DEVELOPMENT AND DEMONSTRATION OF FLUERIC SOUNDING ROCKET MOTOR IGNITION

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16. Abstract

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TABLE OF CONTENTS

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1. SUMMARY

Flueric sounding rocket motor ignition has been found to be feasible using a system without stored energy and with the complete absence of electrical energy and wiring. The flueric ignitor is based on a two-component, aerodynamic resonance heating device called the pneumatic match. Temperatures in excess of 800°C were generated in closed resonance tubes which were excited by a free air jet from a simple convergent nozzle. Using a nitrocellulose resonance tube, ignition of Boron Potassium Nitrate ($BKNO_3$) a commonly used rocket motor ignition material, was accomplished with air supply pressures as low as 0.4 MN/m^2 (55 psig). This report describes an analytical and experimental program which established a flueric rocket motor ignition system concept incorporating a pneumatic match with a simple hand pump as the only energy source. An evaluation was made of this concept to determine the margins of the operating range and capabilities of every component of the system. This evaluation included a determination of power supply requirements, ignitor geometry and alignment, ignitor/propellant interfacing and materials and the effects of ambient temperatures and pressure. It was demonstrated that an operator using a simple hand pump for 30 seconds could ignite $BKNO_3$ at a standoff distance of 100 m (330 ft) with the only connection to the ignitor being a piece of plastic pneumatic tubing.

2. INTRODUCTION

The flueric rocket ignition system can be divided into three basic parts: an energy source of compressed air, the pneumatic match, and the flame producing propellant to ignite the rocket motor. The pneumatic match, the key element of the system, has no moving parts and is powered by the flow of compressed gases.

Basically, the pneumatic match consists of two essential parts: a resonance tube (hollow cavity closed at one end), and a convergent excitation nozzle as shown schematically in Figure 1. The device functions when the open end of the cavity is placed in the compression region of a free jet emanating from the nozzle. When the flow emerges from the nozzle, it accelerates to supersonic speed and then readjusts to subsonic speed by compression through a shock wave. The process creates a series of diamond-shaped cells of alternate supersonic and subsonic flow. These cells or conical shock waves (Mach diamonds) intersect the jet axis throughout the length of the jet (Figure 2). A plot of a typical static pressure distribution along the axis of the jet is also shown in Figure 2. It can be seen that the pressure rises in the conical fronts of the diamonds and drops in the divergent portions to a minimum at the intersections. It was discovered that by placing a cavity in certain portions of the jet a self-sustaining system of oscillations was created by driving the gas in the cavity into resonance. The portions of the jet structure which have been found to give rise to these oscillations are indicated by dashed lines in Figure 2. They are located between the Mach disk and the end of the cell. The first cell has been found to produce the best results.

Although there is continuous flow into and out of the resonant cavity, a portion of the gas remains trapped at the closed end where it is subjected to a succession of waves producing periodic compression and rarefaction of the trapped gas. This periodic compression and expansion of the gas, within the rigid cavity of the resonance tube, produces irreversible temperature increases at the endwall of the cavity sufficient to ignite pyrotechnic materials. The performance of a typical gaseous helium system is shown in Figure 3. When a helium gas supply pressure of 1.5 MN/m^2 (220 psig) is supplied to the pneumatic match as shown in Figure 3, the result is the near optimum temperature output shown.

Historically, the principle of aerodynamic heating of gases in resonance tubes had been generally overlooked by early investigators, such as Hartmann (1), who were mainly interested in the acoustic power generation capabilities of these tubes. Sprenger (2) in 1954 was able to obtain endwall temperatures of almost 425°C in one of his air powered resonance tubes. His tube, however, was over 10 cm in length and took several minutes of steady state operation to reach these temperatures. Thompson (3) and Kang (4), along with Broucher and Moresca (5) have attempted, with some limited success, to theoretically predict and analyze the operation of the resonance heating principles. They have, in general, been able to obtain only order of magnitude estimations of the heating which is experimentally observed.

Beginning in 1968, after preliminary independent research and developmental efforts showed promising performance, additional work was conducted toward applying this principle to ignition of explosive ordnance, under contract to Picatinny Arsenal. In initial work, the ignition of nitrocellulose was accomplished with an ignition device less than 6 cm in length called the pneumatic match. This pneumatic match, as improved under continuing programs, provides significant improvements for safe, simple, nuclear hard, shockproof, reliable and inexpensive Safing, Arming and Fuzing of components and

systems. Primary explosives were ignited in less than 10 ms with helium at 1.4 MN/m^2 (200 psig). Endwall gas tempeatures of over 1250°C were obtained in less than 35 ms with a device 3 cm in length.

The feasibility of adapting the pneumatic match to a restartable solid propellant rocket motor engine ignition system was demonstrated by Rakowsky and Marchese, under contract to the U. S. Army's Advanced Ballistic Missile Defense Agency in early 1970. An improved resonance tube design incorporated into the pneumatic match successfully ignited an explosive/pyrotechnic train which resulted in the ignition of M-1 propellant in a simulated rocket motor ignitor.

The objective of this present study was to develop and demonstrate an inexpensive, safe and foolproof ignition system concept for solid propellant rocket motors. Although first proposed for demonstration in a sounding rocket, this system has broad potential applications in all solid propellant motor vehicles in first stage ground launch, or in upper stages utilizing fluidic programmers. The advantages of such an ignition system would be improved safety and decreased cost without degrading reliability.

The flueric initiation concept, as established by this program, is to pressurize 100 m (330 feet) of tubing which is sealed just outside the rocket motor by a check valve with a hand-driven pump. The check valve releases at a preset pressure of about 0.45 MN/m^2 (65 psig). The air flow from the 100 m reservoir provides energy for the pneumatic match producing temperatures at the end of the cavity sufficient to ignite pyrotechnic materials in less than one second. The feasibility of the concept of a flueric sounding rocket ignitor has been demonstrated both analytically and experimentally in this program. Experimental verification of the margins of operation was obtained by igniting nitrocellulose and BKNO$_3$ with the flueric ignitor over a range of operating parameters.

LIST OF SYMBOLS AND UNITS

The following is a list of the system parameters and the symbols used to designate them throughout the discussion in the report. Definitions of some of the important terms as used in this report are:

Nozzle - a simple axisymmetric convergent, under expanded, sonic flow passage aligned to direct the gas flow into the resonance tube.

Chamber - an interaction region between the nozzle and the resonance tube where the nozzle jet flow couples with the resonance tube flow to create the instability necessary to drive the tube into resonance.

Vent - the portion of the chamber in which the supply gases are allowed to exit into the vent tube.

Endwall - the closed end of the resonance tube where the temperatures are greatest and where the ignition takes place.

a_s	-	speed of sound
A^*	-	nozzle area
A_v	-	vent area
d	-	excitation nozzle exit diameter
δ	-	diameter of transfer tubing
D	-	piston diameter (pump)
γ	-	ratio of specific heats (C_p/C_v)
L	-	length of transfer tubing
ℓ	-	resonance tube length
m	-	molecular weight
P_{amb}	-	ambient pressure
P_c	-	chamber pressure
P_o	-	supply flow pressure
R	-	gas constant
$\mathbb{R}$	-	universal gas constant
s	-	nozzle exit to resonance tube separation
t	-	time
T_w	-	endwall surface temperature
T_o	-	supply flow temperature
V	-	volume of transfer tubing
W	-	mass flow rate through nozzle

3. INSTRUMENTATION

The instrumentation used in the test evaluation of the energy source was a Pace Model P3D differential pressure transducer and a Model CD25 indicator which monitored the gas pressure on each side of the check valve. A similar transducer was located downstream of the relief valve to monitor the actual gas pressure supplied to the nozzle of the flueric ignitor. These pressure transducers were statically calibrated against standard Bourden tube pressure gages. The response of these transducers is flat to 1000 Hz.

Resonance tube performance was evaluated with the use of chromel-alumel thermocouples fabricated from 80 μm diameter wire (0.003 in). The thermocouples, sealed into the end of the resonance tube with a ceramic cement, provided a nearly adiabatic measurement of the resonance tube endwall temperature. Although some heat is lost by conduction through the tube material and the thermocouple wire, the error is estimated to be less than 15%. The response time for these thermocouples is less than 20 ms. For some ignition studies, thermocouples were placed at the resonance tube/propellant ignitor interface as well as on the propellant ignitor material ($BKNO_3$). Other ignition tests were conducted by visually determining that the propellant ignitor material had been ignited.

Permanent recordings of the pressure and temperature measurements were made on a sixteen channel high speed oscillographic recorder (Honeywell Visicorder Model 1912). The frequency response of this recorder is 3 kHz. For most test evaluations the time base used was 0.05 s per division.

4. DESCRIPTION OF APPARATUS

The ignition system concept developed for this study is shown schematically in Figure 4. When the operator wishes to launch a rocket he moves the selector valve to the ENABLE position and begins to exert force on the pump. The check valves allow the supply line gas pressure to increase with each downward stroke of the pump. The relief valve remains closed until the gas supply pressure reaches the ignitor operating pressure. It then opens and remains open, discharging the volume of supply gas from the tubing into the ignitor. For safety considerations, leakage can be built into the system so that the operator will be unable to keep the supply volume charged at pressures close to the relief valve opening pressure. The ignitor converts the gas flow energy into thermal energy through the resonance heating effect. Generation of sufficient thermal energy to cause ignition of the propellant ignitor interface is assured by the proper ignitor design. The interface material accomplishes the ignition of the propellant ignitor material by being in close contact with it. The experimental apparatus can be divided into three distinct areas: the pneumatic match, the energy source including the transfer tubing, and the propellant ignitor.

4.1 PNEUMATIC MATCH

The pneumatic match, flueric ignitor, shown schematically in Figure 5, consists of a nozzle, a resonance tube, a vent tube, and a propellant ignitor interface - nitrocellulose.

Nozzle. - Pneumatic match nozzles are simple, convergent nozzles designed to produce the proper jet cell structure necessary to obtain resonant heating. Since the nozzle diameter and pressure ratio across the nozzle influence the length of the jet cells, these two parameters may be used to determine the proper separation distance between the nozzle and the resonance tube. For this application the nozzle diameter also determines the rate at which the gas supply pressure drops when the valve opens. If the pressure drops too quickly (too large a nozzle) resonance heating will take place for a time too short to develop ignition temperatures. Nozzles used for these investigations had diameters of 0.6, 0.9 and 1.2 mm (0.024, 0.036, 0.047 in).

Resonance Tube. - Resonance tubes of various lengths, internal shapes and materials were evaluated to determine the optimum configuration for this application. Several of the tubes evaluated are shown in Figure 6. Initial tubes were made from a thermally insulating transfer molding material (Hysol MG5F, a glass filled epoxy) in order to minimize the heat transfer loss. Later tubes were made from nitrocellulose. Tube lengths ranged from 7.6 mm to 21.6 mm (0.30 to 0.85 in). The internal tube diameter ranged from 0.6 mm to 1.6 mm (0.025 to 0.062 in).

Resonance Tube/Nozzle Alignment Margin Determinations. - A three degree of freedom micropositioner was used to determine the alignment requirements of the nozzle and the tube in all three linear dimensions: horizontally, vertically, and axially. This mounting apparatus allowed precise translation of the resonance tube along three orthogonal axes with respect to the nozzle while maintaining the axes of the nozzle and tube in parallel.

Vent Tube. - The vent tube, as shown in Figure 5, allows the air being discharged from the chamber to leave the ignitor. Since resonance heating is a flow phenomenon no resonance heating is possible

6

without some means of venting. One parameter which determines the location of the jet cell structure is the pressure ratio across the nozzle, P_O/P_c. With an unrestricted vent where $P_c = P_{amb}$, the ratio is simply P_O/P_{amb}. If the vent area is finite, which it must be for this system, then $P_c > P_{amb}$ and the pressure ratio is reduced. Numerous vent areas and vent configurations were evaluated. Since the ignitor in this system is located inside a rocket motor, the venting must take place through a tube. The optimum vent tube configuration found was a coaxial tube with an inner diameter of 17 mm (0.7 in).

Propellant Ignitor Interface   Nitrocellulose. - A propellant ignitor interface is used to convert the thermal energy associated with resonance heating of the air into sufficient heat and hot particles to ignite the propellant ignitor ($BKNO_3$). Since the resonance tube concentrates the heat generated at its closed end, a nonconsumable type tube must be closed off with approximately 20 mg of nitrocellulose. A nitrocellulose resonance tube is entirely consumable and eliminates the need for an additional interface material. Therefore, a consumable type was selected for this design.

4.2 ENERGY SOURCE

The energy source shown in Figure 7 consists of a mechanical hand pump, check valves to allow the supply volume to be pumped up to the operation pressure of the ignitor, and an abort-enable valve to release the supply pressure bypassing the ignitor, an in line filter, the pneumatic tubing which acts as a supply volume, and a relief valve.

Hand Pump. - The hand pump used for test evaluations was a simple air cylinder with a pump handle attached. The bore diameter was 35 mm (1.375 in) with a 51 cm (20 in) stroke. The air cylinder was used as a standard single stage hand pump.

Check Valves.   - The two check valves control the output or exhaust port of the air cylinder. They allow the compressed air to enter the transfer tubing on each downstroke and the filling of the cylinder with air at atmospheric pressure on each upstroke. The valves used were Hoke Model 6211F2B (ball-type) with a cracking pressure of $2 kN/m^2$ (0.3 psig).

Abort-Enable Valve.   - Any standard two position pneumatic valve (i.e., Hoke Model 458 spring closing toggle valve) can be employed for this application. Its purpose is simply to divert or dump the supply air pressure quickly and safely at any time and at any stage prior to the rocket engine ignition.

In Line Filter. - An in line filter (Hoke Model 6310 F4B) with a 5 μm (200 μ inches) filter element was used to prevent particles from clogging the ignitor nozzle. The in line filter is placed upstream of the supply volume so that it offers no resistance to the flow of gas out of the relief valve.

Supply Volume. - The supply volume is made up of a length of standard plastic pneumatic tubing. The volume of the 100 m (330 ft) long line with an internal diameter of 6.4 mm (0.250 in) is 2944 cm^3 (194 in^3).

<u>Relief Valve.</u> - An adjustable relief valve (Norgen #V96-100-NNK-AU) was used to release the supply gas at the desired pressure. This valve may be set to release at pressures between 1.4 kN/m^2 and 14 MN/m^2 (2 to 200 psig). Once the valve opens it does not close again until the pressure drops to below 10% of the opening pressure. Thus, it will stay open long enough to insure ignition but will automatically reset after each operational cycle.

4.3 <u>PROPELLANT</u>

Boron potassium nitrate ($BKNO_3$) is typically used as an ignitor in solid propellant rocket motors. Once ignited the flame produced is adequate to ignite most solid propellants. Atlantic Research F-ND 2M and 2A cylindrical pellets of $BKNO_3$ were used for this investigation. Each 2M pellet was 3 mm (0.125 in) in diameter by 2.5 mm (0.100 in) long and had a mass of 45 mg. The 2M pellet of $BKNO_3$ was positioned against the nitrocellulose resonance tube end. The 2A pellet was used in the propellant basket.

8

5. PROCEDURE

The basic procedure used (to accomplish the objective of this program) to establish the feasibility of flueric ignition of sounding rocket motors was to determine the pressure/flow/time requirements of the flueric ignitor and develop a power supply to provide this input.

5.1 PNEUMATIC MATCH

Pneumatic matches were evaluated to establish their temperature/time output characteristics for various pressure/time inputs. Thermocouple data were used to determine the thermal output. The thermal output was then compared to the minimum ignition requirements of the nitrocellulose resonance tube to determine which configurations were applicable.

Nozzle. - To determine the pressure/time output characteristics test runs were made with nozzles whose diameters were 0.6, 0.9 and 1.2 mm (0.024, 0.036 and 0.047 in). Since the nozzle diameter influences both the supply pressure/time output to the resonance tube and also the thermal output performance, tests were conducted to determine the pneumatic match input/output characteristics for each nozzle.

Resonance Tube. - Three basic resonance tube shapes were evaluated: cylindrical, tapered, and stepped. Previous comprehensive developmental efforts on resonance tube optimization under contract to the Army's Picatinny Arsenal and the Army's Advanced Ballistic Missile Defense Agency indicated that the stepped tube produced very fast temperature increases and much higher endwall temperatures than the other tube configurations tested. However, since this work was directed toward military applications and used a gas other than air as a supply gas at 2 MN/m^2 (300 psig), the superiority of the stepped tube had to be verified with low pressure air. The thermal output of the three tube types was obtained for air supply pressures up to 1 MN/m^2 (150 psig).

Pneumatic match configurations were developed to provide endwall temperatures with an adequate excess of thermal energy to ignite propellants. A goal of at least 300°C was used. Twenty-two different type resonance tubes were evaluated during this program. Of the 66 possible combinations of tubes and nozzles, 44 were evaluated. Based on these evaluations, a tube was selected to provide sufficient thermal output with a large excess of thermal energy at a minimum gas supply pressure.

Nozzle/Resonance Tube Alignment Margin Determination. - An assessment of the alignment requirements of the nozzle and resonance tube along three axes was made with the three-axis micro-positioner assembly. Steady state temperatures produced by a 2 cm long tube after 1 s operation at a fixed supply pressure of 0.7 MN/m^2 (101 psig) were recorded as the alignment was adjusted in steps of approximately 0.13 mm (0.005 in). Similar data were obtained for a 1 cm long tube with a supply pressure input which is obtained when the relief valve opens and discharges 1960 cm^3 of air at a pressure of 0.4 MN/m^2 (60 psig) through an open nozzle. For these tests the maximum temperature (transient) was recorded. These tests were conducted with both the 0.9 mm and 1.2 mm diameter nozzles. The alignment was adjusted in steps only over the range in which resonance heating took place. The alignment which produced the highest endwall temperatures was chosen as the configuration to be used for ignition feasibility tests.

Vent Tube. - Since the vent area determines an important operating parameter, the nozzle pressure ratio, its limits were evaluated. The largest vent area possible occurs when the nozzle and resonance tube are free standing as is the case when tested in the three-axis microposition apparatus. The vent area, in this case, is the circumference of the resonance tube times the separation distance. The system concept developed for this application requires a vent tube which has a fixed area and a length corresponding to the rocket motor dimensions. The cross-sectional area of the vent tube evaluated was 0.32 cm^2 (0.05 in^2). Its length was varied from 0 to 1 m (39 in) in order to determine if the ignitor would operate with long vent tubes as would be required in sounding rocket motors.

Propellant Ignitor Interface - Nitrocellulose. - Ignition characteristics of nitrocellulose and BKNO$_3$ samples were determined by Differential Thermal Analysis (DTA) using a Dupont Model 900 analyzer with a differential scanning calorimeter. The reference was an empty pan. These data were used to determine a minimum temperature at which an ignition could be expected. Results of the resonance tube thermal output tests were compared with these requirements to choose a suitable ignitor configuration. Since DTA is a dynamic measurement and the rate of heating (10°C per minute) affects the onset temperature, actual ignition tests were conducted to verify the ignitor choice. Ignition tests were conducted with the ignitor supplied with various combinations of supply volumes and initial gas pressures. These tests were compared with corresponding temperature/time traces to establish an ignition criterion which included both temperature and time. It was possible with these tests to determine the effect which changes to supply volume and/or nozzle diameter would have on the system performance.

Propellant Ignitor Interface Margin Determination. - A preliminary determination of the margins of ignition was accomplished. At the optimum alignment position for each of two nozzles, a succession of runs was made at gas supply pressures which were increased until an ignition occurred. The separation distance was then varied from 1.2 mm to 5.0 mm to determine its effect on the gas pressure required for ignition and to compare ignition data with corresponding thermocouple data.

Resonance Tube Margins. - The effect of low ambient temperatures on the ignition capabilities of the ignitor system was evaluated by placing an ignitor system in an environmental chamber maintained at -40°C (-40°F). The system was modified so that the supply gas could also be cooled prior to an ignition attempt. The supply volume was connected to a solenoid valve on the outlet side and to a bottle of compressed air on the inlet side. The supply volume was charged to a pressure slightly higher than the required operating pressure and closed with a valve. After 7200 s (2 hours) at -40°C the gas supply pressure had dropped to the desired operating pressure and the solenoid valve was opened. This test is more stringent than that which would be encountered in an actual ignition attempt at -40°C ambient because the gas is allowed to cool prior to test. The gas would definitely be considerably warmer due to the heat of compression.

Ignition Design Development. - Based on the results of the above investigations, an ignitor was designed and developed to optimize the performance variables and program requirements. Of prime concern was the incorporation of adequate marging and meeting the size envelope of the rocket motor.

5.2 ENERGY SOURCE

Hand Pumps. - Various hand pumps were evaluated to determine if they were appropriate for this application. These pumps had piston areas ranging from 1.6 cm^2 (0.25 to 2.4 in^2) and stroke lengths from 15 to 51 cm (6 to 20 in). These pumps were evaluated experimentally and analytically to determine the maximum pressure output for a 670 N (150 lb) force input. Experimental and analytical evaluations were conducted to determine the maximum pressure which could be obtained in a pump system where compressed air was allowed to bleed off through nozzles of various diameters. The gas supply pressure/flow requirements of the penumatic match ignitor were compared to these test results to determine the type of power supply necessary for this application. Combinations of hand pumps and supply volume were evaluated analytically and experimentally to determine an effective configuration which would provide the necessary pressure/time output with a minimum expenditure of the operator's energy and time.

Check Valves. - The effect of the cracking pressure of the check valves on the pump's output pressure and flow characteristics was experimentally and analytically determined.

Abort-Enable Switch. - The abort-enable switch was experimentally evaluated to determine the time required to dump the supply of compressed air to a safe level.

In-Line Filter. - The in line filter was experimentally evaluated to determine its effect on the pressure/time and flow output characteristics. This was accomplished by comparing test runs made with and without the filter in line.

Supply Volume. - The gas supply volume was varied by using polyethylene pneumatic tubing of various diameters and lengths. The inner diameter of the tubing was either 3.2 or 6.4 mm (0.126 or 0.251 in). The length of tubing was varied from 75 to 100 m (200 to 330 ft). This provided gas supply volumes of 488, 735, 1960 and 2944 cm^3.

Relief Valve. - Relief valve requirements and operating characteristics were experimentally evaluated. Tests were run with the relief valve set to release at pressures from 0.3 to 1.4 MN/m^2 (43 to 200 psig) with the various supply volumes and nozzle diameters. These tests were used to establish the ignition pressure/time margins. To test the repeatability of the relief valve, ten runs were made at each of three pressure settings. The gas pressure in a 2944 cm^3 supply line was slowly increased until the valve opened.

Energy Source Margins Determinations. - Flueric ignitor assemblies were analytically and experimentally evaluated with complete hand pump operated supply systems to establish the feasibility of the flueric ignition concept by actually igniting $BKNO_3$ pellets. Subsequent efforts were directed toward experimentally and analytically defining the operating margins of the ignition system.

5.3 PROPELLANT

Ignition characteristics of $BKNO_3$ samples were determined by Differential Thermal Analysis (DTA) in the same manner as the nitrocellulose. The methods of interfacing the $BKNO_3$ pellets and the ignitor was determined experimentally.

6. RESULTS AND DISCUSSIONS

6.1 Pneumatic Match

The pneumatic match can ignite primary explosives in as little as 5 ms and achieve temperatures in excess of 1200°C in 35 ms. This extraordinary performance is obtained only with an optimum configuration operating with relatively high pressure gas. To design the pneumatic match to allow operation with a low pressure air supply required modifications of the ignitor geometry. The use of low pressure air as the supply gas lowers the maximum temperature and lengthens the time response. Therefore, the thermal output characteristics of the pneumatic match were closely matched to the ignition requirements of the nitrocellulose resonance tube.

Table I presents (in SI units) a summary of the gas pressure and separation distance necessary to obtain the maximum thermal output for each type of tube with each of three nozzles. The tubes are arranged in this table in order of decreasing length. The dimensions of the tubes are tabulated and used to identify them. For example: the first tube (designated SRI 2) has a total length of 21.6 mm which is made up of five cylinders of different diameters. The first cylinder is 1.6 mm in diameter and is 5.72 mm in length while the last cylinder in the tube has a diameter of 0.4 mm and is 0.64 mm in length. This resonance tube was evaluated with two nozzles, 0.9 mm diameter and 1.2 mm diamter. The best temperature performance for each nozzle is given in the table along with the corresponding pressure input and separation distance. With the 0.9 mm nozzle, 400°C was generated at a supply pressure of 0.7 MN/m^2 and at a separation distance of 3.8 mm. Table II presents the identical data in the same format but in English units.

The tube which produced the highest temperature of any tested during this program is 10.2 mm in length and when supplied by a 1.2 mm diameter nozzle at 0.4 MN/m^2 (55 psig) produced temperatures of 500°C. This tube, designated SRI 1, was subsequently tested to determine the minimum pressure required to cause ignition. It was also evaluated at higher pressures at various vent areas to determine its optimum performance. The optimum performance (shown in Figure 8) occurs at a vent area of 0.1 cm^2 (0.016 in^2). The maximum temperature exceeded 800°C for this configuration which was subsequently used for the final design.

Nozzle/Resonance Tube Alignment Margin Determination.-Efforts to establish the margins of operation of the ignitor were concerned with the individual system components and their relationships to other components. Angular misalignment of the nozzle and resonance tube had been previously found to be detrimental to proper operation. The effects of axial misalignment were measured along three orthogonal axes, X, Y, and Z, where Z corresponds to the separation distance between the nozzle and the resonance tube. The results are shown in Figure 9 for both the 1.2 mm and 0.9 mm diameter nozzles with the SRI 1 resonance tube, Figure 6. The effect of misalignment is seen to be a lowering of the maximum temperature attainable. The larger (1.2 mm diameter) nozzle is found to exhibit a somewhat wider range of operation with respect to X and Y axis misalignment than the smaller nozzle. With respect to the separation distance (Z-axis alignment), it has more than twice the operating range than the small (0.9 mm diameter) nozzle.

Similar data shown in Figure 10 taken with a 2 cm long resonance tube (SRI 2), shown in Figure 6, provides a comparison of the effect of the length of the resonance tube. For this longer tube with the 0.9 mm nozzle, there is a slightly wider performance range with respect to X and Y axis misalignment although the maximum temperature is lower for this tube with the 0.9 mm nozzle. The range of usable separation distance is improved considerably with this longer tube.

12

Varying the separation distance was shown (Figure 9) to effect the maximum temperature obtainable. Since ignition of materials (such as nitrocellulose) is dependent on the time history of the thermal input rather than the maximum temperature, further insight into the ignition margins may be obtained with reference to the data presented in Figure 11. These data, taken with thermocouples, show the actual temperature/time histories at six separation distances in intervals of 0.5 mm. For these tests the SRI 1 ignitor was tested with a 1960 cm^3 volume with the relief valve set to discharge at 0.5 MN/m^2 (73 psig). The large nozzle (1.2 mm dia.) was used. At each separation distance temperatures of at least 325°C were obtained. The time that at least this temperature is maintained varies with the separation distance from 0.5 sec to 2.0 sec with the maximum times occuring at a separation distance of 3.5 and 4.0 mm. Peak temperature occurred at 3.5 mm.

The supply pressure can effect the separation distance since it determines the location of the instability region of the jet. Additional insight into the effect of the initial supply pressure may be obtained with reference to the temperature/time traces shown in Figure 12. These traces generated by an SRI 1 ignitor at a separation distance of 3.5 mm demonstrated how the time at ten\.eratures above 325°C increases with increasing supply pressure to about 3.5 seconds at P_i = 0.60 MN/m^2 (87 psig). At pressures above this, only a time delay is the result. The test ignitor shown in Figure 5 operated only when the pressure ratio across the nozzle was between 3 and 6. Thus no further improvement in temperature/time performance was expected with the test ignitor for supply pressures higher than 0.6 MN/m^2 because it would not operate under those conditions. The ignitor used in the final design however, would operate at high supply pressures because it was designed to reduce the pressure ratio across the nozzle by choking at the vent.

Vent Tube.- The ignitor used to generate the data of Figures 11 and 12 was improved by decreasing the vent area, as shown in Figure 8. These data were obtained with P_o = 0.7 MN/m^2 to determine the optimum thermal output which could be expected. As the vent area is reduced, the maximum temperature increases and peaks at about 0.1 cm^2 (0.015 in^2). The output duration is shorter for this vent area because it has an operation band which includes pressures higher than 0.7 MN/m^2. The larger vent configuration does not operate at the higher pressures (note the time delay) but holds the thermal output longer. For vent areas smaller than 0.08 cm^2 one obtains very fast response but loses thermal output due to being at the extreme of the operation range. Therefore, for optimum performance, the ignitor should incorporate a vent area of approximately 0.1 cm^2 at a separation distance of 2.5 mm (0.100 in) and an initial pressure of 0.7 MN/m^2. It was demonstrated that this configuration will provide 800°C, many times the output needed to ignite the nitrocellulose even at ambient temperatures of -40°C.

To evaluate the effect of a long tube as a vent, corresponding to the operation of the flueric ignitor within a rocket motor, ignition tests were run with 6.4 mm I.D. tubing as the only vent. It was found that lengths over 1 m could be attached to the ignitor without affecting the ignition performance. Subsequent evaluations indicated that the optimum venting method was a co-axial tube completely surrounding the ignitor. With such a vent tube the significant vent area becomes the area of the ignitor's vent holes.

Propellant Ignitor Interface - The results of differential thermal analysis of nitrocellulose showed identical traces for tests made in a nitrogen and an air atmosphere. They both indicated an exotherm starting at 150°C. A change in the slope on the exotherm occured at 167°C. The same effect was noted on a literature thermogram in the Stadtler Index for nitrocellulose. In that thermogram obtained on a nitrocellulose sample from Hercules Company, initial decomposition was noted at 165° -203°C, followed by ignition at 203° -242°C.

Propellant Ignitor Interface Margin Determinations. The pressure required to cause ignition was determined for the 1.2 mm diameter nozzle and the 0.9 mm diameter nozzle in a large vent configuration. The minimum pressure to obtain ignition with the 0.9 mm nozzle was 0.41 MN/m^2 (60 psig) whereas it was only 0.31 MN/m^2 (45 psig) for the 1.2 mm diameter nozzle. The separation distance required at this lower pressure and the larger nozzle was 1 mm larger than that for the higher pressure and the smaller nozzle. No upper limit on pressure was found because the pressure must pass through the optimum pressure range if it starts at an initial pressure greater than the optimum. It was found that with an initial pressure of 0.5 MN/m^2 (72 psig) a range of separation distance of almost 2 mm was possible with the 1.2 mm diameter nozzle. To obtain a comparable range for the 0.9 mm nozzle, a pressure of 0.6 MN/m^2 (87 psig) is required.

Ignitor Margins. The effect of cold temperature operation on ignition characteristics of large vent SRI 1 ignitor was evaluated at temperatures of -40°C. All tests conducted at initial supply pressures of at least 0.60 MN/m^2 (87 psig) produced ignitions, even though the ignitor will produce considerably higher temperatures at higher pressures and the smaller vent area.

Ignitor Design Development. - An ignitor was designed based on the results of the experimental test data which indicated that the largest margin for ignition would occur with a reduced vent area. A preliminary design of an ignitor which satisfies the ignition requirements and the envelope requirements is shown in Figure 13. It consists of six parts fastened together by screw threads or compression.

The final design (Figure 14) of the ignitor for this program incorporates the same provisions for attaching the vent and supply tubing but eliminates all screw type connections. It was determined that nitrocellulose will bond to itself very well with the addition of just one or two drops of solvent (i.e., acetone). Thus the resonance tube which will be a molded part will be cemented in place in the molded holder simply by wetting its surface with solvent and placing it into its mating hole. Similarly the molded BKNO$_3$ holder will be loaded and placed into the other holder which will have been just wet with solvent. The bonding accomplished in this way is quite strong and provides a very good seal.

Detailed drawings of the three nitrocellulose components are shown in Figures 15, 16 and 17. It should be noted that the resonance tube has a 1.0 mm endwall which act as the propellant/ignitor interface.

In order to enhance the consumption of the ignitor, it is recommended that BKNO$_3$ powder be mixed with the nitrocellulose for all three molded parts. Ignition tests have shown that the addition of BKNO$_3$ to the resonance tube greatly enhances the flame transfer to the BKNO$_3$ pellets in the holder. A 35% mixture by weight is adequate for this application although this may have to be varied due to the many different types of nitrocellulose available. In general, the less the nitrocellulose is nitrated, the more BKNO$_3$ should be added to enhance flame spreading. High speed motion pictures of test firings indicate that flame spreading is quite acceptable even with no BKNO$_3$ added to the nitrocellulose.

6.2 ENERGY SOURCE

Hand pumps - The energy source was designed to provide an initial gas supply pressure of approximately 0.7 MN/m^2 (101 psig). It is important that the supply pressure remain within the particular optimum operating (resonance heating) range of the ignitor used for a minimum of 1.5 sec. As shown in Figure 18 a pump piston diameter of 35 mm (1.38 in) will produce a pressure of 0.7 MN/m^2 with a force input of 670 (150 lbf). A pump with a smaller diameter piston will also be

14

able to produce the required pressure but will take more strokes to achieve it. A larger diameter piston is not useful for this application because a force greater than that which could be provided by an average person (670 N) would be required to obtain 0.7 MN/m^2.

An alternate approach to the power supply, which eliminates the need for a relief valve, is the use of a pump which produces a greater mass flow of air than can be passed through the nzozle. This causes the pressure behind the nozzle to increase but was found to be impractical.

Check Valves. - The pressure of the air which enters the supply tubing is directly affected by the cracking pressure of the check valve. The pressure produced at the pump exhaust port is reduced by the value of the cracking pressure. Additionally, on each upstroke of the pump's piston the cylinder refills to atmospheric pressure minus the cracking pressure of the input check valve. Thus check valves with very low cracking pressure (2 KN/m^2) were utilized.

Abort-Enable Switch.- Since the ignitor will not function at pressures below 0.2 MN/m^2 (30 psig) the switch had to be able to safely dump the pressure from 0.7 MN/m^2 to 0.2 MN/m^2 in less than 5 seconds. Testing indicated that this could be accomplished within 3 sec.

In-Line Filter.- The 5 micron in-line filter located near the hand pump did not affect the pressure/time or flow characteristics at the relief valve.

Supply Volume. - Tests conducted to determine how long it would take to pump a 2944 cm^3 supply line to 0.7 MN/m^2 (101 psig) indicated that it would require approximately 30 seconds. By contrast it takes less than 15 seconds to pump up a 1960 cm^3 (119 in^3) line to 0.5 MN/m^2 (73 psig). It should be noted, however, that it is not necessary to pump continuously for these times. The operator may stop briefly and then resume without losing much air pressure. For safety considerations leakage can be built into the system so that the operator will not be able to keep the volume charged at pressures close to the relief valve opening pressure.

Relief Valve. - Although the ignition device is relatively insensitive to supply pressure variations above 0.5 MN/m^2 (73 psig), the repeatability of the relief valves was investigated. The relief valve was adjusted to discharge at 0.70 MN/m^2 (101 psig), 0.55 MNm^{-2} (80 psig) and 0.41 NMm^{-2} (60 psig). The following table lists the initial pressure, the ten run average and the standard deviation, σ , for the ten runs at each pressure.

Initial Pressure		Ten Run Average		Standard Deviation	
MNm^{-2}	Psig	MNm^{-2}	Psig	MNm^{-2}	Psig
0.700	101.5	0.695	100.1	0.0030	0.5
0.552	80.0	0.550	79.8	0.0026	0.4
0.414	60.0	0.412	59.8	0.0020	0.3

Energy Source Margin Determinations.- The rate at which the supply pressure decays once the relief valve is opened is a function of the supply volume nozzle diameter and initial pressure and may be analyzed with respect to fluid dynamic principles of gas flow through a nozzle. It can be shown from the mass continuity equation and the ideal gas laws that the pressure at any time after the valve opens, P_o, may be related to the initial pressure P_i by the following:

$$P_o = P_i \ exp \ (- \sqrt{\gamma RT_o \ (\frac{2}{\gamma + 1}) \ \frac{\gamma + 1}{\gamma - 1}} \ \frac{A^*}{V} \ t) \qquad (1)$$

If we assume the initial pressure P_i = 0.7 MN/m^2 then an ignition criterion of at least 2 sec may be met with either the 1.2 mm or the 0.9 mm nozzle and either the 75 m or 100 m line length with 6.4 mm ID tubing. However, with the 3.2 mm ID tubing only the combination of longer length tubing and the small diameter nozzle will meet the ignition criterion.

Ignition System Testing. - The results of testing the complete ignition system showed that ignitions were obtained within 30 seconds after beginning to pump. High speed (200 frames/s) photographs of several ignitions showed very good and uniform flame spreading. Figures 19 and 20.)

6.3 PROPELLANTS

The DTA results for $BKNO_3$ in nitrogen indicated endotherms at 129° (transition from the normal high temperature form to a metastable high temperature structure) and 300°C (melting). These two transitions agree with literature values (Handbook of Chemistry and Physics), for $BKNO_3$ by itself. Several exotherms were noted starting at 350°C, 425°C, 435°C and a major exotherm starting at 475°C. As expected, in air, endotherms were again noted at 129°C and 330°C. An earlier exotherm was noted starting at about 200°C. Other exotherms appeared at 410°C and at 465°C (major).

The $BKNO_3$ pellets were placed within a 3 mm (0.125 inch) diameter nitrocellulose holder whose ID was 4.57 mm (0.18 in). This left room to pack $BKNO_3$ powder around the pellets. The $BKNO_3$ was in direct contact with the 0.64 mm (0.025 in) thick nitrocellulose resonance tube endwall. Thus the burning of the endwall would ignite the powder and pellets which would in turn burn out of their holder and ignite additional pellets in the ignition basket.

16

7. CONCLUSIONS

The objective of this program was to develop, demonstrate and finalize the design of an inexpensive, safe, and foolproof advanced developmental model of an ignition system for sounding rockets. A flueric solid propellant ignitor - the pneumatic match - was developed to operate when powered by a single stage hand pump. The operation of the flueric ignitor is based on aerodynamic resonance heating in closed tubes excited by a free air jet emanating from a simple convergent nozzle. As such it completely eliminates the need for electrical energy and wiring.

Safety is improved with this system, as compared to the commonly used electircal systems, since this system is completely insensitive to stray voltages, EMP and electrostatic voltages. The possibility of inadvertent initiation is virtually eliminated, since the probability of connecting a supply of bleeding pressurized gas with sufficient energy to achieve ignition is extremely remote. No complicated power supplies, or safe and arm devices are needed. Decreased costs can be achieved through very simple molded parts, and the ability to install the motor's complete ignition system during manufacture, thereby decreasing motor complexity and eliminating the need for less reliable field installations.

The diameter of the hand pump piston was optimized at 35 mm (1.375 in) because it would allow pressures of 0.7 MN/m^2 (100 psig) to be developed for a 640 N (150 lb) input. Pumps with smaller diameter pistons which could also develop these pressures were not used because they required a longer period of time to achieve the required pressure.

The minimum supply volume required for this ignition system is 735 cm^3. If the supply tubing length is only 75 m (250 ft), as it could be if this were the desired standoff distance, the 6.4 mm (1/4 in) inner diameter transfer tubing would be required to obtain the necessary supply volume. If at least 100 m (330 ft) of transfer tubing is used, then the 3.2 mm (1.8 inch) tubing may also be used.

The energy source which used a hand pump and a relief valve was chosen for the final system because to pump a supply line without the relief valve (with an open nozzle) required considerable operator effort. The relief valve offered an inexpensive, reusable and consistent method to minimize the time and effort necessary to effect an ignition. The operator could also stop pumping momentarily and not have to start over again. The repeatability of the relief valve was quite good with a standard deviation of less than 3.1 kN/m^2 (0.5 psig). These small pressure variations have no effect on the ignitor performance.

Short resonance tubes (1 cm) were found to have performance characteristics comparable to the larger tubes (2 cm). Since it is desirable to have an ignitor which cannot block the rocket motor nozzle after ignition, the short tube was picked for the final ignitor system. The ignitor is made completely of nitrocellulose which burns completely to further eliminate the possibility of nozzle blockage.

The stepped geometry resonance tube was found to be superior to the cylindrical tube in both maximum temperature attainable and minimum time to achieve the maximum temperatures (response time). The tapered tube was not used although it could generate steady state temperatures almost as high as the stepped tube, because its response time was 35% slower than the stepped tube. Thus, for this application, where the supply pressure may drop lower than the operating range within 2

seconds after the relief valve opens, the tapered tube does not maintain its maximum steady state temperature for the required 2 seconds because the tube takes longer to reach its maximum temperature. The tapered tubes will effect ignition, normally, but does not have the margins which the stepped tube does.

The ignitor separation distance, s, was optimized at 2.5 mm (0.100 in) because at this distance the time that the temperature was above 300 °C was longer than 4 sec and the highest peak temperatures (800°C) was obtained. A preliminary ignition criterion which was found to provide an adequate margin was the generation of at least 300°C for 1.5 sec. There is a minimum initial supply pressure of 0.55 MN/m^2 (80 psig) needed to generate 300°C for at least 1.5 sec in the final design configuration. With a higher initial pressure, P_i = 0.7 MN/m^2 (100 psig), the time above 300°C reaches a maximum of 4.5 sec. It was concluded that to insure reliable ignition results and to maximize safety the higher supply pressures were desirable.

Pressures higher than 0.7 MN/m^2 do not increase this time nor do they increase the maximum temperature unless the vent area is reduced. The time above 300°C remains constant with the only effect of the higher pressure being to delay the start of operation. In fact, by purposely supplying high pressures an accurate time delay may be built into the ignition system. Since it is actually the pressure ratio across the ignitor nozzle which determines the operating range the effect of operation at high elevations will be to slightly increase the delay time. A minor increase in the time to pump the supply pressure would also be expected at the higher elevations. With a reduced vent area pressures higher than 0.7 MN/in^2 will operate the resonance tube and cause a slight thermal improvement. There would be no time delay with the reduced vent area.

The 1.2 mm (0.047 in) diameter ignitor nozzle was chosen for the ignition system because it provided higher temperatures and its wide operating range as far as alignment and supply pressure was concerned allowed the largest margins of operation. The faster pressure decay with this nozzle, which reduces the time at high temperatures, was offset by the higher temperatures obtainable at the wider operation range the ability to operate at lower initial supply pressures. With the 1.2 mm (0.047 in) diameter nozzle, alignment of the resonance tube is not at all difficult. A deviation of ±0.25 mm (±0.010) off axis has little effect on the temperature output. The axial alignment (separation distance) may be changed by ±1.1 mm (0.043 in) without appreciably degrading the performance. However, the use of the same resonance tube with the 0.9 mm (0.036 in) diameter nozzle requires a much closer alignment of ±0.10 mm (0.004 in) off axis and ±0.25 mm (0.010 inch) in separation distance. Standard tolerances of ±0.13 mm (±0.005 in) which are easily obtained even in molded parts will therefore have little effect on the ignitor with the large nozzle but may cause some difficulty with the smaller ones. VEnting of the ignitor's supply gas may be accomplished by using an ignitor holder with 2 vents 2.5 mm (0.100 inch) in diameter. These vents exhaust to a 17 mm (0.75 in) ID tube which carries the gas to the base of the rocket. The 3 mm (0.25 in) ID supply line tubing runs inside if the larger return line.

$BKNO_3$ pellets could not be ignited directly by resonance heating. It is suspected that large amounts of heat flux are needed because temperatures of 800°C were obtained without ignitors. An interface material which produces hot particulate matter was found to be required to ignite the $BKNO_3$ pellets. Nitrocellulose was picked as a suitable interface material because it was easily

18

ignited by the resonance heated air and produced the required hot particles. Since nitrocellulose has an igntion temperature of about 170°C only resonance tube configurations which could produce at leat 300°C were considered for use as an ignitor. The ignitor finally chosen for the system which produced 800°C will provide an adequate margin under all environmental conditions.

In the final design of this flueric ignition system, the operator pressurizes a 100 m (330 ft) length of penumatic tubing with a hand pump to a pressure of about 0.7 MN/m^2 (100 psig). The relief valve then discharges the volume of compressed air through the nozzle and into a stepped resonance tube. The air exists through a vent tube to the atmosphere at the base of the rocket. The resonance condition described above ignites the nitrocellulose at the end of the resonance tube, and its burning ignite the remaining pellets in the rocket motor's ignitor basket.

The ignition system, as fabricated, demonstrates the feasibility of the concept of flueric sounding rocket motor igntion by igniting $BKNO_3$ propellant over a wide range of operating conditions. Every component has been found to have adequate margins for both safety and repeatability of ignitions. The complete ignitor may be molded or cast, at a small cost. The energy source system is also simple and cost effective.

8. REFERENCES

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4. Kang, S.W., "Resonance Tubes," Ph.D. thesis, 1964, Renssalaer Polytechnic Institute, Troy, N.Y.

5. Brocher, E., Maresca, C., and Bournay, M.H., "Fluid Dynamics of the Resonance Tube," Journal of Fluid Mechanics, Vol. 43, Pt. 2, 1970, pp. 369-384.
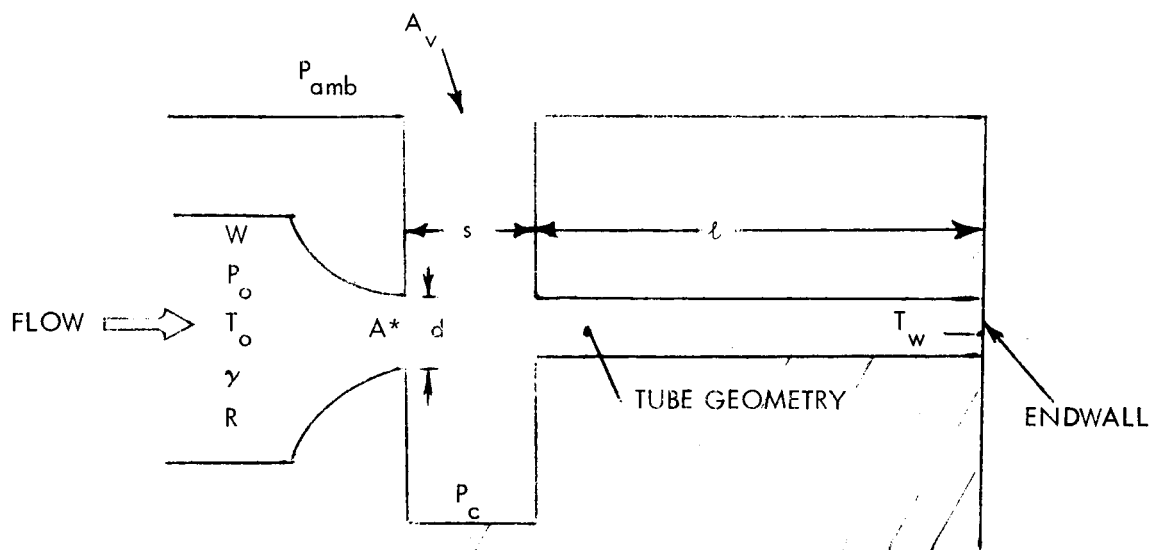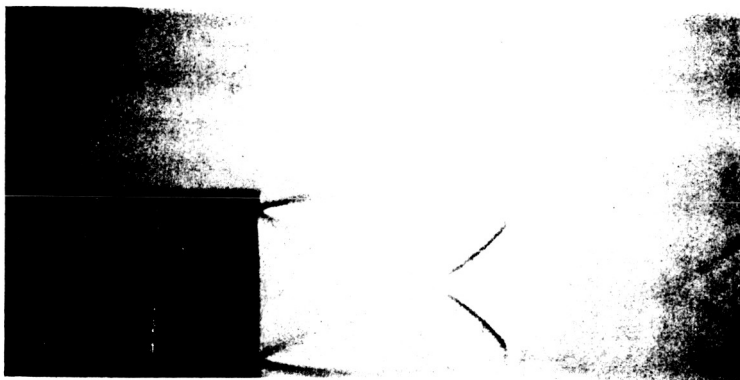
FIGURE 1 CROSS SECTION OF PNEUMATIC MATCH

NOZZLE   MACH DISC   CONICAL WAVE

|← CELL 1 →|← CELL 2 →|← CELL 3 →|

PRESSURE

+

0

INSTABILITY REGIONS
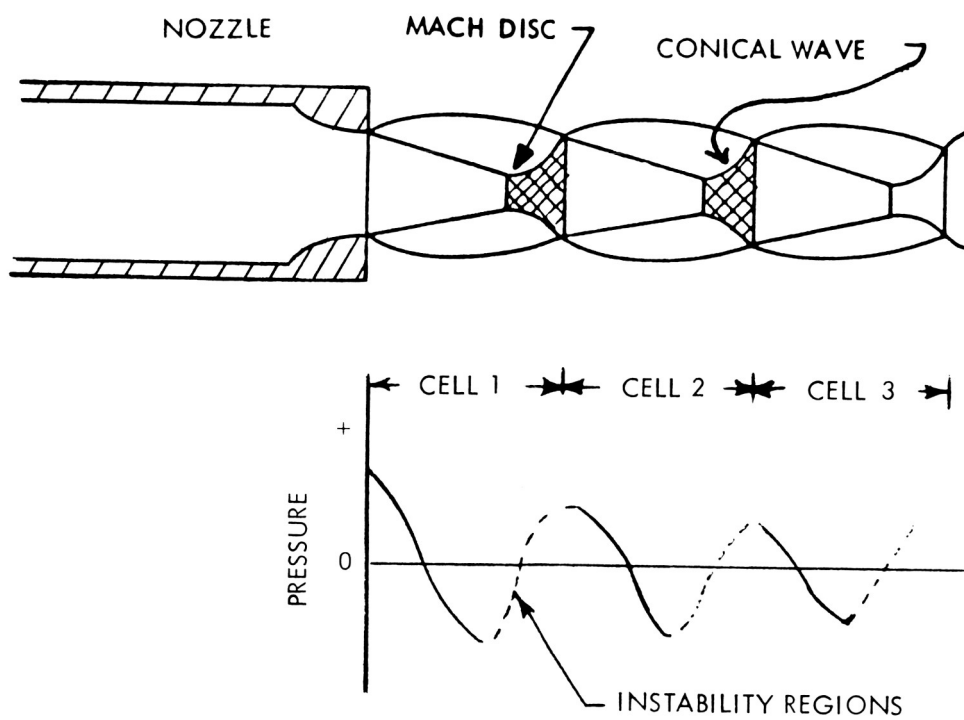
FIGURE 2   PRESSURE VARIATION – SHOCK WAVES
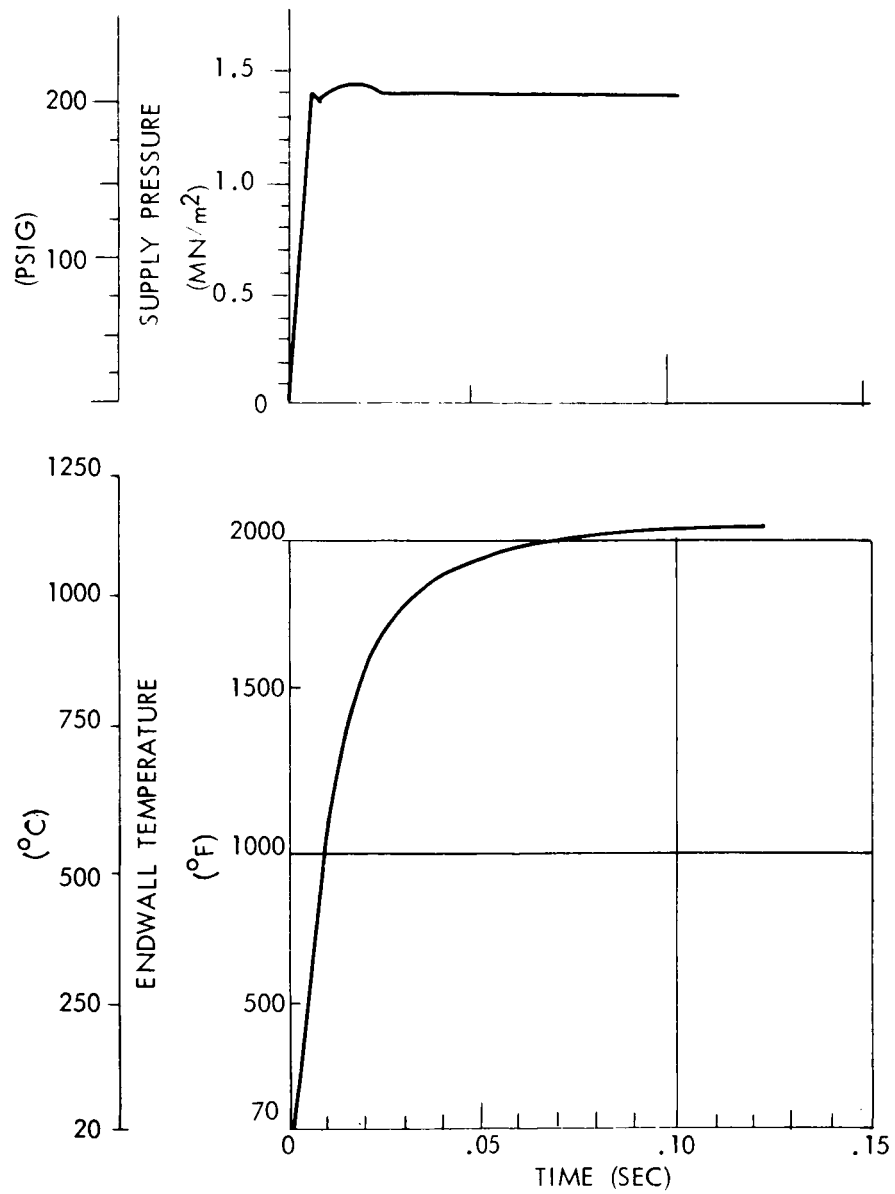
FIGURE 3 TYPICAL PNEUMATIC MATCH THERMAL PERFORMANCE DATA
WITH A HELIUM GAS SUPPLY

PNEUMATIC
MATCH

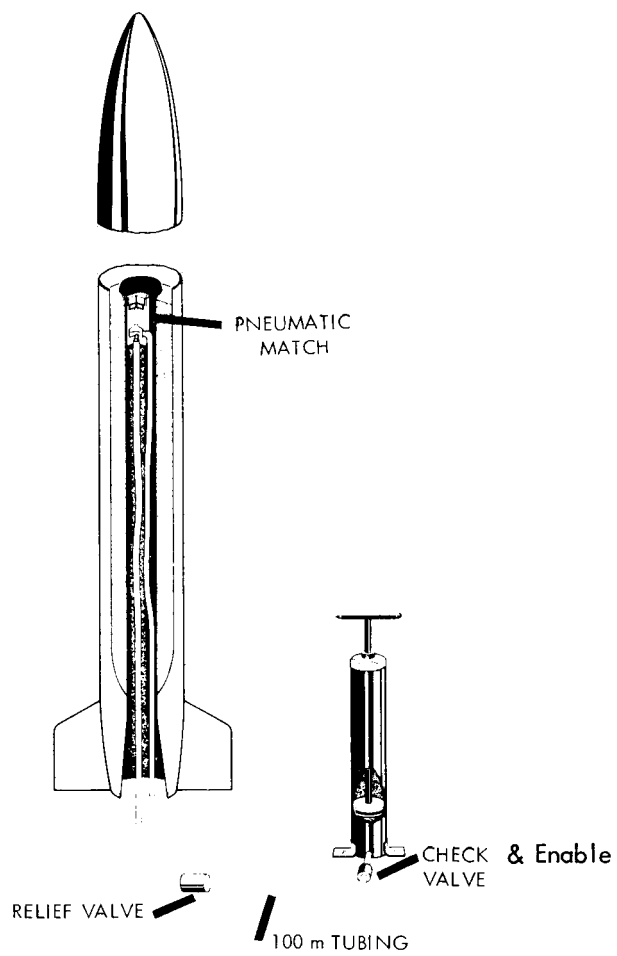CHECK & Enable
VALVE

RELIEF VALVE

100 m TUBING

FIGURE 4   FLUIDIC SOUNDING ROCKET MOTOR IGNITION SYSTEM
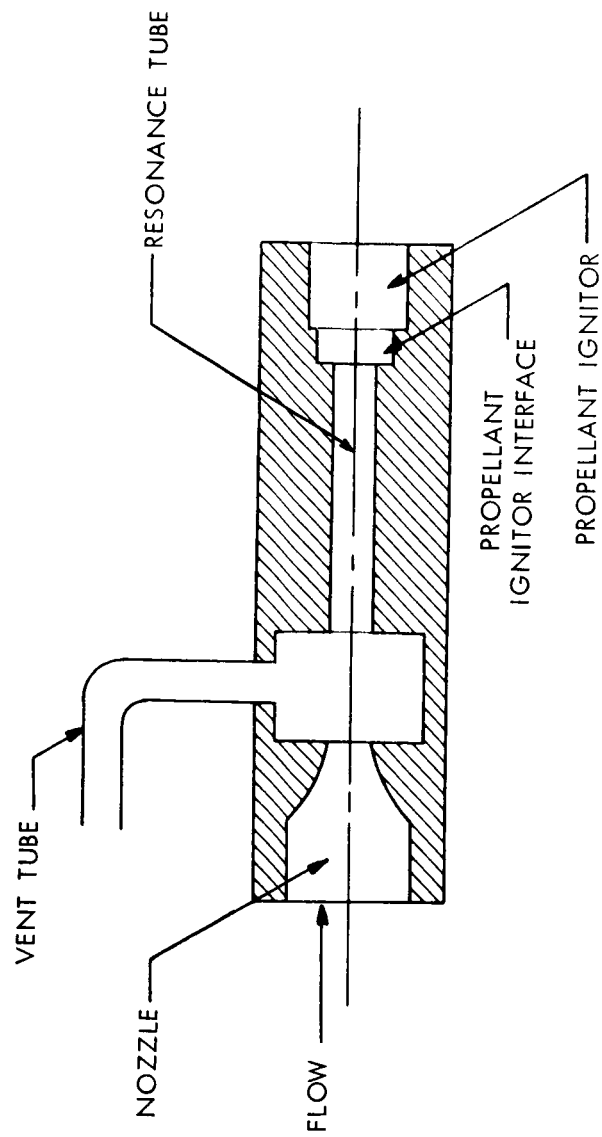
FIGURE 5 FLUERIC IGNITOR SCHEMATIC

RESONANCE TUBE

PROPELLANT
IGNITOR INTERFACE

PROPELLANT IGNITOR

VENT TUBE

NOZZLE

FLOW

SRI 1

TAPERED

CYLINDRICAL

SRI 2

INCH
0.5   1.0   0.5   1.0

0   0.5   1.0   1.5   2.0   2.5
CM
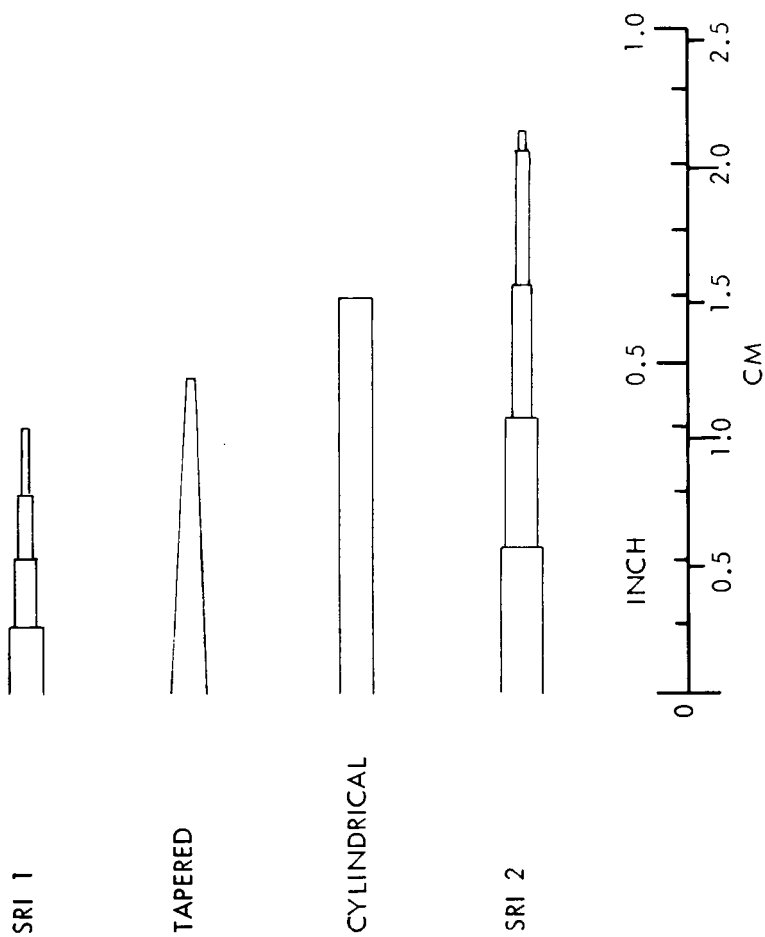
FIGURE 6   TYPICAL RESONANCE TUBE CONFIGURATIONS

TO PNEUMATIC MATCH

RELIEF VALVE

75- 100 m
TUBING

IN LINE FILTER

ABORT
VALVE

INLET
CHECK VALVE

OUTLET
CHECK-VALVE

HAND
PUMP
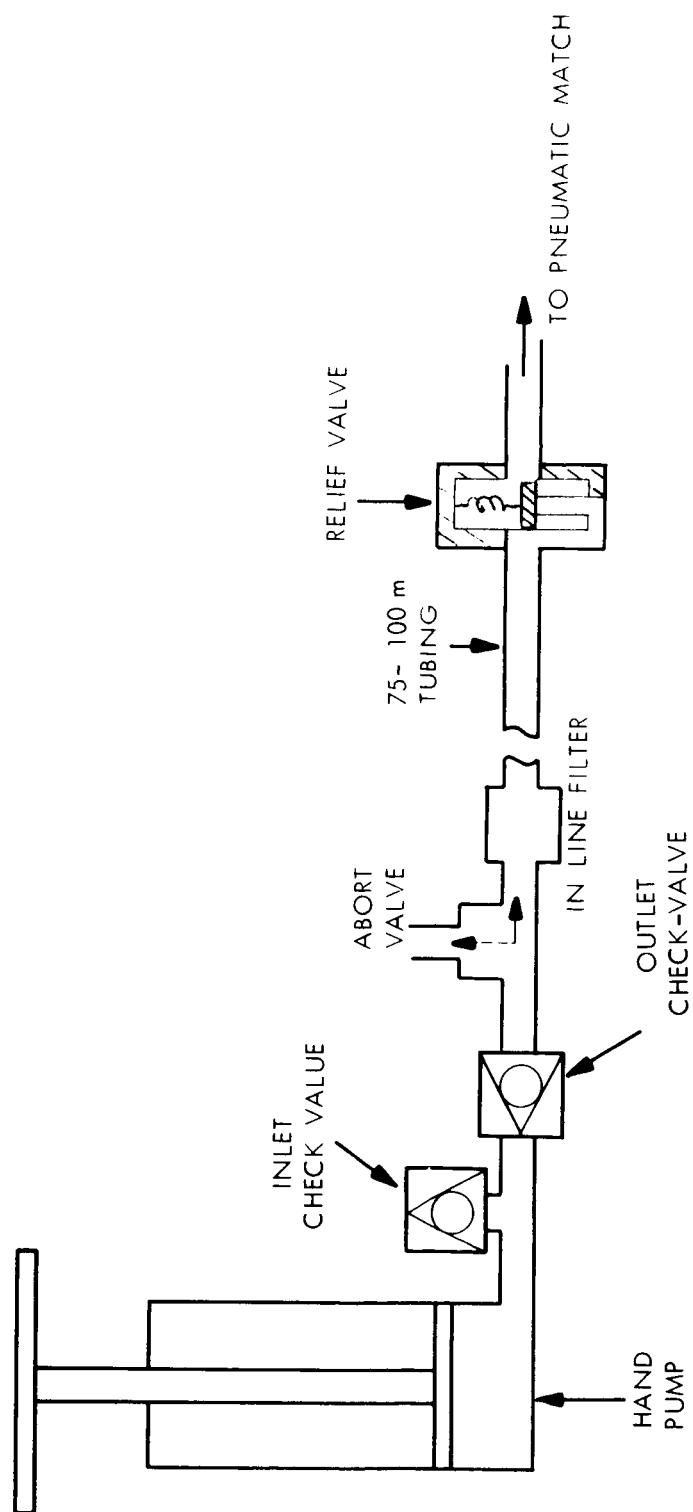
FIGURE 7   ENERGY SOURCE SCHEMATIC
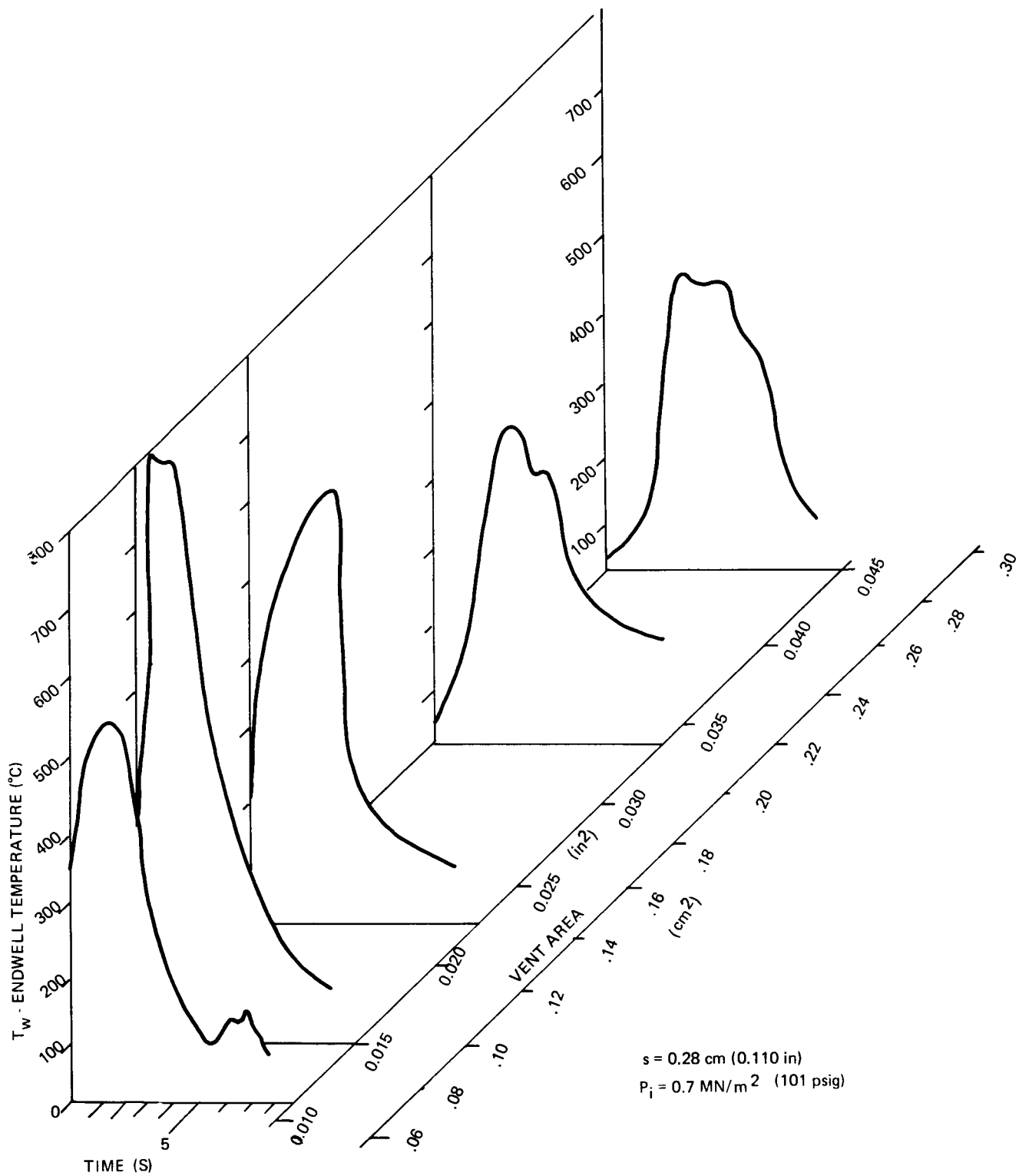
FIGURE 8. EFFECT OF VENT AREA

s = 0.28 cm (0.110 in)

P_i = 0.7 MN/m^2 (101 psig)

28
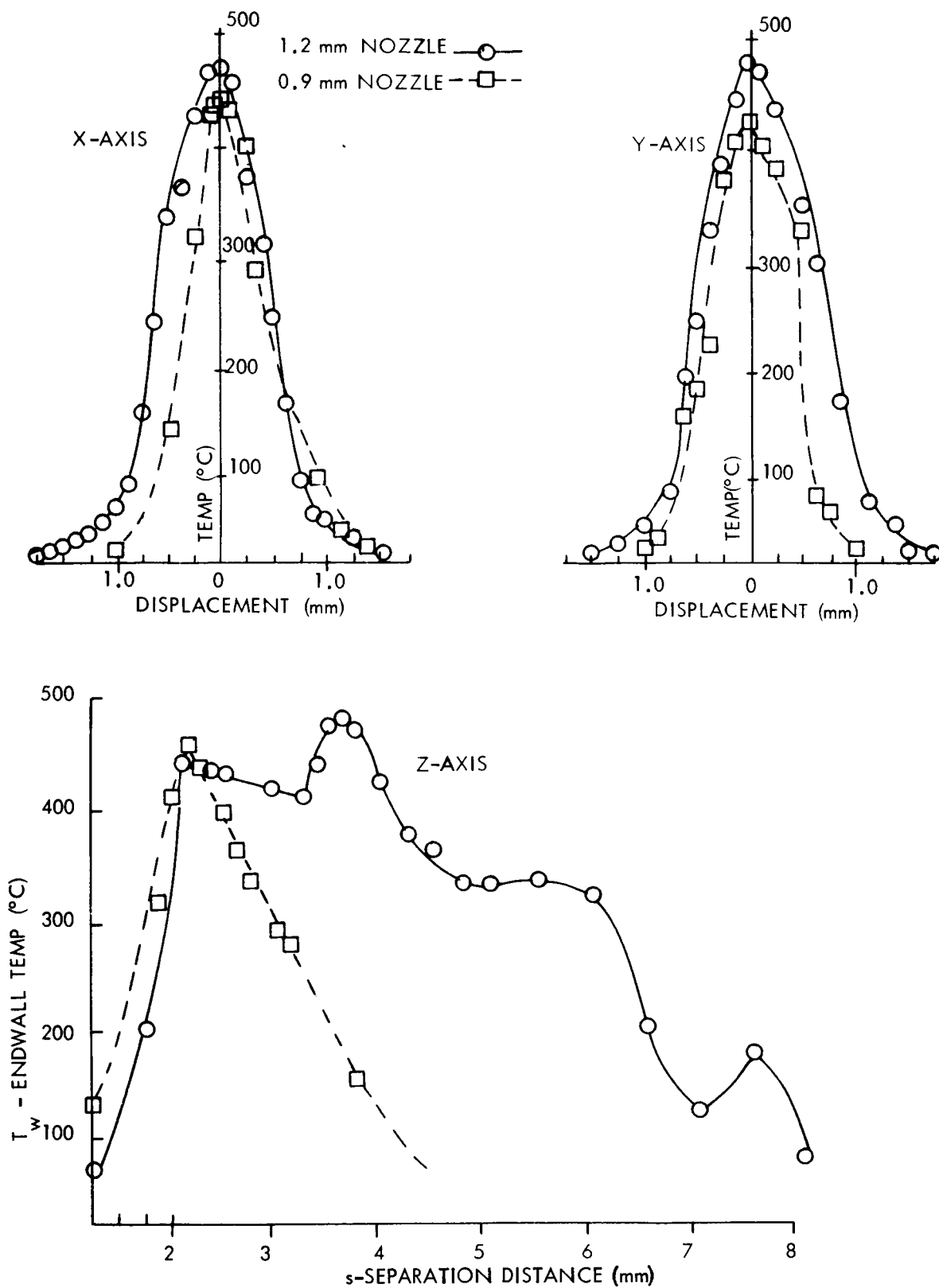
FIGURE 9 EFFECT OF AXIAL MISALIGNMENT ON THERMAL PERFORMANCE FOR SRI 1 TUBE

0.9 mm NOZ ⬚

X-AXIS

Y-AXIS

TEMP (°C)

DISPLACEMENT

TEMP (°C)

DISPLACEMENT

Z-AXIS

T_w -ENDWALL TEMP (°C)
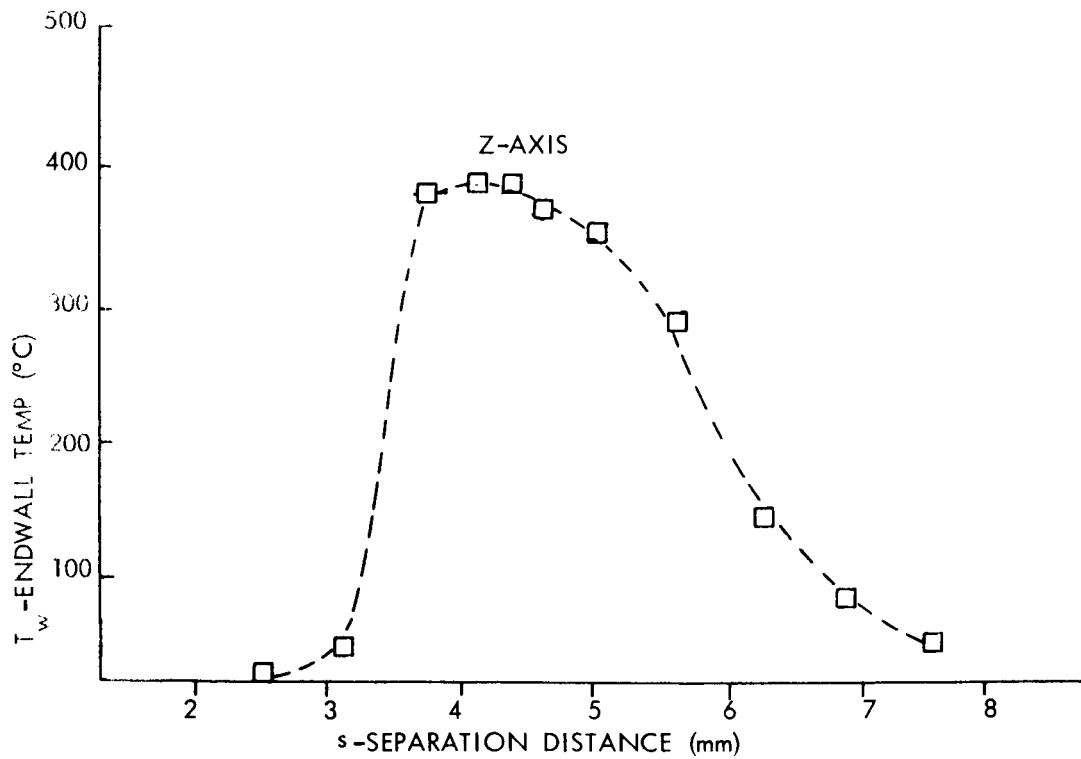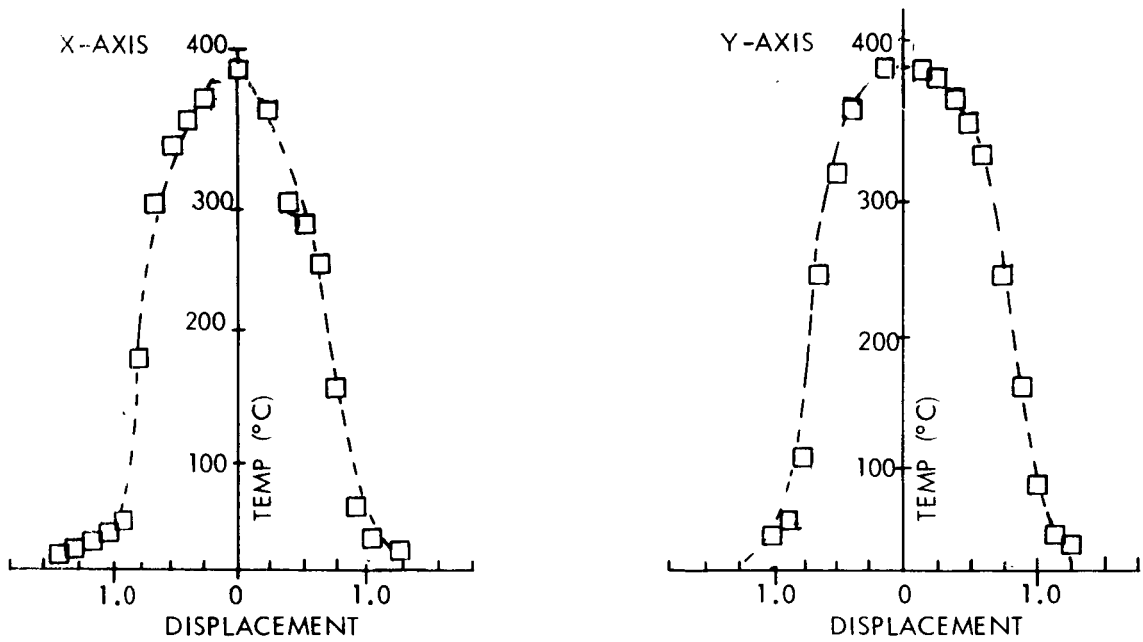
s -SEPARATION DISTANCE (mm)

FIGURE 10 EFFECT OF AXIAL MISALIGNMENT ON THERMAL PERFORMANCE TUBE FOR SRI 2 TUBE
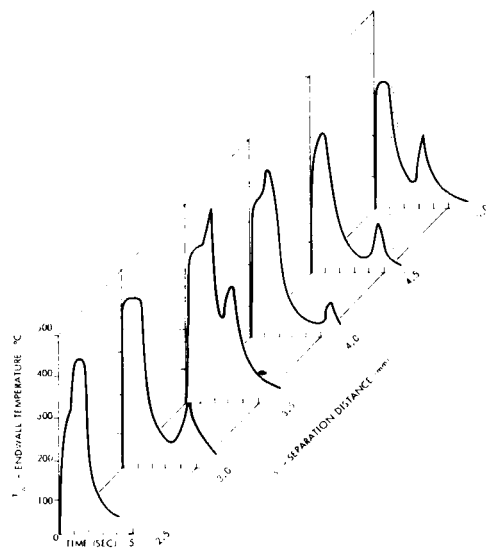
FIGURE 11   THE EFFECT OF SEPARATION DISTANCE ON RESONANCE TUBE
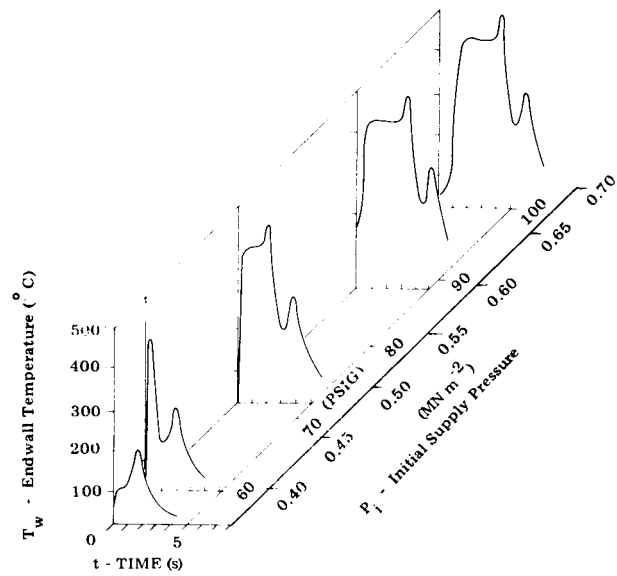THERMAL PERFORMANCE

31

FIGURE 12   THE EFFECT OF INITIAL SUPPLY PRESSURE ON RESONANCE TUBE
THERMAL PERFORMANCE
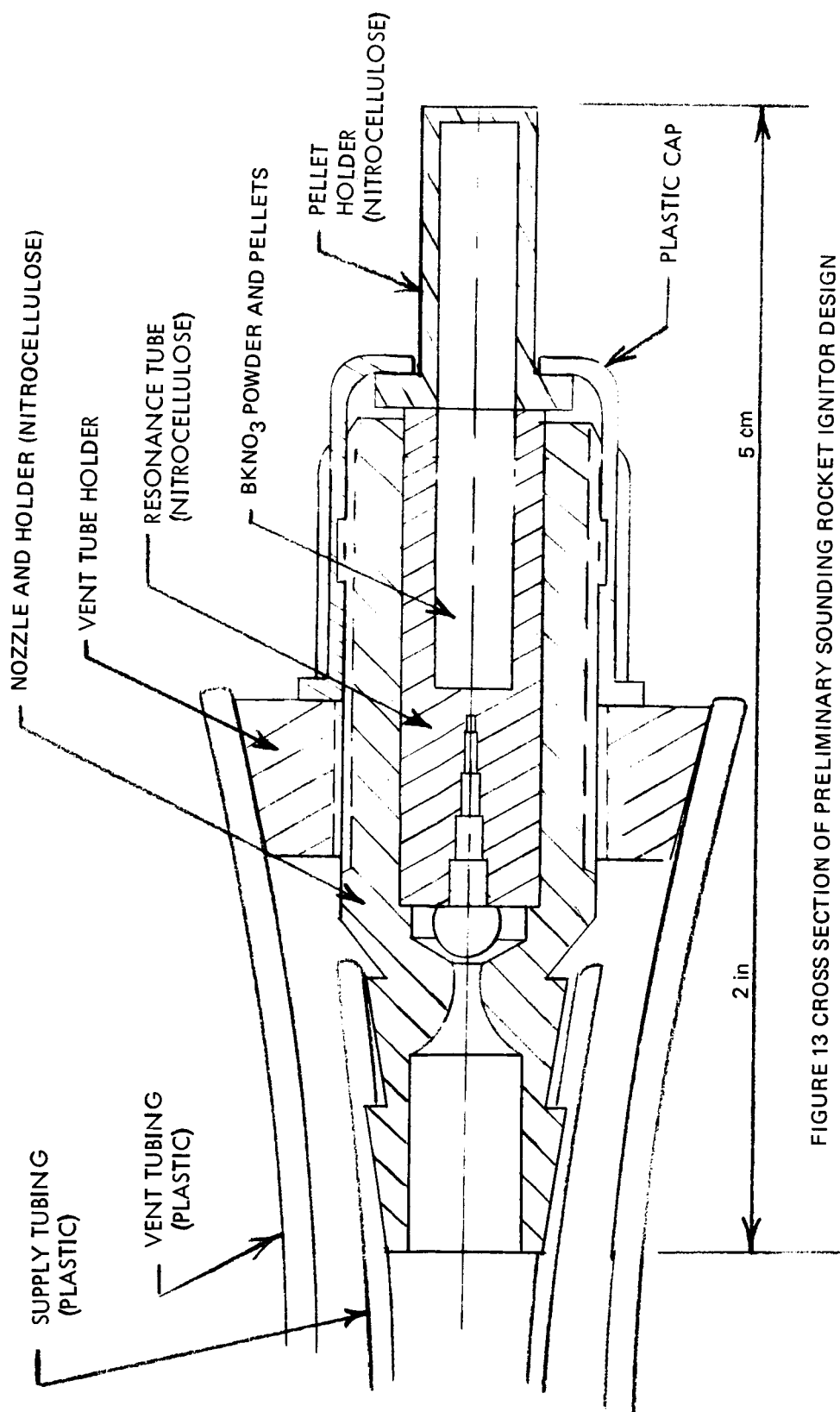
FIGURE 13 CROSS SECTION OF PRELIMINARY SOUNDING ROCKET IGNITOR DESIGN

NOZZLE AND HOLDER (NITROCELLULOSE)

VENT TUBE HOLDER

RESONANCE TUBE (NITROCELLULOSE)

BKNO$_3$ POWDER AND PELLETS

PELLET HOLDER (NITROCELLULOSE)

PLASTIC CAP

SUPPLY TUBING (PLASTIC)

VENT TUBING (PLASTIC)

5 cm

2 in

NOZZLE & HOLDER
(NITROCELLULOSE)

RESONANCE TUBE
(NITROCELLULOSE)

$BKNO_3$ PELLET

$BKNO_3$ POWDER

3.8 cm

1.5 in

RUPTURE
PORTS
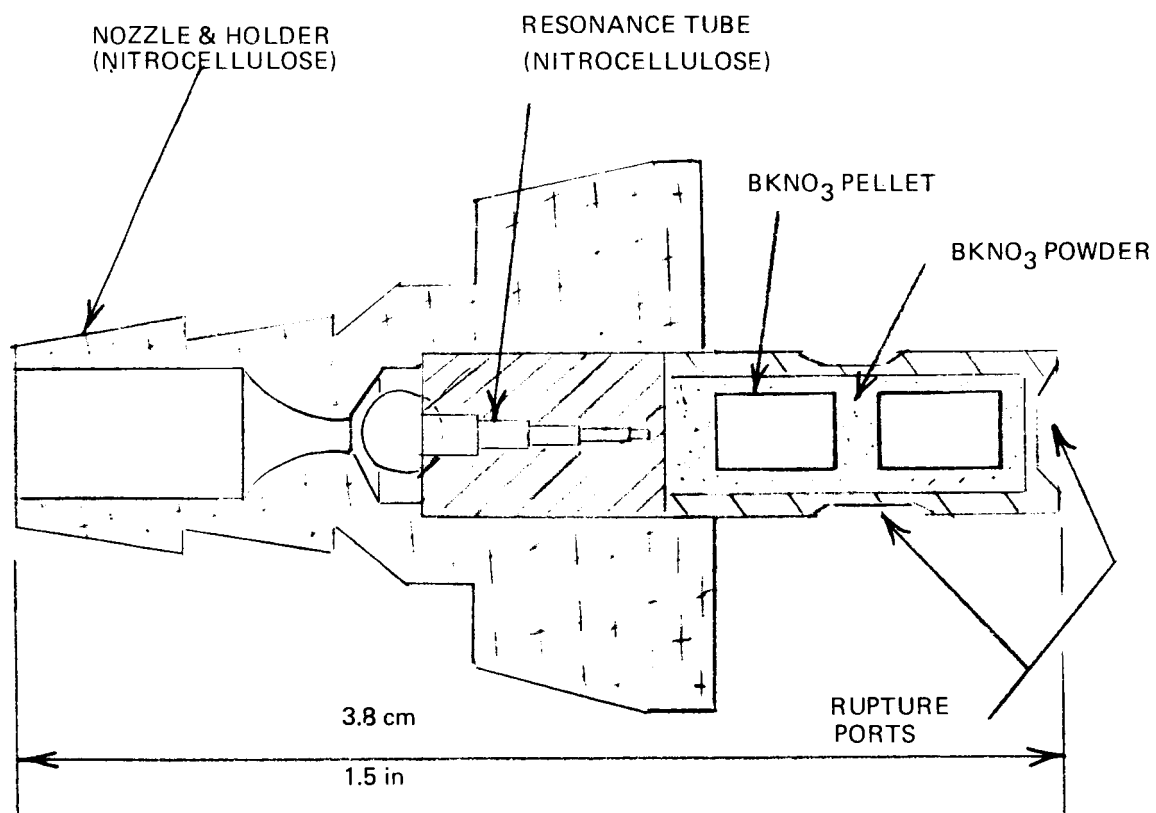
FIGURE 14. CROSS SECTION OF FINAL SOUNDING

ROCKET IGNITOR DESIGN

34
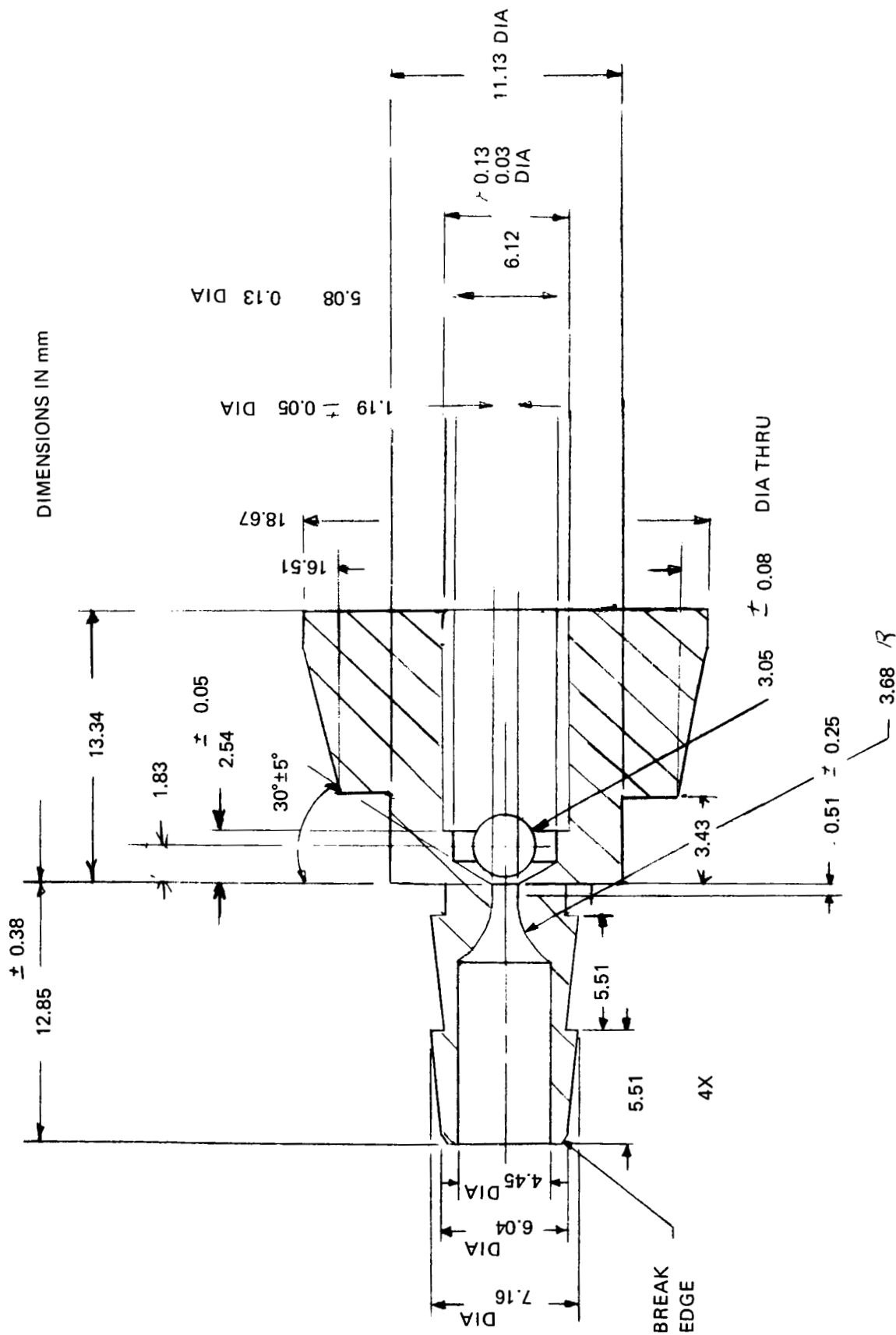
FIGURE 15. CROSS SECTION OF NITROCELLULOSE NOZZLE AND HOLDER

DIMENSIONS IN mm

11.13 DIA

0.13
0.03 DIA

6.12

5.08 0.13 DIA

1.19 ± 0.05 DIA

18.67

16.51

DIA THRU

± 0.08

3.05

3.68 R

13.34

± 0.05
2.54

1.83

30° ± 5°

± 0.25

.51

3.43

± 0.38

12.85

5.51

5.51

4X

4.45 DIA

6.04 DIA

7.16 DIA

BREAK
EDGE

35

DIMENSIONS IN mm

0.3

6.10

8.89

8.26

7.62

5.59

3.81

1.91

1.57 DIA

1.19 DIA

0.79 DIA

0.64 DIA

0.38 ±0.05 DIA
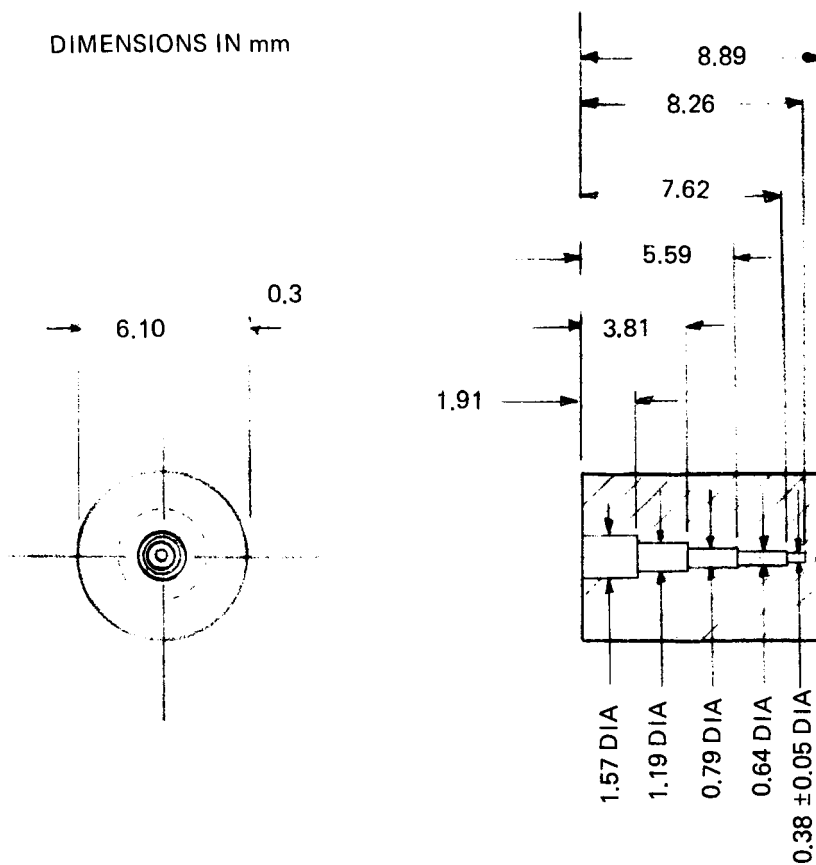
FIGURE 16. CROSS SECTION OF NITROCELLULOSE/BKNO$_3$ RESONANCE TUBE

Dimensions in mm
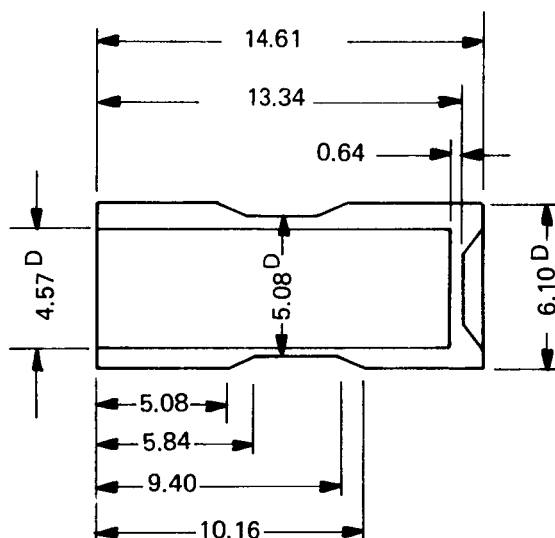

FIGURE 17. CROSS SECTION OF NITROCELLULOSE/BKNO3
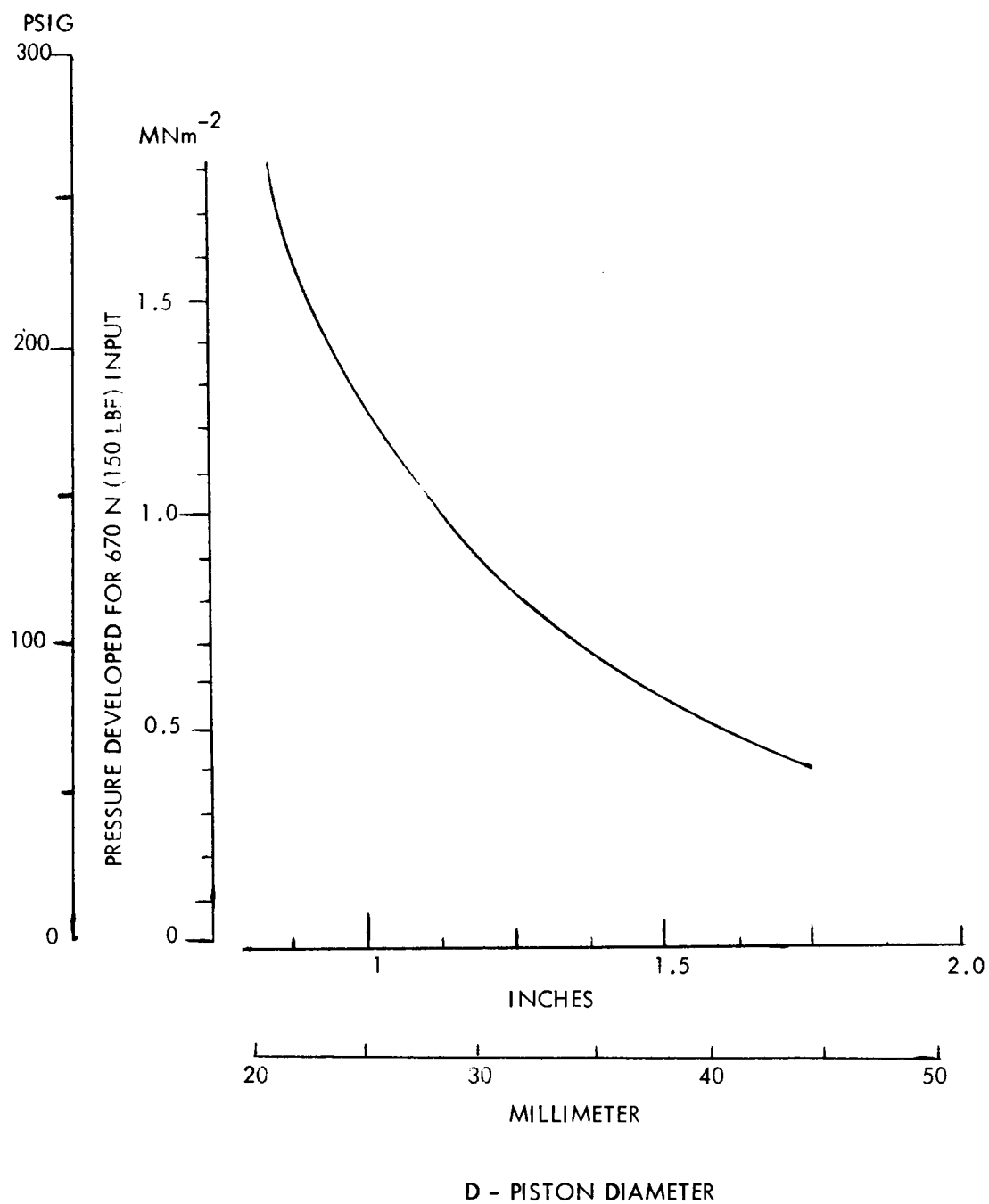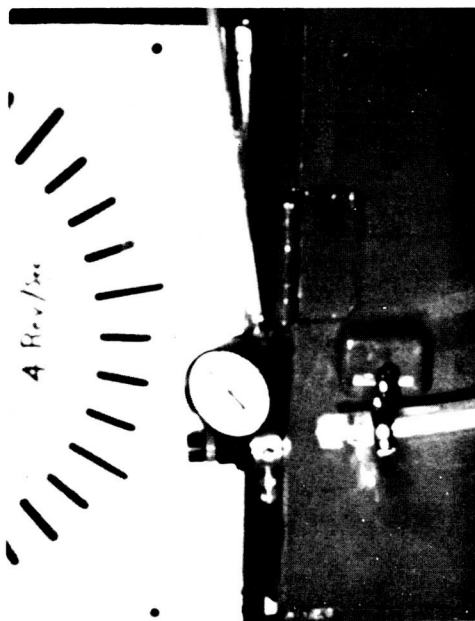PELLET HOLDER

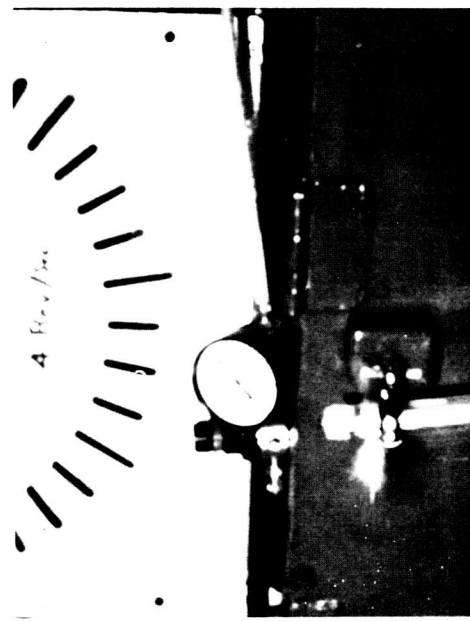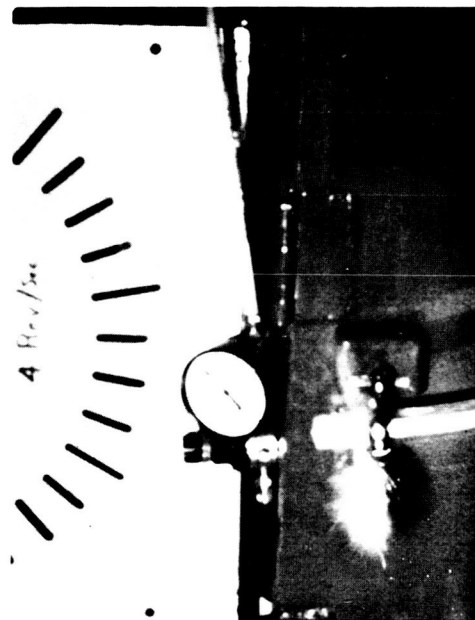D – PISTON DIAMETER

FIGURE 18   MAXIMUM PRESSURE DEVELOPED FOR 670N   INPUT TO PUMPS OF VARIOUS SIZES

t = 0

t = 5 ms

t = 10 ms

t = 15 ms

FIGURE 19. FLUERIC IGNITOR IGNITION SEQUENCE (Sheet 1 of 2)

39

t = 20 ms

t = 25 ms

t = 30 ms

t = 35 ms

FIGURE 20. FLUERIC IGNITOR IGNITION SEQUENCE (Sheet 2 of 2)

40

TABLE I. – SUMMARY OF PNEUMATIC MATCH OPTIMUM PERFORMANCE

FOR VARIOUS RESONANCE TUBES AND NOZZLES

(METRIC UNITS)

SHAPE	TOTAL LENGTH	RESONANCE TUBE — LENGTH OF SECTION WHOSE DIA. IS (mm)					NOZZLE								
							Nozzle dia. = 0.6 mm			Nozzle dia. = 0.9 mm			Nozzle dia. = 1.2 mm		
		1.6	1.2	0.8	0.6	0.4	MAX TEMP (°C)	SUPPLY PRESSURE (MNm⁻²)	SEPARATION DISTANCE (mm)	MAX TEMP (°C)	SUPPLY PRESSURE (MNm⁻²)	SEPARATION DISTANCE (mm)	MAX TEMP (°C)	SUPPLY PRESSURE (MNm⁻²)	SEPARATION DISTANCE (mm)
Step	*21.6	5.72	5.08	5.08	5.08	0.64				400	0.7	3.8	350	1.0	3.8
"	20.4	5.08	5.08	5.08	5.08	--	325	1.0	2.5	368	0.9	3.8	368	0.9	6.9
"	18.6	5.72	5.08	5.08	2.72	--	197	1.0	2.31				400	0.8	3.8
"	18.4	4.45	4.45	4.45	4.45	0.64				347	0.8	3.8	320	0.7	7.6
"	16.6	5.72	5.08	5.08	0.72	--							325	0.8	3.0
"	15.9	--	5.08	5.08	5.08	0.64	400	1.0	2.9	234	0.6	3.8	384	0.6	6.8
"	15.9	3.81	3.81	3.81	3.81	0.64	162	1.0	2.8	393	0.8	4.4	393	0.9	7.1
"	15.2	--	5.08	5.08	5.08	--	464	0.6	3.0	330	0.8	3.8	350	0.6	6.9
Cyl.	15.2	--	14.60	--	--	0.64				220	0.5	3.8			
Step	14.0	--	4.45	4.45	4.45	0.64	247	0.6	2.9	270	0.7	4.7	190	0.6	6.4
"	12.7	--	5.08	5.08	2.54	--				210	0.6	3.2			
Taper	12.7	↕	↕	↕	↕	↕				90	0.5	4.8			
"	12.7	↕	↕	↕	↕	↕				158	0.5	3.4			
Step	12.1	--	3.81	3.81	3.81	0.64	273	1.0	2.7	325	0.7	3.2	295	0.7	6.9
"	10.8	--	2.54	2.54	5.08	0.64	365	0.8	2.8	350	0.7	2.3	375	0.7	3.5
"	10.8	2.54	2.54	2.54	2.54	0.64				393	0.5	2.4	393	0.5	3.7
" **	10.2	2.54	2.54	2.54	2.54	--	125	0.9	1.01	450	0.4	2.3	500	0.4	3.5
"	8.3	1.90	1.90	1.90	1.90	0.60	147	0.9	1.95	350	0.9	3.1	300	0.6	4.6
"	7.6	--	2.54	2.54	2.54	--				341	0.5	3.2			
"	7.6	--	2.54	3.18	1.90	--				280	0.5	3.2			
Taper	7.6	↕	↕	↕	↕	↕				90	0.6	4.8			
"	7.6	--	--	--	--	--				438	0.5	2.8			

* SRI-2

** SRI-1

TABLE II. SUMMARY OF PNEUMATIC MATCH OPTIMUM PERFORMANCE FOR VARIOUS RESONANCE TUBES AND NOZZLES (ENGLISH UNIT)

| | | RESONANCE TUBE | | | | | NOZZLE | | | | | | | | |
| | | LENGTH OF SECTION WHOSE DIA. IS (in) | | | | | Nozzle dia. = 0.024 in | | | Nozzle dia. = 0.036 in | | | Nozzle dia. = 0.047 in | | |
SHAPE	TOTAL LENGTH	0.062	0.047	0.030	0.025	0.015	MAX TEMP (°C)	SUPPLY PRESSURE (PSI)	SEPARATION DISTANCE (in)	MAX TEMP (°C)	SUPPLY PRESSURE (PSI)	SEPARATION DISTANCE (in)	MAX TEMP (°C)	SUPPLY PRESSURE (PSI)	SEPARATION DISTANCE (in)
Step	*0.850	0.225	0.20	0.20	0.20	0.025				400	100	0.150	350	145	0.150
"	0.805	0.20	0.20	0.20	0.20	——	325	145	0.100	368	130	0.150	368	130	0.270
"	0.732	0.225	0.20	0.20	0.105	——				347	116	0.150	400	116	0.150
"	0.724	0.175	0.175	0.175	0.175	0.025	197	145	0.090	234	87	0.150	320	100	0.300
"	0.653	0.225	0.200	0.20	0.028	——				393	116	0.173	325	116	0.120
"	0.626	——	0.200	0.200	0.200	0.025	400	145	0.114	330	116	0.150	384	87	0.268
"	0.626	0.150	0.150	0.150	0.150	0.025	162	145	0.110	220	72	0.150	393	130	0.280
"	0.600	——	0.200	0.200	0.200	——	464	87	0.118	270	100	0.185	350	87	0.275
Cyl. Step	0.600	——	0.575	——	——	0.025				210	87	0.125			
"	0.550	——	0.175	0.175	0.175	0.025	247	87	0.114	90	72	0.189	190	87	0.252
Taper	0.500	——	0.200	0.200	0.100	——				158	72	0.134			
	0.500	↕	↕	↕	↕					325	100	0.125			
Step	0.476	——	0.150	0.150	0.150	0.025	273	145	0.105	350	100	0.090	295	100	0.275
"	0.425	——	0.100	0.100	0.100	0.025	365	116	0.110	393	72	0.095	375	100	0.138
"	0.425	0.100	0.100	0.100	0.100	0.025				450	58	0.090	393	72	0.145
"	**0.400	0.100	0.100	0.100	0.100	——	125	130	0.040	350	130	0.122	500	58	0.140
"	0.325	0.075	0.075	0.075	0.075	0.023	147	130	0.076	341	72	0.126	300	87	0.181
"	0.300	——	0.100	0.100	0.100	——				280	72	0.126			
Taper	0.300	——	0.100	0.125	0.075	——				90	87	0.189			
"	0.300	↕	↕							438	72	0.110			

* SRI-2
** SRI-1