device used in the area of liquid monopropellant ignition testing was Crum's cylindrical transducer[21] (See Figure 1). After the initial reaction obtained in March of 1974, the device

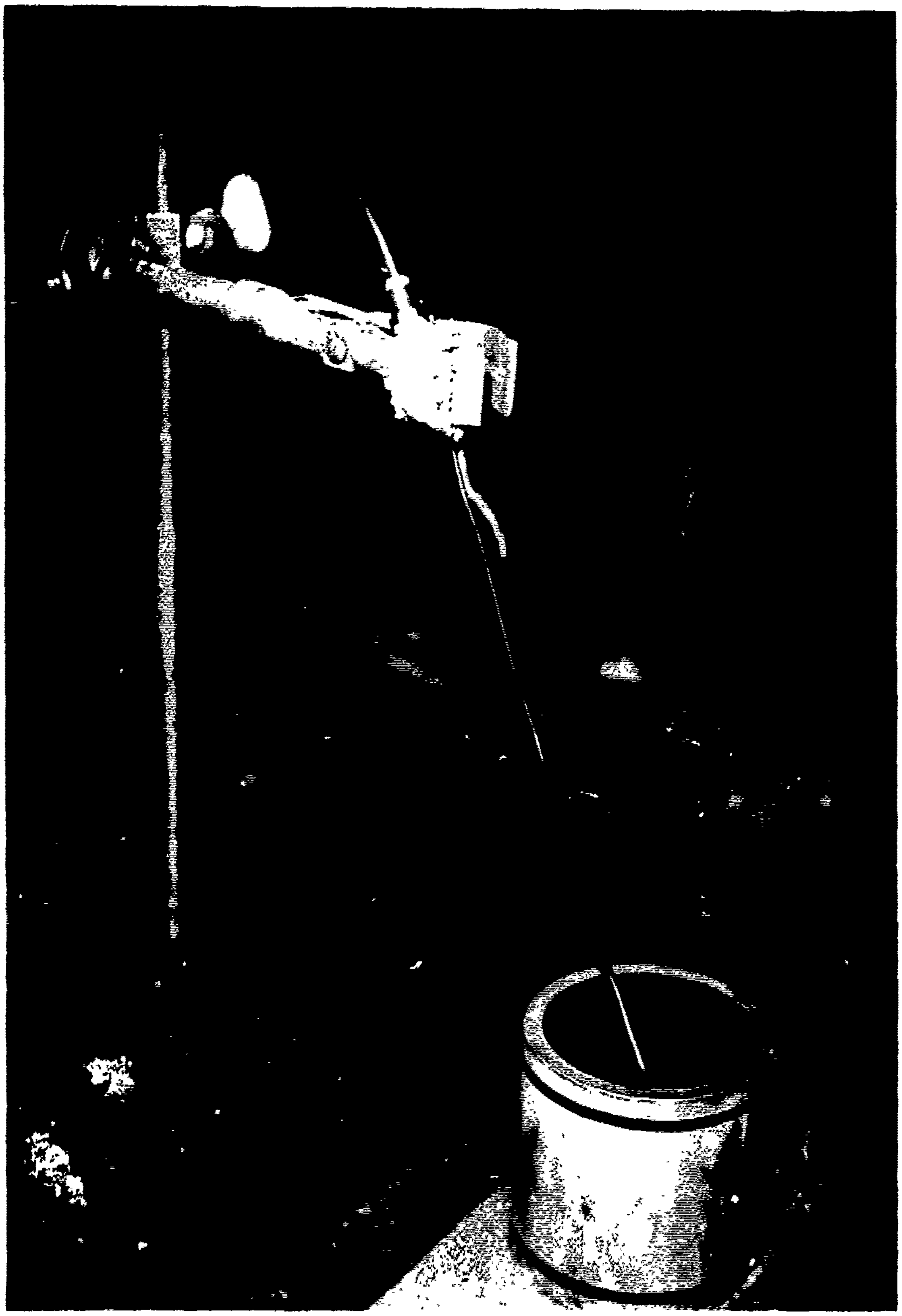


Figure 1. Cylindrical transducer with pressure probe in an experimental arrangement.

was damaged and as a result was not utilized until the fall of 1974. At this time, tests were conducted with the repaired device under the same conditions as occurred in March of 1974. However, no reaction at all occurred. At the time, the only possible explanation for this occurrance lay in the postulated significant difference in the thermal stability of the different lots of the liquid monopropellants used in early and late 1974.[22] At the time of the repeated test with Crum's device there was reason to believe that the lot of propellant used by Dr. Crum during the Spring of 1974 was rather unstable thermally. Later these suspicions proved to be correct.[23]

Several possible schemes were considered for the generation of acoustic cavitation initially. Two early considerations were a focused system of transducer outlets into the gun chamber (See Figure 2) and a large transmission chamber arrangement in which the sound energy is transmitted through another medium resulting in cavitation in the chamber (See Figure 3). These designs, however, were bypassed in favor of the focused horn device shown in Figure 4.[24]

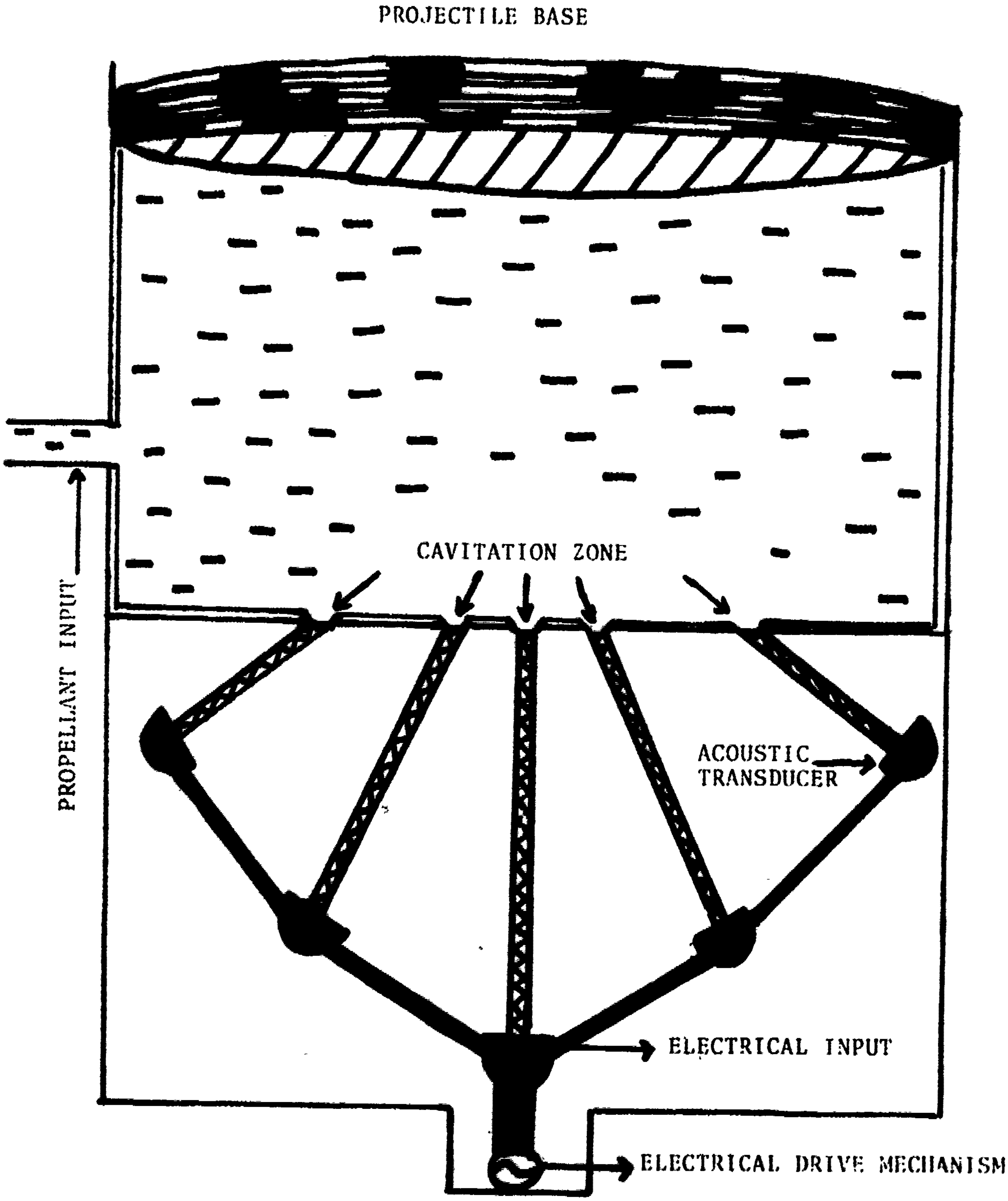


Figure 2. Liquid propellant combustion chamber with focused transducer inputs.

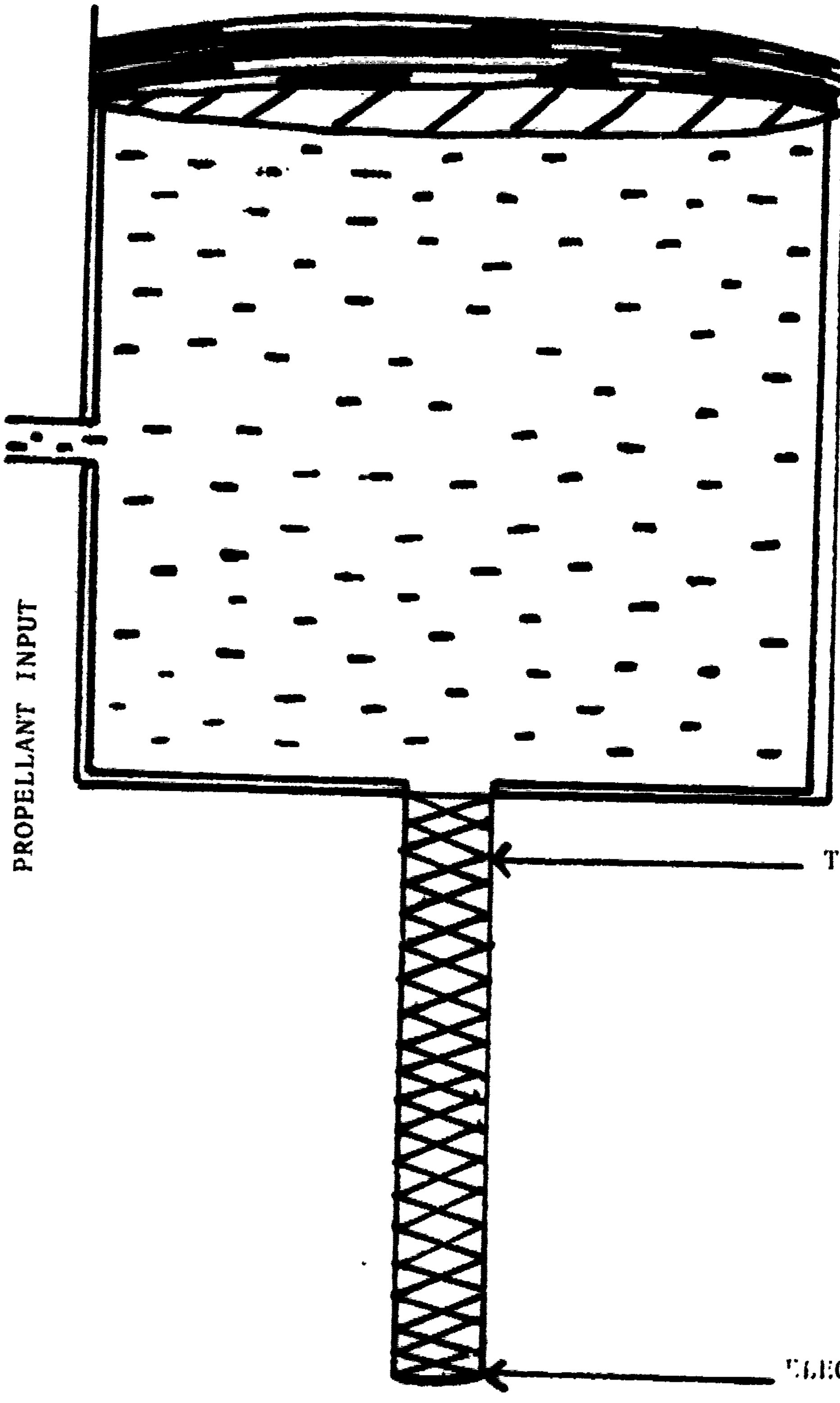


Figure 3. Liquid propellant combustion chamber with recessed transducer design consideration.

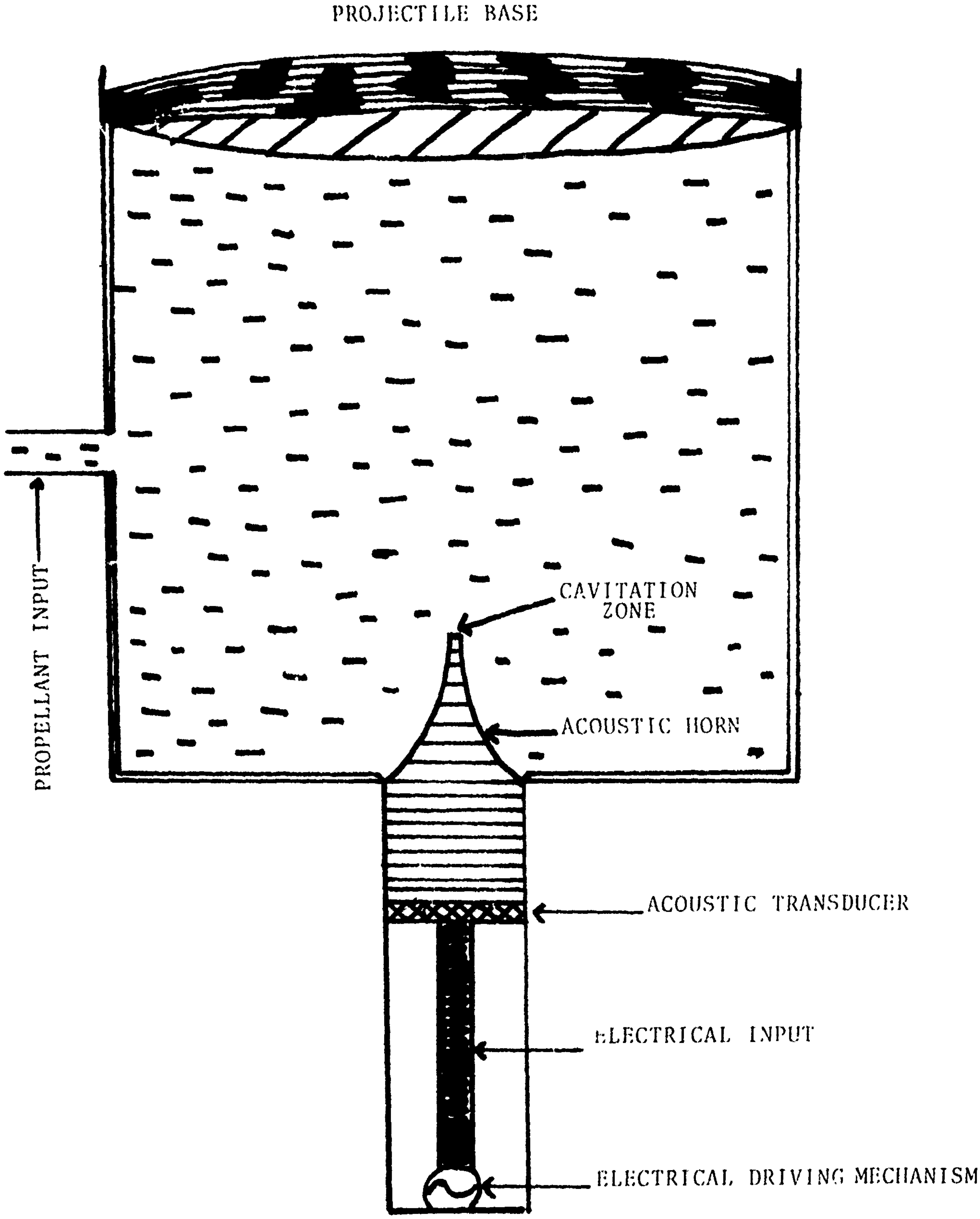


Figure 4. Liquid propellant combustion chamber with acoustic horn device.

C. Design and Ignition Results of Exponential Horns

During the early stages of this investigation initial attempts at designing and machining exponential horns were fairly successful. After a practice horn was machined, work was begun on the first of two exponential aluminium horns, both of which were eventually utilized in liquid monopropellant ignition tests. The machining was accomplished by the author starting with a solid block of aluminum. The finished horn, in the first attempt, was designed such that the amplitude of the tip of the horn was a maximum. A cylindrical disc transducer was mounted to the end of the horn assembly, which included a piece of aluminum as long as the horn between the transducer and the horn. The entire horn was fashioned from one block of aluminum and appeared as shown in Figure 5.

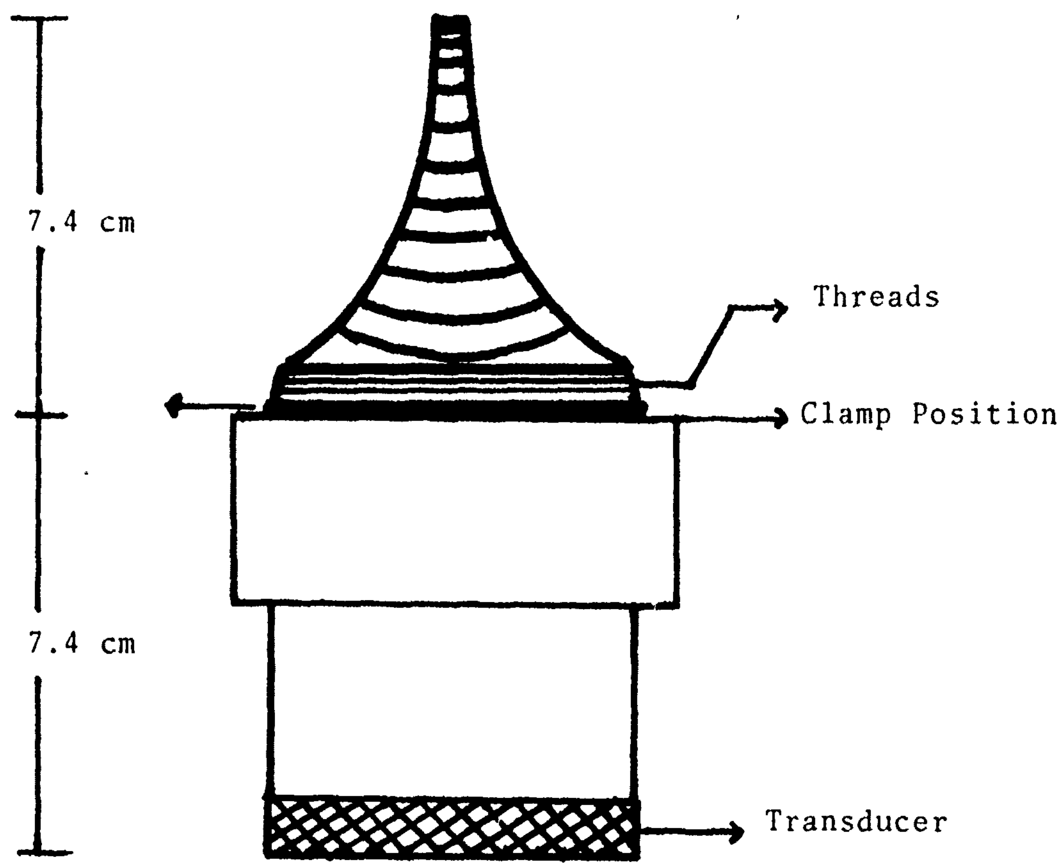


Figure 5. Diagram of exponential horn assembly

The system can be seen in Figure 6 mounted in a glass tube in the firing bay at the Naval Ordnance Station at Indian Head, Maryland. The exponential shape was obtained using a template guide to periodically monitor the gradual machining process until the finished product was achieved. The horn was made 7.4 cm long so that the

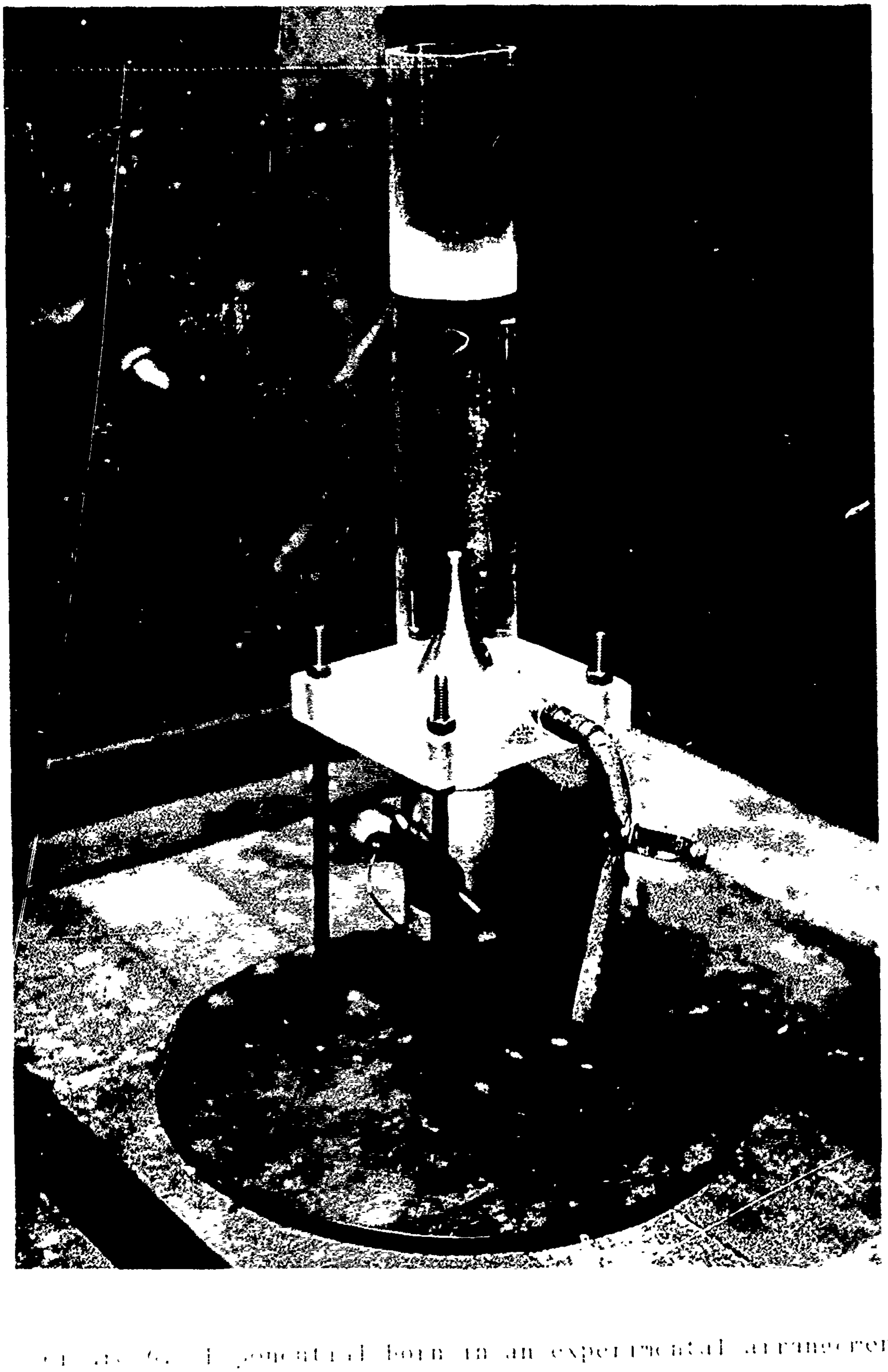


Figure 6. Exponential horn in an experimental arrangement.

maximum amplitude of vibration would occur at the tip. The horn assembly was tested in water and found to cavitate violently at the tip. Due to the nature of the cavitation when observed closely in degassed water, it was ascertained that there was definitely vaporous cavitation present.

The horn assembly was then taken to the Naval Ordnance Station at Indian Head, Maryland to observe the effects of cavitation in the liquid monopropellant. The liquid monopropellant lot number was H-25. The illustration below shows the experimental arrangement:

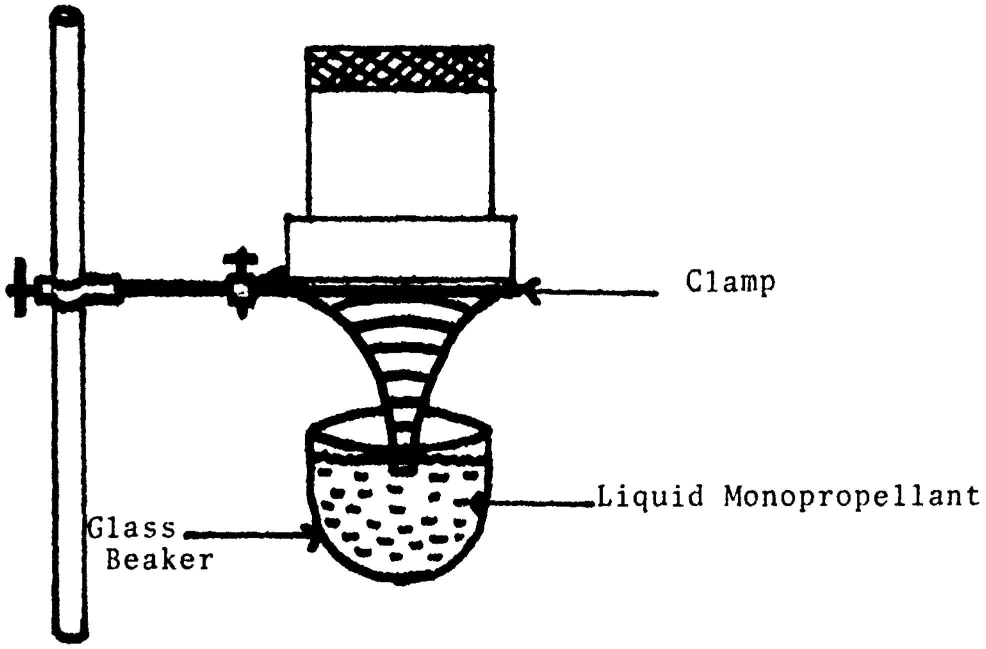


Figure 7. Diagram of experimental arrangement for exponential horn.

The transducer was driven by means of a variable frequency oscillator and a power amplifier. The tip of the horn cavitated violently in the degassed propellant for several minutes after the system was remotely tuned at or near resonance. However, there were no visible effects of the cavitation upon the propellant.

The possible explanations for the negative results postulated at that time were:

1. The resonant frequency of the horn-transducer assembly was not properly engineered.

2. The source of propellant (storage container) was such that it contaminated the propellant so that it was not consistant with proper specifications and, therefore, not representative of the lot as a whole.

3. The size and/or shape of the container affected the cavitation in some way.

At this time it was decided that enough care had not been taken to design an entire horn-transducer assembly. It was, therefore, decided that the design and construction of an improved system was necessary.

D. Design and Ignition Results of a Catenoidal Horn-Transducer System

Since the exponential horn system failed to ignite the monopropellant, and it was thought to be due to design considerations, much care was taken to develop more extensive and exacting design specifications for the catenoidal horn-transducer system.

The catenoidal-shaped horn offered an additional advantage over the exponential horn in that a higher velocity at the tip of the horn was possible (See Figure 8).[25] It was also quite evident that a catenoidal horn offered a greater amplification for a given ratio of large to small diameters (See Figure 9b).[26]

To attain the maximum possible efficiency and effectiveness the catenoidal horn system was designed with several specifications as guidelines initially. The first specification was that the resonant frequency of the system was given according to the formula:[27]

$$f_n = \frac{n}{2}\left(\frac{\ell_1}{C_1} + \frac{\ell_2}{C_2}\right)^{-1} \qquad (3\text{-}1)$$

where ℓ_1 is the length and C_1 the velocity of sound in the transducer material, ℓ_2 is the length and C_2 the velocity of sound in the brass cylinder, and n is the mode of oscillation.

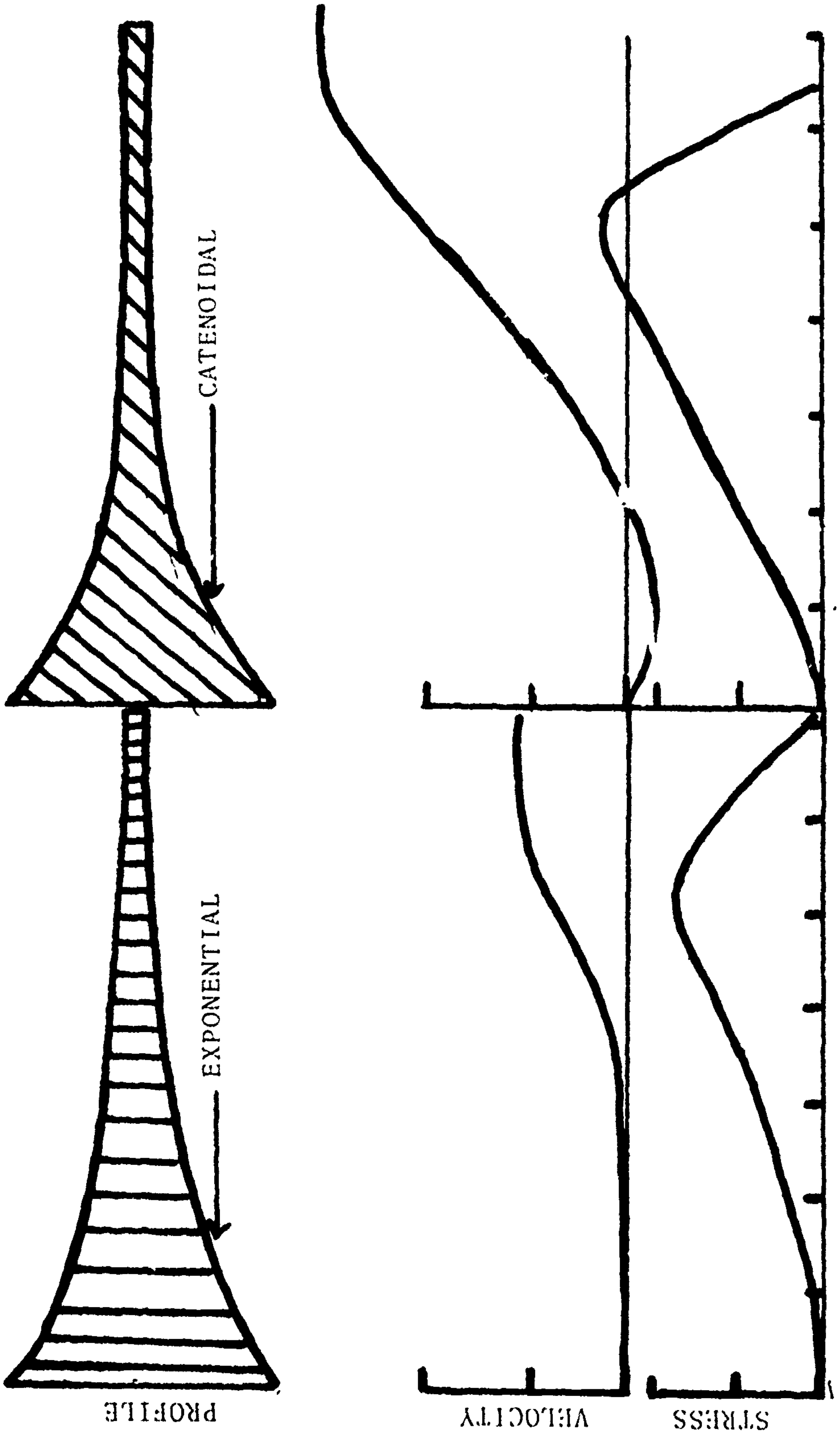


Figure 8. Characteristic comparison of exponential and catenoidal horns for design consideration.

(*Ultrasonic Engineering*, Frederick)

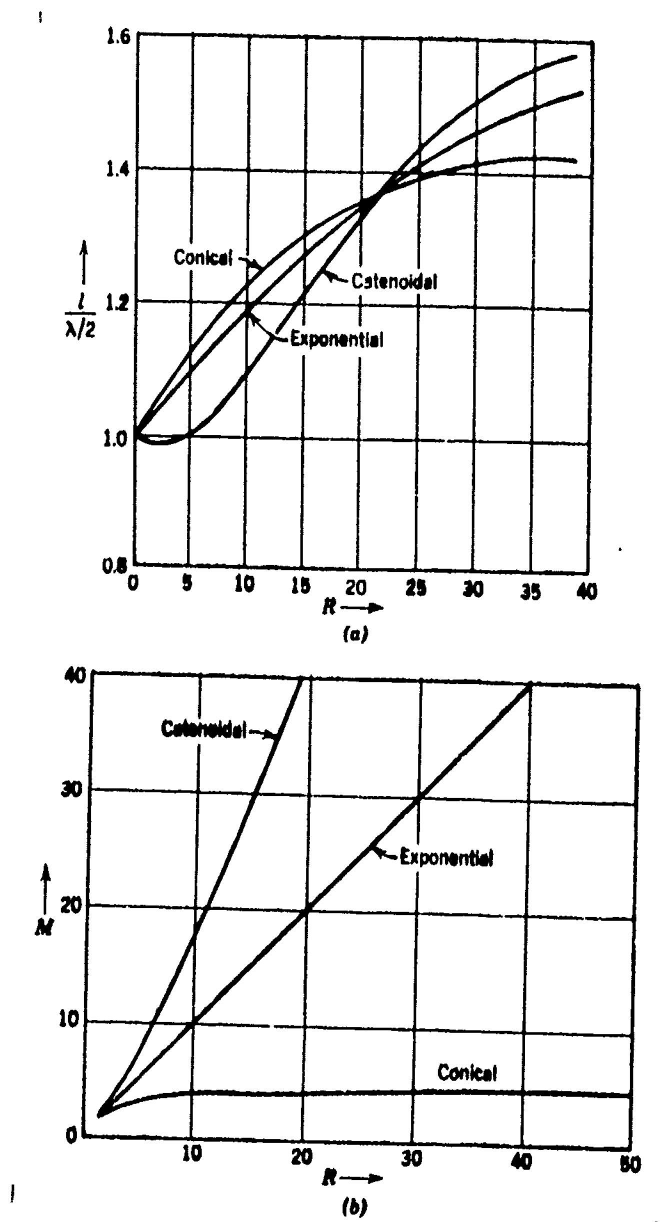


Figure 9. (a) Resonant lengths ℓ for conical, exponential, and catenoidal horns for various ratios of large and small diameters.

(b) Amplification M vs R. (Ultrasonic Engineering, Frederick.)

From Figure 10, the value of f_n can be calculated as 33.3 kHZ.

A new transducer with an individual resonant frequency of 58 kHZ was obtained for use in the design of this horn. The value of λ for this horn was obtained in the following manner:

$$C = \lambda f_n, \qquad (3\text{-}2)$$

where C = speed of sound in aluminum horn = 6.42×10^3 m/sec.

f_n = 33.3 kHZ,

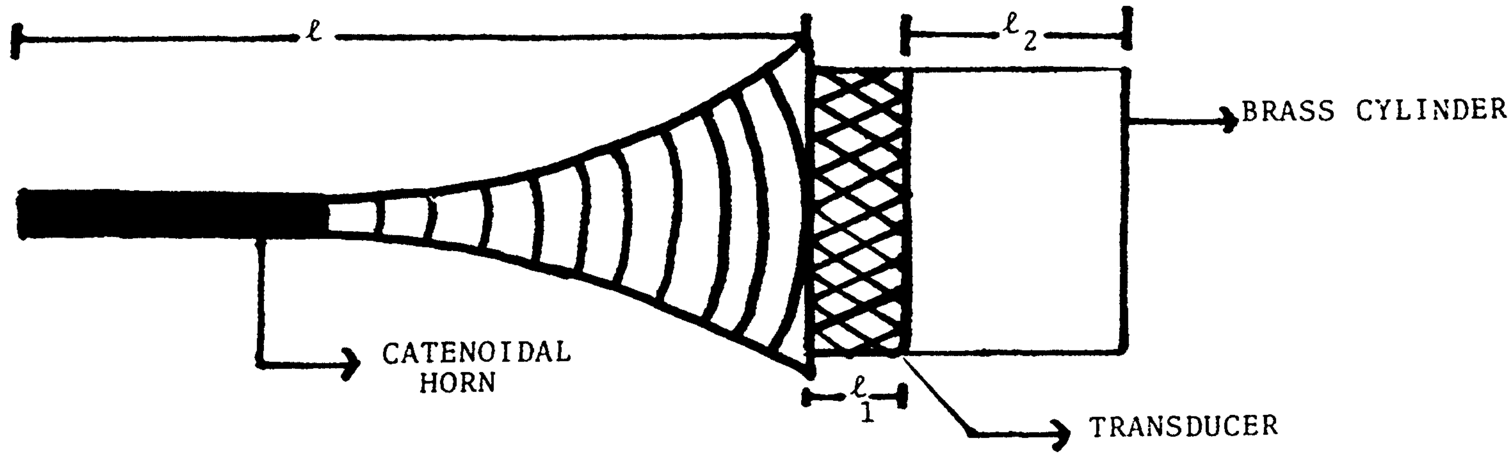
therefore, $\lambda = \frac{6420 \text{ m/sec}}{33.4 \text{ kHZ}} = 0.192$ m.

This calculation of λ can be used in conjunction with figure 9(a)[28], by obtaining a value for $\lambda/2$ of 0.096 m. Obtaining a desired ratio of large and small diameters (10) along with the above information, a resonant length of the catenoidal horn was found as follows:

$$\ell/(\lambda/2) = 1.09 \text{ (From Figure 9(a))},$$

$$\ell = (1.09)\ (0.096) = 0.105 \text{ m}.$$

A further design consideration was the fact that it was not practical to make the large diameter of the horn more than approximately $\lambda/4$ (4.8 cm in this case).[29]



$\ell_1 = 1.28$ cm

$\ell_2 = 3.0$ cm

$c_1 = 1.48 \times 10^3$ m/sec

$c_2 = 4.70 \times 10^3$ m/sec

$$f_n = \frac{n}{2}\left(\frac{\ell_1}{c_1} + \frac{\ell_2}{c_2}\right)^{-1} = 33.3 \text{ kHZ}$$

Figure 10. Design considerations for catenoidal horn at 33.3 kHZ.

The reason is that transverse modes of vibration begin to become excited at larger values, resulting in a loss of energy in the axial mode.

Table 1 summarizes the design specifications and characteristics of the catenoidal horn-transducer system. It can be seen that an extensive effort was made to obtain the maximum efficiency in operation from the system.

TABLE 1

CATENOIDAL HORN DESIGN SPECIFICATIONS AND CHARACTERISTICS	
length ℓ	10.5 cm
small diameter d	0.48 cm
large diameter D	4.8 cm
ratio of diameters R	10.0
system resonant frequency f_n	33.3 kHZ
wavelength λ	0.193 m

When the cavitation test was conducted, the horn was mounted on a glass cylinder with the edge of the glass sloped in order to support the assembly securely at the nodal point (See Figure 11). The horn has been tilted in this figure to present a better picture of how the angle of the glass is cut to contour the horn (note upper edge of glass tube, near red alligator clip). The glass tip at the end of the horn was cemented on to minimize the thermal conduction away from the tip.[30]

The cavitation produced by this horn-transducer system in the liquid monopropellant resulted in an almost identical reaction as the exponential system. The temperature or pressure of the liquid monopropellant did not rise appreciably. At this point it was ascertained that the acoustic energy density input into the liquid monopropellant was not sufficient to initiate a favorable ignition reaction. It was felt that this fact was the result of a combination of two problems:

1. The chamber into which the cavitation was introduced was too large.

2. The energy input potential of the horn transducer assembly was insufficient.

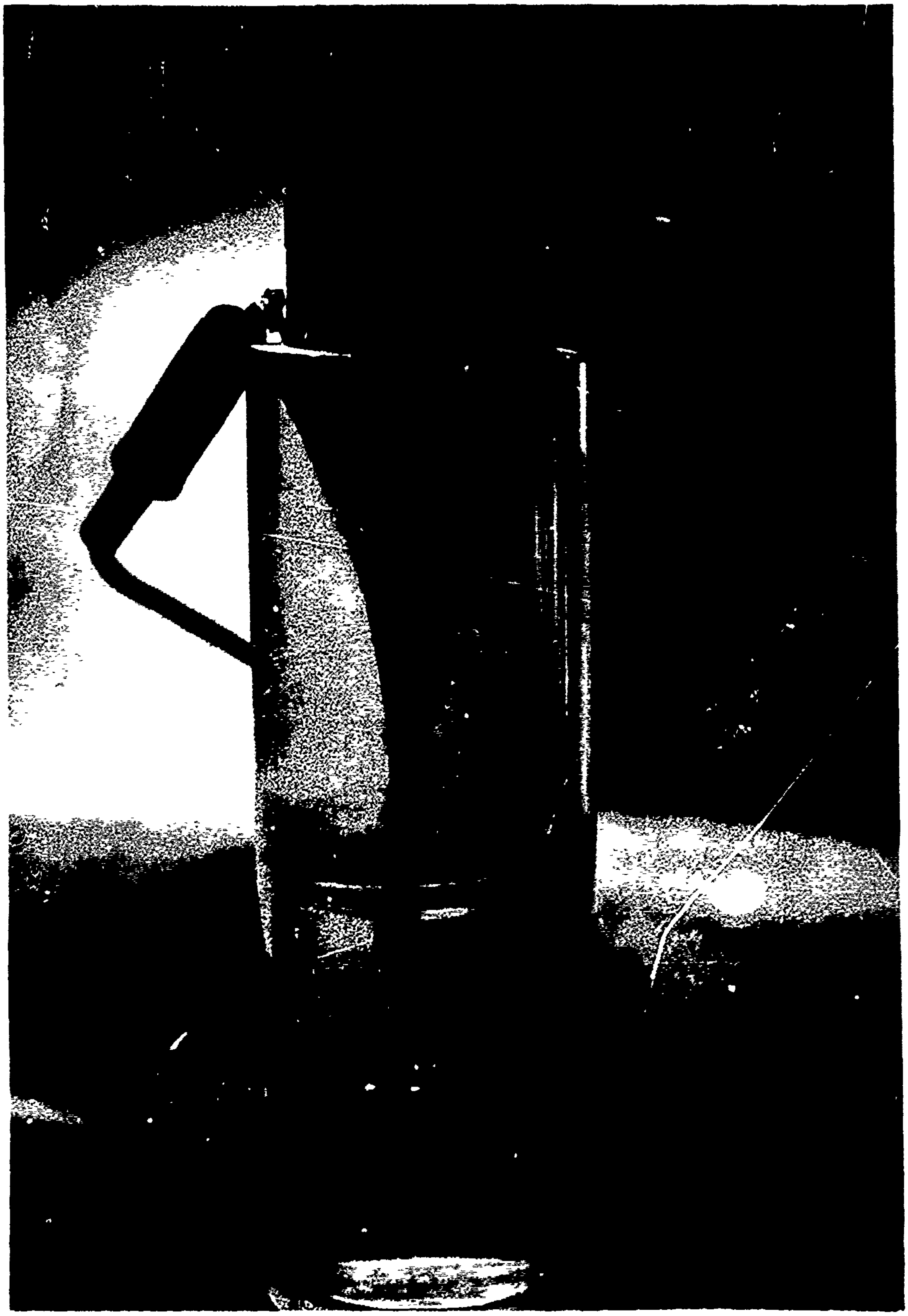


Figure 11. Catenoidal horn in an experimental arrangement.

E. Tests Involving the Dukane Ultrasonic Energy Input System

The Dukane[31] ultrasonic energy input system consisted of a 350 watt ultrasonic generator, a ceramic transducer assembly mounted in a cylindrical housing, and a catenoidal horn for acoustic energy application. In Figure 12 the Dukane horn transducer apparatus is mounted in a ballistics test fixture in the firing bay at the Naval Ordnance Station, Indian Head, Maryland. It was felt that the sophisticated nature of this system, which was precision tuned to 20 kHZ and delivered an exceptionally high amount of acoustic energy at the tip of the horn, would yield a significant result at this point in the investigation.

Before utilizing the horn transducer apparatus for inducing a cavitation reaction in the liquid monopropellant, a test was run in a beaker of water. The cavitation which resulted in the beaker was extremely violent and caused a significant effect on the water, not only cavitating it, but displacing the water and raising its temperature (See Figure 13). Therefore, it was ascertained that due to the high power output of this system, along with the aforementioned favorable system characteristics, a definite statement could be made concerning the feasibility of

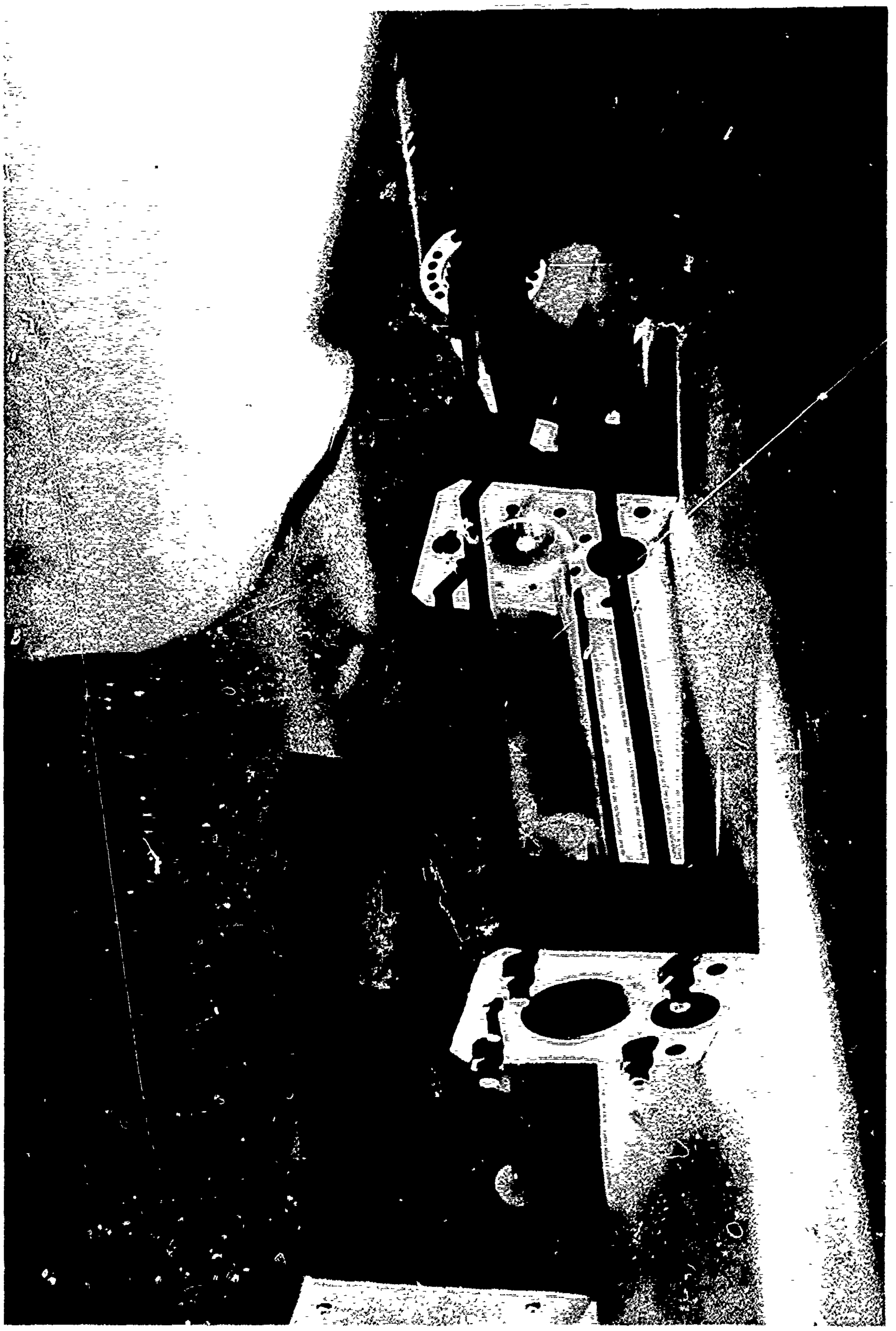


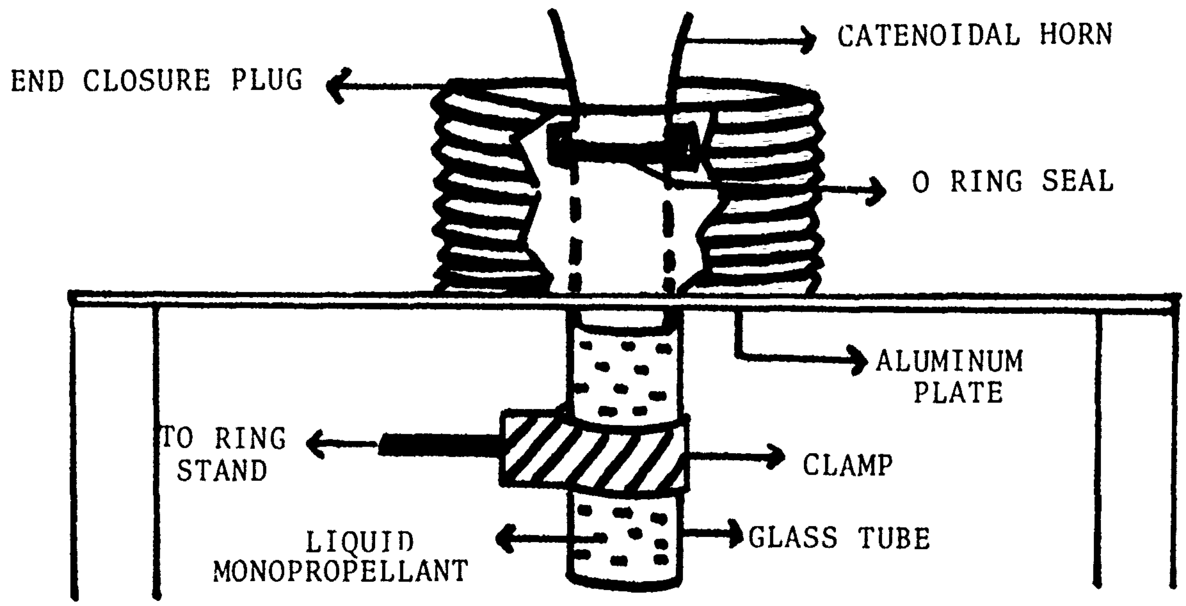
Figure 12. Dukane ultrasonic system as arranged for testing in ballistic chamber.

Figure 13. The Dukane horn as seen cavitating in water within a glass chamber.

ignition of the liquid monopropellant by an acoustic cavitation technique after tests were run in the propellant.

An additional testing consideration examined before an experimental cavitation run was conducted with this system was that of a suitable container to hold the liquid monopropellant. In several discussions with Dr. Michael S. Wieland at the U.S. Naval Weapons Laboratory, Dahlgren, Virginia, additional insight into the above design consideration was obtained.[32] Based on his past tests with ignition of the liquid monopropellant utilizing laser techniques,[33] Dr. Wieland noted that there were probably considerable radiation losses in a test arrangement such as that in Figure 11. Therefore, it was decided to use an arrangement which minimized the amount of excess propellant surrounding the horn tip. An ideal situation would, therefore, be one in which there was propellant only at the face of the horn tip with none on the sides. It was decided that an arrangement using a test tube for holding the propellant, as shown in Figure 14, which was approximately the same inside diameter as the horn's tip should be utilized for testing.

The cavitation test in the liquid monopropellant resulted in a definite reaction, which was later explained



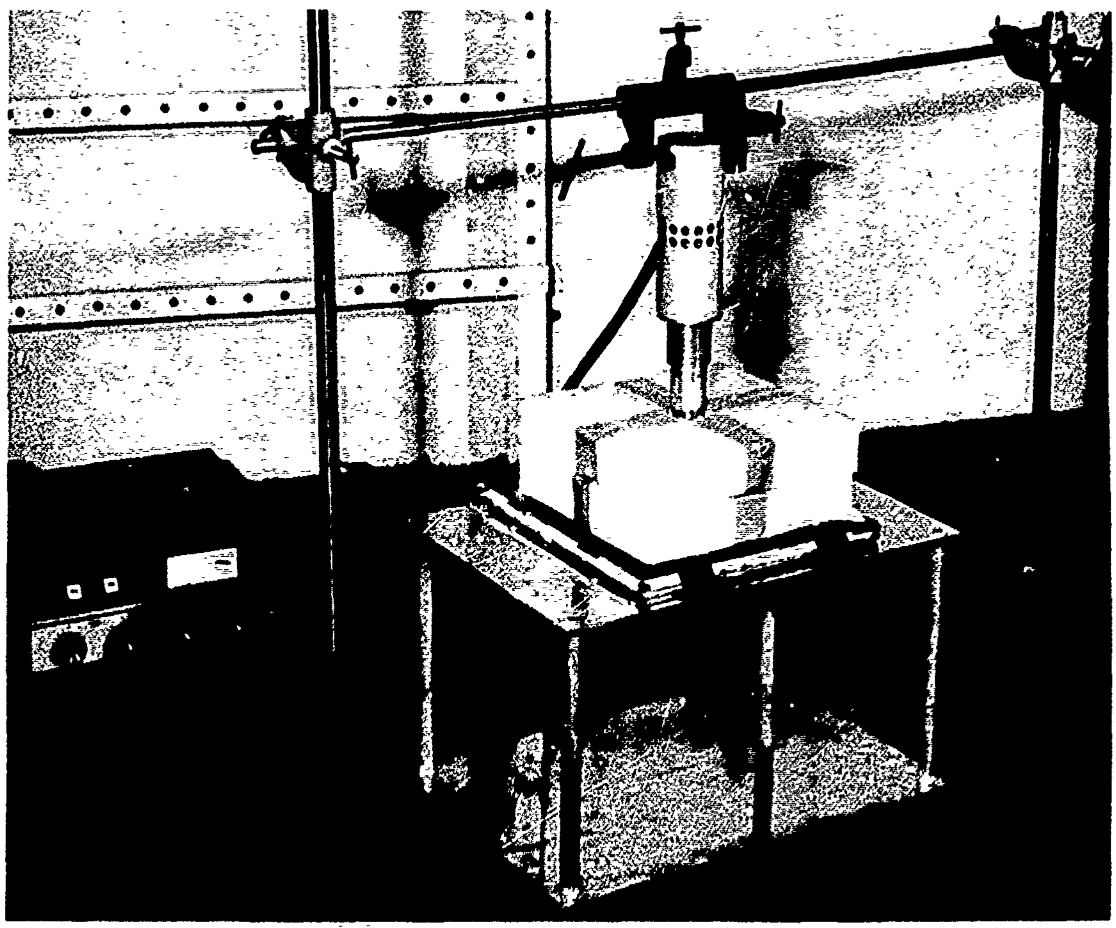


Figure 14. Lab testing set-up for Dukane ultrasonic system. Top shows obstructed section of overall figure.

as an oxidation reaction.[34] The horn was driven for several seconds, and although the event was captured on video-tape, no photographs were taken. However, Figure 15 is the author's conception of the appearance of the tube during the reaction. The contents of the test tube were analyzed by Dr. Chang[35] of the Naval Ordnance Station, Indian Head, Maryland, and she concluded that, had the reaction taken place under a pressurized condition (as opposed to in the open air test tube), rapid combustion of the liquid monopropellant would have definitely occurred.

F. Energy Density Tests: Calibration and Measurement

Due to certain factors which were inherent in the status of the investigation at this point, it was decided to direct the remaining research efforts toward a measurement and determination of the minimum energy density necessary to initi...e the aforementioned chemical reaction at atmospheric pressure*.

*Further details concerning nature of reaction are given in theory section.

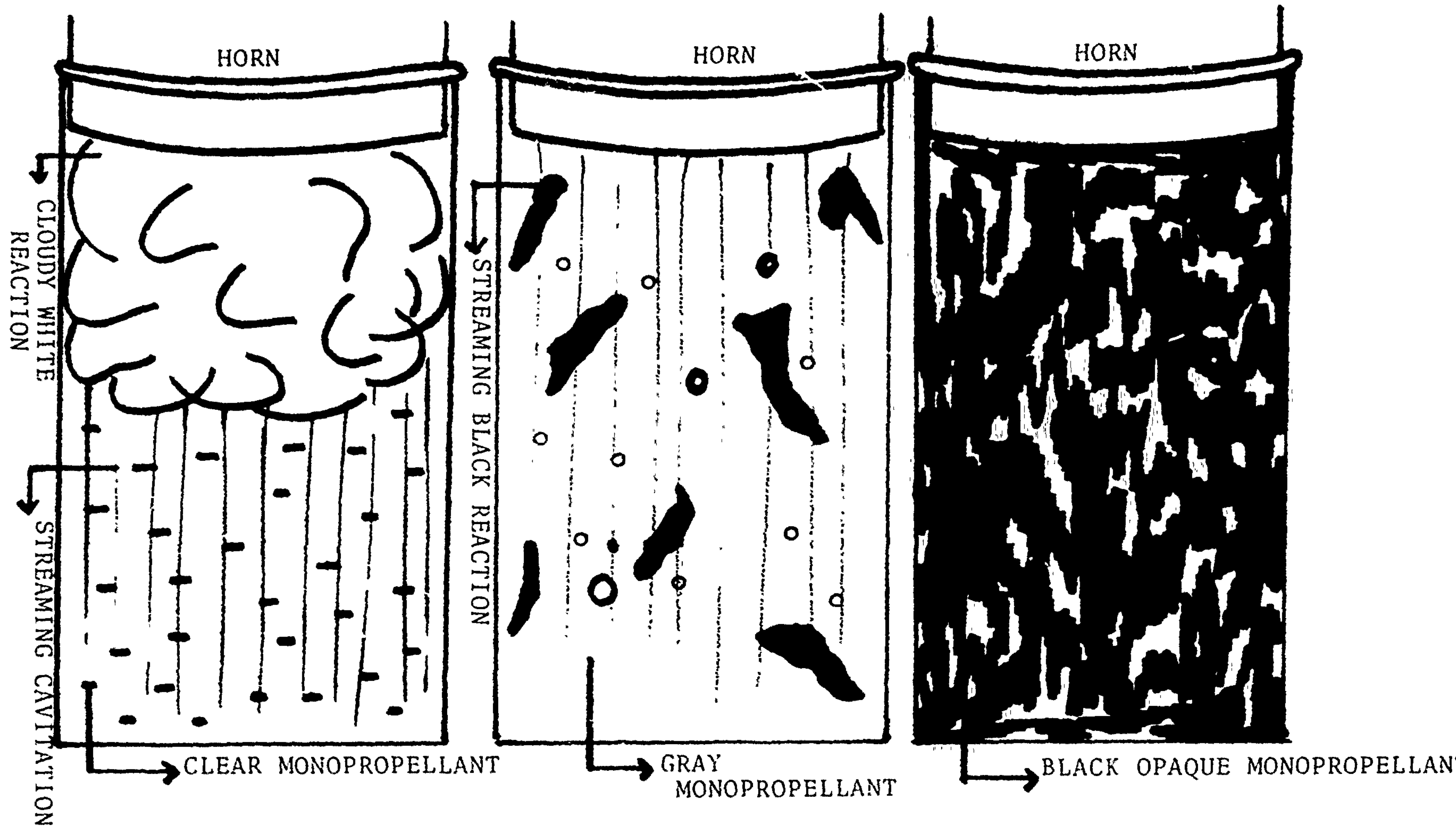


Figure 15. Three stages of reaction induced by acoustic cavitation in tube from Dukane horn.

The factors involved in this decision were as follows:

1. Adaptation of existing research and experimental facilities for the meaningful development of an acoustic ignition scheme would involve a material and financial venture which would not be within the scope of this project at the present time.

2. The decision had been made to direct personnel time and effort toward the development of a much improved pyrotechnic ignition scheme in the near future.

3. Partial ignition had been achieved by Crum and the chemical initiation reaction which was a result of this investigation had been termed as a definite initiation of the combustion sequence by Dr. Klein* and Dr. Chang.

4. The measurement of a value for the minimum energy density required to initiate the chemical reaction in the time frame available at this point on the remaining portion of the investigation would be both possible and significant.

*Dr. Klein is head chemist at the Aberdeen Proving Grounds, Aberdeen, MD., who was also consulted at this point.

To determine a meaningful value for a minimum energy density in Joules/unit volume/sec required to initiate the aforementioned chemical reaction at atmospheric pressure and temperature, the following procedure was utilized:

1. The ultrasonic system was calibrated in a calorimeter using a 38% $ZnCl_2$ aqueous solution which had the same density, consistency and characteristic impedance as the liquid monopropellant.

2. From the calibration curve, the amount of power (Joules/sec) input into the propellant at various dial settings is know. The horn system insonified chambers of various diameter which were cylindrical in shape. The chambers were all 6.35 cm in length with diameters from 0.906 cm to 3.81 cm. The effective "volume of influence" in which the cavitation occurs can thus be calculated in each case.

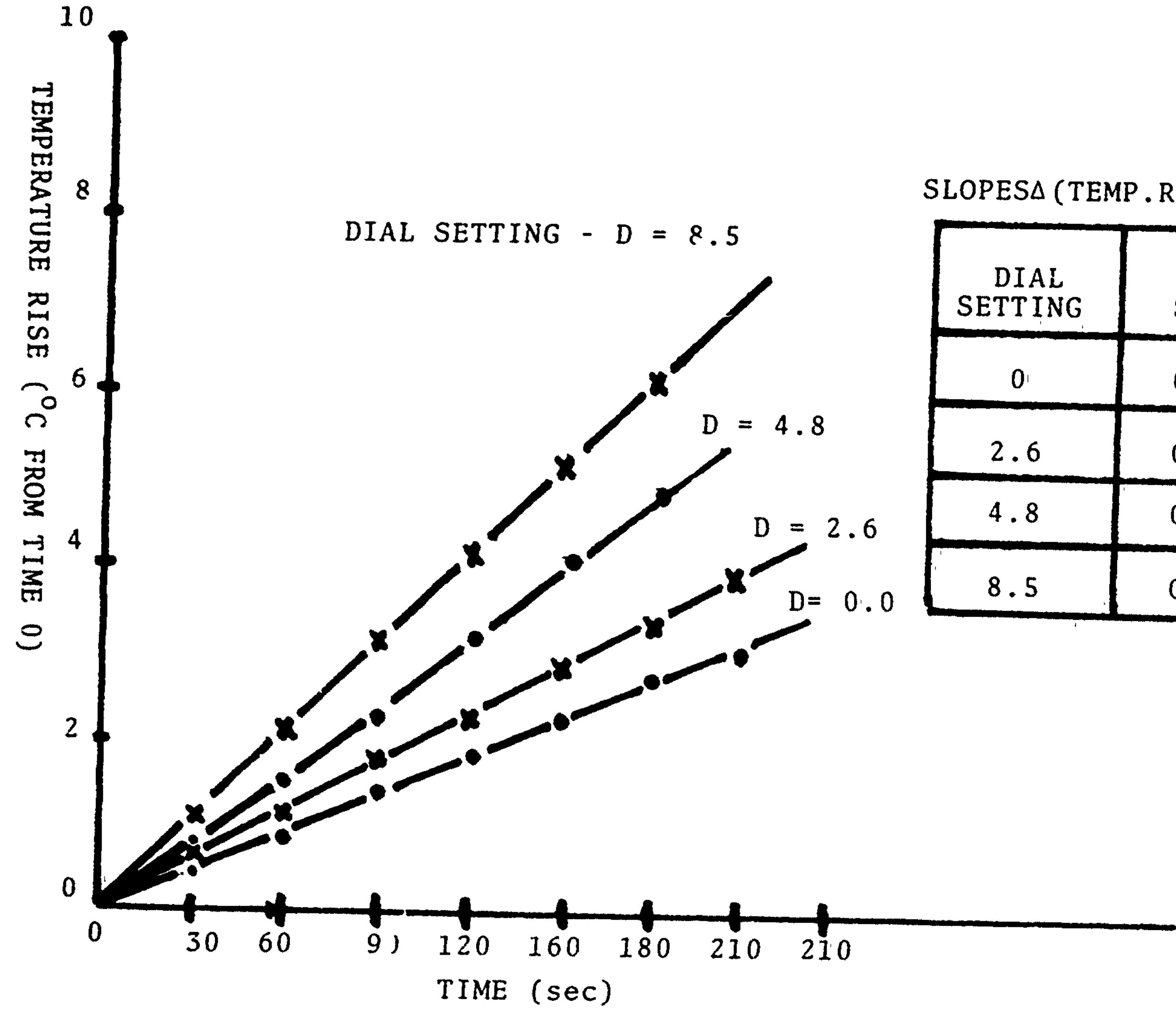
The results of the calorimeter calibration are shown in Table 2 and Graphs 1 and 2. Since the acoustic power input into the monopropellant was determined for the 38% $ZnCl_2$ aqueous solution, it was, therefore, possible to calibrate the output of the horn into the monopropellant.

TABLE 2

Power calibration of Dukane ultrasonic system in calorimeter.

Data:
- ρ monopropellant ≈ ρ 38% $ZnCl_2$ = 1.4 g/ml
- Volume (38% $ZnCl_2$ aqueous soln.) = 250 ml
- Specific Heat $ZnCl_2$ soln. C_Z = 4.180 J/g-°C
- Specific Heat Monopropellant C_m = 2.385 J/g-°C
- Initial Conditions p = 14.7 psi, T_o = 23.7°C
- For this determination, C_Z, C_m, ρ_Z, ρ_m are assumed constant over entire temperature range.
- Additional Information: Horn assembly was mounted vertically in end-closure plug as in Figure 14 to simulate ballistic test chamber condition and placed in double cylindrical calorimeter.

RELATIVE OUTPUT DIAL SETTING (1-10)	0	2.6	4.8	8.5
TIME (sec)	TEMP. (°C)	TEMP. (°C)	TEMP. (°C)	TEMP. (°C)
0	36.3	31.2	23.7	40.3
30	36.7	31.8	24.4	41.45
60	37.2	32.3	25.2	42.4
90	37.7	32.9	26.0	43.4
120	38.1	33.4	26.9	44.4
150	38.5	34.0	27.8	45.4
180	39.0	34.5	28.6	46.4
210	39.4	35.0	29.4	--



SLOPESΔ(TEMP.RISE)/Δ(TIME)

DIAL SETTING	SLOPE
0	0.015
2.6	0.0183
4.8	0.0272
8.5	0.0338

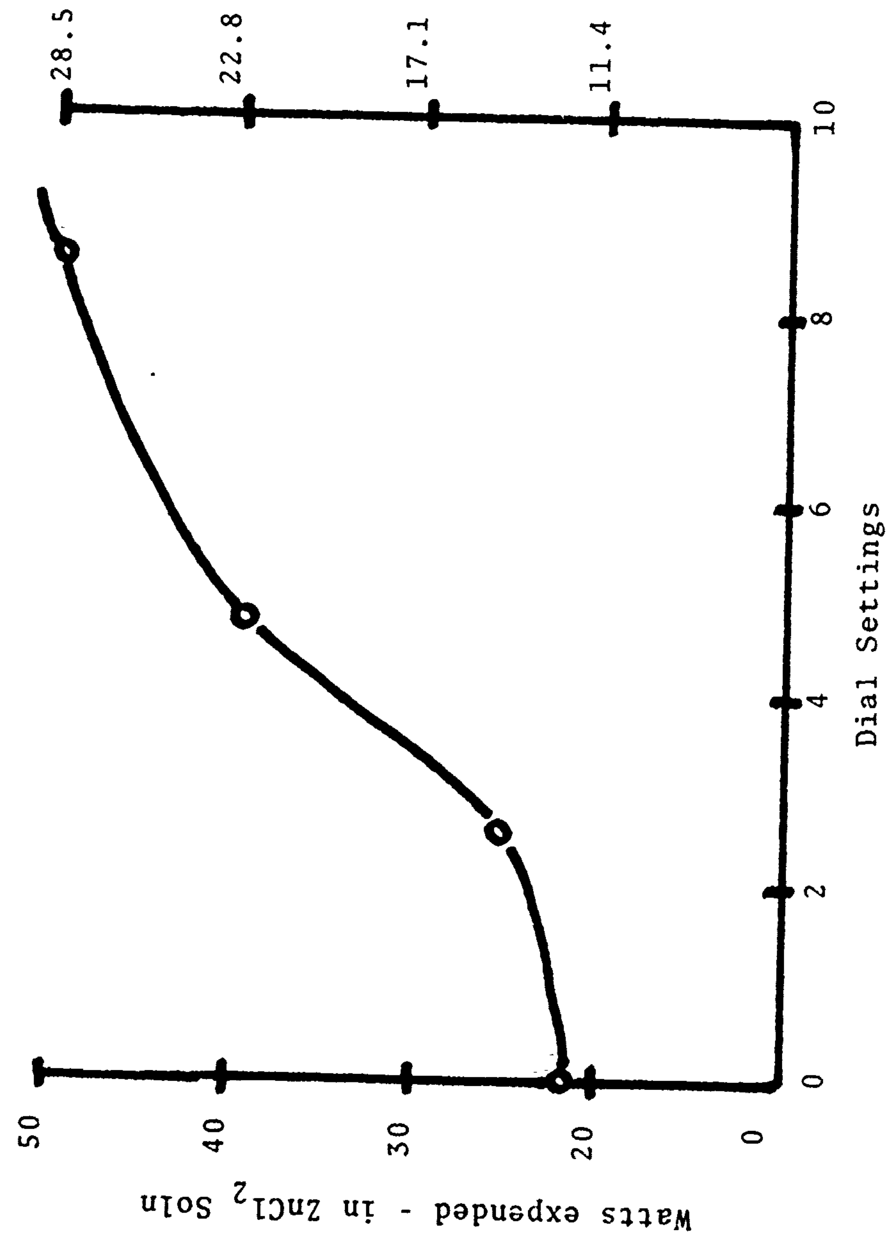
GRAPH 1
Temperature rise (°C) vs. Time (sec)

GRAPH 2

Power (watts) vs Output dial settings

A. 38% $ZnCl_2$ SOLUTION - POWER = (250ml)(4.18J/oCg)(1.4g/ml) $(\frac{\Delta^o C}{\Delta time}) = \frac{J}{sec}$

B. LIQUID MONOPROPELLANT - POWER = (250ml)(2.385J/oCg)(1.4g/ml) $\frac{(\Delta^o C)}{\Delta time}$ = J/sec



A summary of the energy density results is presented in Table 3. The acoustic system was mounted with the horn transducer assembly in a vertical position, as in Figure 14, for all measurements except one. The measurement in the 3.81 cm diameter chamber (existing monopropellant ballistic gun chamber) required a horizontal mounting.

It should be noted that a characteristic "volume of influence" was developed as a standard of measurement. The reasoning behind the utilization of this cone of influence is explained in Table 3.

The results of the energy density measurements, therefore, indicate a low minimum energy density necessary to initiate the chemical reaction at atmospheric pressure. This threshold can be specified as the lowest value of energy density because the requirement of a pressurized gun chamber would increase the energy required. This pressurization has been postulated as necessary to allow the initiation reaction to permit combustion of the propellant. To maintain the minimum negative pressure condition necessary to sustain cavitation, the minimum energy input into the propellant at higher chamber pressures is still required. However, due to greater system inefficiencies at these higher pressures, an

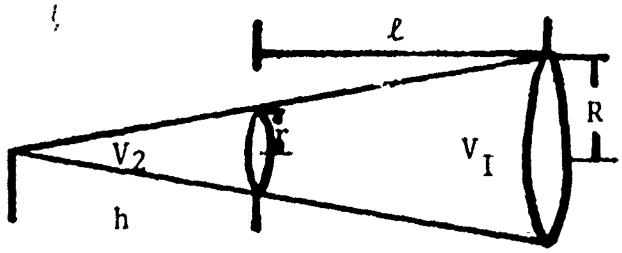
TABLE 3

Energy density determination for monopropellant lot H-27

DIAL/ POWER	RUN #	DIAMETER cm	$\pi r^2 \ell / V_I$*cm^3 cylinder/ cone	$J/cm^3 sec$	REACTION
8.5/28.5W	1	0.9906	4.89/4.85	5.88	POSITIVE
2/17.1W	2	0.9906	4.89/4.85	3.53	POSITIVE
8.5/28.5W	3	1.905	18.1/9.77	2.92	POSITIVE
8.5/28.5W	4	2.54	32.2/15.6	1.83	NEGATIVE**
8.5/28.5W	5	3.81	72.4/30.7	.929	NEGATIVE

**Did not react in computer timed one second burst, but did after another such burst. Therefore, lower limit lies between values of runs #3 and #4. Approximate, although characteristically representative minimum value of $2.5 J/cm^3/sec$ sec is postulated. Due to the amount of uncertainty introduced by both random volumetric distribution of cavitation and calorimeter calibration correlation, this approximation is justified.

* Volume of influence V_I determined from approximate visual limit of cavitation injection into chamber at horn tip radius r, up to length (ℓ) of 6.35 cm. At this length chamber diameter (2 x R) has been reached - therefore, volume of equivalent cone is used (See below illustration).



$$V_T = V_I + V_2 = V_{Total}$$

$$V_I = V_T - V_2$$

$$V_T = 1/3 \pi R^2 (\ell + h)$$

$$V_2 = 1/3 \pi r^2 h$$

$$V_I = 1/3\ \pi\ (R^2(\ell + h) - r^2 h)$$

$$V_I = 1/3\ \pi\ (R^2 \ell + h(R^2 - r^2)$$

increase over the minimum required energy density value at atmospheric pressure will occur.

IV. THEORY

A. Interior Ballistics

The interior ballistics processes in liquid propellant gun systems research are considerably more complex and difficult to investigate than those of solid propellant guns.[36] The two major reasons for this are:

1. The liquid, when burning has no definite surface, which predicates the lack of an adequate surface time history.

2. Liquid flow in the gun makes the standard equations of pressure and density distribution in the gun no longer applicable.

If a propellant injection system is introduced, these problems are eliminated, but the problems of injection rate, ignition delay, and charge-to-mass ratio as a function of time take their place. The fact that round-to-round variations can be typically much higher than in the solid propellant case further complicates the situation. The interior ballistic cycles of preloaded*

*Preloaded gun - where a defined volume chamber is loaded with propellant before each shot.

and injected* liquid propellant guns are substantially different; therefore, a brief treatment of each will be presented.

1. Injection Liquid Propellant Guns

Early in the development of liquid propellant gun systems, studies of the interior ballistics of injection liquid propellant guns were undertaken by Experiment, Inc., in conjunction with other developmental efforts under a contract to Frankford Arsenal. The approach used at this time was to modify existing solid propellant interior ballistics models to match assumptions made of the interior ballistics cycle of liquid propellant guns.

The first study, published in 1952,[37] supported the development of injection systems. The assumptions which were made in this theory were:

- Mass ratio is variable.
- Motion of the oriface value is complete before ignition.

*Injected gun - where a variable amount of propellant may be injected into the chamber, controlling combustion rate and performance.

- Propellant burning is instantaneous.
- Motion of piston to produce initial contact of propellant is insignificant.
- No frictional forces exist.
- No pressure differential from breech to projectile base exists.

An extension of this effort was begun shortly thereafter which incorporated effects of the pressure variation in the base and of the initial velocity of the injected liquid.[38] It was found that the theoretical expression used for the interior ballistics of regenerative (i.e., making use of pressure and energy that would normally be unused) injection liquid propellant guns was similar to the equations for a solid propellant gun with a non-linear burning rate. This is reasonable because with solid propellants, the regression rate is dependent on the pressure, and, in regenerative injection systems, the rate of injection (and, therefore, combustion) is also dependent on the chamber pressure. Experimental and theoretical studies on interior ballistics of liquid propellant guns in the early 1950's[39] evaluated most aspects of liquid propellant gun technology, including thermodynamics, ignition, and combustion chamber geometry.

Theoretical results, which encompassed studies of both injected and preloaded systems, showed that the injection gun would give better overall performance than a preloaded gun, since the pressure drop from the breech to the projectile base is minimal.[40] The studies showed a greater pressure drop in the preloaded gun.

2. Preloaded Liquid Propellant Guns

The initial work done on the preloaded gun systems involved numerous problems due to the characteristic lack of technological experience at that time. Therefore, due to these problems of heat transfer and pressure-time relationships in the early experimental stage of the liquid propellant itself (which involved problems such as hydrodynamic surface instabilities), the preloaded gun systems were judged as generally inferior. However, as the state of the art in the liquid propellant technology field improved, and more extensive research and improvement programs were initiated, advances in the area of preloaded gun systems became significant.

The Army Ballistic Research Laboratory (BRL), presently Aberdeen Proving Grounds, published the first in a series of reports on the interior ballistics of low ullage* preloaded liquid propellant guns[41] in 1963. After 1963, preloaded liquid propellant gun systems progressed until, at the present, the primary thrust of liquid propellant gun research utilizes some form of preloaded ballistic system.

The goal of the existing interior ballistics at this time is to prepare a unified theory that will include the effects of ignition energy input, propellant motion, burning rate, scale factors, gun geometry, hydrodynamic mixing of phases, and wave dynamics. A more specific goal is the development and refinement of liquid propellant gun combustion.

Propellant ignition is the specific area of interior ballistics about which this report is concerned. However, the following information regarding theoretical interior ballistics forms a formidable foundation upon which observations and conclusions can be based.

*ullage - the amount of air trapped in the chamber which the propellant does not displace.

3. Present Methods Used in Interior Ballistic Research

During late 1974,[42] a considerable amount of progress was made in a master modeling effort at the Los Alamos Scientific Laboratory, Los Alamos, N.M. The new code (or experimental approach) known as the CHOLLA code, which was modified to allow for propellant combustion and projectile motion, is shown in Figure 16. Comparison of the CHOLLA code with the previously run RICE code, shown in Figure 16, in which a complete run was made for the same problem, shows good agreement between the codes with minor discrepencies that are directly attributable to differences in the two numerical procedures. It can be seen from this graph how the pressure-time characteristic of a liquid monopropellant gun firing appears in general.

Two comparison runs were made with the RICE code on the effect of the breech face geometry on the igniter jet. Input assumptions which were used to determine the effect of the breech face geometry on the igniter jet are given below (with purely experimental unitless, but interdependent, proportional values)

(1) Number of Computational Cells:

Parameter	r-direction	z-direction
Ignition Chamber	4	5
Vent	2	5
Burn Chamber	15	40

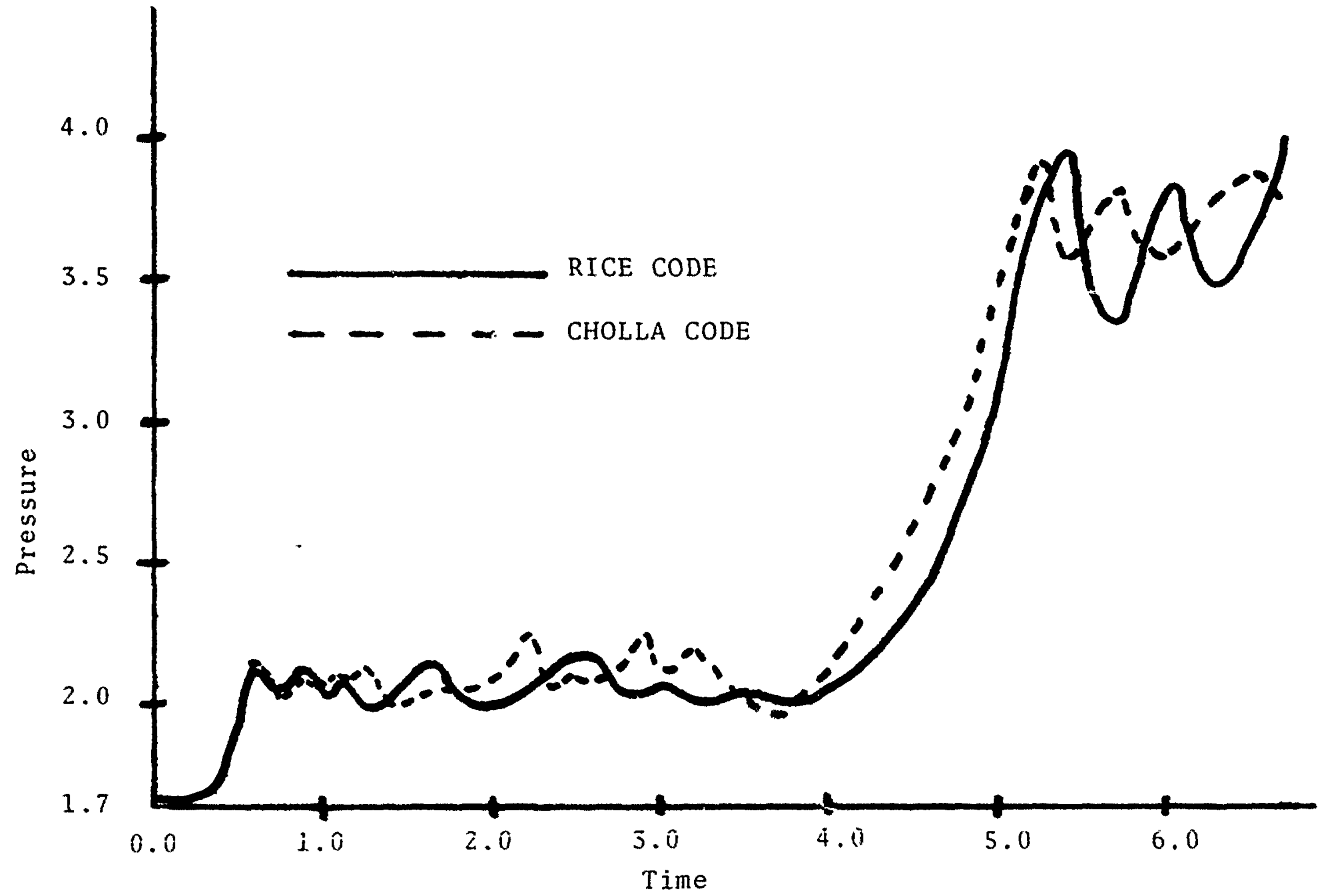


Figure 16. CHOLLA/RICE Code comparison.
(Indian Head N.O.S., Liquid Monopropellant Gun Quarterly Report, Oct-Dec. 1974)

(2) RICE Igniter Region Calculations

Equation of state : $p = (\gamma - 1)\ \rho\ T_{CV}$ (4-1)

$V = 2.0$

$CV = 1.255$ (liquid)

$= 0587$ (gas)

CHEMISTRY: liquid → gas + Q

$K = C_e^{-E/T}$

$C = 75.0$

$E = 10.0$

$Q = 2.82$

(3) Initial Conditions

Parameter	Density (ρ)	Temperature (T)
Ignition Chamber	1.37	8.72
Burn Chamber	1.37	1.00

Figure 17 shows the geometry used in igniter region calculations, and Figures 18(a) and 18(b) show a comparison of the output of the two runs made with the RICE code. The runs assumed fluid properties which were not wholely representative of liquid monopropellants although they had been used previously.

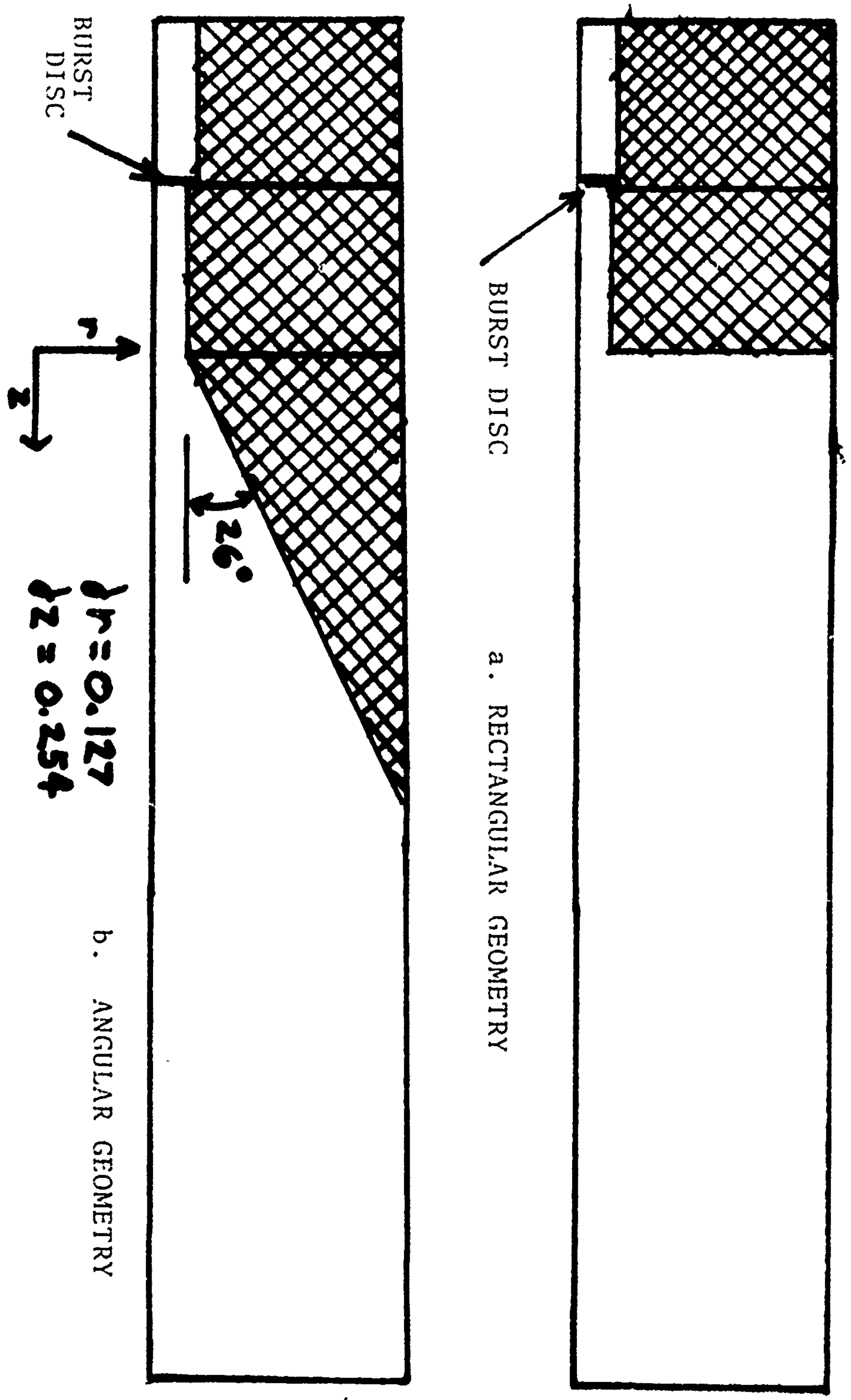


Figure 17. Rectangular angle and angled geometries used in igniter region calculations.

(Indian Head, N.O.S. State-of-the-Art Survey of Liquid Propellant Gun Systems).

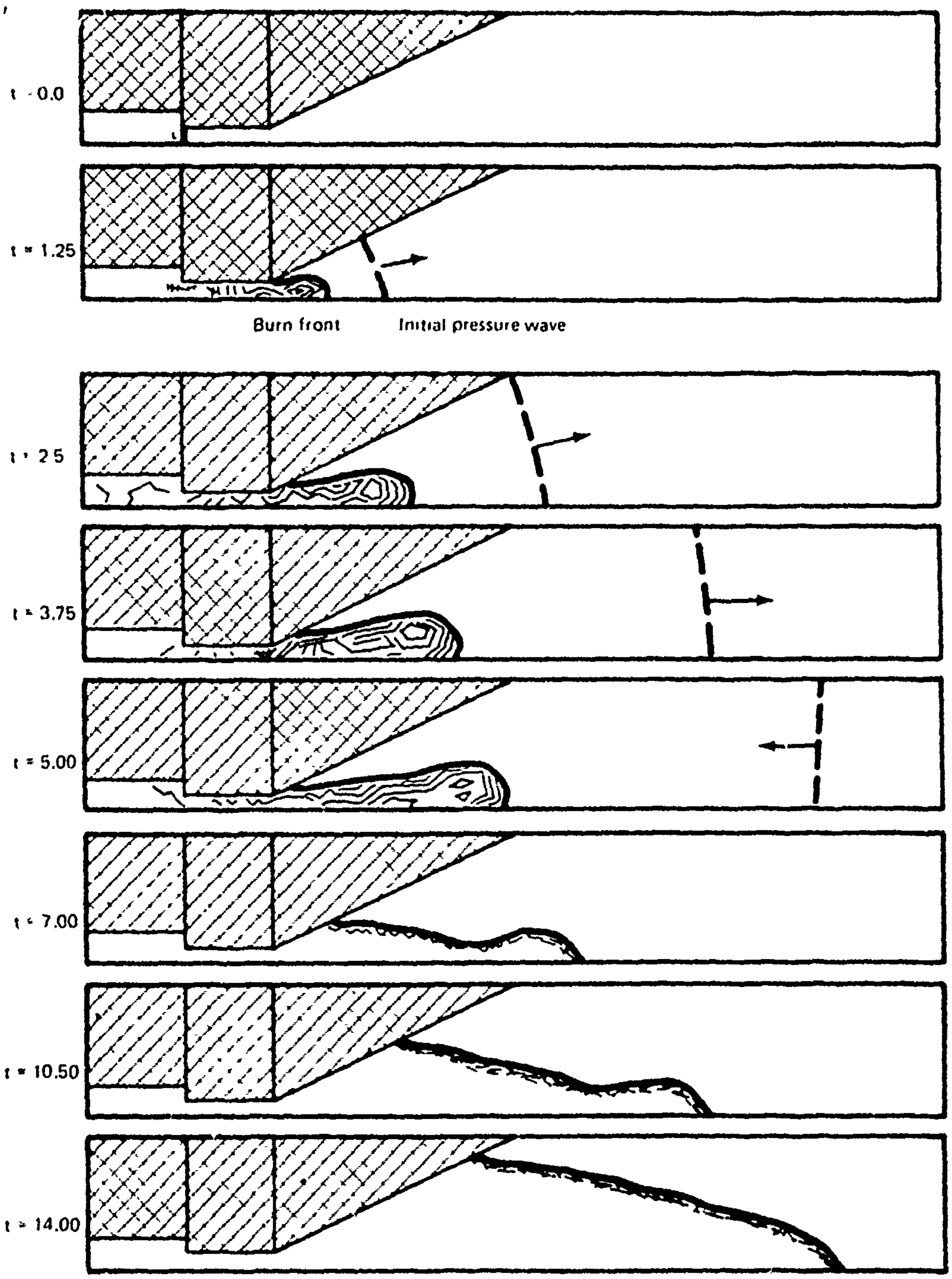


Figure 18(a). Igniter region burn front and initial pressure wave calculation using RICE code and angle geometry.(Indian Head N.O.S. <u>Liquid Monopropellant Gun Quarterly Report October-December 1974</u>).

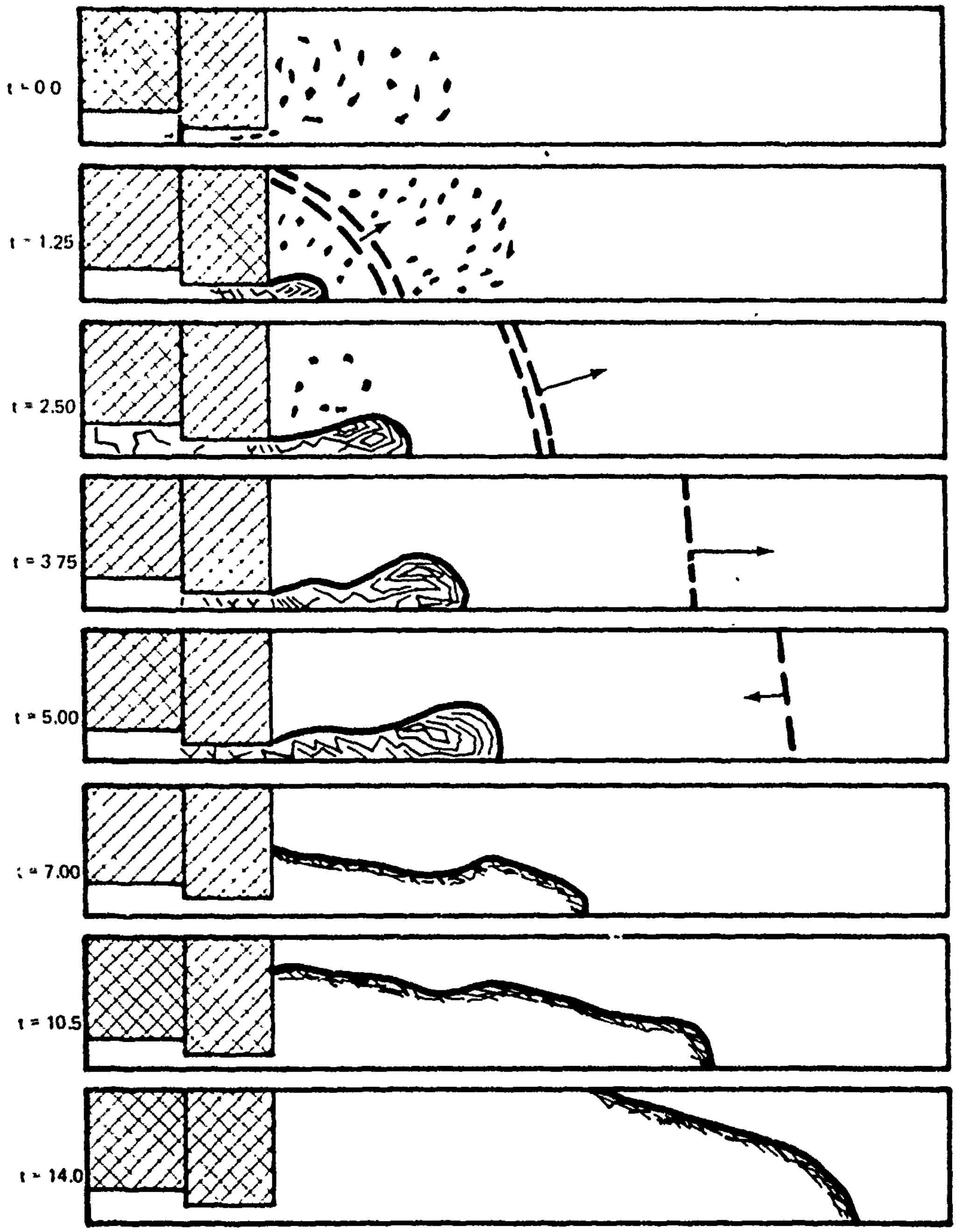


Figure 18(b). Igniter region burn front and initial pressure wave calculations using RICE code and rectangular geometry. (Indian Head N.O.S. Liquid Monopropellant Gun Quarterly Report October-December 1974).

The formation of vortices on the igniter jet is of particular interest, in that the influences of combustion on vortex formation and vice-versa have yet to be determined.

Although qualitatively the two runs were in excellent agreement, several differences are worth noting. The vortex formation in the rectangular chamber is inhibited until time (t) = 2.5. Because of the different geometry, the flow expands at a slower rate at the inlet, taking more time to develop the conditions which are necessary for vortex formation. Additionally, the velocities in the conical system are slightly larger because the flow is more restricted as it enters the burn chamber. For this same reason, the compression wave ahead of the burn is slightly stronger and moves down the tube more rapidly. An observation such as this is very significant in respect to ignition problems. The following section is a discussion of some implications of the above result.

4. Problems in Combustion

The type of characteristic burning of the liquid monopropellant illustrated in the previous discussion is believed to be a significant source of problems in the liquid monopropellant ignition area. The subsequent formation of a burning cavity which moves through the propellant, preceeded by a p ssure shock wave is a phenomenenon which is a source of reasonable correlation between combustion kinetics theory and liquid monopropellant gun systems applied research. This cavity, referred to as the Taylor[43] cavity (See Figure 19) presents a visible evidence of the combustion in the propellant. Through the use of flash x-ray technology, the cavity can be viewed at various stages of its formation. By correlation with pressure-time curves obtained simultaneously, much can be learned concerning the ignition aspect of the monopropellant. For example, it is known that a lagging layer of liquid trapped between the burning interface of the propellant and the side walls of the gun chamber acts as a coolant for the gun barrel as the projectile is forced out of the gun.

Considering the above characteristics of the liquid monopropellant ignition sequence, it is noted at this point that the ideal situation in the gun chamber would be one in which a slow, even burning of the propellant is generated. To achieve this ideal situation, in which the pressure shock wave is moderate, but not excessively strong, and in which the propagation velocities of the system are sufficient, but not potentially dangerous, and the system is, therefore, as potentially reliable, safe

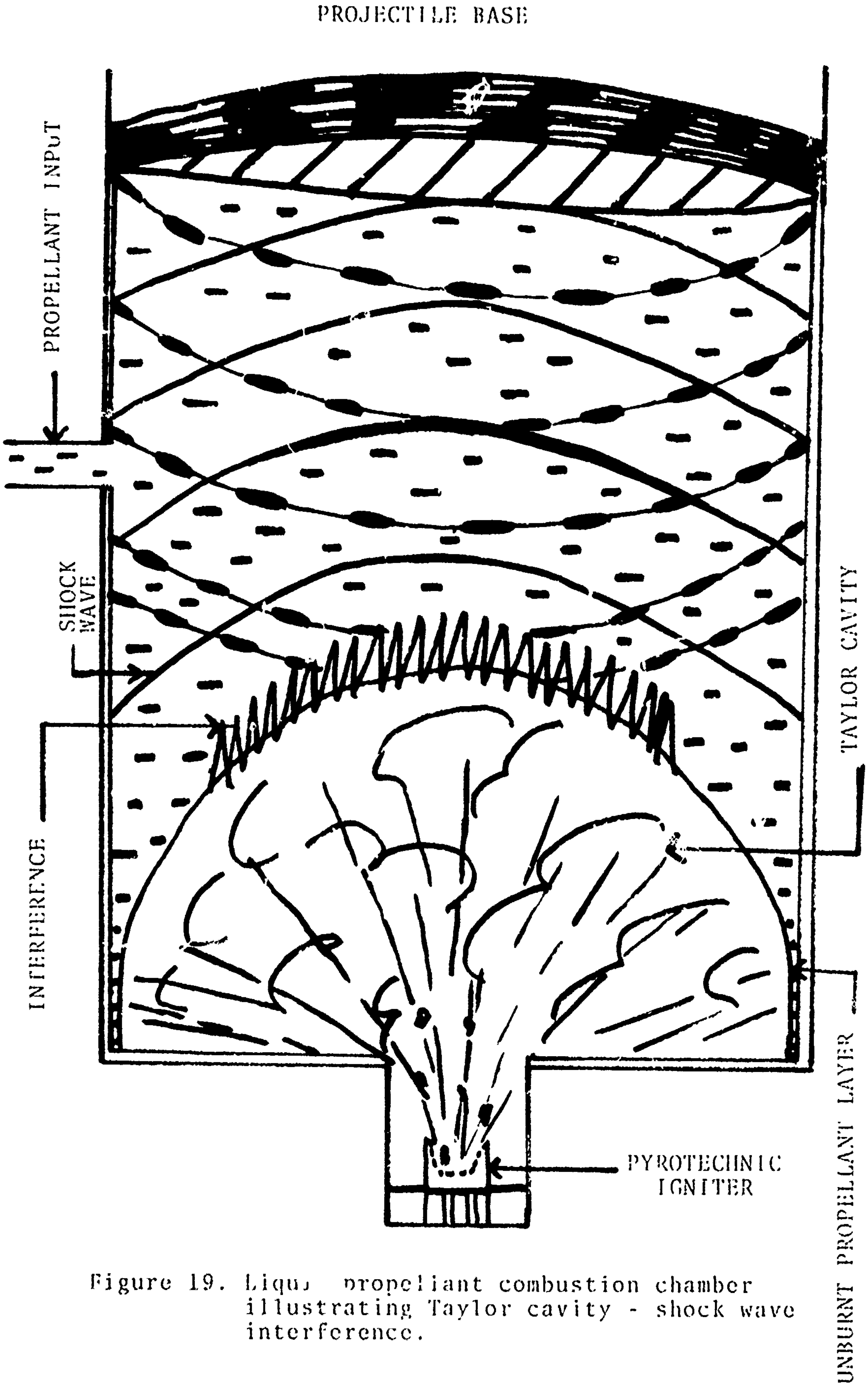


Figure 19. Liqu⌋ propellant combustion chamber illustrating Taylor cavity - shock wave interference.

and consistant as the inherent characteristic qualities of the monopropellant constrain it to be, the system must be one of low energy origin. The ignition scheme, which introduces the necessary impetus to initiate the reaction, should, therefore, be one which introduces the minimum characteristic amount of energy necessary to ignite the propellant properly. Any input above this minimum is potentially dangerous, in that it most probably will cause an irregularity in the burning of the propellant which could cause disastrous effects. Due to the lack of precise knowledge concerning many of the important interior ballistics variables involved in the ignition phase, it is felt that this low energy approach is not only logical, but vital for the future success of the liquid propellant gun program. One such low-energy threshold ignition technique is the acoustic cavitation method.

B. Energy Considerations

Using the methods outlined in the Experimental Observations, Section III of this report, the minimum amount of energy necessary to initiate the reaction in the liquid monopropellant which would lead to ignition was obtained. This value of 2.5 Joules/cm^3/sec corresponds to a power input of approximately 28 watts (28 Joules/sec) into a cylindrical chamber 2.54 cm in diameter and 6.35 cm in length. Although the use of the particular "cone of influence" is rather arbitrary, the amount of energy input can be seen to be significant. When compared to the present systems in existence at this time, only laser ignition approaches the ignition problem in a similar manner. As both the laser and electric spark techniques have given way to the pyrotechnic method in the main thrust of ignition development, the major discussion will be concerned with the pyrotechnic device.

The pyrotechnic ignition device utilizes approximately 100 Joules of energy to ignite the liquid monopropellant. Although input into the propellant is achieved in a time impulse on the order of milliseconds, the volume of influence is comparatively small. A note of comparison should be postulated at this time, concerning the spark ignition and laser ignition techniques. Although spark ignition has been achieved with an energy input of 50 Joules and laser ignition with an energy input of 11.13 J/cm^2 [44], which are both relatively low energy density inputs, an important aspect of the ignition should be noted. That is, a measurement of the minimum activation energy has been obtained for the propellant in a defined, reproduceable form, utilizing the acoustic cavitation ignition scheme.

In Figure 20, a schematic representation of the activation energy ΔE necessary to liberate the energy available during the propellant ignition (E) is presented. Before this time, a meaningful value for ΔE did not exist in terms of gun chamber geometry and qualitative molecular characteristic of the propellant. With respect to this concept it is believed that a meaningful value for the minimum energy necessary for propellant self-activation has been obtained (as a result of the acoustic ignition techniques). Further treatment of this energy measurement, additional factors involved in its implementation to an actual ballistic chamber, and conclusions drawn concerning the significance of this energy measurement are treated in the following section.

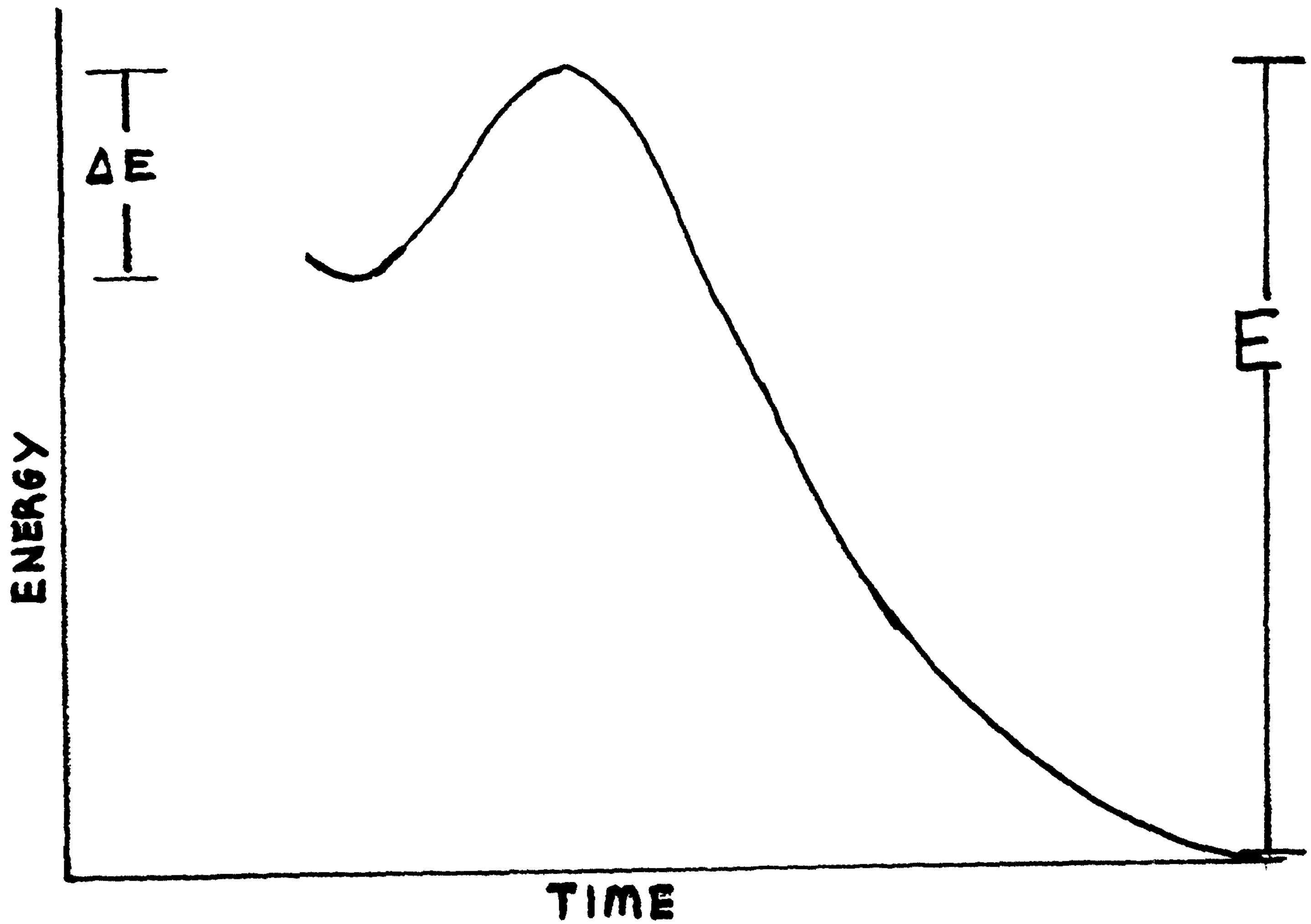


Figure 20. Relationship between activation energy and energy liberated during propellant combustion.

V. ANALYSIS OF RESULTS AND COMPARISON OF THEORY AND EXPERIMENT

A. Analysis of Acoustically Induced Ignition

The chemical reaction, which occurred in the monopropellant when the Dukane ultrasonic system was used, has been analyzed by the chemists at the Naval Ordnance Station labs and by Dr. Klein at the Aberdeen Proving Grounds (Ballistic Research Laboratory) Aberdeen, Maryland. It was postulated by both Dr. Chang and Dr. Klein[45] that the exothermic reaction which took place was the result of and, therefore, initiated by the cavitation in a catalytic manner.

The exact nature of the chemical reaction is virtually undeterminable, considering the fact that the cavitation produced random effects. Three of the constituents of the propellant are Hydroxyl Ammonium Nitrate (HAN), Isopropal Ammonium Nitrate (IPAN) and water. The significant portions of the respective characteristic chemical formulae of the HAN and the IPAN are NH_2OH and HNO_3. It was proposed by Dr. Klein that the cavitation acted to create free hydroxyl radicals, primarily in these three propellant constituents. By creating hydroxyl radicals it is meant that, for example in a water molecule, the following reaction takes place*:

$$H_2O \rightarrow H^o + OH^o.$$

It can be seen that the usual ions H^+ and OH^- are not formed. It is postulated that the molecular disturbance introduced into the propellant induces a situation where, in the above reaction, one of the electrons in a hydrogen-oxygen bond experiences a spin flip, resulting in its having the identical four quantum numbers as its "partner" electron in the bond. Since this situation is in violation of the exclusion principle, and is, therefore, a forbidden state, the water molecule breaks apart. The two radicals which are formed, due to the manner in which the spins of the electron arrangement were developed, do not have net charges, but are terrifically powerful oxidation (OH^o) and reduction (H^o) agents. The energy generated in the above reaction is on the order of 20 eV, which is over 100 times the energy necessary to break any natural chemical bond present in the propellant. Therefore, it can be seen that a situation now exists in the liquid propellant where a natural exothermic reaction has been generated by the cavitation and can perpetuate itself due

*As mentioned in the Historical Background section - proposed initially by Noltingk (See footnote 13) to the more than sufficient amount of subsequent energy generated.

The above result is one which applies to the covalent bonds, not only of water, but of the HAN and IPAN also. When, either directly or indirectly, the various C-C, C-H, and N-O bonds, to name a few, which exist in abundance in the liquid propellant, are broken by the extensive, self perpetuating exothermic reaction, the chemical "stability barrier", which is inherent in the chemical composition of the liquid propellant, is very quickly broken down and the sequence of combustion of the liquid propellant begins.

The black residue which formed in the tests with the Dukane ultrasonic system was probably some partially oxidized carbon nitrogen based compound. Its exact composition would be very difficult to ascertain due to the random and systematically variable and sequential nature of the reaction. However, both Dr. Chang and Dr. Klein have postulated that since the above reaction took place in a non-contained situation (i.e., an open tube), key gases (H_2, O_2, etc.) escaped, which prevented the reaction from progressing beyond this initial state. However, from subsequent discussions with both Dr. Chang and Dr. Klein[46] it was ascertained that, had the reaction taken place under a significant amount of pressure, a further rupture of chemical bonds within the liquid monopropellant would definitely have occurred, which in turn would have resulted in the complete combustion of the monopropellant. The final products of this type of chemical combustion are characteristically clean and convenient*, having been obtained in the laboratory previously[47] and are, in short, the ideal liquid monopropellant combustion end products.

Before proceeding, it should be noted that a similar chemical reaction, induced by mixing two chemicals and inducing an exothermic reaction[48] has been accomplished in the past. This chemical ignition technique is similar to the use of hypergolic bipropellants in principal. An analogy to the results of the acoustic cavitation experiments is seen in that the chemical ignition has been tested by injection of an oxidizer into a preloaded monopropellant, which utilizes the same principle of initiation as the acoustic cavitation scheme (see Figure 21).

*Statement of the nature of the end products would constitute a security violation.

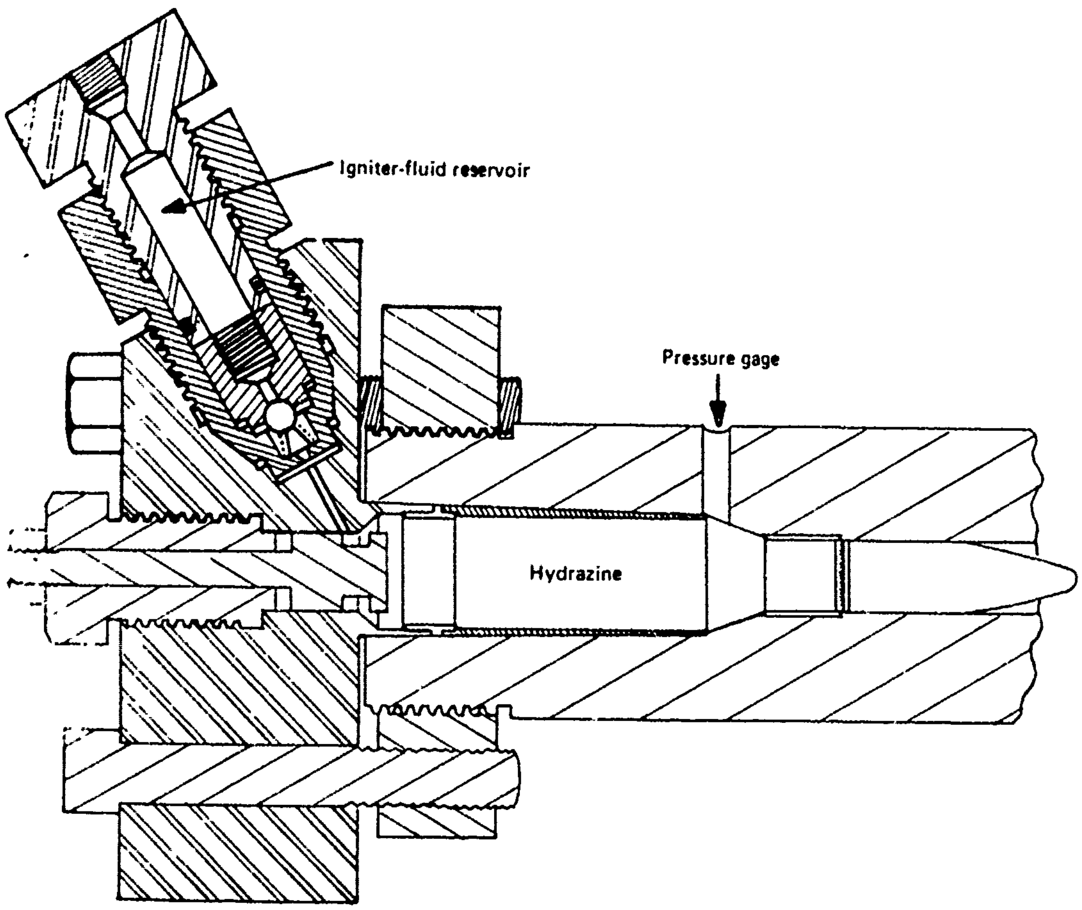


Figure 21. Breech for chemical ignition of hydrazine monopropellant. (Indian Head N.O.S. State of the Art Survey of Liquid Propellant Gun Systems).

A final qualitative observation regarding the specific chemical reaction induced by the cavitation can be observed. It appears that differences in the characteristic intensity of the reaction are functions of the percent of HAN present in the monopropellant. This conclusion is drawn from the fact that on the two occasions where the reaction was most intense and resulted in the greatest chemical change, the amount of HAN present was from 10 to 20% higher than the recommended or theoretical value.[49] At other times, although the reaction took place, the effects were not as dramatic.

Specifically, in the initial attempt by Dr. Crum, using the cylindrical ceramic transducer in early 1974, which resulted in the first positive ignition type reaction, the propellant used had approximately 21.5% more HAN than was required by the formula. As a result, more hydroxyl radicals were liberated to break up the molecular structure of the propellant, along with other radicals which were inherent to the HAN itself, and, therefore, a partial combustion of the propellant occurred to an extent which should not have taken place at atmospheric pressure conditions. Moreover, repeated retests with the same device with lots of propellant which contained under 10% additional HAN, did not result in a repeat reaction.

A similar observation regarding HAN concentration can be postulated, concerning the initial reaction induced by the Dukane ultrasonic system. In this case, the lot of propellant used contained approximately 13% more HAN than was theoretically postulated. The intense black color of the propellant which resulted was characteristic of the increased molecular absorption of the acoustic energy by the amount of HAN. Considering the fact that the amount, percentage-wise, of HAN in solution is more than that postulated theoretically, the increased reaction was logical. Although the propellant lot used in the energy density measurement calculation contained approximately 7 to 10% additional HAN concentration, this amount had been characteristic of current lots. The reaction in this lot, as expected, was not as intense and dark colored as that of the first trial with the Dukane system.

Therefore, it can be seen that the increased HAN is behaving similar to an increase in ullage pressure in its ability to sustain the chemical reaction. By making more radicals available for reaction, the pressure effect is duplicated, in that the key factor of increased exposure of the molecular bonds to the possibility of being broken is obtained. The increase in radical density in the propellant can be seen as the factor which caused the obvious difference in reaction to the cavitation. To obtain a reaction similar to the one that occurs with a higher HAN concentration, it would be necessary, therefore, to increase the energy density input or to increase the pressure of the chamber.

B. Acoustic Ignition: An Advancement in the Liquid Propellant State of the Art.

It has been said, in regard to interior ballistics research, that "Novel approaches, unique to liquid systems, should be examined . . . in order to gain the predictability required for practical gun design."[50] It is believed that a future complete liquid propellant ballistic system must contain an ignition scheme which encompasses this ideal rather than the blatant use of those ignition methods characteristic of existing solid propellant ballistic systems.

The chemical reaction, which is postulated as the desireable result of the acoustic cavitation, is presented here as a viable means of obtaining the optimum ignition sequence in the liquid monopropellant.

Several distinct advantages lie in ignition of the liquid monopropellant which is induced by an acoustic device. The first of these advantages is the low energy nature of the source used in the initiation of the chemical reaction involved. A source such as acoustic cavitation requires an energy impulse of less than 30 Joules in one second as compared to 100 Joules in several milleseconds for the pyrotechnic, for example. The fact that the acoustic energy is introduced into the propellant in a greater time period than the pyrotechnic energy reduces the possibility for the burning liquid propellant interface to be distorted by the resulting shock waves. The higher initial energy impulse characteristic of the pyrotechnic, and also the laser and spark ignition device, is an inherent necessity which results from the crude nature of the ignition. The pyrotechnic device must transfer its mechanical energy to the propellant where the chemical composition of the propellant is shattered to obtain combustion. To accomplish this sudden conversion, the energy impulse must be quite high. However, the acoustic cavitation does not rely on such a direct conversion, but rather indirectly initiates a chemical reaction that leads to ignition. This intermediate step precludes the need for massive energy impulse.

The author feels that the distortion of the even burning of the propellant is a source of a dangerous inconsistency in the ignition sequence. A distorted Taylor cavity (liquid-gas interface) leads to uneven burning and occasionally to detonation, a disastrous result. The minimal risk, therefore, is incurred when the lowest feasible energy impulse or density is utilized to accomplish the desired ignition effect.

A second advantage to this type of ignition scheme is that it does not have to be replaced after every firing as the pyrotechnic device does. The logistic and rate-of-fire advantages in this area are quite obvious, as the acoustic ignition device can be mounted in the gun chamber area permanently and be used for many firings before its removal is necessitated.

The third advantage of this type of ignition system is that the resulting chemical reaction has as its end products, compounds (gases) which are ideal. These end products not only are non-erosive and non-corrosive, but actually clean the barrel as they force the projectile out. There are no grains of powder in the burning propellant such as those which exist in the pyrotechnic igniter residue.

The final and most significant advantage of this acoustic ignition scheme is the fact that the concept upon which it is based, i.e., the attainment of a chemical ignition, is futuristic in nature. It is felt that the necessity definitely exists for the application of a new ignition scheme which is adapted to the inherent physical and chemical characteristics, limitations, and unique potential problems which are presently involved in the state of the art of liquid monopropellant composition. Furthermore, the method utilized in the application of the acoustic cavitation concept to the ignition of the liquid monopropellant is rather simple, and thus reduces the possibility of failure. Finally, it is felt that the principal which underlies this ignition scheme is the most important aspect of its significance. The technological advancement of the liquid monopropellant ballistic gun system to the point where it meets the requirements to be introduced fleet wide depends on development of ideal concepts, not hopeful adaptations of existing ideas, which were conceived for use in solid propellant systems.

C. Conceptual Implementation and Design Considerations

The implementation of an acoustic ignition scheme would involve no more adaption of the general liquid propellant gun chamber configuration that exists presently than would any other liquid propellant ignition system (See Figure 22). There are two general means of implementation which are postulated in this report for consideration in the development of a future acoustic ignition system integration. These concepts are the introduction of cavitation utilizing a horn assembly in a precombustion chamber and the use of a focusing technique whereby the cavitation is induced at a point within the combustion chamber.

A consideration which is essential for the first proposal is that of system efficiency at the higher pressures required for the chemical combustion reaction to go to completion. The system (See Figure 23) would require, as previously postulated, an increase in chamber pressure to sustain the reaction; however, with this increase in chamber pressure goes the additional requirement that the same minimum negative pressure be maintained to allow the cavitation to occur. To maintain this critical negative pressure threshold, and the net influx of acoustic

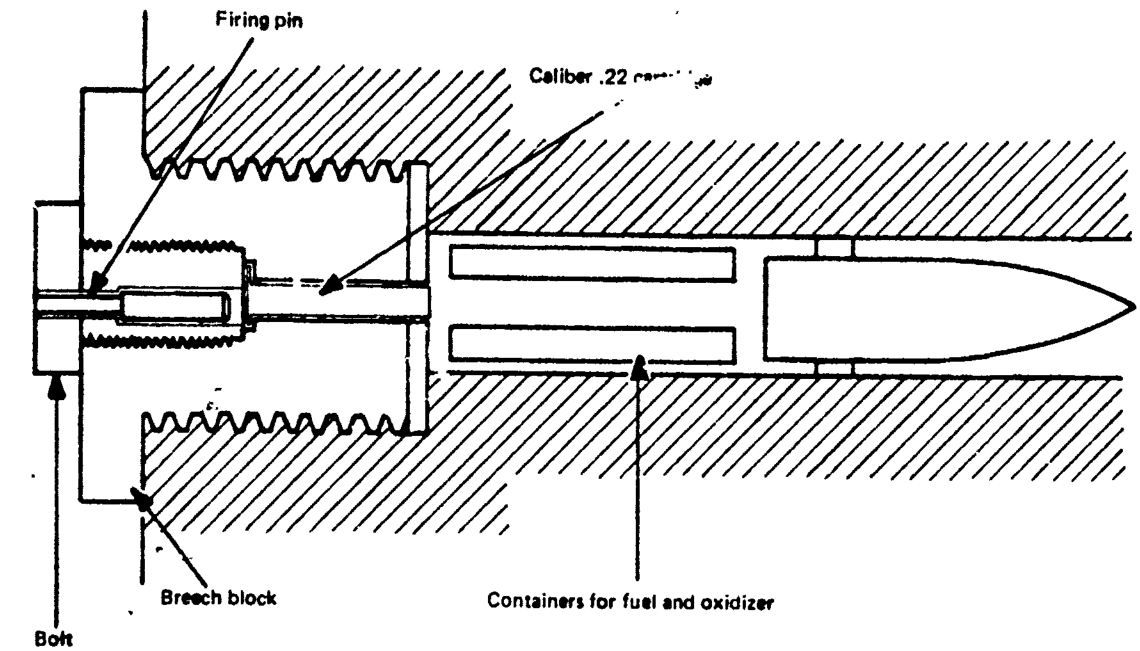


Figure 22. General concept of preloaded hypergolic bipropellant system. (Indian Head Head N.O.S. State of the Art Survey of Liquid Propellant Gun Systems.)

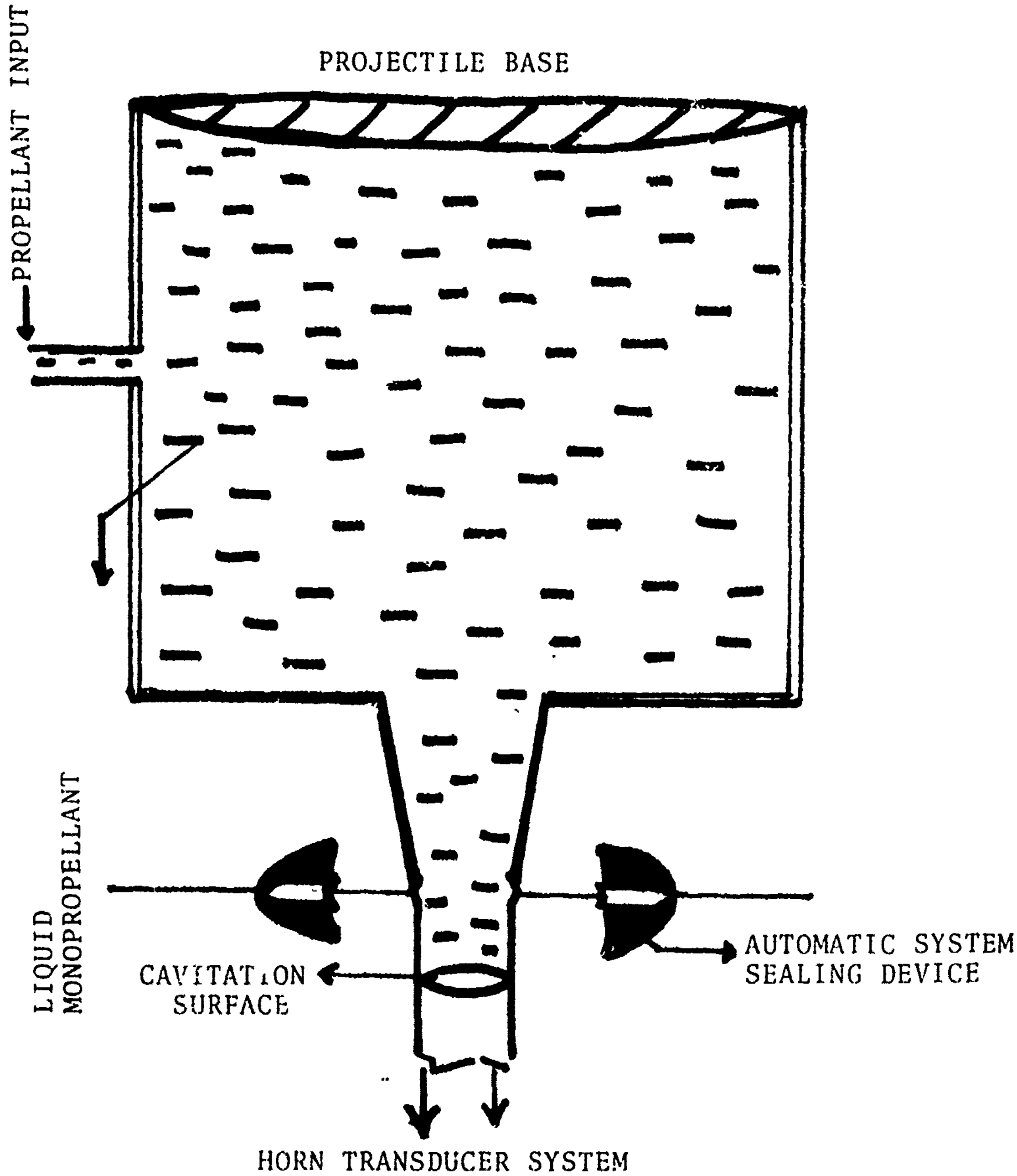


Figure 23. Design concept of precombustion chamber used with horn-transducer assembly.

energy into the propellant in the form of cavitation, it would be necessary to increase the power supplied to the horn. Since the ullage pressurization is typically static, the extra power output is easily calculated and would not be difficult to generate in typical pressurizations anticipated (50-1000 psi). This ignition design is of a conceptual nature in that an exact definition of the precombustion chamber shape and size, along with additional design specifications such as sealing gaskets at the precombustion chamber interface will not be delineated.

The other concept for design consideration is of the type shown in Figure 24. In this case, due to the great amount of loss which would result from the radiative nature of the thermal energy dissipation at the ignition hot spot, a greater amount of energy would have to be available from the source. However, very high intensities have been achieved using an arrangement of this type - on the order of 43,500 W/cm^2 on a focal point of 1.6 mm in diameter.[51] This corresponds to 750 atmospheres at the focal point. There would be no problem in maintaining a sufficient net energy density which corresponds to the same minimum energy density as is introduced into a precombustion chamber. The nature of spherical radiative dispersion, coupled with the characteristic flow

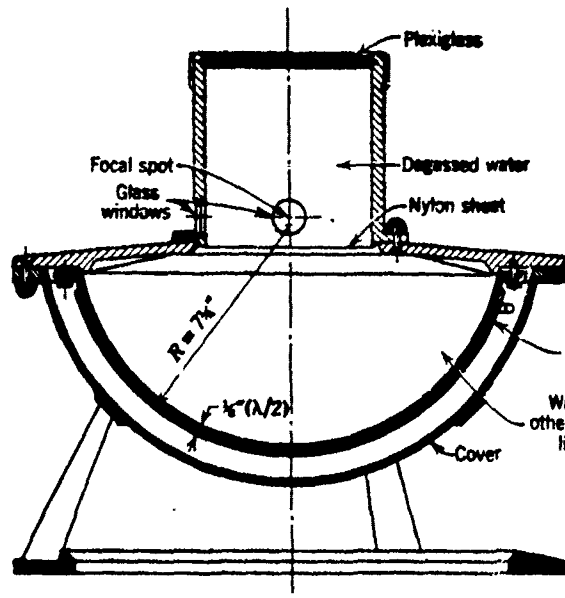


Figure 24. Schematic diagram of a focusing transducer for producing very high intensity ultrasonic energy. This would serve as the type of basic energy source for the acoustic ignition scheme. Several modifications would be necessary for implementation such as the installation of an automatic post-ignition closure system at the propellant-water interface and an extensive sealing system. (<u>Ultrasonic Engineering, Frederick.</u>)

of the propellant in the chamber would present an engineering design problem in calculating the volume of influence for energy density input determination. The means of calculation used will not be treated in this report; however, it can be seen that this method does offer a feasible means of introducing cavitation into a gun chamber, with the additional advantage of not requiring a precombustion chamber.

Mention should be made at this point concerning the adaption of present ballistic test fixtures to acoustic ignition apparatus that was accomplished during this investigation. The Dukane assembly was mounted for measurements in an actual 37 mm test chamber (See Figure 12). A seal was obtained after a hole 1.27 cm wide was drilled through the rear closure plug. The plug was fitted with an O-ring into which the horn was force-fitted. (See Figure 25 below).

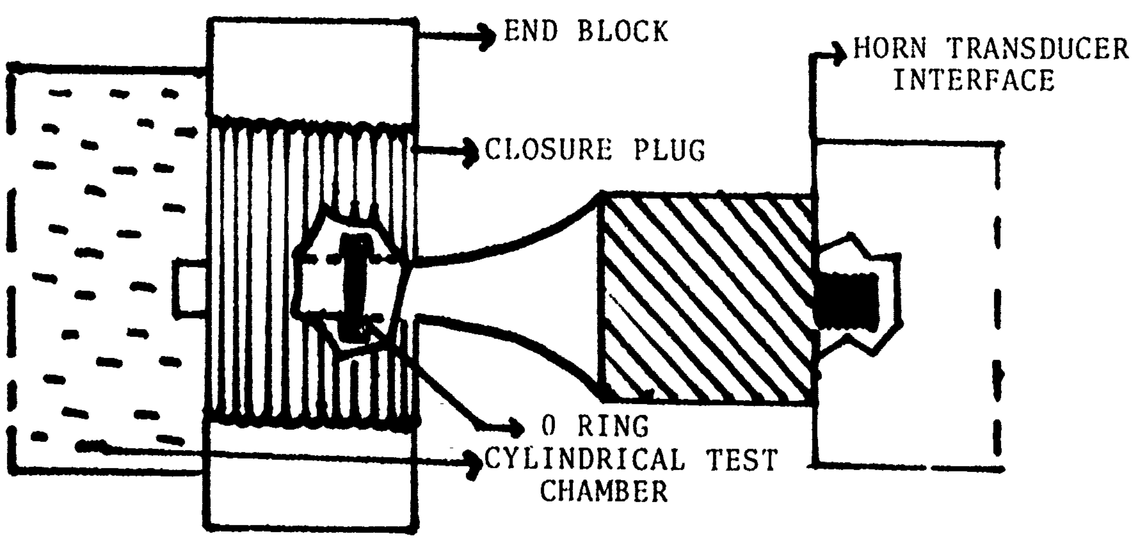


Figure 25. Closure plug adapted for horn insertion

The horn-transducer assembly was then seated in the plug and supported using a wooden apparatus which held the housing in place (See Figure 26 below).

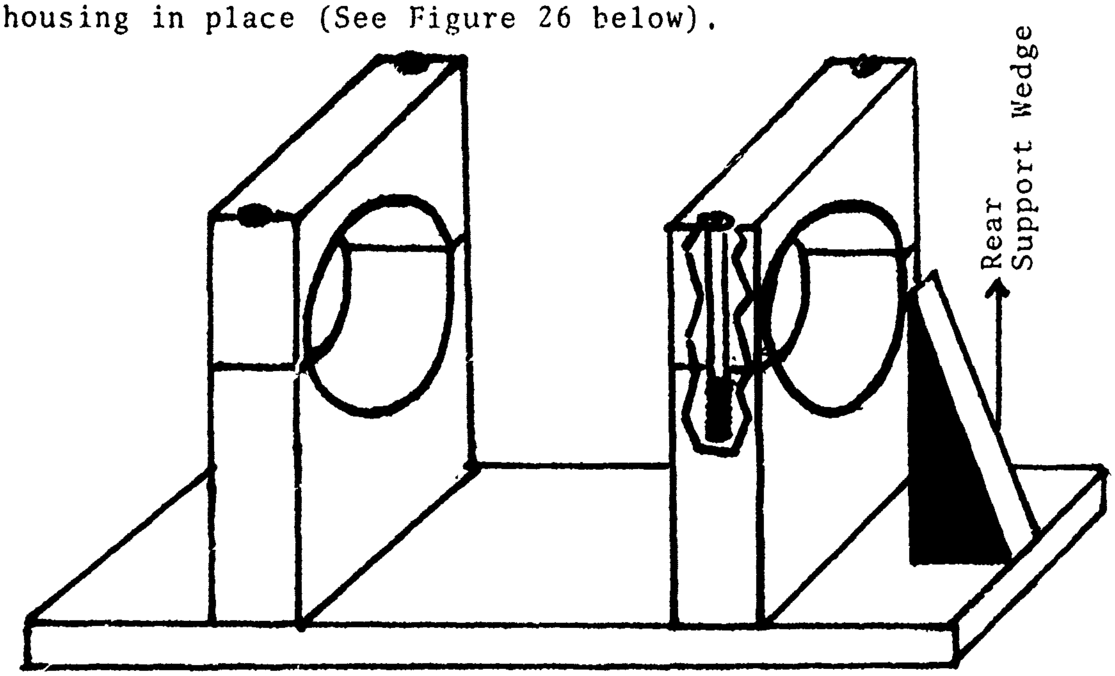


Figure 26. Supporting apparatus used to hold Dukane horn transducer assembly in closure plug.

There was no further adaptation of the test fixture necessary, and this closure plug modification required minimal effort. It can be seen that it was quite possible to adapt an acoustic ignition system to the actual laboratory fixtures for testing purposes with essentially little inconvenience, or expense. Therefore, further tests can be conducted on acoustic cavitation techniques with a minimal amount of hardware, fixture adaptation or time-consuming feasibility complications.

A final point concerning liquid propellant composition should be treated at this time. The design consideration in the construction of a liquid monopropellant ballistic system must take into account the factor of uncertainty which exists concerning the chemical composition of the propellant. This uncertainty would necessitate extensive tests to determine the reaction of the monopropellant to many different geometries of influence in the gun chamber. As seen in the discussion concerning interior ballistics in the Theory Section (Section IV), the burning rate, shock wave propagation, and other related factors vary with a characteristic alteration of the combustion chamber. In the same manner, the many variables which are inherent in the ignition and combustion of the liquid monopropellant present a challenge to the developmental researchers to further define additional chemical and physical parameters of the propellant, along with a refinement of the existing data. It is the opinion of one of the leading chemists in the liquid monopropellant developmental research field,[52] Dr. Klein of Aberdeen, that before a modern, acceptable and advanced ballistic gun system can be developed, progress must be made in this field of monopropellant refinement and development. It is postulated that the acoustic cavitation ignition scheme presents a progressive, novel and inherently adaptable method of ignition. Due to the molecular nature of its effect, the acoustic cavitation scheme has the potential to progress in technological development along with the advancement of the propellant developmental and refinement techniques. It can, therefore, be stated that the acoustic cavitation method is an ignition scheme which contains an inherent capacity for expansion and improvement proportional to and parallel with the overall improvement and development in the state of the art of liquid monopropellant technology.

VI. SUMMARY AND CONCLUSIONS

The subject of this report is the ignition of a liquid monopropellant by acoustic cavitation. An experimental result of this study was the successful preliminary ignition of the monopropellant by an acoustic horn-transducer assembly. Upon examination of these ignition results, it was postulated that the reaction initiated by the acoustic device would definitely result in combustion of the monopropellant under proper pressure conditions. This combustion, which had been obtained in the laboratory by different initiation methods, results in the most ideal combustion of the monopropellant and is, therefore, very desirable.

The principal conclusions of this report are:

1. The ignition of liquid monopropellant is possible using acoustic techniques under proper conditions.

2. A value for the minimum energy density necessary to initiate the combustion sequence of the liquid monopropellant has been obtained.

3. The acoustic ignition method is a precise and efficient technique. The aspect of directly inducing

cavitation in the monopropellant precludes the present problem of correlating a mechanical application of energy to the chemical ignition which takes place. This cavitation molecularly induces the desirable, chemical combustion reaction in smooth fashion by minimizing unnecessary energy requirements.

4. The acoustic cavitation ignition technique has a valuable characteristic simplicity and adaptability. This exhibits its extensive potential to advance in conjunction with future developments in liquid monopropellant technology.

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16. Haukland, page 18.

17. Bullseye: A highly effective derivative of gun powder with a much higher impetus.

18. Exact system characteristic pressures and times are of a confidential nature.

19. Haukland, page 18.

20. During tests conducted by Dr. M. Wieland of the U.S. Naval Weapons Laboratory, Dalghren, Virginia in the early 1970's.

21. All experimental acoustic ignition tests were conducted in conjunction with the research facilities at the Naval Ordnance Station, Indian Head, Maryland.

22. For further discussion, see Section IV.

23. As a result of analytical comparisons during subsequent testing with different lots of monopropellant.

24. Concept initially conceived by Dr. Lawrence Crum, U.S. Naval Academy, Annapolis, Maryland.

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30. For further discussion, see Section IV, p.52.

31. Dukane Ultrasonics Inc., of Chicago, Ill., made the entire horn-transducer-generator apparatus available to the author for use during the period of this research effort.

32. Information obtained during private conversation with Dr. M. Wieland of U.S. Naval Weapons Laboratory, Dalghren, Virginia, during early 1975.

33. See Section I-A, p.7.

34. The contents of the test tube were immediately analyzed by chemists at the Naval Ordnance Station, Indian Head, Maryland.

35. Primary experimental analysis and determination was made by Dr. Chang, head chemist, Naval Ordnance Station, Indian Head, Maryland.

36. Haukland, p. 28.

37. Haukland, p. 49.

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45. Dr. N. Klein, a leading chemist, at the U.S. Army Aberdeen Proving Ground, Ballistic Research Laboratory, Aberdeen, Maryland, was consulted at this time.

46. Information obtained in private discussion with Dr. Klein on 8 Apr 1975.

47. Information obtained in private discussion with Dr. Klein on 29 Apr 1975.

48. Haukland, p. 23.

49. Data obtained and compiled by Dr. Chang at Naval Ordnance Station, Indian Head, Maryland, during 1974-1975.

50. Haukland, p. 47.

51. Frederick, p. 103.

52. Information obtained in private discussion with Dr. Klein on 1 May 1975.

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