

DESIGN OF AN UNDERWATER EXPLOSION SIMULATOR

by

LT. JOHN A. McMORRIS II, U.S.N.

SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS  
FOR THE DEGREE OF NAVAL ENGINEER

and

FOR THE DEGREE OF MASTER OF SCIENCE  
IN NAVAL ARCHITECTURE AND MARINE ENGINEERING

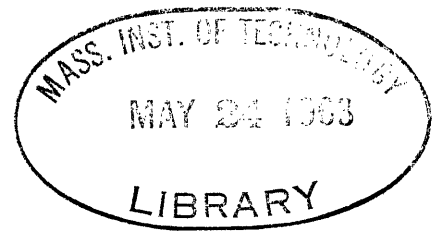
at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May, 1963

THESIS SUPERVISOR: HAROLD E. EDGERTON, SC.D., D.ENG.

Professor of Electrical Measurements



DESIGN OF AN UNDERWATER EXPLOSION SIMULATOR

by

JOHN A. McMORRIS II, LIEUTENANT, U.S. NAVY

B.S., U.S. Naval Academy

(1957)

SUBMITTED IN PARTIAL FULFILLMENT OF THE  
REQUIREMENTS FOR THE DEGREE OF NAVAL ENGINEER

and

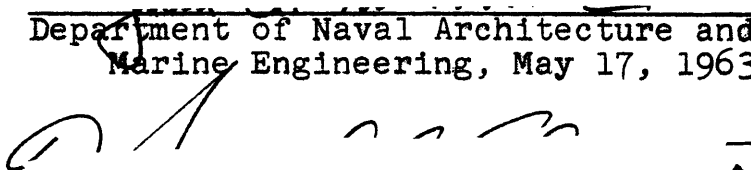
FOR THE DEGREE OF MASTER OF SCIENCE IN  
NAVAL ARCHITECTURE AND MARINE ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May, 1963


Signature of Author:

  
Department of Naval Architecture and  
Marine Engineering, May 17, 1963

Certified by:

  
Thesis Supervisor

Accepted by:

  
Chairman, Departmental Committee  
on Graduate Students

## DESIGN OF AN UNDERWATER EXPLOSION SIMULATOR

by LT. JOHN A. McMORRIS II, U.S.N.

Submitted to the Department of Naval Architecture and Marine Engineering on May 17, 1963, in partial fulfillment of the requirements for the Master of Science degree in Naval Architecture and Marine Engineering and the Professional degree, Naval Engineer.

### ABSTRACT

Desired characteristics of a hydraulic shock test facility are discussed, and the relative merits of possible driver configurations are examined. Primary emphasis is given to the experimental development of a magnetically actuated hydraulic shock generator, based on the "boomer" developed by Dr. H. E. Edgerton of M. I. T. The results of systematic variation of available design parameters are displayed in a series of plots, and these are used as the basis for a proposed design of an underwater explosion simulator. Basically, it was found that any combination of parameters which resulted in an electrical rise time of less than 50 microseconds resulted in an output pressure pulse with rise time less than 1 microsecond, for the driver configurations investigated. Pulse amplitudes obtained were computed to be approximately 1000 p.s.i., with an electrical input of 700 joules. Additional test series are recommended to verify performance of a driver-pressure chamber combination suitable for use as a test facility.

Thesis Supervisor: Harold E. Edgerton, Sc.D., D.Eng.  
Title: Professor of Electrical Measurements

## TABLE OF CONTENTS

	<u>Page</u>
List of Figures .....	4
List of Tables .....	5
I Introduction .....	6
A. Background .....	6
B. Characteristics of an Underwater Explosion	7
C. Characteristics Desired of Test Facility ..	10
D. Objectives in Development of Electrical Drive .....	12
II Procedure .....	14
A. Preliminary Selection of Driver Design ....	14
B. Investigation of Test Media .....	17
C. Investigation of Driver Characteristics ...	20
D. Instrumentation .....	27
E. Summary of Test Series .....	28
III Results .....	33
A. Electrical Performance .....	33
B. Pressure Pulse Characteristics .....	36
IV Discussion of Results .....	46
A. Comparison of Liquids .....	46
B. Performance of Driver .....	48
C. Proposed Design for Test Facility .....	55
V Conclusions .....	59
VI Recommendations .....	61
Appendix .....	62
A. Tabulation of Data .....	63

TABLE OF CONTENTS (cont'd)

	<u>Page</u>
B. Power Supply Circuit Diagram .....	70
C. Bibliography .....	71

## LIST OF FIGURES

<u>Number</u>		<u>Page</u>
I	Illustration of Pressure Waveforms.....	8
II	5 1/4" Boomer.....	21
III	Design of Test Instruments.....	29
IV	Driver Arrangement for Test Series.....	32
V	Influence of L, C, and Plate Thickness on Rise Time and Peak Current.....	34
VI	Influence of L, C, and Plate Thickness on Ring Frequency and Decay Time Constant.....	35
VII	Influence of $V_0$ on Rise Time and Peak Current....	37
VIII	Influence of C on Rise Time and Peak Current.....	38
IX	Influence of L, C, and Plate Thickness on Pulse Amplitude and Duration.....	40
X	Influence of $V_0$ on Pulse Amplitude and Duration..	42
XI	Influence of Plate Composition on Pulse Amplitude and Duration.....	43
XII	Influence on C on Pulse Amplitude and Duration...	44
XIII	Suggested Driver Design.....	56
XIV	Schematic of Proposed Test Facility.....	58

## LIST OF TABLES

<u>Number</u>		<u>Page</u>
I	Characteristics of Coils Used in Test Series.....	26
II	Pressure Pulse Characteristics of Water, Pentane, and Glycerine.....	36
III	Comparison of Test Tanks.....	45
A-I	Influence of Coil Inductance, Bank Capacitance and Plate Thickness on Electrical Signature of Driver with 500 Joule Input.....	63
A-II	Influence of Initial Voltage on Electrical Signature of Driver with Other Parameters Fixed.....	65
A-III	Influence of Capacitance on Electrical Signature of Driver with Other Parameters Fixed.....	65
A-IV	Influence of Coil Inductance, Bank Capacitance, and Plate Thickness on Pressure Pulse with 500 Joule Input.....	66
A-V	Influence of Initial Voltage on Pressure Pulse with Other Parameters Fixed.....	68
A-VI	Influence of Plate Composition on Pressure Pulse with Other Parameters Fixed.....	68
A-VII	Influence of Capacitance on Pressure Pulse with Other Parameters Fixed.....	69

## I. INTRODUCTION

### A. Background

Within the last 20 years, considerable advances in the methods and materials of naval architecture have led to the emergence of the deep diving submarine as a promising naval weapons system. In addition to the improved technology required for the design and fabrication of the pressure hull of such a ship, basic design modifications have been demanded for nearly every fitting or device penetrating that hull or mounted external to it. Each such modification must obviously be subjected to thorough testing prior to its acceptance in a final design: One facet of component testing is the verification of hydrostatic performance by subjecting each component to a specified pressure level in a pressure chamber. A second is the examination for possible fatigue problems by imposing a cyclic variation in pressure level over a period of time. A third is the investigation of dynamic response to a pressure pulse, such as might be generated by an underwater explosion.

In fact, this last pressure test is of particular interest to naval engineers. Despite advances in the theory, response to such dynamic loading is difficult to predict analytically, particularly when the pulse is superimposed upon a given hydrostatic loading. To date, precise knowledge has been contingent upon explosive testing at depth. As this procedure is both slow and expensive, attempts have been made to artificially



produce the pressure history of an underwater explosion within a pressure chamber. It is the purpose of this thesis to examine the design considerations involved in the development of such a test facility, with particular emphasis on the design of an electrically actuated "driver" to produce the desired pulse.

## B. Characteristics of an Underwater Explosion

Presumably, the first step in simulating an underwater explosion is to obtain a detailed description of the phenomenon which we desire to simulate. Accordingly, the pertinent characteristics as described by Keil (1)\*, are summarized below:

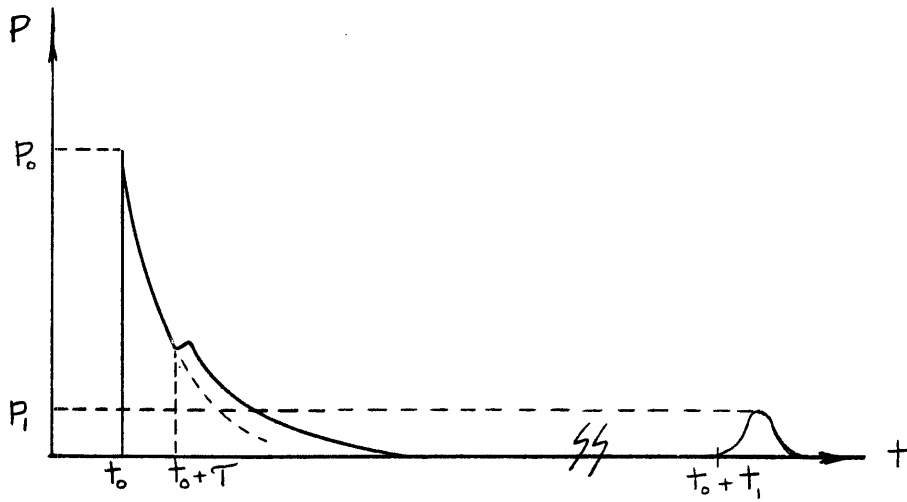
When a high explosive detonates underwater, the almost instantaneous release of energy produces a shock wave which propagates radially outward from the point of detonation. Initially, the velocity of this pressure pulse is about three times the local speed of sound, but its velocity quickly drops to a value just over the local speed of sound. The general profile of such a pulse is as indicated in Figure Ia. It is characterized by an essentially vertical leading edge, and an initial value  $p_0$  which is a function of the amount of energy released (weight of charge) and standoff (distance of observer from explosion). The initial decay is exponential, with time constant  $\tau$ , and the "hump" shown occurs about one

---

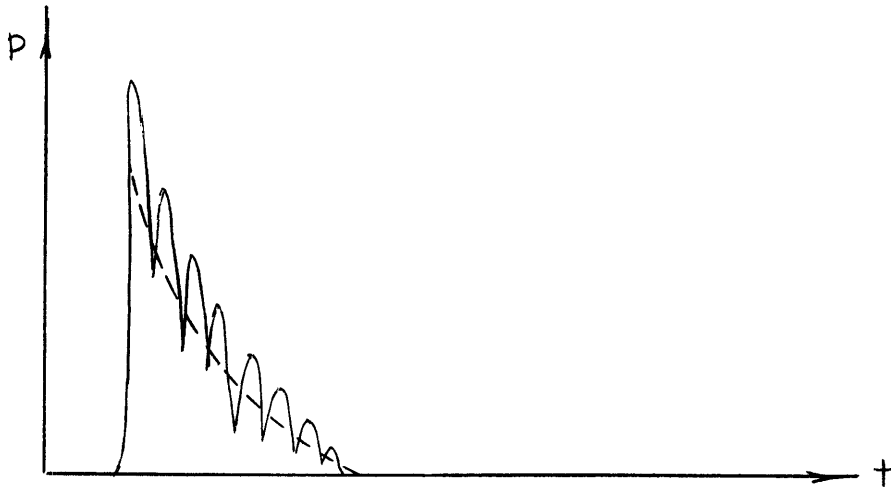
\* Numbers in parenthesis refer to references tabulated in the bibliography.

FIGURE I

ILLUSTRATION OF PRESSURE WAVEFORMS



A. PRESSURE HISTORY OF AN UNDERWATER EXPLOSION



B. PRESSURE HISTORY OF A SIMULATED EXPLOSION

time constant from the leading edge. (It is attributed to energy reflections within the gas bubble generated by the explosion.) Specifically, the following empirical relationships hold:

$$p_o = 21,600(W^{1/3}/R)^{1.13} \quad \text{psi} \quad (1)$$

$$\tau = 58W^{1/3}(W^{1/3}/R)^{-0.22} \quad \mu\text{sec} \quad (2)$$

where W is the equivalent charge weight in pounds of TNT (one pound of pentolite releases as much energy as 1.3 pounds of TNT; one pound of HBX is equivalent to about 1.5 pounds of TNT, etc.), and R is the standoff in feet.

About half the energy of the explosion remains in the gas bubble, which expands, overshoots its equilibrium size, and collapses. Upon collapsing in a minimum, the bubble emits a second pressure pulse, about 1/10 the magnitude of the first pulse, and without the vertical leading edge characteristic of a shock front. Roughly, if  $T_1$  is the interval between the first and second pulses, and  $p_1$  is the peak pressure of the second pulse:

$$T_1 = 4.36W^{1/3}/Z_o^{5/6} \quad \text{sec} \quad (3)$$

$$p_1 = 2000W^{1/3}/R \quad \text{psi} \quad (4)$$

where  $Z_o$  is equal to the charge depth plus 33 feet.

The gas bubble continues to oscillate for some time after the explosion, but experience indicates that the energy contained in the first two pulses generally accounts for such damage as may be done.

### C. Characteristics Desired of Test Facility

From an engineer's viewpoint, for test purposes it is neither necessary nor desirable to produce an exact duplicate of the rather complex pressure signal described above. Perhaps, a minimum standard for a test facility might be the generation of a single pulse of "reasonably short" rise time and an "approximately exponential" decay. Just how "reasonable" and how "approximate" one can be depends, ultimately, on what can be readily achieved, and upon the desired degree of correlation between the outcome of laboratory tests and actual explosive testing.

Ideally, equipment design must be based upon the hypothesis of withstanding the explosion of a given weight of charge at a given standoff, without serious damage. By contrast, current test practice converts such a standard to the more approximate specification that the equipment withstand a given impulse--- that is, that the integral under the pressure-time curve as measured at the equipment be of a particular value without resulting in serious damage--- and laboratory tests are conducted accordingly. Such a specification leaves the particular combination of peak pressure and decay rate used to realize the desired impulse a characteristic of the specified test facility, rather than a characteristic of some hypothetical explosion. Again, justification of such an approximation is based strictly upon the results obtained.

Considering the above, it would seem advisable to base the evaluation of any proposed test device upon a comparison

with an operating test facility. Such a facility is located at the Portsmouth Naval Shipyard. It consists of a cylindrical pressure chamber of 8" internal diameter, about 20" long, mounted vertically. The upper end of the chamber is fitted with a piston, upon which a weight is dropped to produce the desired pressure pulse. The lower end of the chamber is flanged to receive test specimens. Normally, the chamber is filled with glycerine for test purposes.

According to Mr. C.J. Chwalek of the Impedance, Shock, and Vibration Test Section, Portsmouth Naval Shipyard, the impact of the weight upon the piston produces a steep pressure pulse with a rise time of about 0.2 ms and a total duration of about 0.4 ms. However, this pulse is reflected repeatedly from the ends of the chamber, so that a test specimen is struck by a series of overlapping pulses of decreasing amplitude, with a repetition frequency of about 3 kc. The disturbance continues for a period of about 3 ms before dying out. The general appearance of this waveform is shown in Figure Ib. The suitability of this waveform as a "synthetic explosion" is based upon the hypothesis that, providing all natural resonances of the equipment under test occur well below 3 kc, the item under test does not respond to the individual pulses but rather to the mean envelope of the overall waveform. Obvious problems can arise if the item under test does have a mechanical resonance near or above 3 kc.

It might be noted in passing that the device described

has several pertinent features, aside from the waveform produced, which affect its suitability as a test instrument: For example, one can easily control magnitude of the impulse generated by varying the size of the weight or the height of drop. In addition, once the chamber has been brought to the desired hydrostatic pressure, it is possible to conduct repeated tests at various impulse levels on the same specimen without pausing to bleed down and empty the chamber between tests. This can result in a significant saving of time when a large number of tests have been scheduled. Further, though the test facility is intended to produce simulated underwater explosions, water is not used as a test medium. Obviously, other liquids may offer advantages as regards the generation and propagation of hydraulic shock. Finally, by restricting the cross sectional area of the test chamber, it is possible to produce relatively intense pressure pulses with relatively low energy input: thus, it is possible to simulate the pressure history of a given explosion with much less total energy than is released by an explosive charge. An obvious limit to the economics offered by a small chamber, however, is the contemplated size of specimens to be tested.

#### D. Objectives in Development of Electrical Drive

The basic motives for developing an electrically driven test facility are many and varied. First, it is anticipated that most or all of the operational advantages of the current

mechanical facility--- e.g., ease of adjustment, etc--- could be retained, and second, there is the distinct possibility of better control over the waveform generated. Specific items of interest are faster rise time, better control of the shape of the envelope, provision for generating the second pulse described in the section on underwater explosion characteristics, and, possibly, greater range of variation of the size of the impulse generated.

## II. PROCEDURE

### A. Preliminary Selection of Driver Design

Although the energy level utilized to create an artificial explosion within a pressure chamber may be small compared to the energy released by detonation of a large explosive charge, it is not small by normal standards. The driver contemplated for this facility must be capable of receiving a pulsed electrical input of 10,000 joules or more, and coupling this energy with minimum attainable rise time into the test medium. Presumably, if an electrical driver is used, a rapid discharge capacitor bank would be the optimum means of storing the energy, pending its rapid release into the chamber. Selection of a device to convert this electrical energy into pressure pulse energy is not so obvious, however. There are relatively few devices which are capable of operation at the indicated energy levels, while still offering some promise of being adaptable to an output rise time in the microsecond range. During preliminary study of this problem, three devices were considered:

1. Exploding wires: Since the mid-1700's, it has been recognized that if a large capacitor bank is discharged through a short length of fine wire, the wire will explode, emitting a brilliant flash of light and a cylindrical shock wave. Chace (2) advances the theory that resistive heating quickly raises the wire far above its boiling point, but that the absence of a container, (i.e., the lack of a micro-



scopically dirty surface at which vaporization can be initiated) causes the liquid-vapor transition to be delayed for beyond equilibrium. He hypothesizes that when finally "triggered", the transition occurs with explosive violence. Conceivably, such a technique could be used to generate the desired test pulse.

Unfortunately, the use of exploding wires seems to involve three significant disadvantages for the application considered: First, energy release occurs within a very small volume, a situation which is not conducive to the development of planar pressure fronts within the short length of a pressure chamber. Second, use of this technique might present problems were it considered desirable to use a flammable liquid as the test medium. Finally, and perhaps, most seriously, it would be necessary to replace the wire before a second pulse could be generated. As mentioned above, any requirement that the chamber be opened between "shots" would comprise a serious operational drawback.

2. Electric arc: Given sufficiently high voltages, one could dispense with the wire described above by striking an arc between two electrodes immersed in the test liquid. Normal electrode life should permit several tests before it became necessary to reopen the chamber. (In fact, electrode life might be prolonged by the fact that the electrodes would be liquid cooled.) However, this technique would still suffer from the other disadvantages described above, and might present an even greater safety hazard if used in con-

junction with flammable liquids.

3. Sonar transducer: Finally, it might be possible to "speed up" a conventional sonar transducer in which the interaction between electric or magnetic fields and a material body are used to drive that body forcibly into a liquid medium, thereby creating a pressure signal. One advantage of such a device is that the diameter of the driven element can be nearly as large as the internal diameter of the chamber, thus simplifying the development of a planar wave front. Further, Dr. H.E. Edgerton of M.I.T. has recently pioneered the development of a high-speed transducer (known as a "boomer") which produces steep, high intensity pressure pulses for use in oceanographic research (3,4). The pulse characteristics of production model boomers are not dissimilar to those of the driven pulse of the Navy's mechanical test facility: i.e., rise time of about 0.2 ms, and duration of 0.4 to 0.5 ms.

The major components of Dr. Edgerton's boomer are a flat, spirally wound coil of ribbon wire (rectangular cross section), and a flat, circular aluminum plate of slightly greater diameter than the coil. The coil is encapsulated in an epoxy pancake, and the plate is clamped to the coil with steel (or rubber) springs. When a capacitor bank is discharged through a triggered spark gap into the coil, the rapid buildup of an intense magnetic field gives rise to strong eddy currents in the plate. Interaction of these eddy

currents with the field gives rise to a force which tends to violently separate the plate and the coil. The springs limit the motion of the plate to about 3/4", then return it to rest against the coil.

Early models of the boomer were designed to operate in conjunction with a 500 to 1000 joule capacitor bank, and had an efficiency of conversion of electrical to pressure pulse energy of about 12%. The demand for more powerful pulses has led to the development of models which utilize a 13,000 joule bank. To avoid coil damage in the more powerful models, two coils are counted in series, back-to-back, and a plate is mounted to the outer face of each coil. In this array, the front plate serves as the driver, while the rear plate serves primarily to develop a balance of forces, so that the coils will not be hurled backwards as violently as the plate is hurled forwards.

Inasmuch as the boomer has none of the disadvantages discussed for exploding wire or electric arc drivers, and offers promise of being adaptable to even shorter rise time than that cited above, it was tentatively selected as the driver for the contemplated test facility.

#### B. Investigation of Test Media

When a given quantity of energy is released at a given rate in a liquid medium, the rise time, peak magnitude, and duration of the resultant pressure pulse are a function of the physical parameters of that liquid. Theoretically, it

should be possible to compute the relationship between these parameters and the desired pulse characteristics, and thus determine the optimum liquid to use with a given driver. Unfortunately (as pointed out by Dr. Donald Ross of the firm of Bolt, Beranek, and Newman), such calculation must be based on the high pressure equation of state of the liquid under consideration: a relationship which, in general, is unknown. Dr. A.H. Keil (currently Technical Director, David Taylor Model Basin) verified the lack of theoretical groundwork as regards high pressure behavior of real liquids, and further stated that very little experimental data was available for liquids other than water. It would appear that there has been relatively little motivation for research in this particular field.

All the above notwithstanding, it is still apparent that not all liquids are equally suitable as test media. Aside from the question of compatibility with materials under test (e.g., neoprene seals, etc.), the most basic problem governing choice of a particular liquid is probably the relative ease of forming a pressure pulse which rises faster than the electrical input to the system. Certainly, such behavior is a necessity if true shock fronts are to be achieved. Further, at least qualitatively, two variables are known to affect this facet of liquid response to a given energy input: compressibility, and variation of acoustic velocity with pressure.

Specifically, Cdr. J.R. Baylis has stated that low com-

compressibility was the primary reason that glycerine was selected as the test medium of the Portsmouth facility. He indicated that initial tests were conducted in water, but that glycerine was tried on an experimental basis and proved to yield higher peak pressures and shorter rise time for the same input. He also mentioned that the above improvements in pulse characteristics vanish if even small quantities of water contaminate the glycerine.

Variation of acoustic velocity with pressure--- specifically, an increase in acoustic velocity with increasing pressure--- is a characteristic which results in pulse steepening as a pressure disturbance propagates through a liquid. Keil (1) provides an empirical relationship valid for water at pressures up to 10,000 psi:

$$C = c(1 + 6 \times 10^{-6} p) \quad \text{ft/sec}$$

where  $c$  is the local velocity of sound at one atmosphere. Swanson (5) plots data for several organic liquids in the range 1-300 atmospheres. Swanson's data exhibit two interesting characteristics: first, all liquids tested exhibit a linear relationship between acoustic velocity and pressure within the range examined, and second, the slope of this relationship is very nearly identical for all liquids tested except ethyl ether and pentane. The latter two exhibit a slope approximately twice that of the others. Swanson further plotted the relationship

$$c = \sqrt{1/\rho \epsilon}$$

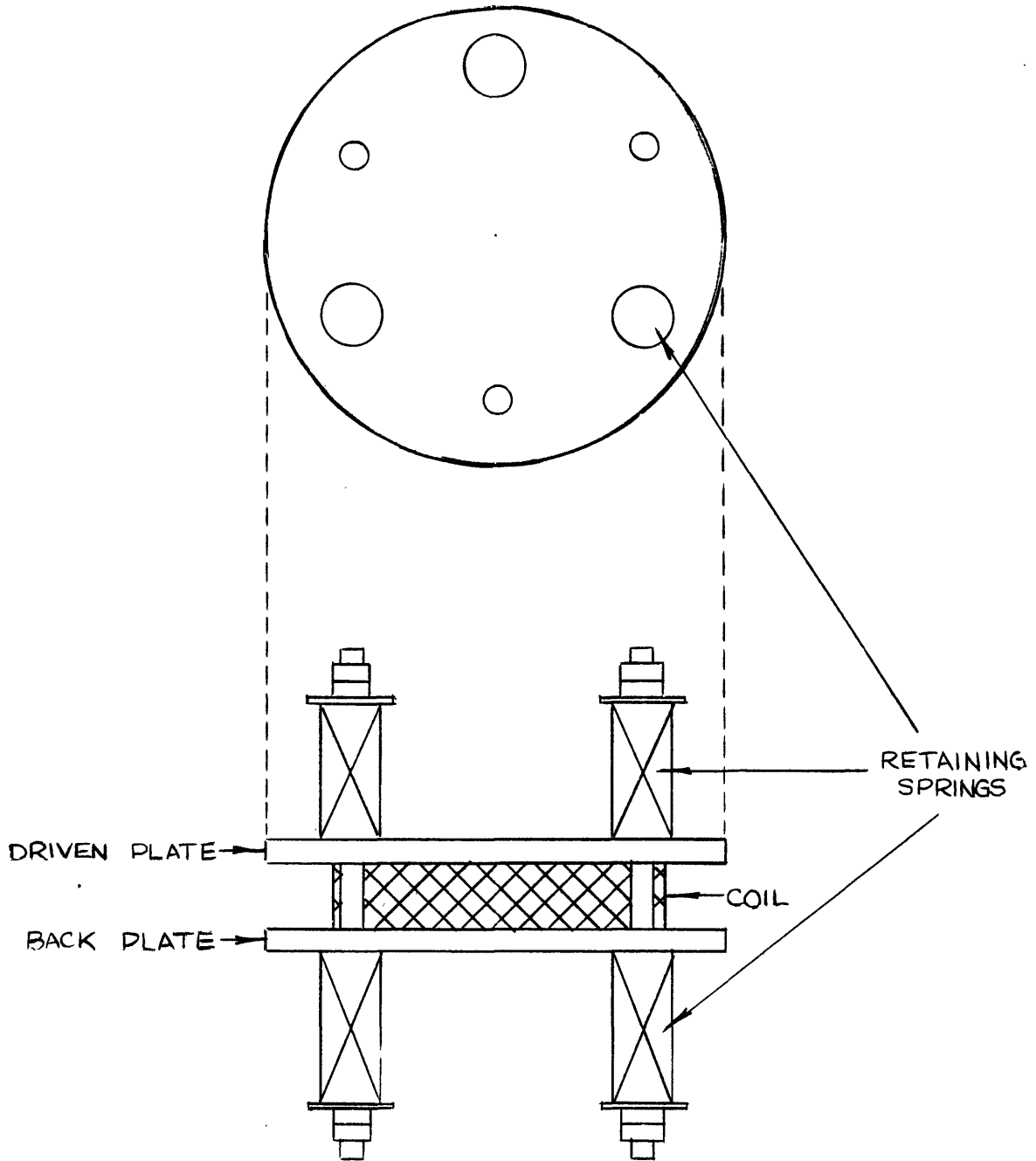
for four liquids for which  $\rho$  and  $\beta$  were known as functions of pressure over the range investigated. In each case, the above relationship proved to be non-linear, and although it did result in an increasing trend for C as a function of p, it did not correlate well with experimental observations.

Considering the uncertainties indicated by the above discussion, and the limitations on available time and facilities, a simple three point check was conducted using available hardware to verify boomer performance driving into different liquids: Specifically, tests were conducted in water, as a reference standard, glycerine, and pentane. The driver used was a small, two-plate model (of the type discussed in the preceding section) illustrated in Figure II. A commercially available boomer power supply was used as the energy source, adjusted for 500 watt-second electrical input to the driver. Inasmuch as no improvement in performance resulted from the use of glycerine or pentane (see section on RESULTS for details), it was decided that all further tests would be conducted in water.

### C. Investigation of Driver Characteristics

Analysis of the boomer is complicated by the fact that the instrument is clearly a field-driven device, yet the geometries involved are sufficiently complex to preclude mathematical analysis on the basis of field theory. Further, the dynamics of the problem are of sufficient import to pre-

FIGURE II  
5 1/4 " BOOMER



clude the use of such static computational aids as a teledeltos analogue: the motion of the driven plate is sufficient to cause significant variation of the degree of coupling as a function of time. In short, the best analogue which has been found to cope with the behavior of the boomer is the device itself. Accordingly, an experimental program was undertaken with two basic objectives: First, to determine whether the boomer could be modified to produce true shock fronts--- or, failing that, determine the minimum attainable rise time--- and second, by systematic variation of the basic parameters of the device, to obtain a quantitative measure of the effect of such variation on the pressure pulse produced. It is hoped that such data can at least establish trends of use to future designers.

Recognizing the limitations of available facilities, no attempt was made to experiment at energy levels typical of a full-scale test facility. Most tests were conducted with a standard electrical input of 500 joules. The maximum input level for any test was 2100 joules. Within these limits, experiments were conducted to determine the effect of variation of the following parameters:

- mass of the driven plate
- conductance of the driven plate
- inductance of the driving coil
- capacitance of the energy bank
- operating voltage



To begin with the first item listed above: however complex its behavior, the boomer exhibits the terminal characteristics of an underdamped RLC circuit. At the risk of oversimplification, it can be stated that to reduce the rise time of the pressure pulse, one need only reduce the electrical rise time of the driver circuit, and to reduce the rise time of the driver circuit, one need only reduce the total inductance and capacitance as seen at the terminals. As mass is the mechanical analogue of capacitance, it follows that some reduction of rise time might be realizable by reduction of the mass of the driven plate.

Since production model boomers utilize an aluminum alloy plate roughly 20 inches in diameter, considerable reduction in mass would seem inevitable, all else remaining equal, should one accept the concept of a driver which must fit within an 8 inch pressure chamber. It was presumed that additional mass reduction could be effected by reducing plate thickness to the minimum capable of withstanding the stresses developed without permanent deformation\*. To determine whether or not such additional reduction would significantly improve the output pulse, and how much reduction might be possible, a number of aluminum plates were prepared for testing.

---

\* For oceanographic work, allowance for erosion by cavitation has resulted in a driven plate somewhat thicker than might otherwise be required. As these plates are readily machined, it is assumed that a shorter life cycle would be acceptable for a test facility, and thus erosion would be no problem.

All were approximately 8 inches in diameter and most were of the higher strength aluminum alloys with a conductivity in the range of 35% to 40% that of copper. Thicknesses ranged from 1/4 inch down to 1/16 inch.

In the absence of any plate, one would presume the field generated by a boomer coil would be toroidal in nature. The presence of a conducting plane (such as the plates described above) adjacent to the coil distorts this field, excluding it from a particular region of space. In a sense, the force acting upon the driven plate can be attributed to this containment or "bottling up" of the magnetic field. Two factors act to reduce the degree of such containment: the plate is driven away from the coil, and (since the plate is not a perfect conductor), the field begins to penetrate the plate. Presumably, any change which would tend to nullify these factors would increase the impulse acting on the plate.

Unfortunately, as the first factor cited is also the mechanism by which energy is transferred to the liquid, little could be profitably done to reduce it\*. On the other hand, use of a more highly conductive plate would obviously reduce the rate at which the field penetrated the plate--- though at the cost of added mass, considering such factors as yield

---

\* A possible exception to this statement would be the use of a less compressible liquid, provided that: 1) the driver and the liquid completely filled a constant-volume system, and 2) provision were made to exclude the liquid from the region between the plate and the coil.

strength and density of available metals. The effectiveness of such a change would presumably depend upon the increase in conductivity attainable and the relative importance of the two factors cited.

To investigate the above considerations a second family of plates was prepared. These plates were all approximately 8 inches in diameter by 1/16 inch thick, but varied in composition from aluminum alloy, through various copper-aluminum laminates to pure copper. (The laminated plates were prepared by bonding various thicknesses of copper and aluminum with Emerson and Cuming ECCOSEAL W19 low viscosity epoxy.) Naturally, laminated plates were tested with the copper side adjacent to the coil.

Coil inductance was one parameter which gave more direct access to electrical rise time. The decision was made to return to a single layer coil, as contrasted with the back-to-back series array, to reduce total inductance. The rear plate was eliminated, and replaced with a rigid, insulating backing material which firmly supported the coil to prevent recoil.

Conceptually, at least, the upper limit of coil inductance is set by the desire to achieve the shortest feasible electrical rise time, and the lower limit is set by the higher peak currents which result from reduced impedance: eventually, more energy would be consumed by resistance of the leads than would be transferred to the plate. Practically, however, physical size--- which bears a direct relationship to induct-

ance--- is the determining factor. If the array is to fit within an 8 inch pressure chamber, the maximum feasible coil diameter is something under that dimension. Further, if the coil is to drive an 8 inch plate, the localized stresses resulting from the use of any coil appreciably smaller than that dimension create a serious structural problem.

For experimental purposes, a series of three coils was prepared to investigate the effects of varying inductance within the limits discussed above. Pertinent parameters are summarized in Table I below:

TABLE I  
CHARACTERISTICS OF COILS USED IN TEST SERIES

Coil No.	R1	R0	N	L	Q
1	2"	5 1/2"	25	49.8 $\mu$ h	11.7
2	2"	6 1/4"	31	80.1 $\mu$ h	14.0
3	2"	7 7/8"	43	172.0 $\mu$ h	21.5

All coils described above were wound of 0.050" by 0.500" rectangular, cloth wrapped copper wire. Coils were impregnated with ECCOSEAL W19 epoxy for insulation and structural strength. In addition, a 1/16" bakelite sheet was bonded to that face of the coil which contacted the metal plate for additional insulation.

The final item of the electrical circuit available for manipulation was the energy storage bank. Commercial boomers are controlled by a power supply which provides a 160 $\mu$ f storage

bank for operation at an energy level of approximately 1000 watt seconds. Provision is made for disconnecting and shorting half these capacitors for operation at 500 watt seconds, or for connecting additional storage banks of 2000 watt-second increments for operation at higher energy levels.

To produce pulses with a shorter rise time, the decision was made to reduce capacitance while increasing voltage, thus remaining at a constant energy level. As a practical matter, the range of such testing was limited by available facilities: The firm of Edgerton, Germeshausen and Grier loaned three Sangamo Electric energy discharge capacitors, each rated at 14  $\mu$ f, 20 KV. A power supply was constructed for use in conjunction with these capacitors which produced a half-wave rectified output adjustable between 0 and 13 KV\*. These factors established the limits of the test range.

#### D. Instrumentation

As the boomer is a high energy, magnetically driven device, suitable instrumentation of the test series presented some problems: Peak currents through the driver were found to exceed 20,000 amperes. Coupled with a rise time well under a millisecond, considerable experimentation was required to avoid inductive coupling with stray fields. Careful attention to lead dress, shielding and positioning of components was found to be mandatory. In addition, instruments

---

\* Circuit diagram provided in Appendix B.

with a relatively high level output were found to have obvious advantages over instruments with low level output.

Transients were displayed on a Tektronix Model 545 oscilloscope with Type 53/54K fast-rise ( $.006\mu\text{s}$ ) preamp, and recorded by scope photography. In general, it was necessary to use a 10 - to - 1 attenuator in series with the scope input.

Current through the boomer coil was measured by placing a 0.00275 ohm resistor between the coil and ground, and observing voltages developed across the resistor. This resistor was designed and constructed by Floyd M. Minks (see Figure IIIa). The major advantage of the design was that test leads were introduced to the resistor in such fashion as to be completely shielded from fields induced by current flow through the resistor: thus, voltages observed must be attributed solely to the IR drop across the resistor.

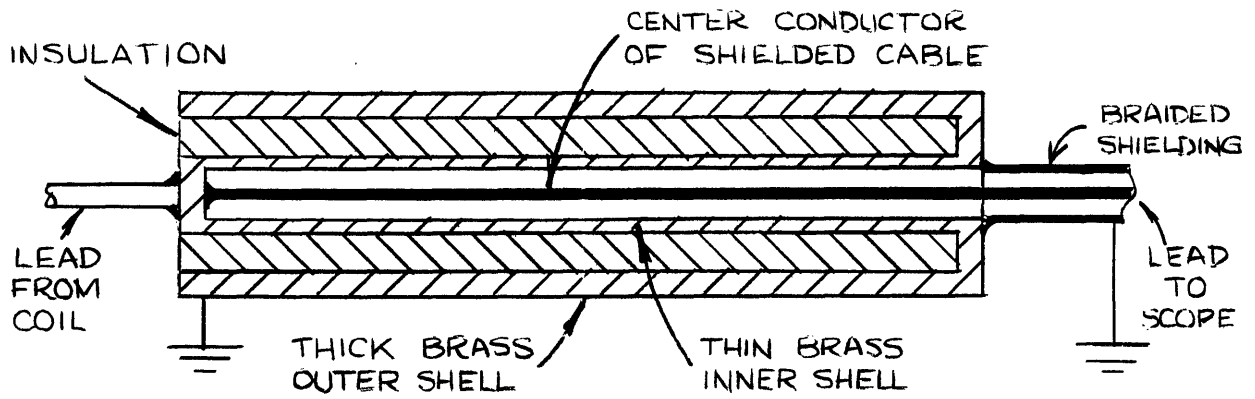
Initially, pressure measurements were made with a Chesapeake Instrument Model SB-154D "eight-ball" hydrophone. As the minimum rise time of this device was found to be about  $40\mu\text{s}$ , a series of replacement hydrophones were manufactured and tested, culminating in the design shown in Figure IIIb. This device, which utilized a 0.400" by 0.060" PZT-5 wafer as a pickup, was found to have a minimum rise time of about  $1\mu\text{s}$ . In all tests, hydrophones were positioned 5" from the rest position of the driven plate, centered with respect to the plate.

#### E. Summary of test series

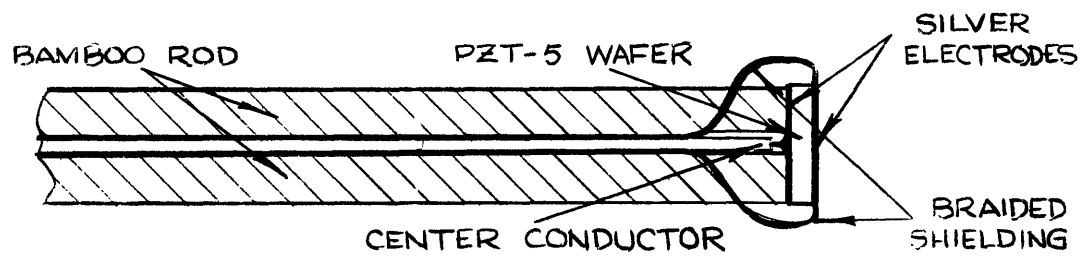
The below list summarizes the various test series which

FIGURE III

DESIGN OF TEST INSTRUMENTS



A. GENERAL DESIGN OF MINKS RESISTOR



B. DESIGN OF PZT-5 WAFER PRESSURE PROBE

were conducted during this investigation:

1. Test of existing hardware in water, glycerine, pentane, and air.

2. Test of each of 3 coils described above with 1/4", 1/8" and 1/16" Al plates, 500 watt-second input, with supply voltage corresponding to an energy bank capacitance of 80 $\mu$ f, 42 $\mu$ f, 28 $\mu$ f, and 14 $\mu$ f.

3. Test of 49.8 $\mu$ h coil with 14 $\mu$ f energy bank, 1/4" Al plate at 2, 4, 6, 8, 10, and 11.4 KV.

4. Test of laminated plates with 49.8 $\mu$ h coil, 14 $\mu$ f bank, at 10 KV.

5. Test of 1/4" Al and 1/16" Cu plates at 10 KV with, 49.8 $\mu$ h coil, 14 $\mu$ f, 28 $\mu$ f and 42 $\mu$ f bank.

6. Spot comparison of driver performance in large open tank and 10" cylinder.

Although most tests were conducted in a large, open tank, series 1 and 6 were run in a thin-walled, 10" diameter metal cylinder. Again, availability of facilities was largely the determining factor: while it was recognized that the pressure field produced by the un baffled driver in an open tank differed vastly from that which would be produced in the hypothesized cylindrical test facility, it was felt that data obtained from open tank tests would suffice to establish a relative basis for comparison of the various driver configurations tested.

The 10" cylinder described above was used as a means to determine device performance under a better approximation of

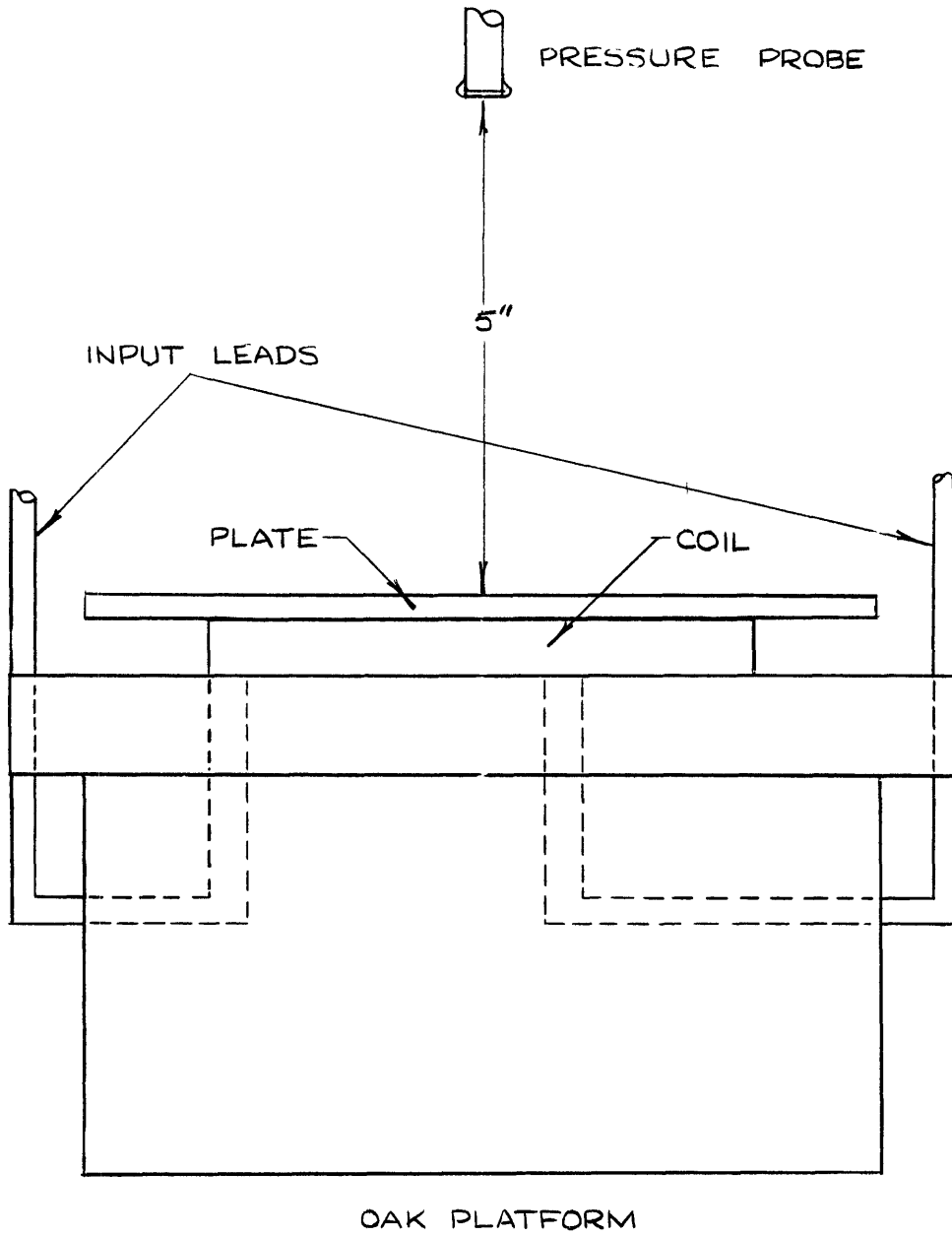


contemplated operating conditions. As it was feared that this cylinder would not have sufficient structural strength to withstand the complete test series contemplated, its use was restricted to the tests cited.

In series 2 through 6, the driving coil was supported on a wooden platform, as shown in Figure IV, with the driven plate rested atop the coil in the horizontal plane. In the interests of minimizing rise time, no springs or other mechanical constraints were used: the plate was allowed to return to the coil under the action of gravity. As mentioned above, hydrophones were positioned 5" above the rest position of the plate, on the centerline of the array.

FIGURE IV

DRIVER ARRANGEMENT FOR TEST SERIES



### III. RESULTS

#### A. Electrical performance

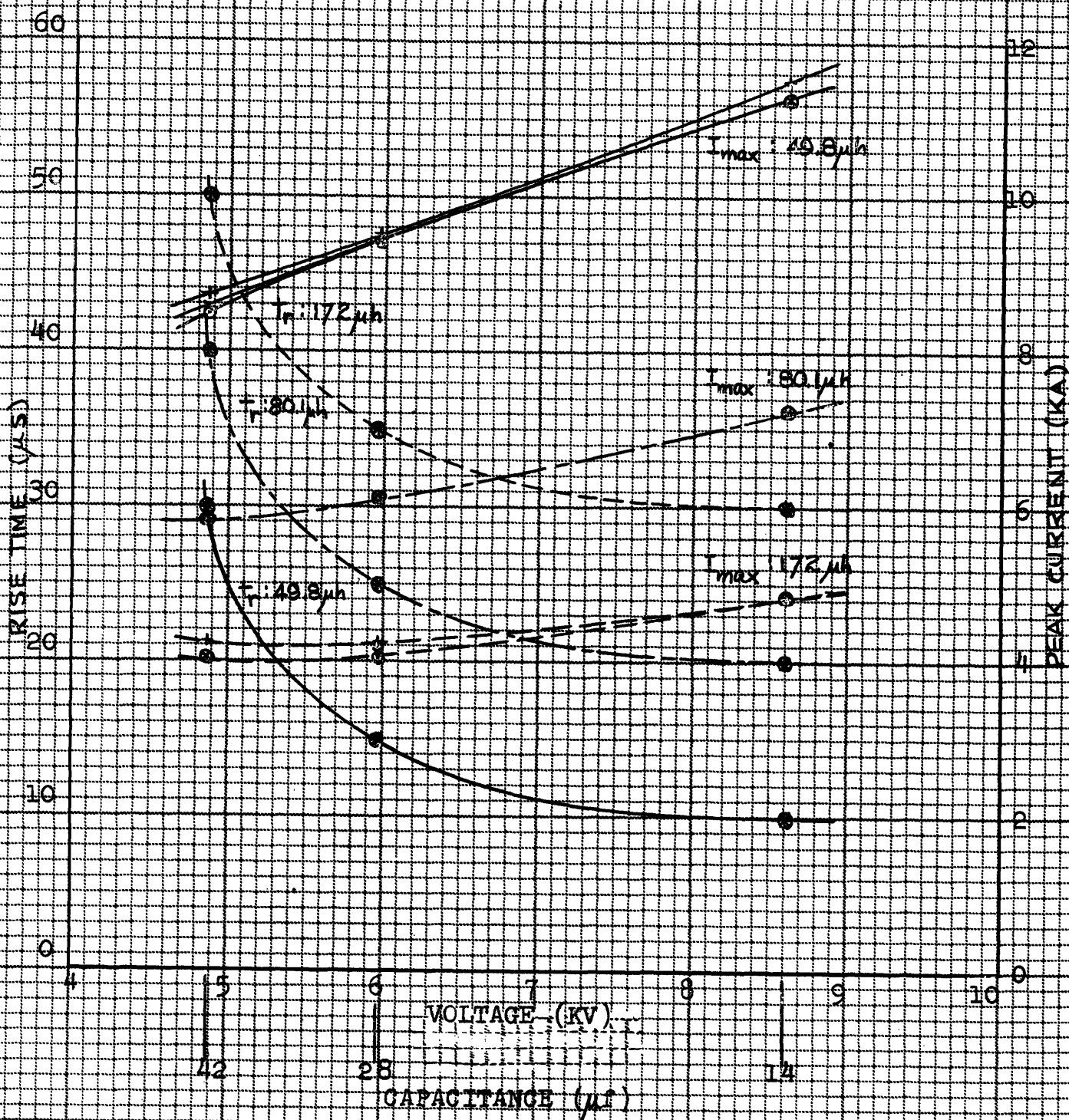
1. Comparison of liquids: Changing the characteristics of the liquid used as the test medium had no discernible effect upon the electrical signature of the boomer. Tests were conducted in water, glycerine, pentane, and air, using the driver illustrated in Figure II in conjunction with an  $80\mu\text{f}$ , 500 watt second energy bank. In each case the electrical circuit exhibited a rise time of  $61\mu\text{s}$ , reaching a peak current of about 7640 amperes. Once excited, the circuit exhibited a ring frequency of about 3KC, with a decay time constant of about  $200\mu\text{s}$ .

2. Variation of L, C, and plate thickness at constant energy: The effect of varying bank capacitance and plate thickness while holding energy input constant (at 500 joules) is plotted, for each coil, in Figures V and VI. Figure V shows variation of electrical rise time and peak current with the above parameters, while Figure VI shows variation of ring frequency and decay time constant. The latter two plots are, of course, approximate: the change in coupling between the coil and the plate cause these factors to vary with time. Thus, the "ring frequency" plotted represents an average over a number of cycles, while "decay time constant" is, in fact, the time required for the envelope of the waveform to decay from  $I_{\text{max}}$  to  $1/e$  times that value.

FIGURE V

INFLUENCE OF L, C, AND PLATE THICKNESS ON  
RISE TIME AND PEAK CURRENT

500 JOULE INPUT

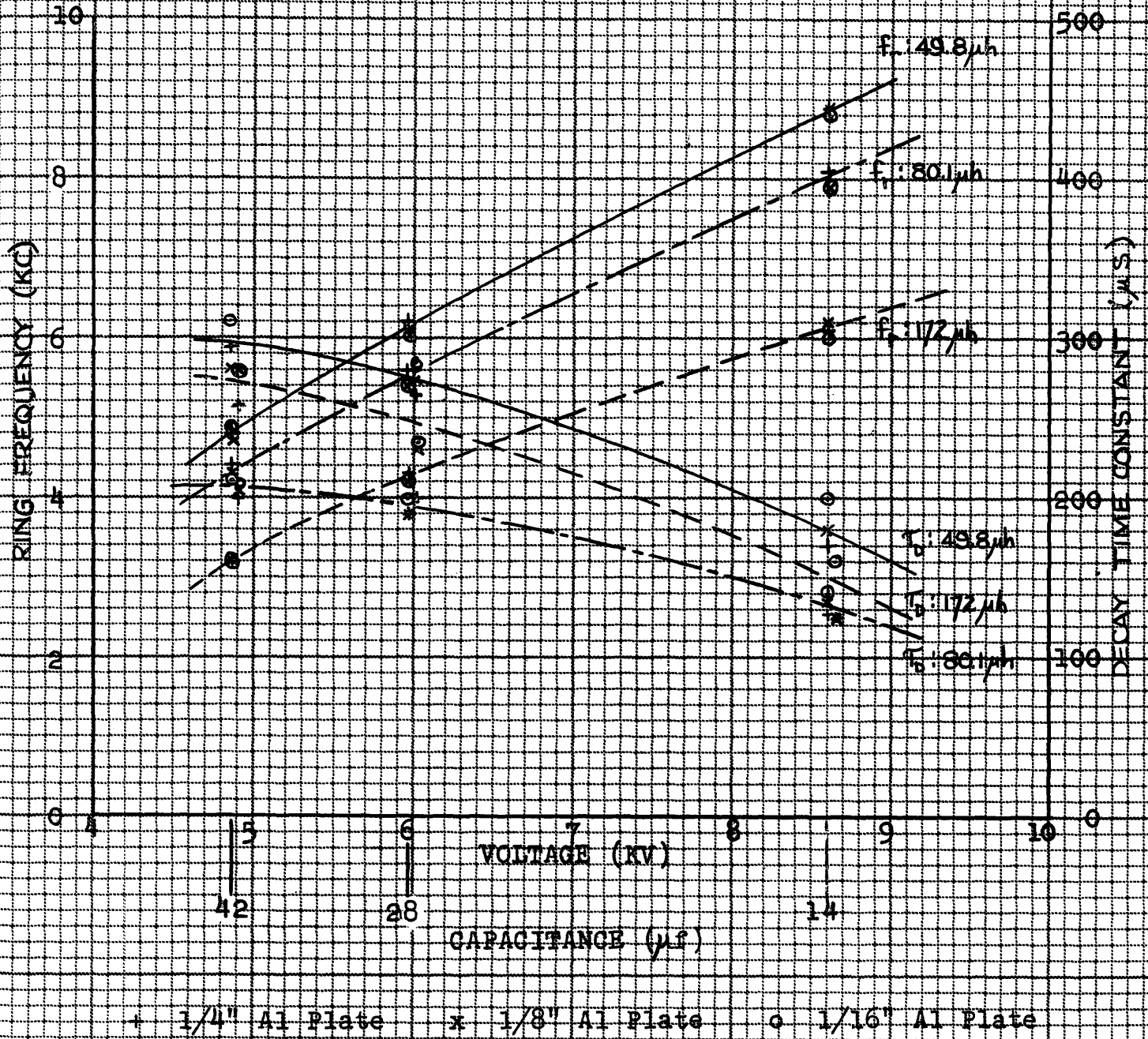


\* 1/16" Al Plate    x 1/8" Al Plate    o 1/4" Al Plate

FIGURE VI

INFLUENCE OF L, C, AND PLATE THICKNESS ON RING FREQUENCY AND DECAY TIME CONSTANT

500 JOULE INPUT



3. Variation of  $V_o$ : The changes in electrical rise time and peak current which result from increasing energy input by variation of capacitor bank voltage with other parameters fixed ( $L = 49.8\mu h$ ,  $C = 14\mu f$ ) are shown in Figure VII.

4. Variation of C: The changes in electrical rise time and peak current which result from increasing energy input by variation of energy bank capacitance with other parameters fixed ( $L = 49.8\mu h$ ,  $V_o = 10$  KV) are shown in Figure VIII.

## B. Pressure Pulse Characteristics

1. Comparison of liquids: the characteristics of the driven pulse\* produced in each of the three liquids subjected to comparative testing are summarized in Table II below. Tests were conducted in an open, 10" cylinder, using the driver illustrated in Figure II, and a Chesapeake Instrument Model SB 154-D hydrophone.

TABLE II

PRESSURE PULSE CHARACTERISTICS OF WATER, PENTANE, AND GLYCERINE

Liquid	Rise Time ( $\mu s$ )	Peak Hydrophone Output (Volts)	Pulse Duration ( $\mu s$ )
water	75	450	170
pentane	75	352	168
glycerine	75	312	180

\* The first positive pulse produced by the driver. In general, the subsequent history of the pressure signal proved to be a function of overall system characteristics, in that it depicted resonances of the driven plate, the tank, and the hydrophone used in the test. As the system used did not closely resemble the contemplated facility, it is feared that relatively little useful information can be extracted from the "tail" of the waveform. See DISCUSSION OF RESULTS.

FIGURE VII

INFLUENCE OF  $V_0$  ON RISE TIME AND PEAK CURRENT

$L = 49.8 \mu\text{h}$

$C = 14 \mu\text{F}$

1/4" Al Plate

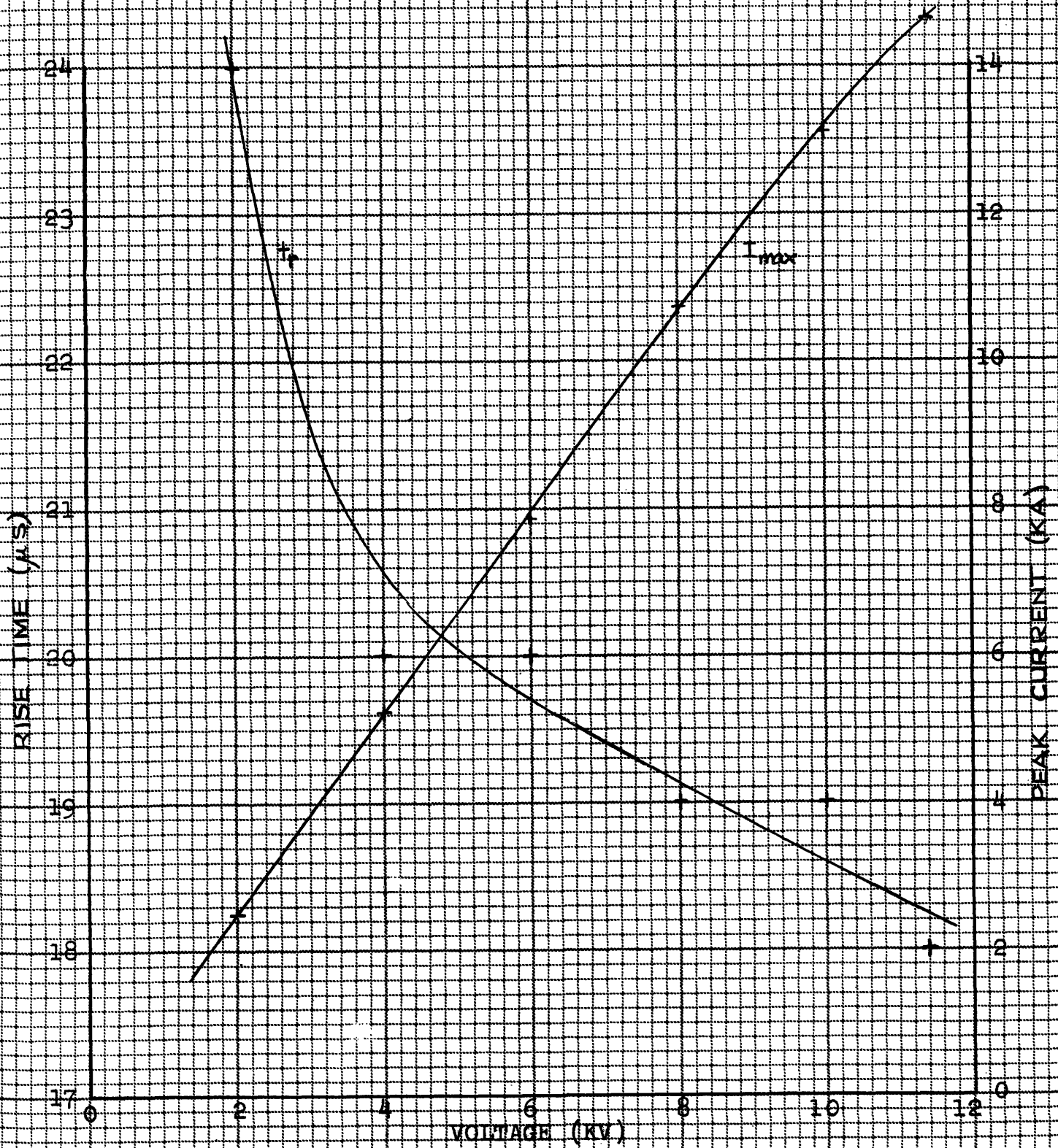


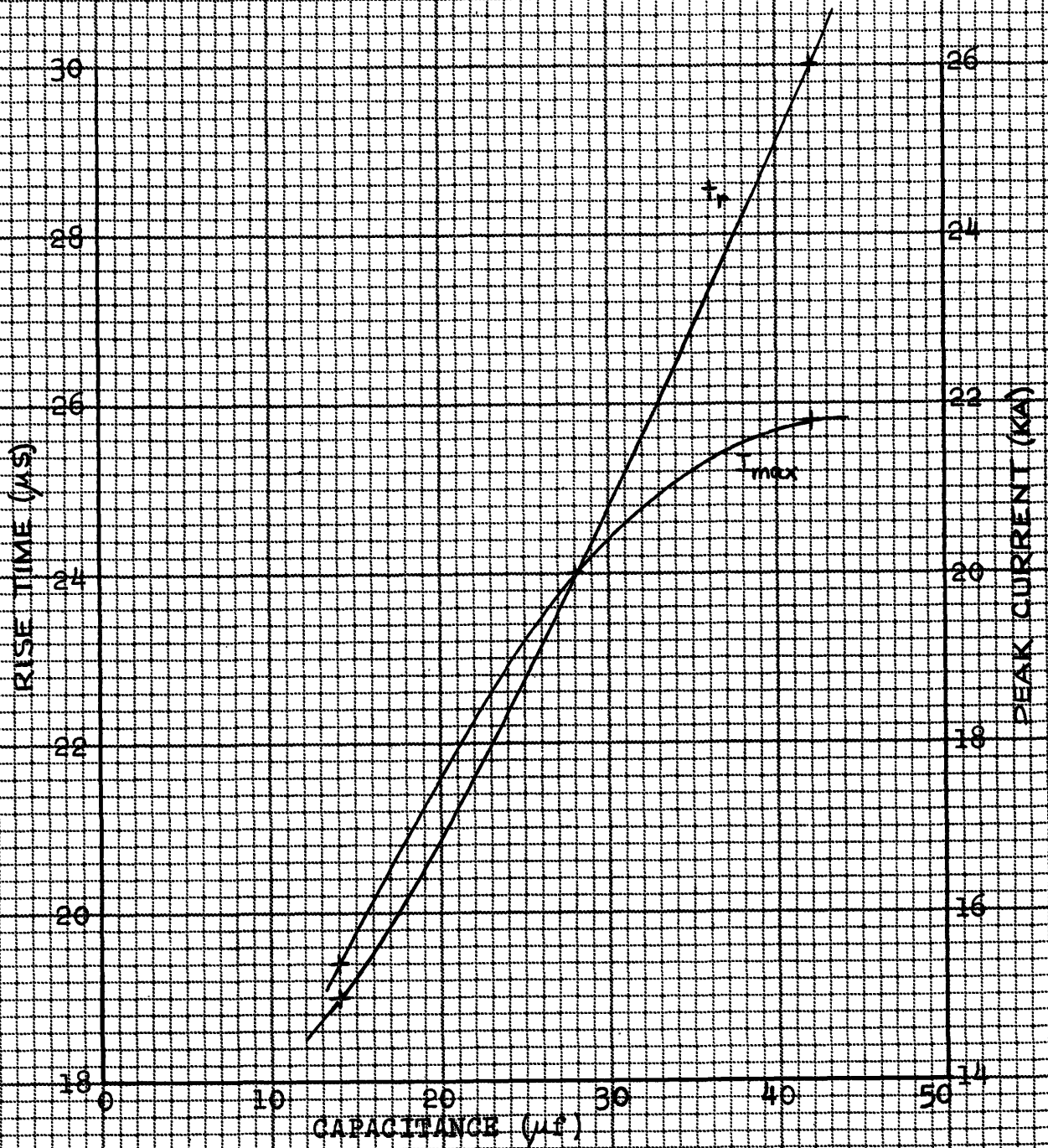
FIGURE VIII

INFLUENCE OF C ON RISE TIME AND PEAK CURRENT

$L = 49.8 \mu H$

$V_0 = 10 KV$

1/4" Al Plate





Inasmuch as neither pentane nor glycerine offered any significant advantage over water, the decision was made to use water as the test medium in all further tests.

2. Variation of L, C, and plate thickness at constant energy: In terms of the pressure pulse, vice electrical signature, the plot which corresponds to Figures V and VI is Figure IX, which depicts variation of peak hydrophone output and pulse duration (for a given variation in bank capacitance and plate thickness) for each coil tested. As mentioned in PROCEDURE, tests were conducted in a large, open tank: thus, test results--- particularly, peak amplitude--- are not directly comparable to results anticipated under more favorable conditions. (See Section 6 below.) Despite the above limitation, the data are of value in obtaining a relative assessment of driver performance following a given change in basic parameters. In short, the data can be used to establish trends, which in turn will be of use in system design.

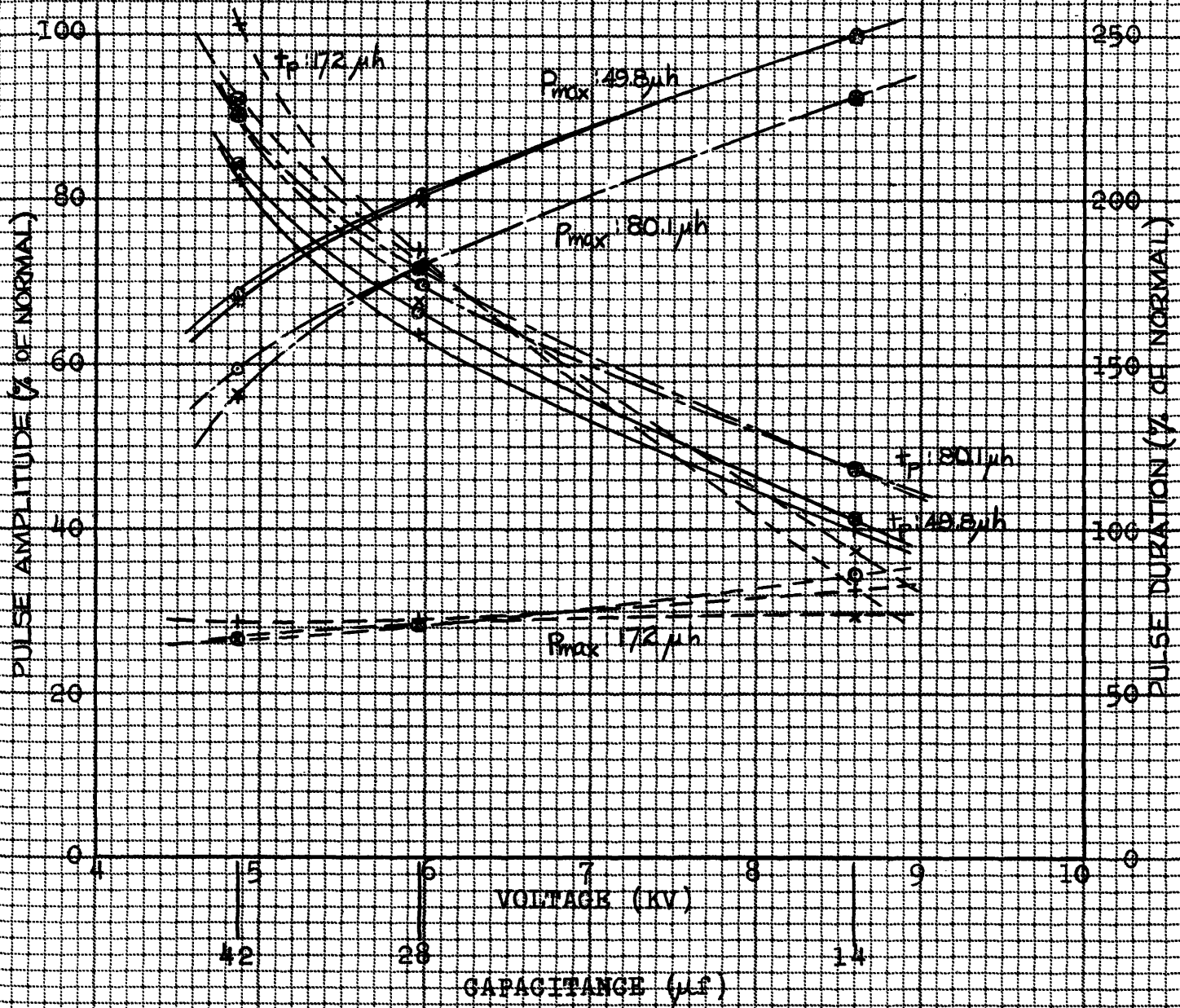
To emphasize that facet of test data which is presumed to be of most value, and to facilitate correlation of test data recorded by various hydrophones, pressure pulse data have been plotted on a normalized basis, with a  $49.8 \mu\text{h}$ ,  $14 \mu\text{f}$ , 500 watt second system with  $1/4"$  Al driven plate taken as the reference standard for this series. The original, unnormalized data are tabulated, for reference purposes, in tables A-IV through A-VII of Appendix A.

It is interesting to note that in all tests in the range  $14 \mu\text{f} \leq C \leq 42 \mu\text{f}$ , observed rise time was pickup

FIGURE IX

INFLUENCE OF L, C, AND PLATE THICKNESS ON  
PULSE AMPLITUDE AND DURATION

500 JOULE INPUT



+  $1/4''$  Al Plate    x  $1/8''$  Al Plate    o  $1/16''$  Al Plate

limited: that is, the rise time of the pressure pulse was apparently less than or equal to  $1 \mu\text{s}$ , which was the minimum attainable rise time of the "fastest" hydrophone constructed. (This statement covers test series 2 through 5.) As can be seen in Table A-IV, some slowing of rise time was evident for  $C = 80 \mu\text{f}$ . The  $C = 80 \mu\text{f}$  points were omitted from Figure IX, however, as it was later learned that, due to an inaccurate voltmeter, these runs were conducted at an energy level of 695 watt seconds.

3. Variation of  $V_0$ : The changes in peak pressure and pulse duration which result from increasing energy input by variation of capacitor bank voltage with other parameters fixed ( $L = 49.8 \mu\text{h}$ ,  $C = 14 \mu\text{f}$ ) are shown in Figure X. The 8.6 KV level is used as a reference standard.

4. Variation of plate composition: Figure XI displays variation in peak pressure and pulse duration as a function of relative thickness of copper for a series of laminated plates of  $1/16$ " nominal thickness. Tests were conducted at 10 KV, using the  $49.8 \mu\text{h}$  coil and a  $14 \mu\text{f}$  bank. All tests are related to a  $1/4$ " Al plate standard.

5. Variation of  $C$ : The changes in peak pressure and pulse duration which result from increasing energy input by variation of energy bank capacitance with other parameters fixed ( $L = 49.8 \mu\text{h}$ ,  $V_0 = 10 \text{KV}$ ) are shown in Figure XII. Reference standard is  $1/4$ " Al plate with  $C = 14 \mu\text{f}$ .

6. Comparision of open tank and 10" cylinder: The characteristics of the driven pulse observed in each of the

FIGURE X

INFLUENCE OF  $V_0$  ON PULSE AMPLITUDE AND DURATION

$L = 49.8 \mu H$

$C = 14 \mu F$

1/4" AT PLATE

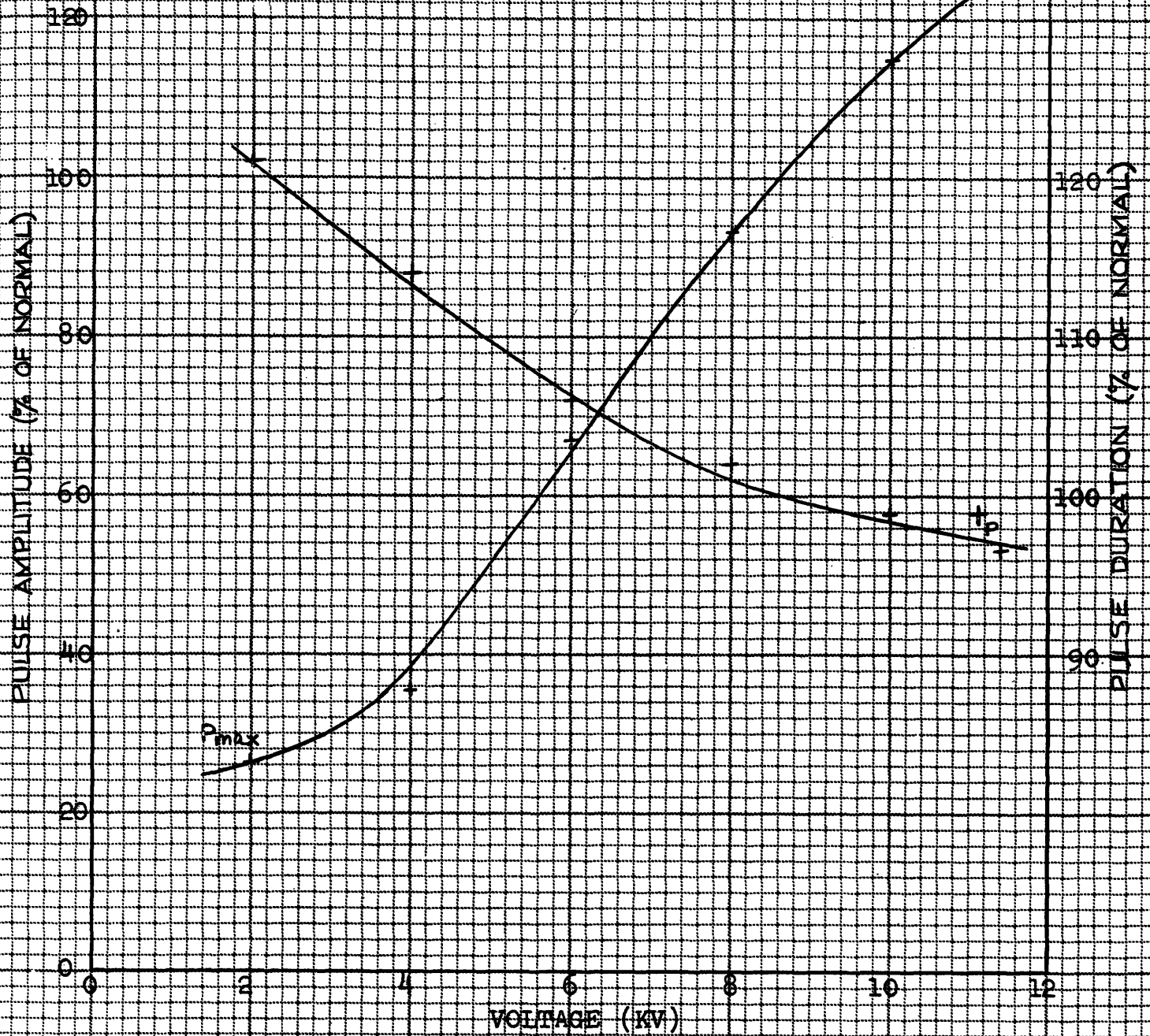


FIGURE XI

INFLUENCE OF PLATE COMPOSITION ON PULSE AMPLITUDE AND DURATION

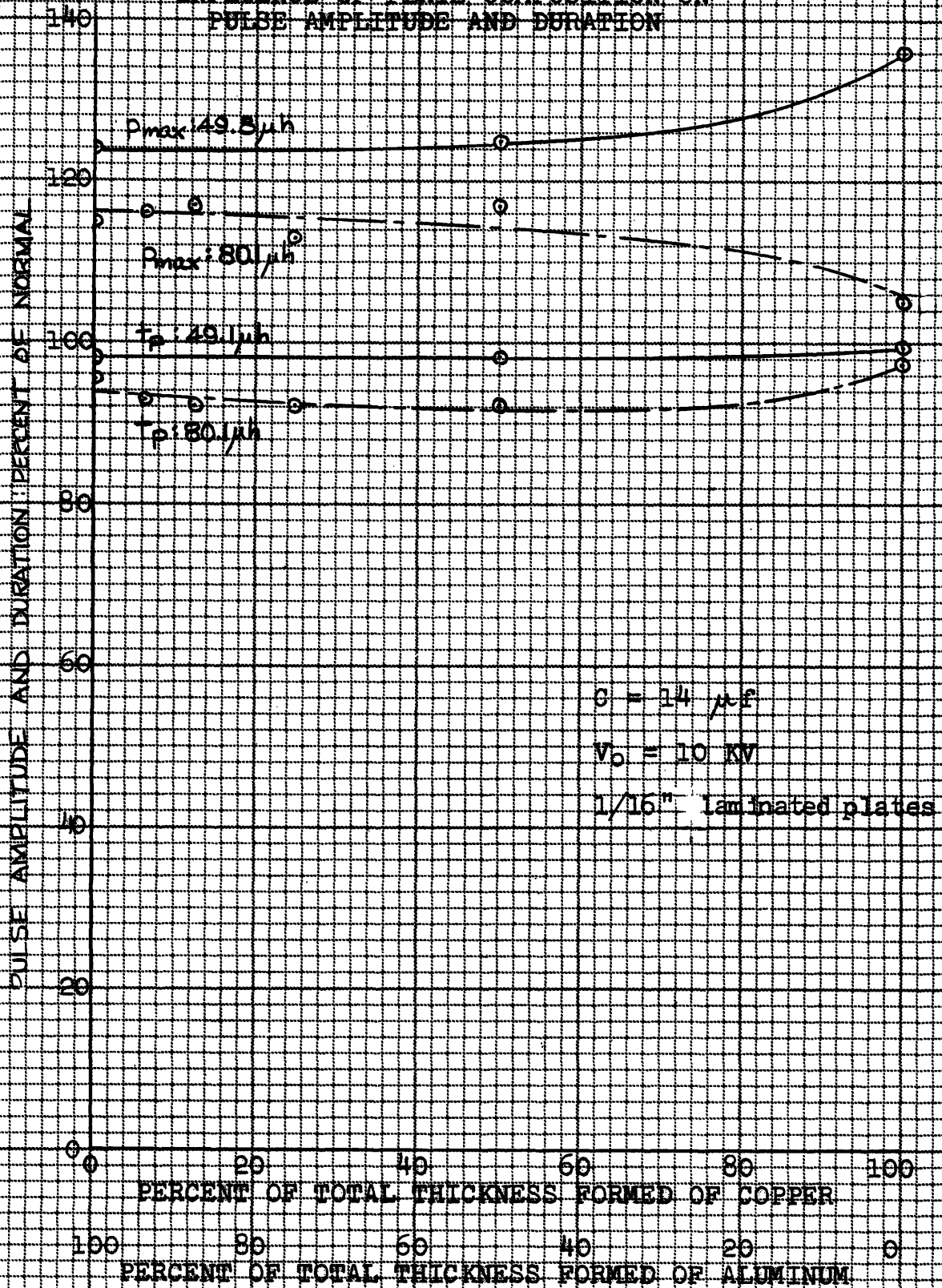
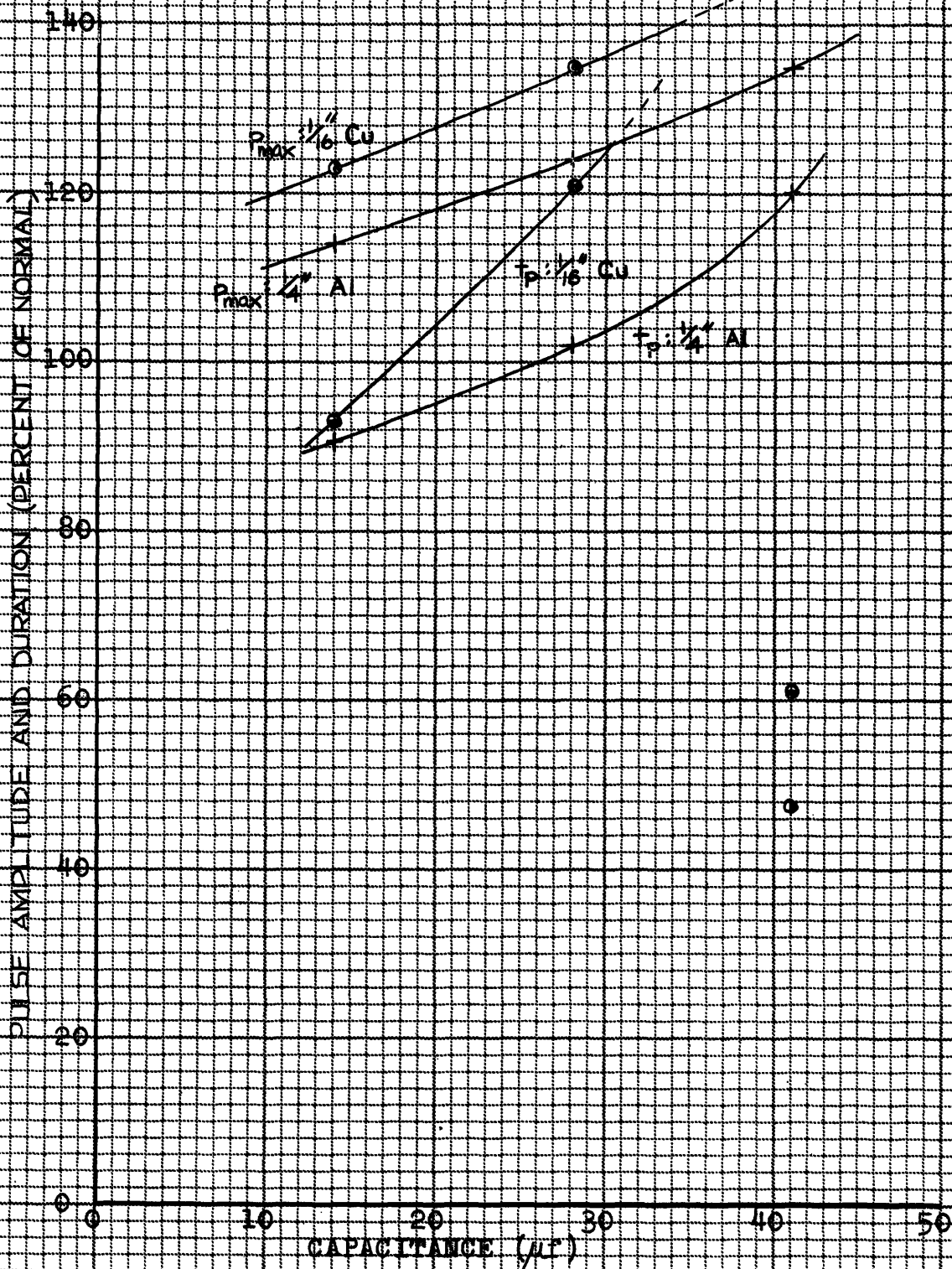


FIGURE XII

INFLUENCE OF C ON PULSE AMPLITUDE AND DURATION

$L = 49.8 \mu h$

$V_0 = 10 \text{ KV}$



two test tanks cited are summarized in Table III below. This comparison was made at 10 KV, with  $L = 49.8 \mu\text{h}$ ,  $C = 14 \mu\text{f}$ :

TABLE III

COMPARISON OF TEST TANKS

Tank	Rise Time ( $\mu\text{s}$ )	Peak Hydrophone output (volts)	Pulse Duration ( $\mu\text{s}$ )
large, open tank	1	24.0	12
open 10" cylinder	6*	-520	28

---

\* Vertical jump to -400 volts, followed by gradual rise to -520 volts.

## IV. DISCUSSION OF RESULTS

### A. Comparison of Liquids

As has been stated before (see Table II), neither pentane nor glycerine offered any significant advantage over water as a test medium, based on experiments conducted in an open cylinder. Perhaps, in retrospect, this is not astonishing: As stated, pentane was selected for testing because the relatively rapid increase of acoustic velocity with pressure indicated that liquid might effect significant pulse steepening as the pressure pulse propagated through the test chamber. However, the 5" spacing between the driver and the pressure pickup would permit very little pulse steepening unless the pressures generated on the face of the driving plate were quite intense. Such was found not to be the case.

The selection of a 5" separation between the driver and the pressure probe was based on the assumption of a 5" spacing between the driver and the "target" end of the hypothesized test facility. As mentioned, the existing mechanical facility uses repetitive internal reflection as a means of generating prolonged pulses. Actually, there is little choice in this matter: In general, it is not possible to match acoustical impedances sufficiently well at the ends of the chamber as to eliminate reflections, nor is it feasible to construct a chamber sufficiently long that reflections can be ignored. Thus, they must be utilized. However, the reflected pulse repetition frequency of 3 KC achieved with the glycerine



filled 20" chamber has proven to be a disadvantage: Cdr. J.R. Baylis has mentioned that some components subjected to testing were found to have mechanical resonances sufficiently close to that frequency as to create problems. Reducing the length of the chamber would raise the repetition frequency, thus easing the problem of mechanical resonance, and would also help compensate for the relatively shorter duration pulses produced by the electrical driver, by spacing them closer together in time. Considering the above, it would appear reasonable to eliminate pentane from consideration as a possible test medium.

On the other hand, despite its poor performance in the experiment cited, glycerine may yet be worthy of consideration as a test medium. As discussed in PROCEDURE, it is possible that a liquid less compressible than water might result in higher conversion efficiencies, provided that the liquid were excluded from the region between the driving coil and plate, and provided that the driver and the liquid completely filled a constant volume system.

As it happens, the first provision mentioned above must be met, in any event, in order to adapt the boomer for service in an environment involving high hydrostatic pressures: The output of early boomers was found to decrease rapidly with increasing hydrostatic pressure. High-speed motion pictures revealed that the driven plate separated from the coil so rapidly that a vapor pocket formed behind the plate. Thus, a pressure drop developed across the plate, equal to

the difference between the hydrostatic pressure on the face of the plate and the vapor pressure on the rear of the plate. Because of this, increased hydrostatic pressure (while vapor pressure remained essentially constant) resulted in decreased output.

A solution to this problem has been devised by H.E. Edgerton and S.O. Raymond (6,7). Basically, it consists of encasing the driver assembly in a rubber boot, and utilizing a regulated air supply to maintain air pressure in the boot within a few psi of the hydrostatic pressure outside the boot. A grooved plate is used to ensure a supply of air between the plate and coil, and thus minimize pressure drop when the plate is "fired". (Though the reduction in coupling caused by the grooves has been found to result in about a 10% reduction in output--- compared to a flat plate at one atmosphere--- the output of the compensated array has actually been found to increase with hydrostatic pressure up to about 2000 psi, reaching a maximum about 25% higher than the flat plate at one atmosphere.)

In any event, a driver so compensated--- immersed in a pressure chamber--- fulfills both "provisions" discussed above. It might well prove worthwhile to conduct a second comparative test of water and glycerine, under such conditions.

#### B. Performance of Driver

In line with the above discussion of test media, it is interesting to note that the degree of coupling between the

driving coil and plate is sufficiently "loose"--- as evidenced by the low conversion efficiencies measured for commercial boomers--- as to completely divorce the electrical behavior of the driver from the test medium. This is certainly verified by the identical electrical performance observed when testing the driver illustrated in Figure II in various liquids and in air, and is again reflected by the very slight dependence on plate thickness--- i.e., driven mass--- observed in Figures V and VI.

Figure V displays the effect of successively reducing L and C in an attempt to reduce electrical rise time while remaining at a given energy level. Above 6 KV, very little was gained by further reduction of C, though rise time remained sensitive to reduction of coil inductance. However, it is apparent that peak currents increased rapidly as L was reduced below  $80 \mu\text{h}$ , thus increasing losses due to lead resistance. Again, it is felt that it would not be feasible to work with coils much smaller than  $50 \mu\text{h}$ , if for no other reason, because of the reduced service life resulting from higher stresses of thermal and electrical origin, due to the higher currents involved.

Figure IX depicts the variations in pressure pulse amplitude and duration which correspond to the electrical phenomena displayed in Figure V. As can be seen, use of the  $49.8 \mu\text{h}$  coil resulted in a slight increase in maximum pressure, compared to the  $80.1 \mu\text{h}$  coil, with a very slight reduction in pulse duration. Accordingly, the  $49.8 \mu\text{h}$  coil was selected

as the standard for further experimentation.

As was mentioned in RESULTS, it was found that any electrical rise time less than  $50\mu\text{s}$  resulted in the generation of a pulse with an essentially vertical leading edge. Comparison of Figures V and IX reveals an additional item of interest in this situation: Reduction of electrical rise time below the  $50\mu\text{s}$  level resulted in a gradual increase in peak amplitude, but a much more rapid decrease in pulse duration. Thus, it would appear unprofitable to reduce electrical rise time any further than that level which just suffices to produce the desired pressure signal.

It is also interesting to note that Figure IX again indicated the relative unimportance of the mass of the driven plate as a design parameter--- at least, within the ranges considered. Though a very slight improvement in pressure pulse characteristics resulted from the use of a thin plate at low voltage levels (i.e., slower electrical rise time), this improvement was hardly significant and, in general, disappeared at higher voltages.

Figure XI represents the investigation of plate composition as a parameter affecting driver output. It is recognized that some variation of driven mass resulted from the use of laminated plates of constant thickness; however, this variation was of lesser magnitude than that investigated by the tests depicted in Figure IX. Further, if Figure IX is to be believed, these latter tests were conducted in a region in which the variation of mass, per se, should not have affected output.

At best, the test results depicted in Figure XI were inconclusive. Certainly, there would appear to be no advantage in the use of laminated plates, as contrasted with solid plates of a single conductor. However, of the solid plates tested, the relative merits of Cu and Al were not clearly established by this test series. Accordingly, the decision was made to conduct further comparative testing.

Figures VII and VIII display the electrical performance of the driver as input energy level was systematically increased to the limits of the available facilities. In Figure VII, voltage was increased while capacitance was held fixed. As might be expected, peak currents increased nearly linearly with voltage, while rise time decreased. It is interesting to speculate about the deviation from linearity in the I-V relationship above 8 KV: Since the energy transferred to the liquid is electrically equivalent to a resistive loss, it is possible that this increase in apparent resistance might represent closer coupling to the driven plate. Perhaps the more rapid buildup of the magnetic field resulted in greater energy transfer before the plate could move away from the coil, thus decoupling the system. Figure X displays the related pressure pulse data, and it can be seen (as contrasted with the constant energy-increasing voltage case) that pulse duration fell much less rapidly than before, while peak pressure rose much more rapidly.

Figure VIII displays the effect of increasing supply bank capacitance to increase energy, while remaining at a con-

stant operating voltage. Electrical rise time is seen to increase rapidly, while peak currents rise, but at a decreasing rate. Inasmuch as electrical rise time remained well below the  $50\ \mu\text{s}$  level discussed previously, it would appear that considerably more capacitance could be tolerated in the circuit at 10 KV than at 4 KV--- or, in other words, it would be possible to design for an energy input in excess of the 2100 joules achieved here at 10 KV. It is also apparent, however, that an order of magnitude increase in energy level would require a voltage level higher than 10 KV.

Figure XII, in addition to being the companion piece to Figure VIII, again investigates the influence of plate conductivity on the output pulse. To minimize the effect of mass difference, a  $1/4$ " Al plate and a  $1/16$ " Cu plate were subjected to comparative testing. This time, the relative merits of Cu and Al would seem much more apparent: Use of the copper plate resulted in a reasonable improvement in both pulse amplitude and duration, and more significantly, the degree of improvement increased as more capacitance was added to the circuit to raise the energy input. On the other hand, the lower strength of the copper plate proved to be a fatal shortcoming: at an input level of 2100 joules, the copper plate failed structurally, resulting in permanent deformation and a sharply reduced output.

Now, granting that driver performance has been insensitive to mass within the range examined, it would obviously be possible to use a thicker copper plate to avoid failure at 2100 joules.

On the other hand, if we consider an eventual order of magnitude increase in energy level, it is certainly possible--- if not probable--- that eventually, the lower strength per unit mass realizable with copper would preclude the use of that metal in the driven plate.

As a final item in the analysis of test data, it is of interest to estimate the magnitude of the pressure pulse which might be produced by the boomer if driven, as contemplated, into an 8" closed cylinder.

Table III indicates that when driven into a thin-walled, 10" cylinder the magnitude of the hydrophone output was 520 volts. The hydrophone utilized for this test was the PZT-5 pickup illustrated in Figure IIIb. According to the manufacturer (8), nominal parameters for this crystal are:

$$g_{33} = 24.4 \times 10^{-3} \text{ volt-meter/newton}$$

$$K_{33} = 0.675$$

$$\epsilon\epsilon_0 = 15.9 \times 10^{-9} \text{ farads/meter}$$

$$Y = 5.85 \times 10^{10} \text{ newtons/square meter}$$

Further, in metric units, cross-sectional area of the disk is  $8.10 \times 10^{-5}$  square meters, and its thickness is  $1.522 \times 10^{-3}$  meters. Using the method expounded by F.E. Perkins and P.S. Eagleson (9) to compute crystal sensitivity:

$$C_0 = \epsilon\epsilon_0 \frac{A}{t} = 84.6 \times 10^{-12} \text{ farads}$$

$$\alpha = \frac{g_{33}\epsilon\epsilon_0YA}{t} = 1.209 \times 10^{-1} \text{ coulombs/meter}$$

$$V_0/F = K_{33}^2/\alpha(1 + K_{33}^2) = 2.59 \text{ volts/newton}$$

$$V_o/p = 1.442 \text{ volts/ p.s.i.}$$

The crystal was placed in series with 63" of shielded conductor, rated at  $24 \times 10^{-12}$  farads/foot, and an oscilloscope with input capacitance equal to  $20 \times 10^{-12}$  farads. Allowing for the attenuation of a total series capacitance of approximately  $150 \times 10^{-12}$  farads:

$$V_s/p = V_o [C_o/(C_o + C_s)] = 0.521 \text{ volts/psi}$$

Thus, very crudely, an output level of 520 volts corresponds to a pressure signal of roughly 1000 psi.\* Considering that this was the free-stream pressure--- analogous to the positive-going wave on a transmission line--- a test specimen mounted to a rigid end plate in a pressure chamber would see a pulse of roughly twice this magnitude, or 2000 psi. It might be noted that this pressure was developed with an energy input of 700 joules.

The fact must be stressed that the above estimate is quite crude: It would be valid for dynamic response within the "flat" portion of the crystal characteristics, but as is evidenced by the fact that rise time was observed to be pickup limited, appreciable pressure energy must have been distributed at frequencies above the crystal cutoff frequency. Actually, the only accurate method of determining pressure level would be to calibrate the crystal used by subjecting

---

\* Albers (10) reports that W. Eisenmenger has achieved 700-atmosphere shock wave by using a similar driver to implode a piece of copper foil into a water-filled tube.



it to a pressure step in a calibrated shock tube, thus measuring response to a dynamic signal more representative of the type produced by the boomer.

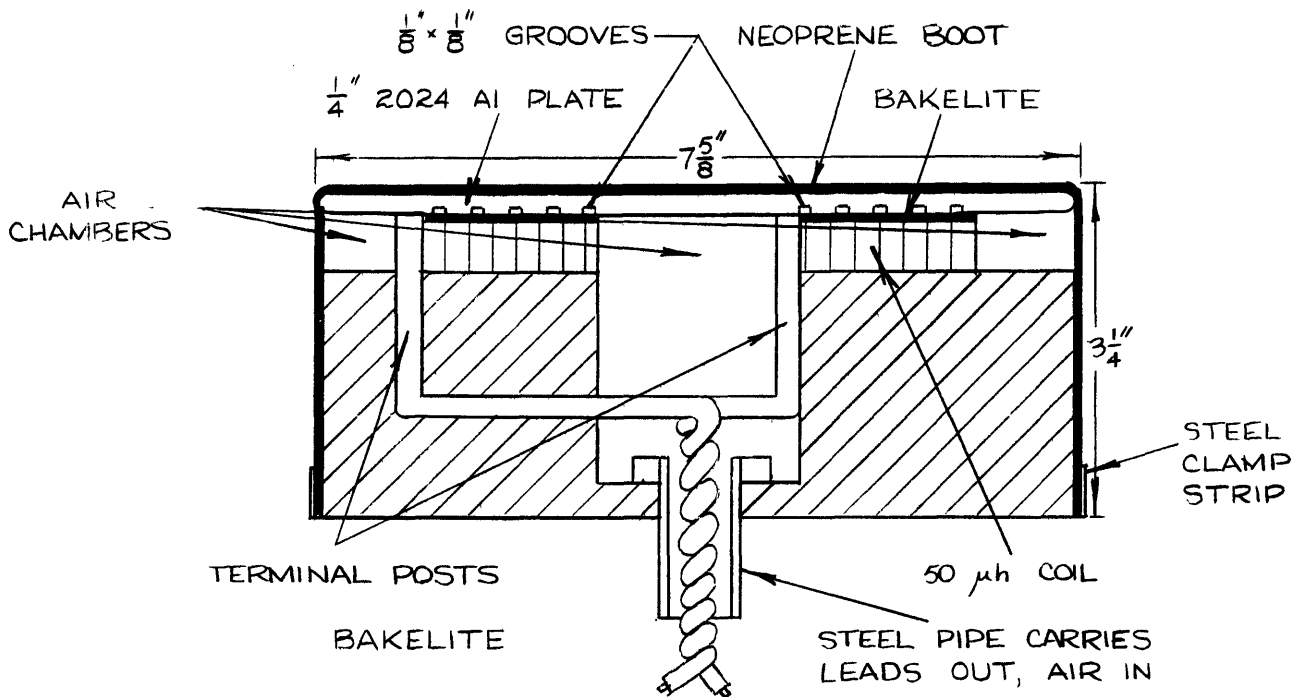
### C. Proposed Design for Test Facility

Based on the results of these experiments, it would appear that the modified boomer offers sufficient promise as a hydraulic shock generator to warrant extended testing in the interest of developing a prototype test facility. Specifically, this would involve:

1. Construction of an 8" I.D. by 8" long pressure chamber, suitable for use with pressure-compensated boomer.
2. Calibration of dynamic response of crystal pickup.
3. Additional testing at current energy levels, in pressure chamber, to verify system performance, as contrasted with driver performance, at various hydrostatic pressures.
4. Additional comparative testing of water and glycerine as test media.
5. Further examination of input energy-output pulse relationships by extending available bank capacitance to about twice the current range, and extending operating voltage to about 20-25 KV.

A suggested design for the driver to be used in conjunction with the above facility is shown in Figure XIII. A 50  $\mu$ h coil has been specified for the driver for the various reasons discussed above, plus one additional factor: The metal of the pressure chamber constitutes a shorted turn in close proximity to the driving coil. As such a shorted turn will adversely

FIGURE XIII  
SUGGESTED DRIVER DESIGN



affect driver performance, it would be well to minimize the degree of coupling between the coil and the pressure chamber. The less the inductance of the coil used, the smaller its outer diameter--- thus, less coupling with the chamber should occur at the lower limit of the range of inductance discussed.

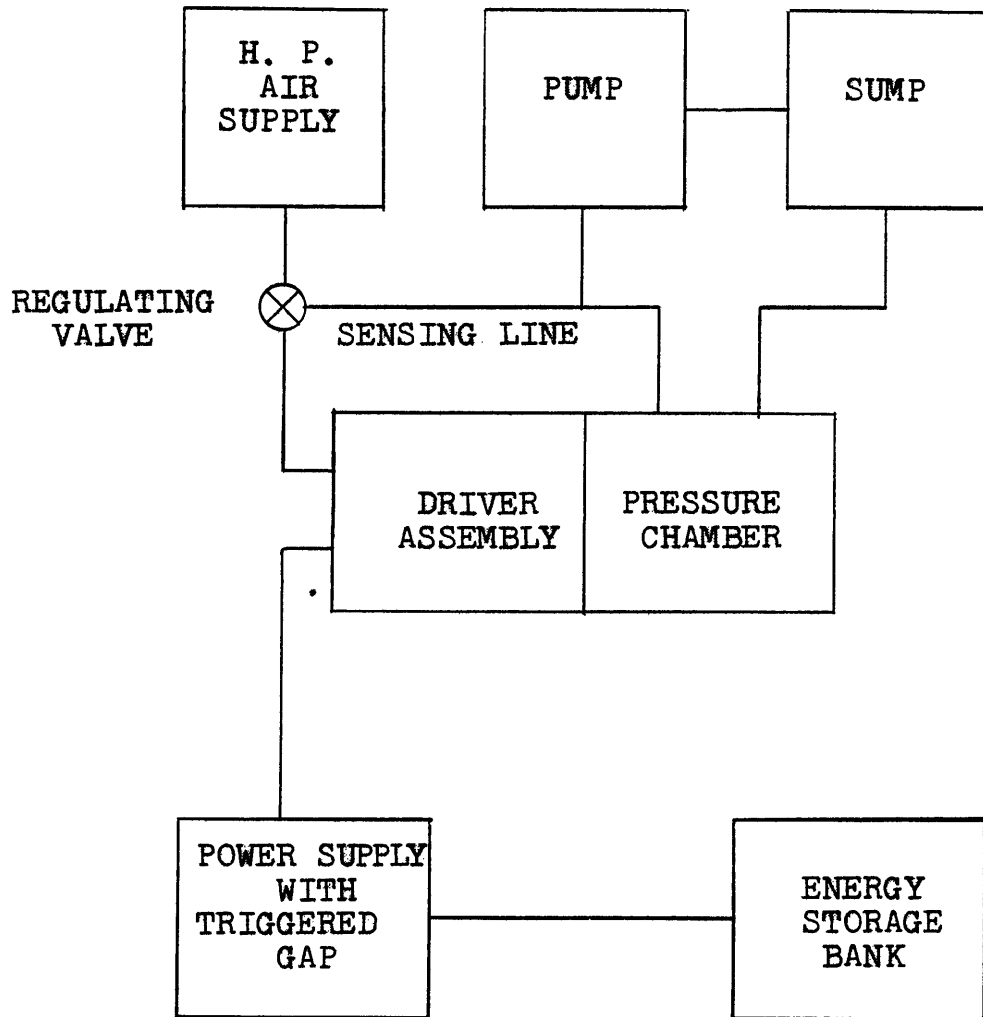
Though a 1/4" 2024 Al alloy plate has been specified, it may prove necessary to shift to a 7075 alloy and/or a thicker plate, at higher energies. In this respect, it would also be interesting to further investigate the possible use of copper to capitalize upon the improved output characteristics discussed above.

Figure XIV is a rough schematic of the proposed facility.

Pending successful completion of the additional tests indicated, it would tentatively appear feasible to develop an electrically driven hydraulic shock generator, with input energy of up to 25,000 joules, operating at 25 KV. It might prove feasible to develop an even more powerful test facility.

FIGURE XIV

SCHEMATIC OF PROPOSED TEST FACILITY



## V. CONCLUSIONS

1. The boomer has been found to hold real promise as a driver for an underwater explosion simulator.

2. Modification of the basic boomer design to provide for an electrical rise time of about 50  $\mu$ s, in conjunction with other modifications discussed in the text, appears to be the optimum design for generation of hydraulic shock.

3. Given the above conditions, it is estimated that the boomer will produce a pressure pulse, as seen by the test specimen, with a rise time of 1  $\mu$ s or less, a peak pressure of 2000 psi or higher, and a duration of about 35  $\mu$ s, for an energy input of 700 joules. Increases in peak pressure and pulse duration can be achieved by operation at higher energy levels.

4. Pending the successful conclusion of additional testing, energy inputs in excess of 25,000 joules would seem feasible.

5. Either water or glycerine appear to hold promise as a test medium for use in conjunction with this type of driver: In any event, the relatively loose coupling of the driver to the liquid permit substitution of different test media with no effect on electrical performance of the driver.

6. The pressure chamber used in conjunction with the above driver should be of a length not to exceed 8": However, should it become necessary to test specimens which penetrated more than 4" into the chamber, additional flanged sections could

be used to extend the length of the chamber for such tests.

## VI. RECOMMENDATIONS

A. It is recommended that the proposed driver design be subjected to extended testing, as follows:

1. Additional testing at current energy levels, but within the proposed pressure chamber, to verify system performance at various hydrostatic pressures.
2. Additional comparative testing of water and glycerine as test media.
3. Further investigation of input-output energy relations by extension of energy bank capacitance, in steps, to a level of approximately twice the range covered herein, and by extension of operating voltage, in steps, to a level of about 25 KV.
4. Further investigation of the feasibility of using a copper driven plate at high energy levels.

B. Contingent upon the successful conclusion of the above test program, it is recommended that serious thought be given to the establishment of an electrically driven hydraulic shock test facility.

## APPENDIX



APPENDIX A

TABLE A-I

INFLUENCE OF COIL INDUCTANCE, BANK CAPACITANCE, AND PLATE THICKNESS  
ON ELECTRICAL SIGNATURE OF DRIVER WITH 500 JOULE INPUT

$L(\mu h)$	$C(\mu f)$	$V_o(KV)$	Plate	Rise Time ( $\mu s$ )	$I_{max}$ (KA)	Ring Frequency (KC)	Decay Time Constant ( $\mu s$ )	
49.8	80	3.6	1/4" A1	45	2.91	3.2	280	
			1/8" A1	45	2.88	3.1	280	
			1/16" A1	45	2.88	3.1	285	
	42	4.87	1/4" A1	1/4" A1	30	8.77	4.8	295
				1/8" A1	30	8.59	4.7	280
				1/16" A1	30	8.47	4.9	310
	28	5.97	1/4" A1	1/4" A1	15	9.53	6.2	265
				1/8" A1	15	9.41	6.1	275
				1/16" A1	15	9.41	6.0	285
14	8.60	1/4" A1	1/4" A1	10	11.52	8.9	170	
			1/8" A1	10	11.28	8.9	180	
			1/16" A1	10	11.28	8.8	200	
80.1	80	3.6	1/4" A1	50	2.48	2.8	280	
			1/8" A1	50	2.33	2.8	300	
			1/16" A1	50	2.40	2.9	290	
	42	4.87	1/4" A1	1/4" A1	40	5.86	4.4	200
				1/8" A1	40	5.86	4.3	210
				1/16" A1	40	5.86	4.2	220
	28	5.97	1/4" A1	1/4" A1	25	6.14	5.6	190
				1/8" A1	25	6.14	5.4	190
				1/16" A1	25	6.14	5.4	200

TABLE A-I (cont'd)

L( $\mu$ h)	C( $\mu$ f)	V <sub>o</sub> (KV)	Plate	Rise Time ( $\mu$ s)	I <sub>max</sub> (KA)	Ring Frequency (KC)	Decay Time Constant ( $\mu$ s)
	14	8.60	1/4" A1	20	7.23	8.1	128
			1/8" A1	20	7.23	7.9	135
			1/16" A1	20	7.23	7.9	142
172	80	3.6	1/4" A1	60	1.74	2.0	300
			1/8" A1	60	1.60	2.1	340
			1/16" A1	55	1.60	2.1	330
42	4.87	1/4" A1	1/4" A1	50	4.25	3.2	258
			1/8" A1	50	4.04	3.2	280
			1/16" A1	50	4.04	3.2	280
28	5.97	1/4" A1	1/4" A1	35	4.25	4.3	200
			1/8" A1	35	4.14	4.2	230
			1/16" A1	35	4.04	4.2	235
14	8.60	1/4" A1	1/4" A1	30	4.86	6.1	125
			1/8" A1	30	4.86	6.2	125
			1/16" A1	30	4.86	6.0	160

TABLE A-II

INFLUENCE OF INITIAL VOLTAGE ON ELECTRICAL SIGNATURE  
OF DRIVER WITH OTHER PARAMETERS FIXED

<u>L(<math>\mu</math>h)</u>	<u>C(<math>\mu</math>f)</u>	<u>Plate</u>	<u>V<sub>0</sub>(KV)</u>	<u>Rise Time (<math>\mu</math>s)</u>	<u>I<sub>max</sub> (KA)</u>	<u>Ring Frequency (KC)</u>	<u>Decay Time Constant (<math>\mu</math>s)</u>
49.8	14	1/4" A1	2	24	2.47	11.2	190
			4	20	5.24	9.3	175
			6	20	7.86	9.3	160
			8	19	10.77	9.1	144
			10	19	13.10	9.1	160
			11.4	18	14.62	8.9	160

TABLE A-III

INFLUENCE OF CAPACITANCE ON ELECTRICAL SIGNATURE  
OF DRIVER WITH OTHER PARAMETERS FIXED

<u>L(<math>\mu</math>h)</u>	<u>Plate</u>	<u>V<sub>0</sub>(KV)</u>	<u>C(<math>\mu</math>f)</u>	<u>Rise Time (<math>\mu</math>s)</u>	<u>I<sub>max</sub> (KA)</u>	<u>Ring Frequency (KC)</u>	<u>Decay Time Constant (<math>\mu</math>s)</u>
49.8	1/4" A1	10	14	19	15.4	9.1	165
			28	24	20.0	6.2	200
			42	30	21.8	4.5	204

TABLE A-IV

INFLUENCE OF COIL INDUCTANCE, BANK CAPACITANCE, AND  
 PLATE THICKNESS ON PRESSURE PULSE WITH 500 JOULE INPUT

Measurements taken with a 0.710" x 0.044" quartz disk pickup

$L(\mu h)$	$C(\mu f)$	$V_0(KV)$	Plate	Rise Time ( $\mu s$ )	Peak Hydrophone Output (Volts)	Pulse Duration ( $\mu s$ )
49.8	80	3.6	1/4" A1	8*	46.6	71.4
			1/8" A1	8	50.0	71.4
			1/16" A1	8	56.0	71.4
42	4.87	3.6	1/4" A1	6*	57.0	50.5
			1/8" A1	6	57.0	51.5
			1/16" A1	6	57.7	52.0
28	5.97	3.6	1/4" A1	6*	67.5	39.0
			1/8" A1	6	67.0	41.5
			1/16" A1	6	67.8	40.0
14	8.60	3.6	1/4" A1	6*	84.0	24.5
			1/8" A1	6	84.0	26.2
			1/16" A1	6	84.0	26.4
80.1	80	3.6	1/4" A1	8*	37.7	77.5
			1/8" A1	8	39.6	77.5
			1/16" A1	8	44.3	77.5
42	4.87	3.6	1/4" A1	6*	47.0	55.5
			1/8" A1	6	47.5	55.5
			1/16" A1	6	50.0	55.5

\* This figure represents the attainable rise time (i.e., impulse response) of the hydrophone used, vice the actual rise time of the pressure pulse.

TABLE A-IV (cont'd)

$L(\mu h)$	$C(\mu f)$	$V_0(KV)$	Plate	Rise Time ( $\mu s$ )	Peak Hydrophone Output (Volts)	Pulse Duration ( $\mu s$ )
	28	5.97	1/4" A1	6*	58.5	44.6
			1/8" A1	6	58.5	44.6
			1/16" A1	6	58.5	43.4
	14	8.60	1/4" A1	6*	77.5	29.2
			1/8" A1	6	77.5	29.0
			1/16" A1	6	77.5	29.0
172	80	3.6	1/4" A1	8*	22.8	85.0
			1/8" A1	8	23.9	85.0
			1/16" A1	8	24.3	85.0
	42	4.87	1/4" A1	6*	24.0	62.0
			1/8" A1	6	22.4	56.1
			1/16" A1	6	22.4	56.0
	28	5.97	1/4" A1	6*	24.4	45.4
			1/8" A1	6	24.0	44.0
			1/16" A1	6	24.0	43.0
	14	8.60	1/4" A1	6*	27.2	20.6
			1/8" A1	6	24.6	22.8
			1/16" A1	6	29.2	24.6

\* This figure represents the attainable rise time (i.e., impulse response) of the hydrophone used, vice the actual rise time of the pressure pulse.

TABLE A-V

INFLUENCE OF INITIAL VOLTAGE ON PRESSURE PULSE  
WITH OTHER PARAMETERS FIXED

Measurements taken with a 0.400" x 0.060" PZT-5 disk pickup

<u>L(<math>\mu</math>h)</u>	<u>C(<math>\mu</math>f)</u>	<u>Plate</u>	<u>V<sub>0</sub>(KV)</u>	<u>Rise Time (<math>\mu</math>s)</u>	<u>Peak Hydrophone Output (Volts)</u>	<u>Pulse Duration (<math>\mu</math>s)</u>
49.8	14	1/4" Al	2	1*	5.0	16.0
			4	1	7.0	15.1
			6	1	12.8	14.0
			8	1	18.0	13.5
			10	1	22.0	13.1
			11.4	1	24.0	12.8

TABLE A-VI

INFLUENCE OF PLATE COMPOSITION ON PRESSURE PULSE  
WITH OTHER PARAMETERS FIXED

For a series of Cu-Al laminated plates of 1/16" nominal thickness

<u>L(<math>\mu</math>h)</u>	<u>C(<math>\mu</math>f)</u>	<u>V<sub>0</sub>(KV)</u>	<u>% Cu</u>	<u>Rise Time (<math>\mu</math>s)</u>	<u>Peak Hydrophone Output (Volts)</u>	<u>Pulse Duration (<math>\mu</math>s)</u>
80.1	14	10	0	50*	890 (1)	145
			6.5	50	900	141
			12.5	50	905	140
			25	50	875	140
			50	50	910	140
			100	50	814	148

(1) Measurements taken with Chesapeake Instrument Model SB 154-D hydrophone

\* This figure represents the attainable rise time (i.e., impulse response) of the hydrophone used, vice the actual rise time of the pressure pulse.

TABLE A-VI (cont'd)

$L(\mu h)$	$C(\mu f)$	$V_o(KV)$	% Cu	Rise Time ( $\mu s$ )	Peak Hydrophone Output (Volts)	Pulse Duration ( $\mu s$ )
49.8	14	10	0	1*	24.0 (2)	13.0
			50	1	24.2	13.0
			100	1	26.2	13.2

(2) Measurements taken with 0.400" x 0.060" PZT-5 wafer

TABLE A-VII

INFLUENCE OF CAPACITANCE ON PRESSURE PULSE WITH  
OTHER PARAMETERS FIXED

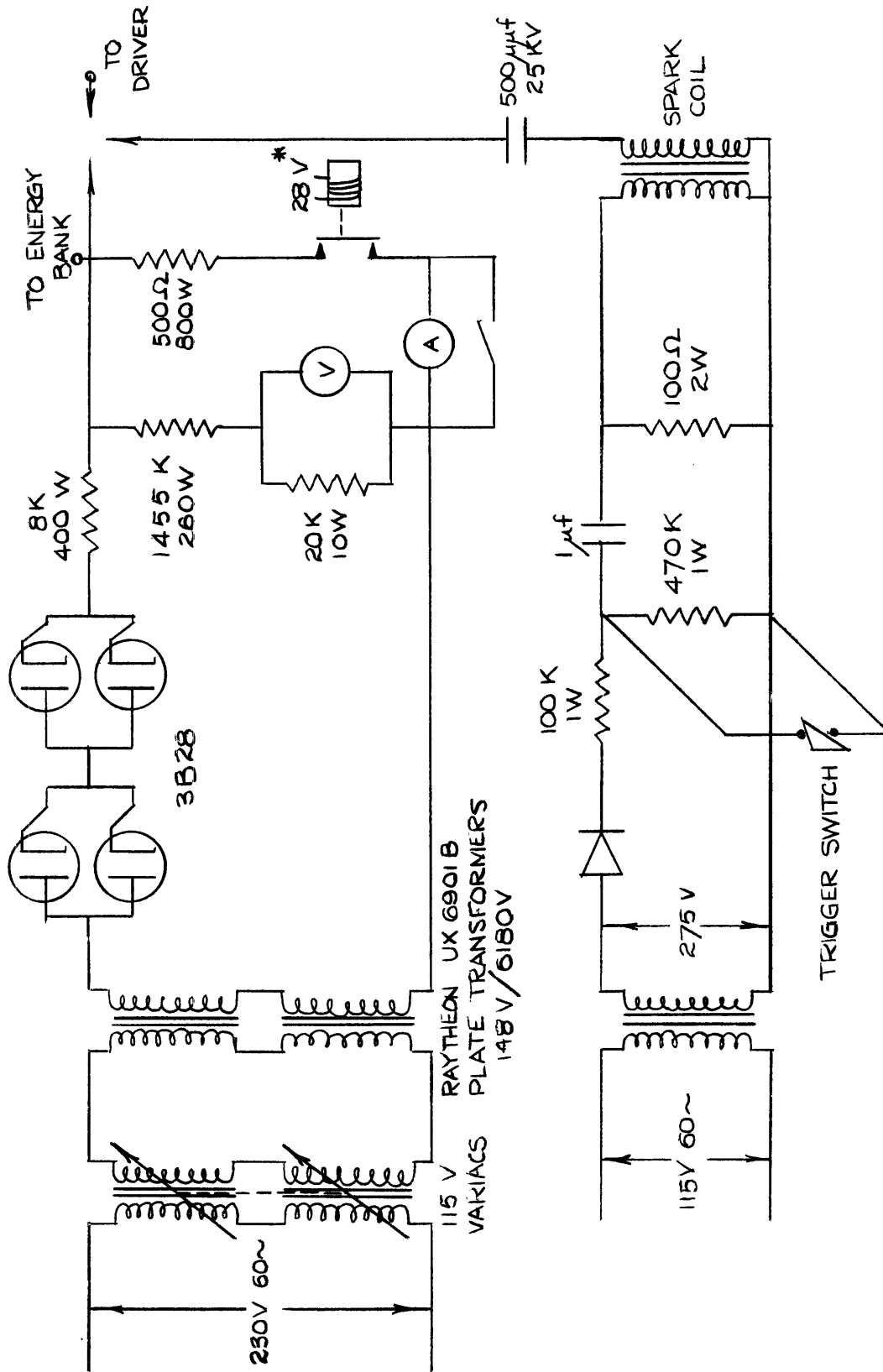
Measurements taken with 0.400" x 0.060" PZT-5 wafer

$L(\mu h)$	$V_o(KV)$	Plate	$C(\mu f)$	Rise Time ( $\mu s$ )	Peak Hydrophone Output (Volts)	Pulse Duration ( $\mu s$ )
49.8	10	1/16" Cu	14	1*	23.8	12.3
			28	1	26.0	16.0
			42	1	9.2	8.1
		1/4" Al	14	1*	22.0	12.0
			28	1	24.0	13.5
			42	1	26.0	15.9

\* This figure represents the attainable rise time (i.e., impulse response) of the hydrophone used, vice the actual rise time of the pressure pulse.

APPENDIX B

POWER SUPPLY CIRCUIT DIAGRAM



\* 28V RELAY INTERLOCKED WITH POWER SWITCH AND MICROSWITCHES ON ACCESS PANELS TO DISCHARGE ENERGY BANK AS A SAFETY FEATURE.



## APPENDIX C

### BIBLIOGRAPHY

- (1) Keil, A.H., "The Response of Ships to Underwater Explosions", SNAME Paper, November, 1961.
- (2) Chace, W.G. and Moore, H.K., "Exploding Wires".
- (3) Edgerton, Germeshausen & Grier, Inc., "Oceanographic Instrumentation", Oceanographic Catalogue 0-62.
- (4) Edgerton, Germeshausen & Grier, Inc., Report No. B-2257, "Model 230 Sonar Boomer".
- (5) Swanson, J.C., "Pressure Coefficients of Acoustic Velocity", Journal of Chemical Physics, Vol. 2 (1934), p. 689.
- (6) Edgerton, Germeshausen & Grier, Inc., Report No. B-2440, "Report No. 2: Submersible Boomer Study and Experimental Program".
- (7) Edgerton, Germeshausen & Grier, Inc., Report No. B-2498, "Report No. 3: Submersible Boomer Study and Experimental Program".
- (8) Clevite Electronic Components Division of Clevite Corporation Bulletin No. 9244, "Modern Piezoelectric Ceramics".
- (9) Perkins, F.E., and Eagleson, P.S., "The Development of a Total Head Tube for High Frequency Pressure Fluctuations in Water", M.I.T. Hydrodynamics Laboratory Technical Note No. 5.
- (10) Albers, V.M., "Underwater Acoustics", p. 142.