ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

RESEARCH AND DEVELOPMENT OF IMPROVED IGNITION SYSTEMS

PROGRESS REPORT NO. 1

Period Covering May, 1 1955 to April 30, 1956

Department of Electrical Engineering

By: Lyman W. Orr
Gordon A. Roberts
Hal F. Schulte, Jr.
Thomas W. Butler, Jr.
Joseph Otterman

Approved by: JA Boyd
J. A. Boyd

ERI Project 2370-2

THE CHRYSLER CORPORATION
Engineering Division
Detroit, Michigan

May, 1956

TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS iv

ABSTRACT vii

1. PURPOSE 1

2. OBJECTIVE 1

3. REVIEW OF RESEARCH ACTIVITY 1

4. BASIC PRINCIPLES AND PRACTICAL REALIZATION 2
    4.1 The Two Stages of Ignition 2
    4.2 One-Stage Systems 3
    4.3 Two-Stage Systems 4
    4.4 High Current Systems 5
    4.5 The Ideal System 5

5. CAPACITOR DISCHARGE SYSTEMS 6

6. CAPACITOR SWITCHING MEANS FOR CD SYSTEMS 7
    6.1 Mechanical Contact Switching 7
    6.2 Thyratron Switching 9
    6.3 Cold-Cathode Gas Switches 11
        6.3.1 Introduction 11
        6.3.2 Circuit Operation 13
        6.3.3 Circuit Determined Switch Requirements 17
    6.4 Triggered Gap Switch 18
        6.4.1 Physical Structure 19
    6.5 Characteristics of Cold Cathode Gas Switches 23

7. STATISTICAL ANALYZER FOR ENGINE PERFORMANCE 30
    7.1 Introduction 30
    7.2 Circuit 30
    7.3 Results and Recommendations 33

8. PERFORMANCE TESTS ON CFR ENGINE 33
    8.1 Ignition Performance Criterion 34
    8.2 Test Procedure 35
    8.3 Equipment Data 36
    8.4 Test Set-Up 36

9. DESIGN AND CONSTRUCTION OF PULSE TRANSFORMERS FOR CAPACITOR DISCHARGE SYSTEMS 45
    9.1 Requirements for Automotive Use and Typical Transformer Specifications 45
    9.2 Practical Transformers 46

10. POWER SUPPLY SYSTEMS 49
    10.1 Introduction 49
    10.2 Mechanical Vibrator Power System 52

10.3 Motor-Generator Power System 52
10.4 Transistor Power Converter System 53
10.4.1 Description of the Transistor Power Converter Oscillator 54
10.4.2 Transistor Power Limitations 57
10.4.3 Power Output Limitations of the Transistor Oscillator 57

11. VOLTAGE DIVIDER DESIGN FOR HIGH VOLTAGES 59
11.1 Basic Circuit 60
11.2 Distributed Stray Capacitance 61
11.3 Electric Breakdown Precautions 63

12. PIEZOELECTRIC VOLTAGE GENERATOR 65
12.1 Hydraulic Ram Experiment 65
12.2 Impact Experiment 67
12.3 Conclusions 69

13. CONCLUSIONS 70

14. PROPOSALS FOR FUTURE PROGRAM 70
14.1 Modification of CD System to Improve Fuel Economy 70
14.2 Switching Means for the CD System 71
14.3 Transistor Power Converter 71
14.4 Consulting Service 71

APPENDIX A DEFINITIONS OF SWITCH CHARACTERISTICS 72

APPENDIX B COLD CATHODE GAS SWITCH CHARACTERISTICS 76

APPENDIX C TRANSISTOR POWER SUPPLY REFERENCES 77

DISTRIBUTION LIST 78

LIST OF ILLUSTRATIONS

Figure No.		Page
6.1	Switching in CD System	8
6.2	Breaker Point Assembly for CD Mechanical Contact System	8
6.3	Thyratron CD System	9
6.4	Physical Appearance of the Flash Tube Switches	12
6.5	Practical Capacitor Discharge System for Use with a Cold Cathode Gas Switch	14
6.6	Instantaneous Voltage on Capacitor C_1	15
6.7	Instantaneous Capacitor Voltage and Transformer Current in the Discharge Period	16
6.8	Triggered Gap Switch, Model 1	20
6.9	Triggered Gap Switch, Model 1	19
6.10	Triggered Gap Switch, Model 2	21
6.11	Triggered Gap Switch, Model 2	22
6.12	Trigger Characteristics for Trigger Gap Switch, Model 2	22
6.13	The Circuit for Measuring Switch Voltage Drop and Ionization Time	24
6.14	Single-Shot Photograph of the Switch Voltage Drop for a Sprague FA-100	25
6.15	Trigger Voltage Characteristics of New Switches	26
6.16	Trigger Voltage Characteristics of New Switches	27
6.17	Comparison of Gas Switch Trigger Characteristics	28
6.18	The Circuit for Measuring the Cold Cathode Gas Switch Trigger Voltage, E_T	29
7.1	Block Diagram of Statistical Analyzer for Engine Performance	31

Figure No.		Page
8.1	CFR Engine Test Setup	37
8.2	Standard 12 Volt Ignition System	38
8.3	Capacitor Discharge System, Type A	40
8.4	Typical Curves for Standard Ignition System	41
8.5	CFR Engine Power Output VS Spark Plug Gap for the Standard Ignition System	43
8.6	Plot of the Minimum Primary Supply Voltage that Will Just Sustain Engine Operation VS Spark Plug Gap	44
9.1	Comparison of Peak Open Circuit Secondary Voltage for Transformer with Ferrite Core and Air Core	47
9.2	Circuit Used to Study the Linearity of the U of M Pulse Transformers	48
9.3	Typical Unpotted Pulse Transformer	50
9.4	Experimental Capacitor Discharge System Transformer Potted in Oil	51
10.1	Transistor Power Converter Oscillator Circuits	55
10.2	Hysteresis Loop for Square Loop Core Material	56
10.3	Current and Voltage Waveforms in Transistor Power Convertor	56
10.4	Power and Voltage Limitations for Grounded Base Transistor	58
10.5	Typical Germanium Power Transistor Derating Chart	58
11.1	Basic Circuit	60
11.2	Waveforms	60
11.3	Divider with Distributed Stray Capacitance	61
11.4	Response of Divider to 120 cy Square Wave	61
11.5	Divider Compensated for Distributed Strays	62
11.6	Waveforms Showing Response of Voltage Divider with Compensation for Distributed Strays	62
11.7	Construction of High Voltage Divider	64

Figure No.		Page
12.1	Hydraulic Ram Experiment	66
12.2	Peak Open Circuit Volts vs Peak Pressure in PSI x 10^3 on 1-1/4" Ram	66
12.3	Impact Experiment	68
12.4	Peak Open Circuit Volts vs Distance Through Which 7 lb Brass Slug Falls	68
A.1	Instantaneous Switch Voltage Drop	73

ABSTRACT

A capacitor discharge ignition system was developed which was shown to be superior to the standard ignition system in its ability to fire badly fouled spark plugs with gaps up to 70 mils. Optimized design values of system parameters were derived, and confirmed on an analog computer. The electrical behavior of the system was investigated in laboratory tests, and the system performance studied with engine tests. Considerable engineering development was done on the important components of the system including the pulse transformer, the switching means, and the power supply.

Equipment constructed for the investigation included a statistical analyzer for engine performance tests, auxiliary equipment for engine tests, triggered gap switches, and high voltage dividers.

It is concluded that a practical capacitor discharge ignition system suitable for an automobile can be achieved in the near future.

RESEARCH AND DEVELOPMENT OF IMPROVED IGNITION SYSTEMS

1. PURPOSE

The present report reviews the work done at the University of Michigan on ignition research under Contract C741 from May 1, 1955 to April 30, 1956.

2. OBJECTIVE

The objective of the project is the investigation of various means to improve ignition systems for internal combustion engines, and to design a specific system capable of reliable operation under all engine conditions when used with a 70 mil plug gap, and a fouling resistance of 200,000 ohms. These requirements were brought out in several conferences with Chrysler representatives, and the advantages of the 70 mil spark gap were indicated in a previous Chrysler report (No. 4801.13, June 12, 1951).

3. REVIEW OF RESEARCH ACTIVITY

During the period covered by this report, the capacitor discharge system was developed and tested, and was found to satisfy the above requirements. An analysis of this system, as well as of the radar and line type systems, was made and the results were presented in Technical Report No. 1 by Dr. J. L. Stewart, issued December 1955. A computer analysis of the capacitor discharge and line discharge systems was made and the results were reported in Technical Report No. 2 by Dr. Joseph Otterman, issued May 1956.

Copies of approximately fifty ignition system patents were obtained and reviewed to avoid duplication and to re-evaluate previous work. One of these described the use of a piezoelectric ceramic element to generate sparking voltage, and this was investigated. The results of the piezoelectric investigation are reported here in Section 12.

The use of a cold-cathode gas-filled switch tube in capacitor discharge ignition systems was conceived and tested. This was felt to be a patentable idea, and was disclosed to the Chrysler Corporation in January 1956. The development of a suitable switch tube was continued, and the results of this investigation are given in Section 6.

Other activities for the interval include the design and construction of a statistical analyzer for engine performance, performance tests on the CFR engine, pulse transformer design, voltage divider design, and design of transistor power supplies. These are discussed in later sections of the report.

4. BASIC PRINCIPLES AND PRACTICAL REALIZATION

4.1 The Two Stages of Ignition

The ignition of a fuel-air mixture by means of a spark is a two-stage operation. The first stage is the breakdown of the spark gap by the application of a sufficiently large voltage, V_g. The capacity to ground of the plug and its associated wiring and circuit may be lumped together as a total capacity C. In the standard ignition system this has a value of about 70 µµf. During stage one, the gap voltage is rapidly reduced from the sparking voltage, V_g, to the arc drop voltage. In this discharge, a current of about 100 amperes flows through the gap for about 10^{-7} seconds.[1] The energy delivered to the spark in this interval is $1/2\ CV_g^2$ joules.

---

[1] In the case of an ignition system using resistor plugs, the total capacitance C is separated into two portions, C_a and C_b. C_a is the plug electrode capacitance while C_b is the remaining portion of C on the other side of the plug series resistor, R_a. In this case the discharge in phase one consists of two parts. The first part is the rapid discharge of C_a giving a spark current of several hundred amperes with a duration of 10^{-8} sec. This is followed immediately by the discharge of C_b through R_a giving an exponentially decaying arc current having an initial value of approx. V_g/R_a (typically 1 amp) and a decay time constant R_aC_b (typically 1/2 microsec.). The total elapsed time for phase one in this case is about 10^{-6} sec. The energy delivered is $1/2\ C\ V_g^2$ joules less the resistance loss.

This is immediately followed by the second stage. In this stage, an arc is sustained at a relatively small arc drop for a much longer interval. The arc current is generally below the value found in stage one. In the standard ignition, the arc current is of the order of one ampere, and the duration is in the range 10^{-3} to 10^{-4} seconds. The energy delivered to the arc in stage two is determined largely by the external circuit.

The combined energy delivered to the spark gap in both stages of ignition should produce sufficient heat to initiate a satisfactory burning of the fuel mixture. If this energy is very small, the spark may fail to ignite the fuel and a misfire occurs. If the energy is somewhat larger, a small volume of the fuel mixture may be ignited. However, if this volume is below the critical volume, a flame front cannot be sustained, and a second type of misfire occurs.

A certain minimum energy must therefore be furnished by the ignition system for satisfactory ignition, and the shape and duration of the energy pulse is considered to have considerable effect upon the initiation of a self-propagating flame front.

4.2 One-Stage Systems

Under certain circumstances, enough energy is stored in the capacity, C, so that adequate heat for fuel ignition is obtained in stage one. This is the situation when a large gap (70 to 100 mils) is used, and the energy stored (i.e., $1/2\ CVg^2$) is large by virtue of the high voltage Vg required for breakdown. Further, a large gap allows a large interaction space with the fuel. The spark electrodes which act as heat-sinks absorb less heat, which reduces the input energy requirement. However, the voltage insulation requirements are high.

Another type of one-stage system might use a relatively small plug gap (10 to 15 mils) having a small breakdown voltage, Vg. By placing an additional capacitor across the gap, the energy stored ($1/2\ CVg^2$) could be raised above the minimum value in spite of the lower Vg. In this case the breakdown voltage is small, leading to reduced plug leakage loss and lower voltage insulation requirements. However, the heat-sink loss is increased by virtue of the shorter gap. Thus, more input energy is required for adequate ignition of the fuel, and the high spark current produces greatly increased erosion of the plug points, which makes severe demands on the plug design and reduces plug life.

The cylinder pressure at the time of ignition varies widely under different engine operating conditions. This gives rise to a wide variation in the value of the sparking voltage, Vg. In a one stage system, where the total energy for ignition depends so heavily on Vg, it is seen that either inadequate energy will be furnished at the low values of Vg, or excessive energy will be furnished at the high values of Vg, depending on system design. For this reason a one stage system is unsatisfactory for automotive ignition requirements.

4.3 Two Stage Systems

All practical ignition systems are of the two stage type. It appears highly desirable to be able to make independent adjustments of system parameters to satisfy the requirements of both stages of ignition. The standard ignition system can be adjusted to furnish adequate voltage for stage one, but one then obtains more than adequate spark duration in stage two. That is, the standard system does not readily lend itself to independent adjustment for the requirements of both stages of ignition.

This independence of adjustment was realized, however, in a special ignition system developed by the Plessey Company of Ilford, England under British Patent No. 608,324. This system uses a high-voltage, high frequency pulse from a Tesla transformer to ionize the gap in stage one, while a low-current, low-voltage arc discharge follows in phase two. An external spark gap is used to excite the high frequency oscillations in the Tesla transformer and the system is claimed to fire plugs with a fouling resistance as low as 1/4 megohm. The system uses inductive energy storage and a breaker point to break the battery current. Hence, it is subject to the same difficulties of breaker point wear as is the standard ignition system. This, plus the external spark gap, represent two of the disadvantages of this system.

4.4 High Current Systems

Considerable success has been shown with high arc current systems,[1] which are characterized by a short duration high current arc in phase two. In this case the transition from phase one to phase two is not as distinct as in other systems. In fact, the entire discharge has a duration of only 10^{-6} sec. or less. A small plug gap is used to reduce Vg, and some systems use a "surface gap" in which the spark is produced across a ceramic surface.

A capacitor is charged to a voltage in excess of Vg. When a spark is desired, this capacitor is switched directly across the plug. Thus, means must be furnished for switching in both charging and discharge operations.

Because of the large current in the sparking circuit, transformer coupling with switching in the low voltage primary circuit does not appear practical at present. It is therefore necessary to revert to switching in the high voltage side. This may be done by means of the distributor or an auxiliary high voltage switch.

The plug electrodes, because of the smaller gap,absorb more of the spark energy as heat sinks than in systems using standard plugs, so that the input energy to the plug must be larger. A more serious disadvantage is the rapid rate of erosion of plug gap and distributor gap resulting from the large spark currents.

4.5 The Ideal System

The ideal ignition system would give constant energy per spark, independent adjustment of the electrical requirements for stage one and stage two of the ignition process, and a close control over the shape and duration of the arc current in stage two. This ideal is closely approximated by a hard-tube pulser or radar type ignition system, which uses a high vacuum tube to control the primary current of the pulse transformer. The close control is obtained by generating a suitable low-power voltage pulse, and applying it to the gird of the tube. The radar ignition system is fully described and

---

[1] An example of the high arc current system is the Smitsvonk ignition system demonstrated before the SAE in Detroit in January 1951.

analyzed in Technical Report No. 1. The chief difficulties in reducing this system to a practical design are the cost and the undesirably long heating time of the vacuum tube.

Since experimental research was being conducted at the Chrysler Engineering Laboratories on radar type ignition, the activity of the University in this area was confined to theoretical analysis and consulting. No experimental work of any significance was conducted.

5. CAPACITOR DISCHARGE SYSTEMS

The realization of a practical two-stage ignition system using a capacitor discharge showed so much promise that the major effort was placed on this activity. Because the system did not lend itself to precise analysis (as did the radar system), the analysis of the CD system reported by Dr. Stewart in Technical Report No. 1 was supplemented by a computer study reported by Dr. Otterman in Technical Report No. 2. These two studies give a thorough analysis of system behavior and means for optimizing the circuit parameters.

To reduce the CD system to a practical working model for demonstration and engine tests, it was necessary to develop specific circuit elements which would satisfy the circuit and automotive requirements. A large amount of engineering effort was therefore devoted to the investigation and development of these components.

Of primary importance was the switching means for charging and discharging the capacitor. Suitable circuits were developed for this, and several types of switches were investigated. The results of this study are given in Section 6.

A transformer design best suited to the requirements of the CD system was developed based on the findings of Technical Report No. 1. The engineering design and construction of suitable transformers is discussed in Section 9.

A source of dc power is needed to operate the CD system. It appears desirable to furnish this power at about 300 volts. This voltage gives a satisfactory transformer design, and works well with several types of switches. Three means for obtaining this power are: (a) the vibrator power supply, (b) the motor-generator and (c) the transistor power converter. These are discussed in Section 10.

The engineering design of the CD system to date has been primarily concerned with the choice of parameters to satisfy stage one requirements; i.e., to optimize the electrical efficiency and satisfy the requirements for Vg, given a 70 mil gap plug having a 200,000 ohm leakage resistance and a total secondary circuit capacitance of 50 μμf. Parameter values for these conditions have been determined exactly. Some modification of these values may be desired, depending upon the particular properties of the switch used.

Further modification of the system parameters is possible, and may be desirable to approximate more closely the energy,arc duration and arc current required for stage two, particularly for improved fuel economy. When more information on these electrical requirements is obtained, an intelligent approach to these changes can be made.

6. CAPACITOR SWITCHING MEANS FOR CD SYSTEMS

6.1 Mechanical Contact Switching

The simplest and cheapest switching means for a CD system is by mechanical contacts. In the CD system, the contacts do not have to break a current, as they do in a standard ignition system.

Referring to Figure 6.1, assume no charge in C_1 and switch S open. When switch S closes on contact A, capacitor C_1 charges to approximately twice the power supply voltage V_{ps}. This occurs by virtue of the resonant charging inductance L_1 and hold-off diode D_1. This charging time is given by $\pi\sqrt{L_1 C_1}$ and can be made shorter than the minimum contact dwell so that no current is flowing when contact A opens. At the proper time, switch S closes on contact B, and the capacitor discharges rapidly. When contact B is opened, there is again no current in the contact. The peak primary current on discharge must be carried by contact B, and is generally on the order of 30 amperes. A breaker point assembly for this type of switching is shown in Figure 6.2, in which the contact arms are insulated from the frame.

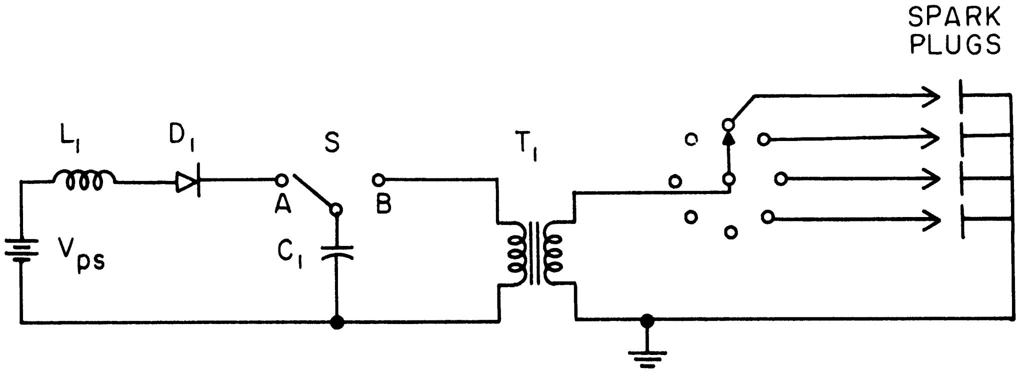


FIG. 6.1 SWITCHING IN CD SYSTEM

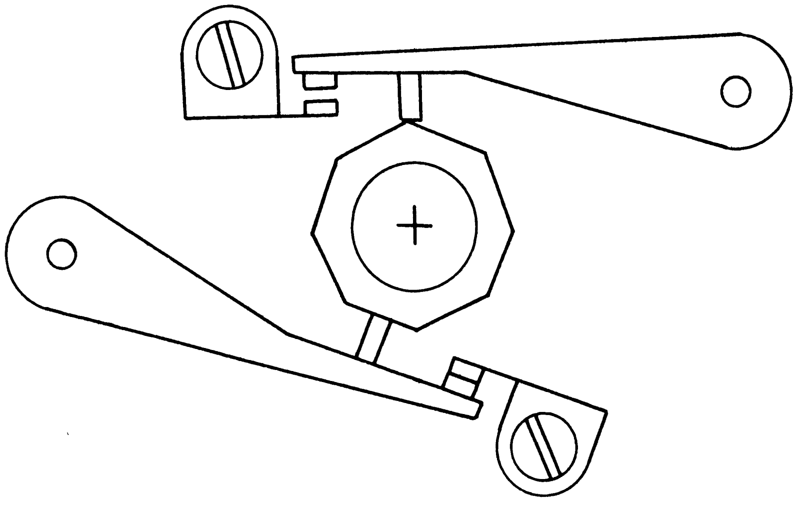


FIG. 6.2 BREAKER POINT ASSEMBLY FOR CD MECHANICAL CONTACT SYSTEM

The chief difficulty is the bounce on closure of contact B. If bounce occurs within the first 50 microseconds of closure, when the primary current in a typical CD system has a relatively large value, sparking and rapid erosion will take place.

Measurements made on different Mallory vibrator contacts indicated that the first bounce occurred anywhere from 20 to 200 microseconds. This indicates that the time to the first bounce is greatly affected by contact design, and thus it appears possible to increase the bounce time to a safe value with the proper design of contacts. The leaf type of contact used in the Model 1701 Mallory vibrator gave a time to the first bounce in excess of 100 microseconds, and in several tests showed freedom from bounce altogether.

Since a contact research program is now under way at the Chrysler Engineering Laboratories, it has been agreed that further research in mechanical contact switching for the CD system be continued there as a part of this program. This form of switching shows promise of yielding a dependable and economical solution.

6.2 Thyratron Switching

Figure 6.3 shows the basic circuit of a thyratron[1] CD ignition system. In this system, the resonant charging circuit is permanently connected to the capacitor C_1.

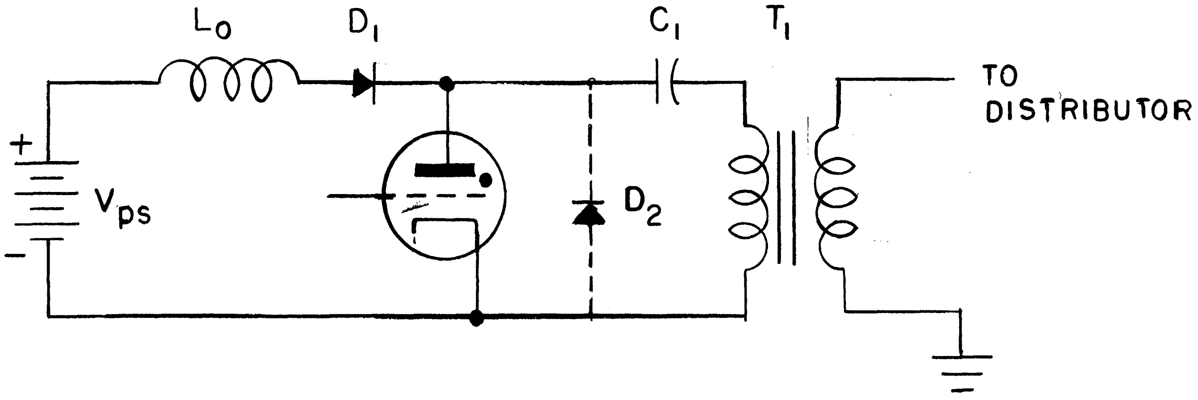


FIG. 6.3 THYRATRON CD SYSTEM

---

[1] This system was proposed in a recent article by H. W. Lawson, Jr., "Electronic Ignition System," Radio and Television News, p. 62, July 1955.

After the first operation, which removes the charge on the capacitor, the resonant charging system charges capacitor C_1 to approximately 2 V_{ps} with the polarity indicated.

The thyratron is fired by applying a positive grid pulse. This discharges the capacitor C_1 across the primary of T_1. A diode, D_2, permits the reverse flow of current in the capacitor and transformer primary so that some of the capacitor voltage is recovered, and the length of time of primary current flow is approximately doubled. To allow the thyratron time to deionize, the charging inductance L_o is chosen large enough for an adequately slow reapplication of voltage. However, L_o must be small enough to charge the capacitor to its value of $2V_{ps}$ in time for the next operation at the maximum operating speed

Two main difficulties are encountered with this system. Because of variation in deionization time, the thyratron occasionally goes into continuous conduction. This places a short circuit across the power supply, and may damage the tube. The second difficulty is the time required for warmup. The warmup time of a thyratron is determined in part by its peak current capability. Of the miniature gas types, the 2D21 and the newer 502A both have a peak pulse current rating of 10 amperes, and a minimum warmup time of 10 seconds. Longer warmup time is needed in cold weather.

A system was constructed using a 2D21 and the circuit shown in Fig. 6.3. The circuit would operate satisfactorily for short periods, and then appeared to go into continuous conduction.

Hydrogen thyratrons have much shorter deionization times, and it is possible that satisfactory operation would be obtainable with these. However, the additional cost of the hydrogen thyratron, and its finite warmup time remain as disadvantages.

The investigation of thyratron switching circuits has been discontinued.

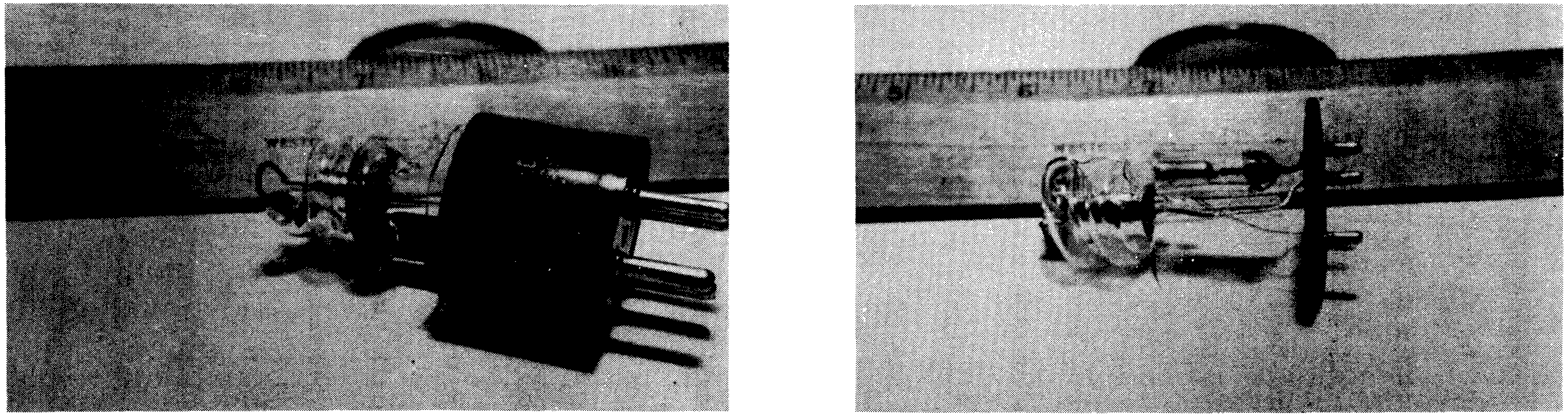
6.3 Cold-Cathode Gas Switches

6.3.1 Introduction. The disadvantages cited above for the mechanical switch and the thyratron tube instigated a search for other possible methods of discharging the storage capacitor. A practical switch must be able to initiate and sustain peak currents of the order of 50 to 100 amperes within a few microseconds after the start of current flow, must operate reliably at 400 switching cycles per second (corresponding to top engine speed of 6000 rpm), and have a lifetime of the order of 300 million switching cycles (equivalent to 25,000 miles).

It was known from other work that the electronic photoflash tube, a cold cathode gas tube used extensively for high speed photography, can sustain 50 to 100 amperes during conduction. The main difference in the photographic application is in the matter of energy dissipation, where it is desired to dissipate as much energy as possible in the flash tube. The converse of this is true for CD switching service.

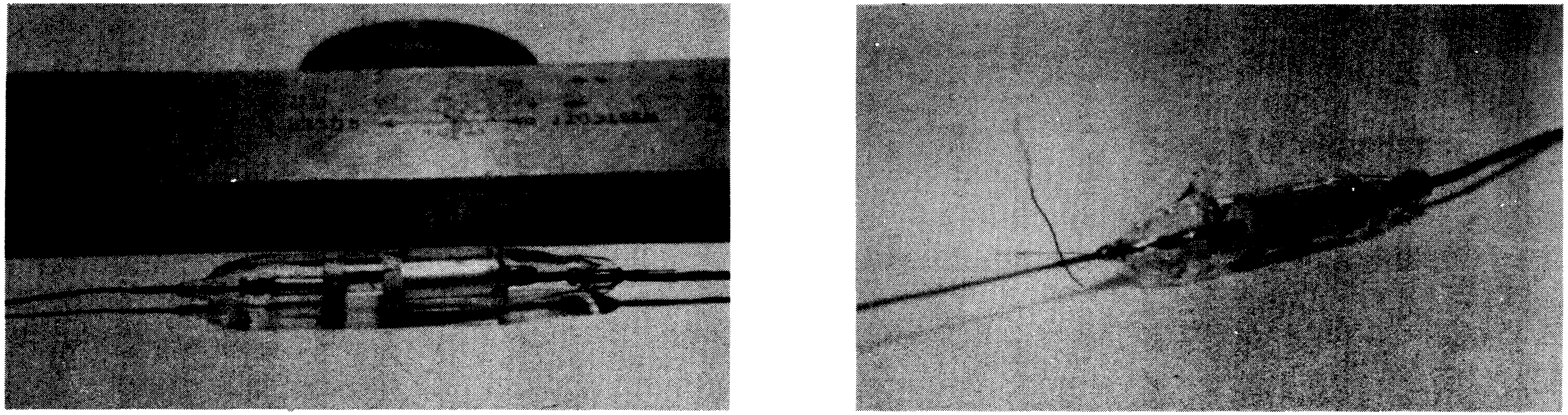
Initial experiments with the flash tube switch were conducted using standard photographic flash tubes illustrated in Figures 6.4a and 6.4b. These devices are Xeon-filled glass tubes with an anode at one end and a cold cathode at the other. The tubing is in the form of a helix to concentrate the light in a small area. A trigger electrode to initiate the discharge is applied to the outside of the tubing. As was anticipated, the long conduction path resulted in excessive tube voltage drop and long ionization time.

Discussions with the Amglo Corporation resulted in the fabrication of a series of special discharge tubes illustrated in Figures 6.4c and 6.4d. These tubes are the first models designed specifically for performance in CD switching service. Tests showed that the new Amglo tubes exhibit significant improvements in operation over photographic flash tubes. Operating data for both types of tubes are contained in Section 6.5 of this report. The life-test data shows the present tubes to have considerably less durability than that desired, but it is felt that with further modifications in tube design the life-time can be increased considerably.



(a) SPRAGUE FA-100

(b) SPRAGUE FA-104



(c) AMGLO X4SI
(SIDE VIEW)

(d) AMGLO X4SI
(LOOKING INTO CATHODE)

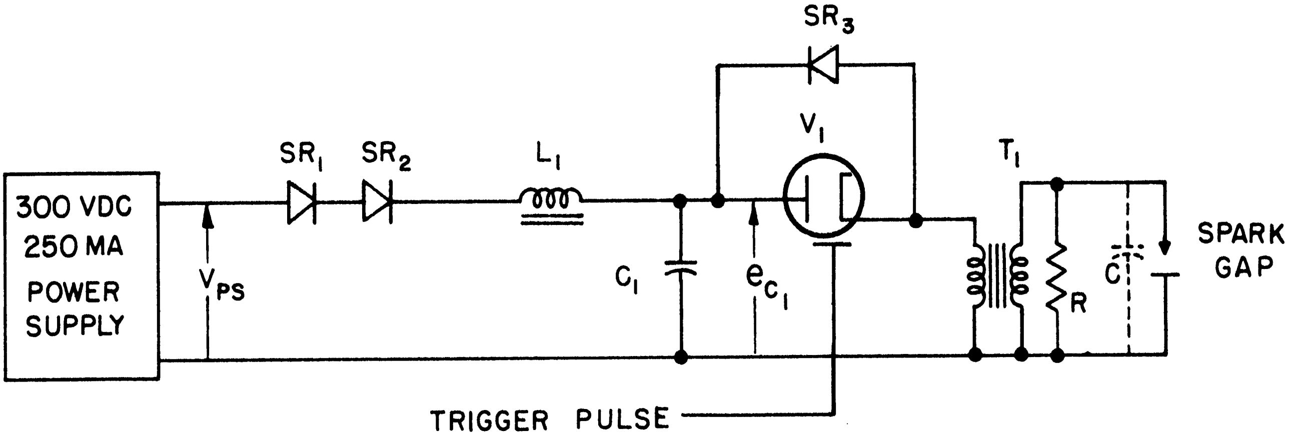
FIG. 6.4 PHYSICAL APPEARANCE OF THE FLASH TUBE SWITCHES

The triggered gap switch discussed in Section 6.4 is similar to the flash tube in its operation but different in physical construction and in the initiation of conduction. Before proceeding with the discussion of particular switch characteristics, it will be helpful to consider circuit and switch requirements discussed in the following two sections.

6.3.2 Circuit Operation. The circuit of a practical CD system is shown in Fig. 6.5. Capacitor C_1 receives a charge from the power supply during the charging cycle, and discharges through the switch tube V_1 and primary of T_1 during the discharge cycle. During the charge cycle, C_1 charges to approximately 2 V_{ps} and remains at that point. Diodes SR_1 and SR_2 prevent the reverse flow of current. The capacitor voltage varies during charging as indicated in Fig. 6.6. It is seen that after a certain interval, the switch is subjected to a voltage in excess of the steady-state switch drop. This interval is the maximum time available for deionization as determined by the circuit. The deionization time of the switch must be less than this interval to avoid false firing, or continuous conduction.

The charging cycle must be completed in slightly less than 2.5 milliseconds, so that at the maximum operating rate of 400 sparks per second, C_1 will recharge completely between operations. The charging time (as noted in Section 6.1)is $\pi\sqrt{L_1C_1}$, and this determines the value of L_1.

The discharge cycle is initiated by the application of a trigger pulse to the switch tube V_1. The switch becomes ionized and discharges C_1 through the primary of T_1. The capacitor voltage and current on discharge are indicated in Fig. 6.7. The frequency of oscillation is determined approximately by the capacitor C_1 and the primary leakage inductance L of the transformer. At some point in the discharge, usually during the first quarter cycle of primary current, the spark plug fires, accompanied by an increase in the rate of rise of primary current, as indicated. The discharge current may consist of two or three half cycles, leaving a small voltage on the capacitor. Should the switch tube V_1 pass current in one direction only, it is desirable to connect the diode SR_3 across it, to carry the reverse current pulse.



C	TOTAL CAPACITANCE ON THE HIGH VOLTAGE SIDE OF THE SYSTEM
C_1	1 μf 600 VDC PAPER CONDENSER
L_1	0.45 HENRY 250 MA INDUCTANCE
R	PLUG LEAKAGE RESISTANCE
V_1	COLD CATHODE GAS SWITCH
SR_1, SR_2	IN152 SILICON DIODE
SR_3	30 AMPERE PEAK SILICON DIODE WITH A PEAK INVERSE VOLTAGE RATING OF 800 VOLTS
T_1	U OF M HIGH VOLTAGE PULSE TRANSFORMER NO. 12

L_M	2000 μH
L	6 μH
C_{SEC}	28 $\mu\mu$fd
N_{PRI}	20 TURNS
N_{SEC}	2750 TURNS
INSULATION	MYLAR 3.0 MILS

FIGURE 6.5 PRACTICAL CAPACITOR DISCHARGE SYSTEM FOR USE WITH A COLD CATHODE GAS SWITCH

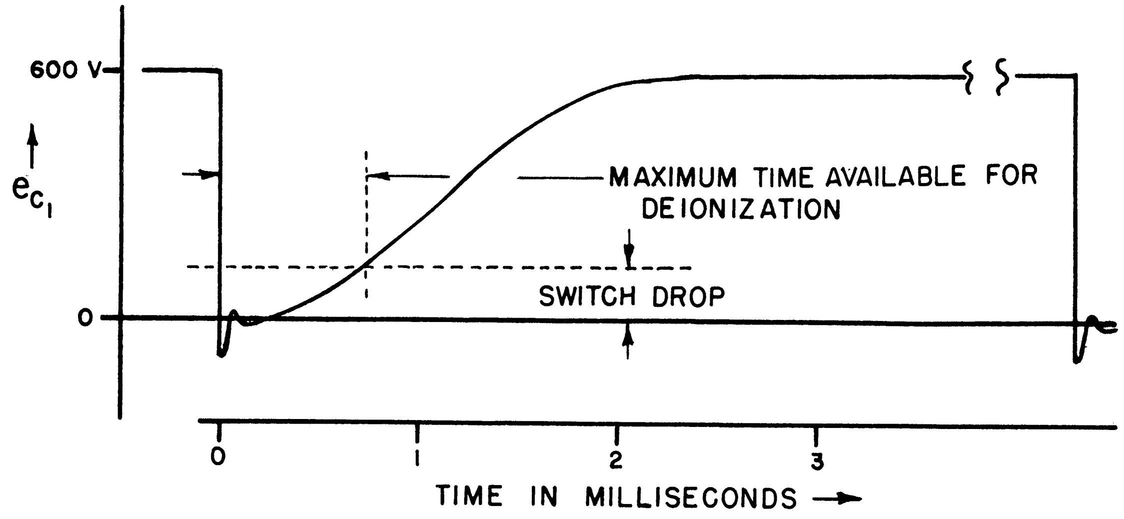


FIGURE 6.6 INSTANTANEOUS VOLTAGE ON CAPACITOR C_1

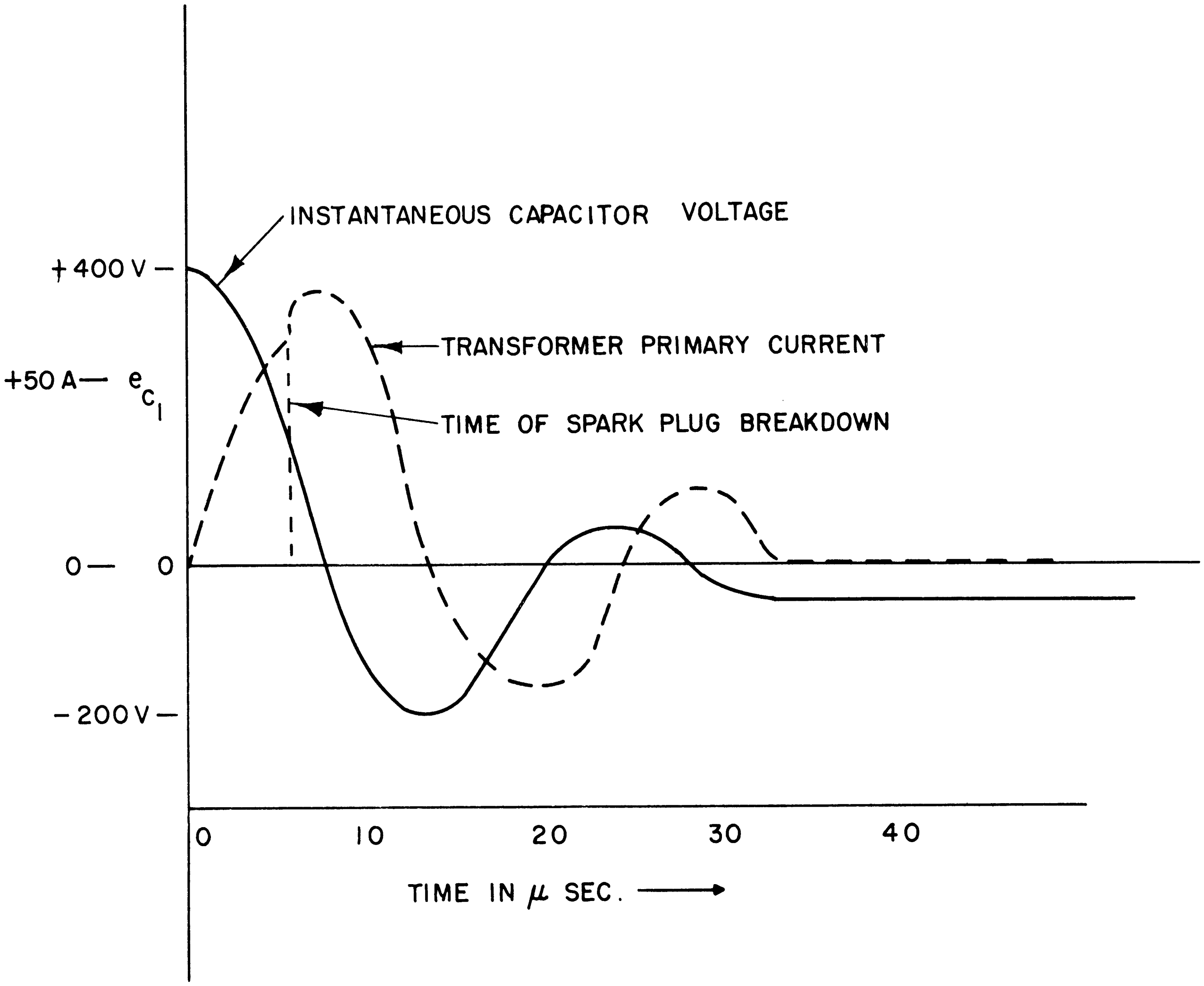


FIG. 6 .7 INSTANTANEOUS CAPACITOR VOLTAGE AND TRANSFORMER CURRENT IN THE DISCHARGE PERIOD.

6.3.3 Circuit Determined Switch Requirements. The following symbols[1] are used to denote the various switch parameters;

T_d - Deionization Time
T_i - Ionization Time
e_s - Instantaneous Switch Voltage Drop
E_s - Steady-State Switch Voltage Drop
w_L - Switch Energy Loss per Operation
i_s - Instantaneous Switch Current
I_{sp} - Peak Switch Current
E_{HO} - Hold-Off Voltage
E_T - Trigger Voltage required for 100% triggering

The circuit determined switch requirements are as follows:

1. Deionization Time, T_d

As seen from Fig. 6.6 and from the previous discussion, T_d must be less than the time available for deionization which is determined by the charging circuit.

2. Ionization Time, T_i

The ionization time, T_i, should be short relative to the frequency of oscillation of C_1 and the primary leakage inductance, L. If t_m represents the time for the secondary voltage to reach its first maximum, then a desirable criterion for T_i is that it be equal to or less than $1/5\ t_m$. This reduces that portion of the switch energy loss, w_L, which occurs during ionization, to a reasonable value.

3. Steady-State Switch Drop, E_s

The steady state switch voltage should be small compared to V_o to reduce to a reasonable value that portion of the energy loss occurring after ionization. A desirable criterion is $E_s = 1/10$ to $1/5\ V_o$. $(V_o \cong 2\ V_{ps})$

4. Energy Loss, w_L

This should be kept to a low value since it is wasted energy, and must be furnished by the power supply. Means for removing this energy as heat at the maximum operating rate must also be furnished to prevent excessive tube temperature, and reduced

---

[1] These symbols are defined fully in Appendix A.

tube life. As noted above, w_L is a function of E_s and the switch current, i_s. In a practical gas tube switch, it is difficult to reduce E_s below about 60 volts. Efficiency may therefore be increased by designing the system around a higher V_{ps}, and lower i_s.

5. Peak Current, I_{sp}

This is determined by the circuit parameters, the tube drop, E_s, and the time of firing of the spark plug. In the circuit of Fig. 6.5 with V_{ps} = 300 volts, and the spark plug firing at 4 µsec., I_{sp} = 144 amps[1], for $E_s = 0$. If E_s is assumed constan at 60 volts, I_{sp} = 130 amps.

6. Hold-Off Voltage, E_{HO}

Because the full capacitor voltage is applied to the switch when not conducting, E_{HO} must be greater than 2 V_{ps}. An additional safety factor must be introduced to account for power supply voltage variations and the normal decrease in E_{HO} with age. A satisfactory criterion is $E_{HO} = 6\ V_{ps}$, giving a safety factor of 3. For V_{ps} = 300 volts, E_{HO} should be 1800 volts or more.

7. Trigger Voltage, E_T

A low trigger voltage, such as 2 to 3 kilovolts, is desirable, but the actual value is not of great importance since the trigger energy is small. However, the trigger voltage should be made as independent as possible of the switch life. This will reduce the excess trigger voltage above E_T that is necessary to insure 100% triggering throughout the life of the switch.

8. Life

For automotive use, the switch life should be 3×10^8 operations at a maximum rate of 400 pulses per second. This represents a car mileage of approximately 25,000 miles.

6.4 Triggered Gap Switch

The triggered gap switch is a three electrode, cold-cathode, gaseous conduction device. Two electrodes of similar size and shape are used for the cathode

---

[1] This was measured using a mercury relay in place of the switch tube.

and anode. The third electrode surrounds the cathode and anode and is termed the trigger electrode. The main gap is triggered by a spark simultaneously produced between the trigger electrode and both the cathode and anode. With this type of triggering it is possible to design a switch that will operate with a low V_o (300 to 1000 V) using cathode materials that erode slowly.

6.4.1 Physical Structure. Two experimental triggered gaps have been built. The first model was made of brass and no air tight enclosure was provided. Photographs of model 1 are shown in Figure 6.8. The dimensions of the electrode structure are shown in Fig. 6.9.

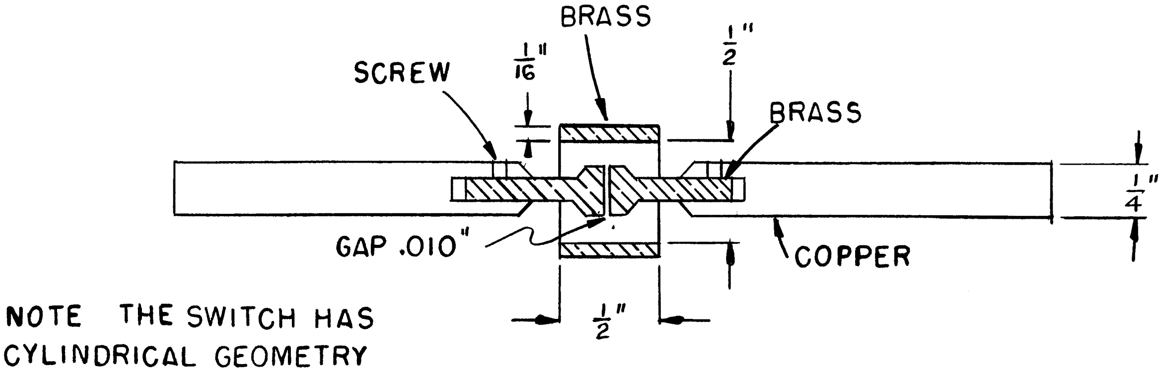
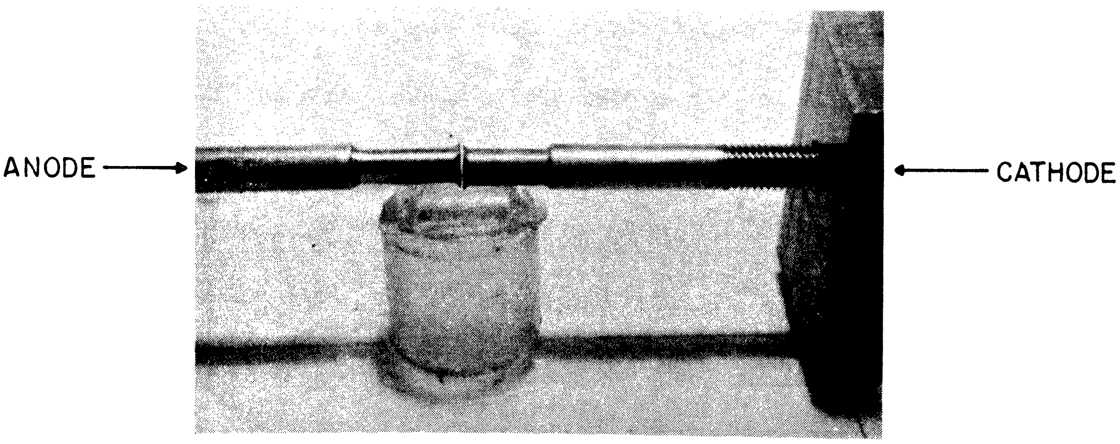


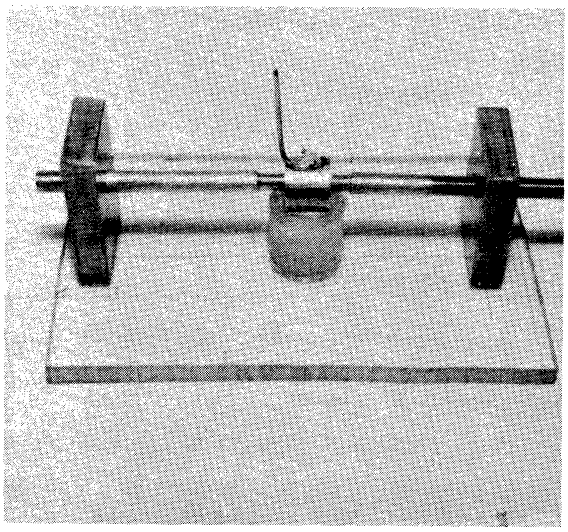
FIG. 6.9 TRIGGERED GAP SWITCH, MODEL 1

Model 2 was constructed inside a plexiglas box, and is shown in Fig. 6.10. Two stopcocks were provided to allow control of the gas and gas pressure. The electrodes were machined from molybdenum, which has a high resistance to erosion and fair machinability. The shape of the cathode and anode electrodes are similar to model 1. The configuration of the trigger electrode was changed to a molybdenum disc with a hole in the center. This disc was mounted concentric with the axis of the cathode and anode and located in a plane passing through the gap as shown in Fig. 6.11.

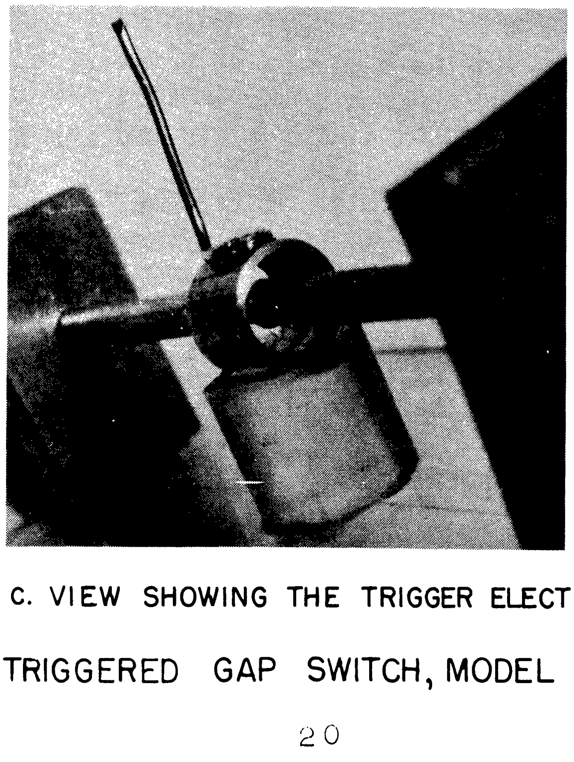
A gap spacing of 0.01 inches between the cathode and anode was experimentally found to provide reliable triggering with a gas pressure of 1 atmosphere. Under these conditions the hold-off voltage, E_{HO}, is 2600 volts. Figure 6.12 shows a plot of the



a. SWITCH WITH THE TRIGGER ELECTRODE REMOVED

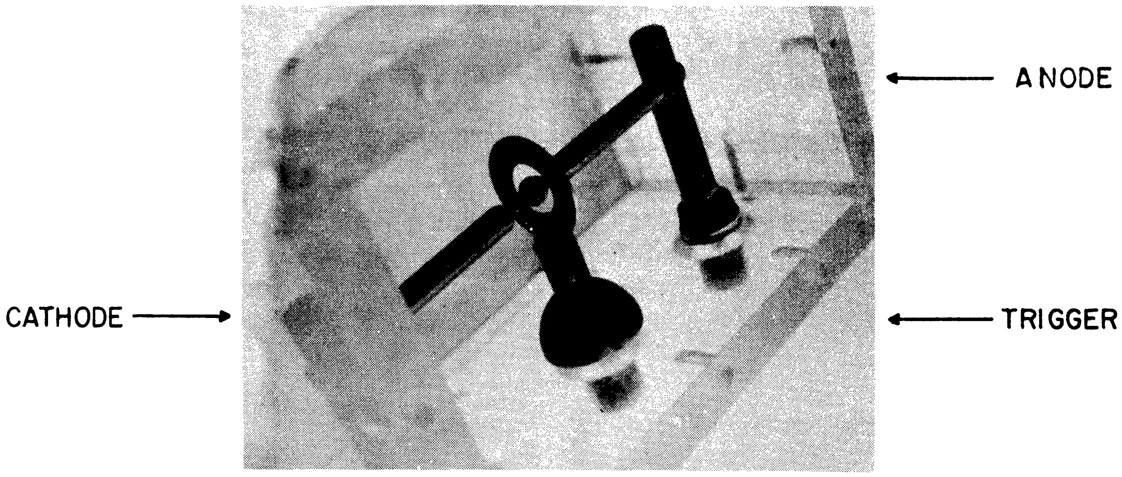


b. OVERALL VIEW OF THE SWITCH

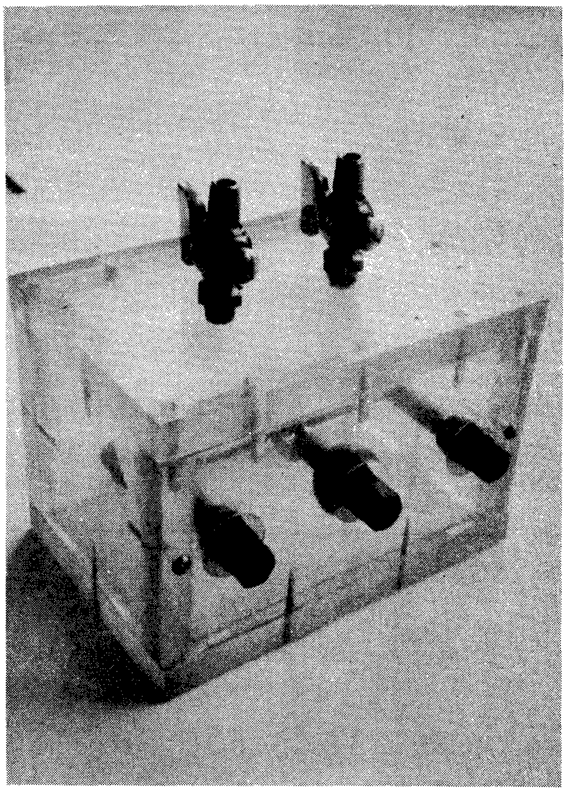


c. VIEW SHOWING THE TRIGGER ELECTRODE

FIGURE 6.8 TRIGGERED GAP SWITCH, MODEL 1



a. ELECTRODE STRUCTURE



b. SWITCH ASSEMBLED IN AIR TIGHT ENCLOSURE

FIGURE 6.10 TRIGGERED GAP SWITCH, MODEL 2

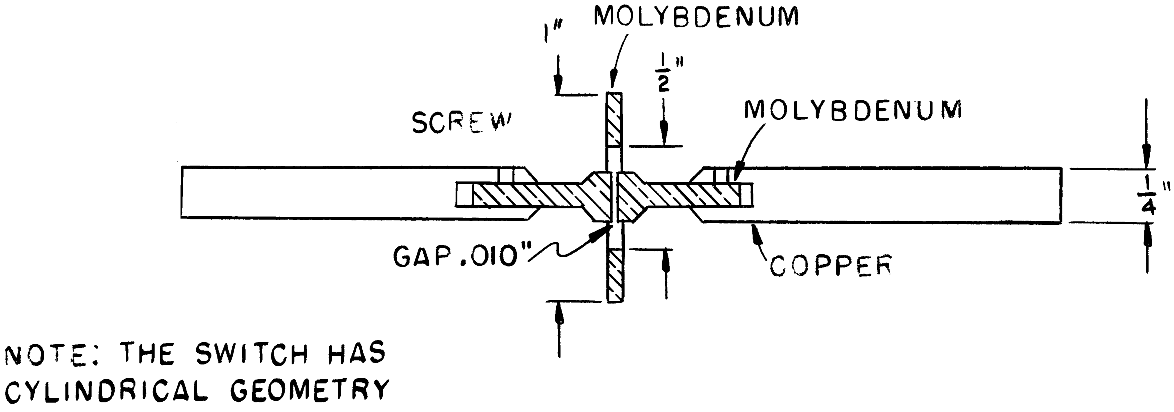


FIG. 6.11 TRIGGERED GAP SWITCH, MODEL 2

trigger voltage requirements for trigger electrodes with 3/8" and 1/2" holes.

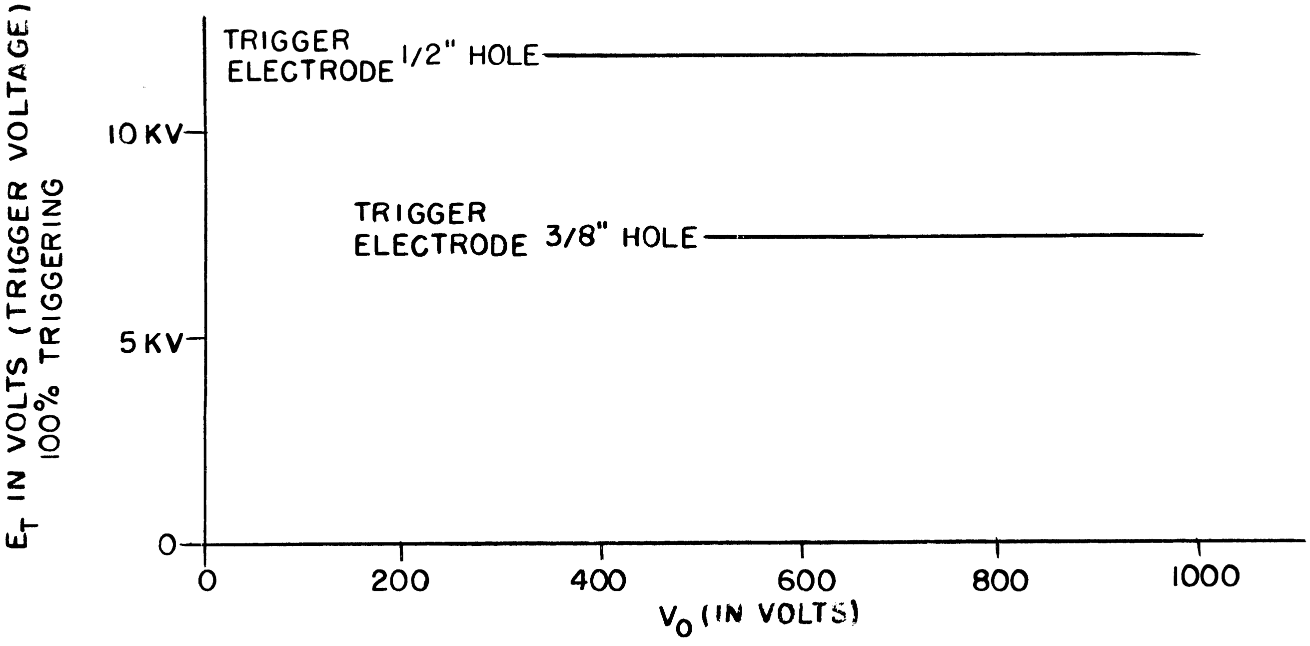


FIG. 6.12 TRIGGER CHARACTERISTICS FOR TRIGGERED GAP SWITCH, MODEL 2.

The triggered gap, cold-cathode, gas switch appears to hold considerable promise for automotive service, and further research is suggested to achieve the best electrode geometry, electrode material, type of gas and gas pressure for maximum switch life and greatest reliability.

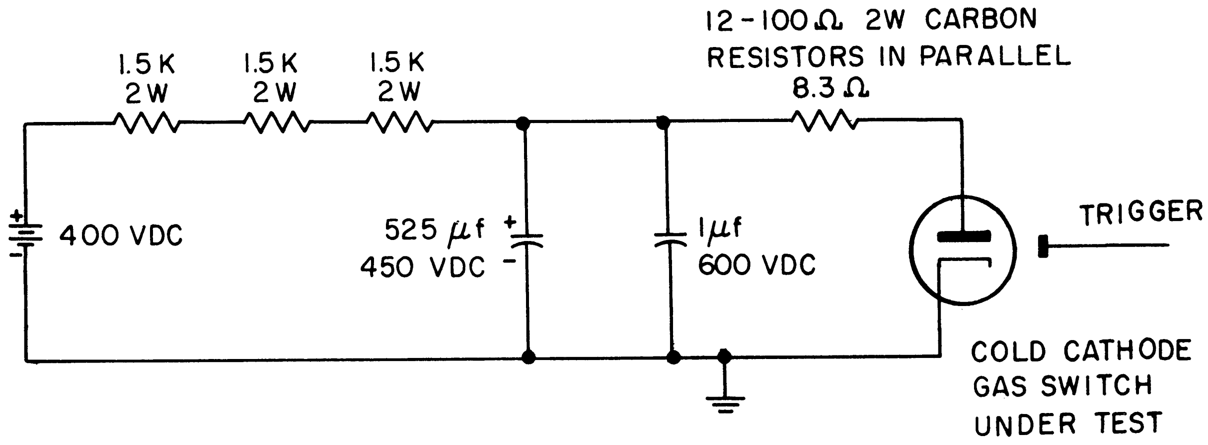
6.5 Characteristics of Cold Cathode Gas Switches

A number of cold-cathode gas switches have been tested. The results are shown in Appendix B. The switch voltage drop and ionization time were measured with the circuit in Fig. 6.13 and the data were photographed on 35 mm Linagraph film. To measure the switch voltage drop and ionization time, the oscilloscope is calibrated for voltage on the vertical axis and for time on the horizontal axis. The switch is triggered once to give a single shot exposure. Figure 6.14 is a typical photograph, indicating an ionization time of approximately 15 microseconds, and a switch drop of approximately 190 volts.

Data on deionization time have not been obtained. Observations indicate, however, that the deionization time for all of the Amglo tubes is on the order of 50% too long for operation at maximum speeds of 6000 rpm. The Sprague Flash Tubes and triggered-gap tubes appeared to have a sufficiently short deionization time for use at 6000 rpm.

The trigger voltage characteristics are shown in Figures 6.15, 6.16, and 6.17. These curves are plots of the minimum trigger voltage, E_T, as a function of the initial voltage, V_o, for 100% triggering of the switch. The data for these curves were obtained using the circuit of Figure 6.18. To measure the trigger voltage, E_T, as a function of the initial capacitor voltage, V_o, is set at a specified value, and E_T is then increased until the switch triggers 100%. As V_o is reduced, a point will be reached at which the maximum trigger voltage will not produce 100% triggering. At the other extreme, a point is reached where the switch will go into continuous conduction or relaxation oscillation. These end points thus define the usable range of V_o for the particular switch.

Life tests were run on two switches. Figure 6.17 shows a typical change in switch characteristic with age. The life tests were run using the circuit shown in Fig. 6.5. The spark gap required approximately 20,000 volts for breakdown. The switch was triggered 50 times per second. No shunt load was used across the spark gap. The life in both cases was approximately 3 x 10^6 operations of the switch, which is equivalent to about 400 miles of automobile driving. Since the FA-100 was not designed for this type of service, and the X-3S2 is only a first attempt toward improved design,



NOTE: AN OSCILLOSCOPE IS CONNECTED
ACROSS THE SWITCH AND IS TRIGGERED
BY THE TRIGGER VOLTAGE.

FIG. 6.13 THE CIRCUIT FOR MEASURING SWITCH VOLTAGE DROP AND IONIZATION TIME.

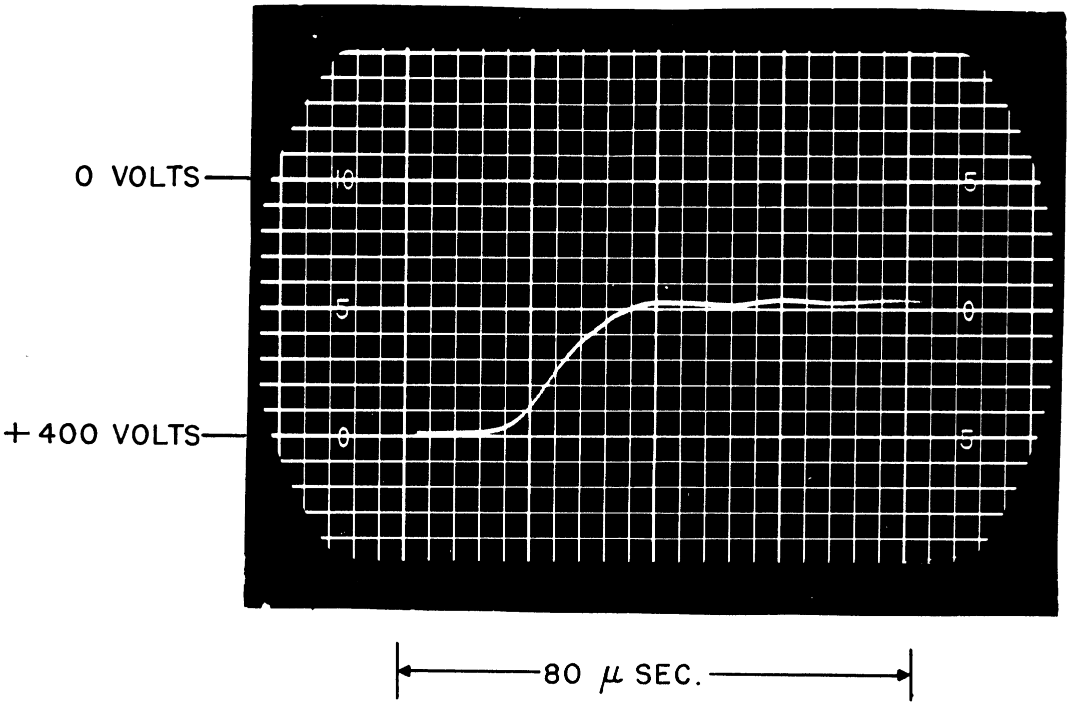


FIG. 6.14 SINGLE SHOT PHOTOGRAPH OF THE SWITCH VOLTAGE DROP FOR A SPRAGUE FA-100.

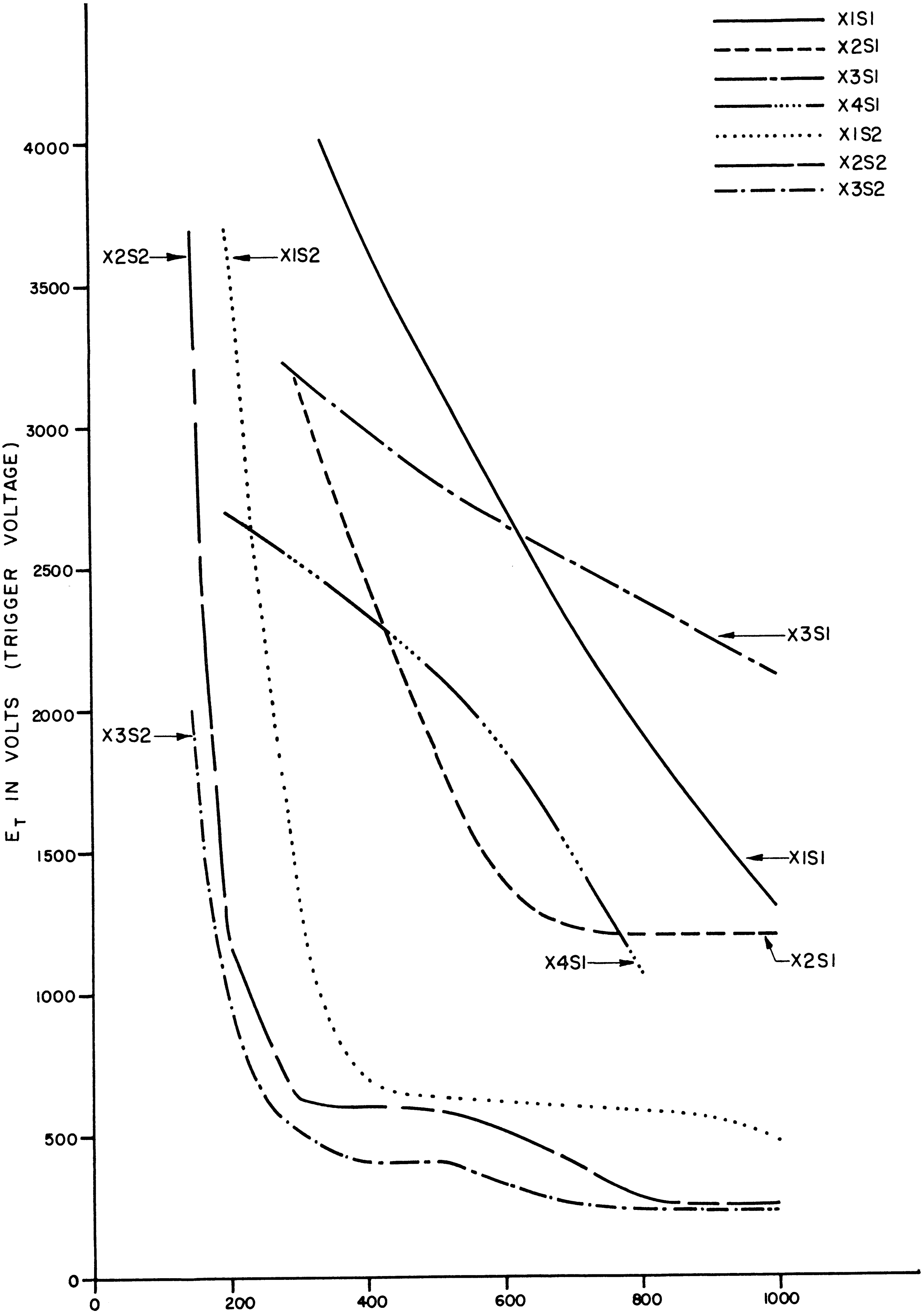


FIG. 6.15 TRIGGER VOLTAGE CHARACTERISTICS OF NEW SWITCHES

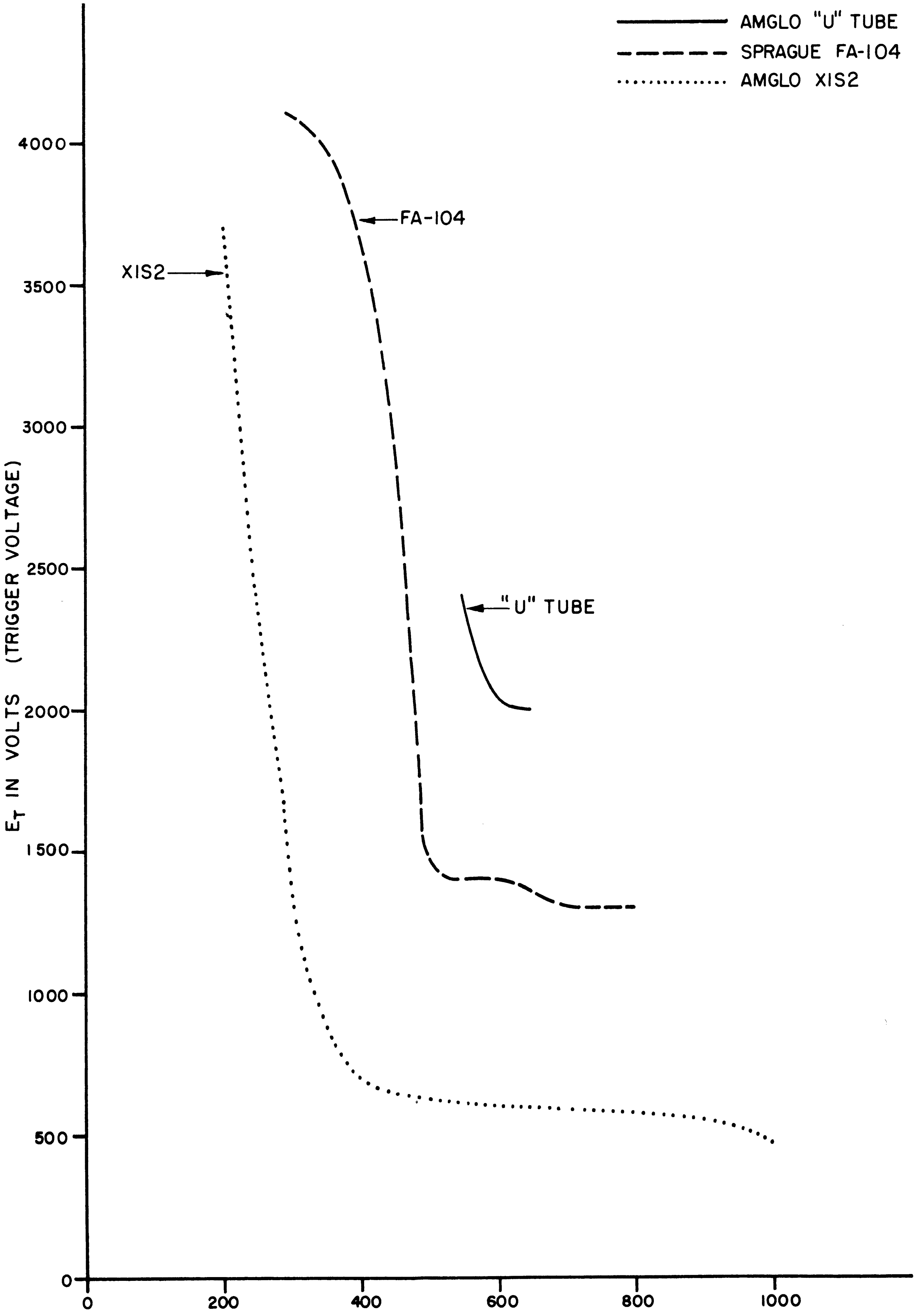


FIG. 6.16 TRIGGER VOLTAGE CHARACTERISTICS OF NEW SWITCHES

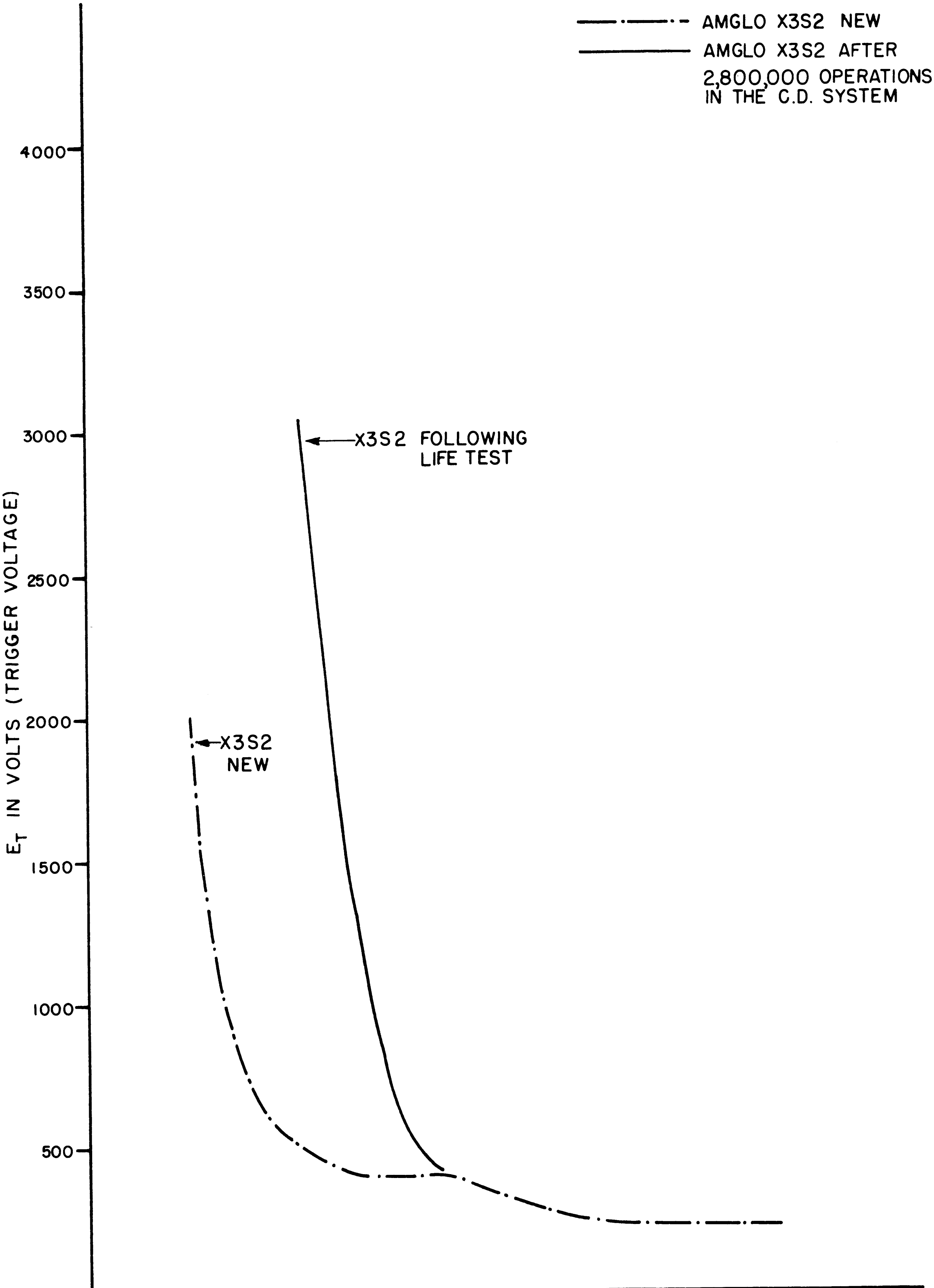


FIG. 6.17 COMPARISON OF GAS SWITCH TRIGGER CHARACTERISTICS

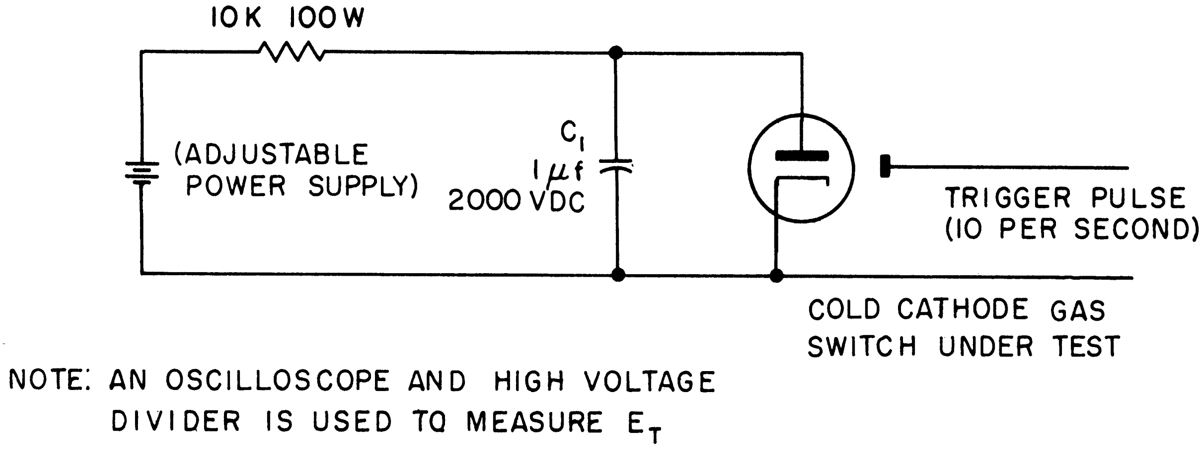


FIG. 6.18 THE CIRCUIT FOR MEASURING THE COLD CATHODE GAS SWITCH TRIGGER VOLTAGE, E_T.

further improvements may be expected. The triggering characteristics of X3S2 (as shown in Fig. 6.17) indicates a shift to the right of the trigger curve with age. This is probably due to loss of some of the rare earth metals from the cathode and anode.

The investigation to date indicates some progress in the development of a suitable gas switch of the flash tube types, and has shown the limitations of present tube designs. It is believed that considerable progress in this development can be made, and that a satisfactory gas tube switch for automotive use appears to be possible.

7. STATISTICAL ANALYZER FOR ENGINE PERFORMANCE

7.1 Introduction

A statistical analyzer was constructed to study engine performance with different types of ignition systems. Its primary purpose is to count the number of engine misfires, and to attempt to determine the type of misfire.

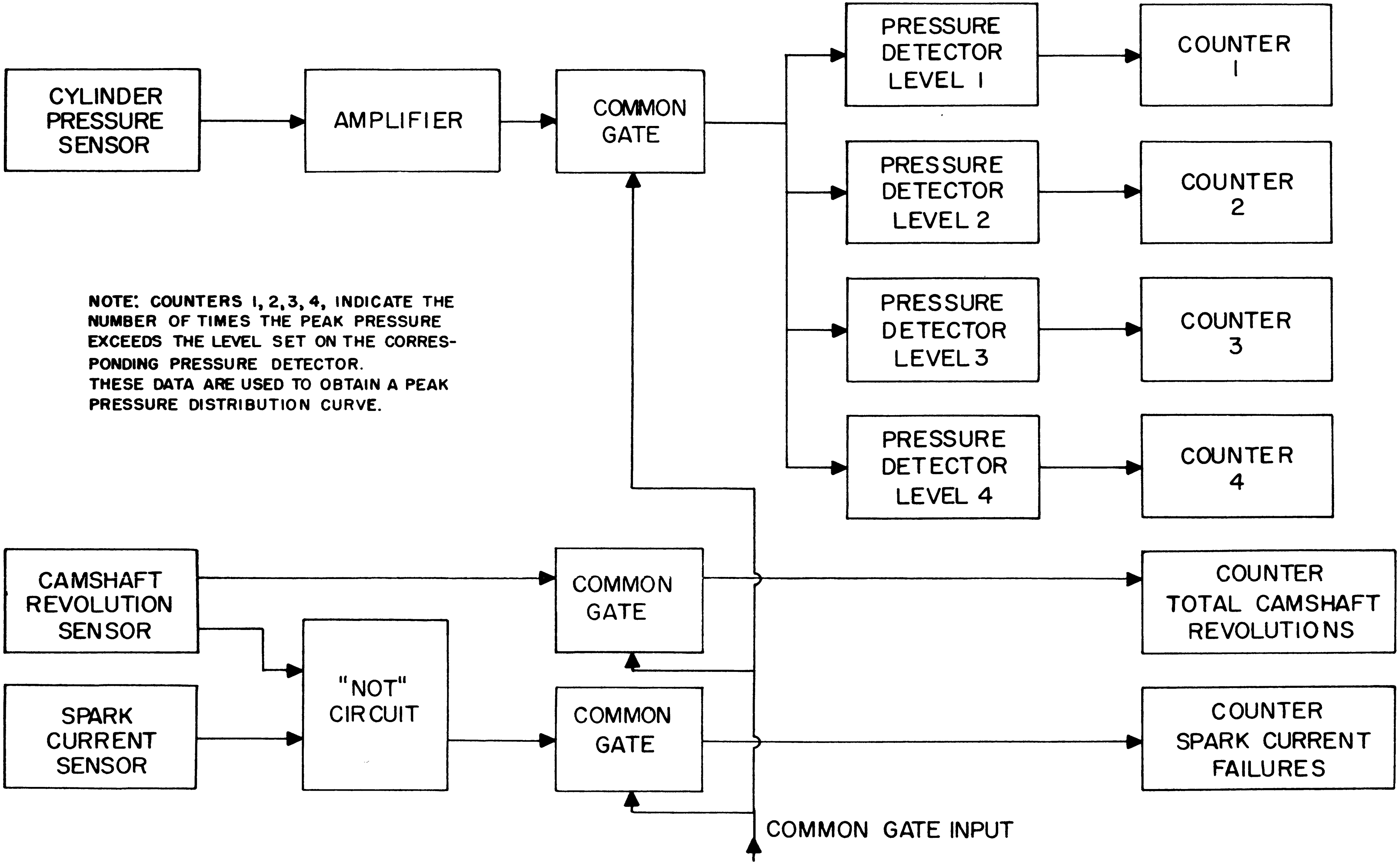
The analyzer determines, for a given interval, the total number of camshaft revolutions, the number of spark failures in the plug, and the number of times the peak cylinder pressure exceeds each of four specified pressure levels.

7.2 Circuit

Figure 7.1 shows a block diagram of the statistical analyzer. The circuit has three input signals. These indicate the occurrence of a spark, the revolution of the camshaft, and the instantaneous cylinder pressure.

All of the output data are collected on electrically operated counters. In order to make the data on these counters represent information that was collected during a common time interval, it is necessary to turn all of the information channels on and off simultaneously. This simultaneous switching is performed by the common gate circuit controlled by a toggle switch or push button.

FIG. 7.1 BLOCK DIAGRAM OF STATISTICAL ANALYZER FOR ENGINE PERFORMANCE



NOTE: COUNTERS 1, 2, 3, 4, INDICATE THE NUMBER OF TIMES THE PEAK PRESSURE EXCEEDS THE LEVEL SET ON THE CORRESPONDING PRESSURE DETECTOR. THESE DATA ARE USED TO OBTAIN A PEAK PRESSURE DISTRIBUTION CURVE.

In the following discussion, the common gate circuit is assumed to be on. The total number of camshaft revolutions is counted by applying the impulses from the camshaft revolution sensor to an amplifier whose output operates the camshaft revolution counter.

To count the number of spark plug spark failures, a more complicated circuit is needed. Information is available to indicate when the spark plug fires, and to indicate when the crankshaft makes a revolution. These two information channels can be combined in a "not" circuit to indicate when the spark plug fails to fire. The "not" (or anti-coincidence) circuit is a logical circuit that produces an output when either of its two inputs fail to coincide with the other. Thus the "not" circuit will provide an impulse whenever the spark plug was supposed to fire but actually failed to fire. This impulse is then coupled to the spark plug failure counter.

The measurement of the peak pressure distribution requires more than just a "present or not present" detector. In order to measure the number of pressure peaks that occur between various pressure levels, it is necessary to have circuits that do not produce an output for an input signal below a certain critical level but do generate an output pulse for any input signal above this critical "trigger" level. Several of these trigger circuits are therefore set up to operate at different levels. Therefore, the number of peak pressures occurring between the trigger levels can be obtained. This type of voltage-sensitive trigger circuit is known as a Schmidt Trigger Circuit.

The cylinder pressure sensor in Fig. 7.1 is a strain gage pressure pickup which senses the instantaneous pressure in the engine cylinder. The output of the strain gage bridge is amplified, and this amplified output is applied to the inputs of four Schmidt Trigger circuits. The trigger level of each Schmidt circuit can be adjusted anywher between 25% and 100% of normal peak cylinder pressure. Since four counters are used, any set of four distribution levels can be selected in this range. The output of each Schmidt circuit is counted by a separate counter. By taking the difference between the counter readings, the number of cylinder pressure peaks that occur at various levels can be determined.

7.3 Results and Recommendations

A model of the statistical analyzer was constructed and set up on the CFR test engine. The equipment was tested out in part, but difficulty was encountered in operating the CFR engine under marginal operating conditions; therefore, the pressure distribution equipment could not be evaluated on this particular engine. The reason for the difficulty here is that it is a single cylinder engine and as soon as the engine fails to fire once, it fails completely. If the engine were driven by a synchronous dynamometer this difficulty could be eliminated.

For ignition performance tests, the following setup is recommended. A statistical analyzer should be used in conjunction with a single cylinder engine with a synchronous motor drive. Instead of using peak pressure as the analyzer input, a more suitable quantity would be the output torque integrated over one camshaft revolution. This integrated output would be applied to the Schmidt circuits. Every time the camshaft makes one revolution the integrator would be reset. Integrated torque is a better measure of output power than peak cylinder pressure and, therefore, is more indicative of ignition performance on fuel economy.

8. PERFORMANCE TESTS ON CFR ENGINE

Engine performance tests were run on a CFR engine to compare the operation of the standard 12 volt Auto-Lite ignition system with the experimental capacitor discharge system. The objective of these tests was to cover a wide range of compression ratios, fuel-air ratios, and spark plug gaps. In this manner any trends in ignition performance could readily be identified. The tests on the standard ignition system have been completed. The tests on the capacitor discharge system are just getting under way.

The CFR engine has advantages and disadvantages for ignition performance tests. Some of the advantages are as follows: The CFR engine is a single cylinder fuel research engine. The compression ratio is adjustable from 4:1 to 10:1. The fuel-air ratio is adjustable from a point on the lean side of the ideal value to a point on the rich side. Several holes are available on the cylinder head for insertion of spark plugs or pressure pickups. Some of the disadvantages are as follows: The engine operates poorly under partial throttle. With a standard nonsynchronous dynamometer at full load the engine fails to operate after one misfire. This is of course not true under light load at high speeds. The combustion chamber is not representative of modern engines.

8.1 Ignition Performance Criterion

Evaluation of ignition performance requires some criteria that are representative of the conditions met in automotive service. Three factors can be considered important in selecting the criteria. These are: (1) the primary supply voltage, (2) the engine power output, and (3) the shunt load resistance across the spark plug.

Any automobile ignition system will probably be dependent upon the primary voltage supply of the car for its power. Therefore, the evaluation of an ignition system should be based upon the influence of a change in the primary supply voltage on its operation. For example, if the input voltage to ignition system A is reduced to a point where the engine just begins to misfire, and the input voltage is then increased by some factor (e.g., 1.2) then the performance of the ignition system is tested at this point. A resistive load may then be placed across the spark plug and the resistance reduced until misfiring begins. This same procedure would be repeated with ignition system B, and a comparison made between the load resistances in each case. The ignition system with the ability to operate with the lowest resistance would be superior in firing fouled plugs. This illustration demonstrates the manner in which the primary supply voltage can enter into setting up performance criteria.

The minimum shunt resistance that can be placed across the high voltage side of the ignition being evaluated is a second important factor in setting up performance criteria because spark plug fouling is one of the major causes of ignition system failure. A third important factor in ignition system performance is fuel economy, or engine power output under given conditions.

In combining these three factors to evaluate ignition performance, the primary supply voltage should be used as the independent variable. The minimum shunt resistance and fuel economy are then each determined in terms of the primary supply voltage. The best ignition system will then show superior performance in terms of resistance loading and fuel economy. This improved performance should exist for all engine operating conditions.

8.2 Test Procedure

The development of a new ignition system that is better than the present standard ignition in all respects is a tremendous job. In order to study the operation of an ignition system on an engine and determine the present requirements, a large number of factors must be varied in an attempt to obtain data that will show important trends. With this objective in mind, the following test procedure was followed. All tests were run at 900 rpm and full throttle. The only exception was that 600 rpm was used to evaluate the starting of the engine. The primary supply voltage was used as the independent variable. For each different primary supply voltage condition, a subscript number was provided to identify the condition. The subscripts and conditions are as follows:

(1) Denotes the primary supply voltage condition that will just initiate spark plug breakdown. This does not mean that ignition will occur, nor does it mean that primary supply voltage is constant. Actually, the primary supply voltage condition must be defined by a curve.

(2) Denotes the primary supply voltage condition at which the engine will start when cranked at 600 rpm without choking when the engine is at normal operating temperature.

(3) Denotes the primary supply voltage condition that will just sustain engine operation at 900 rpm with full throttle and as high a load resistance across the spark plug as is practically realizable.

(4) Denotes the primary supply voltage condition that has a primary supply voltage 1.2 times greater than the corresponding voltage under condition 3.

(5) Denotes the primary supply voltage condition that has a primary supply voltage 2.0 times greater than the corresponding voltage under condition 3.

(6) Denotes the primary supply voltage condition that has a constant primary supply voltage equal to the nominal primary supply voltage found in automotive service.

The engine tests were run on the CFR engine with standard gasoline (about 80 octane) except when measurements were made at a 10:1 compression ratio, which necessitated the use of 100 octane gas. Tests were run with the following compression ratios: 4:1, 6:1, 8:1, and 10:1. Fuel to air ratios of 0.375 K_1, 0.425 K_1, 0.475 K_1, 0.565 K_1, and 0.625 K_1 were used. K_1 is a calibration constant and has not been evaluated so far.

The CFR engine requires 1 hr operation at 900 rpm for measurements to stabilize. Other symbols that require definition are as follows: θ is the distributor advance setting, T is the load reading on the dynamometer scale, HP is equal to $T \cdot RPM/5000$, V is the primary supply voltage, C.R. is compression ratio, R is the shunt resistance across the output terminals of the high voltage transformer, and d is the gap spacing of the spark plug electrodes in mils.

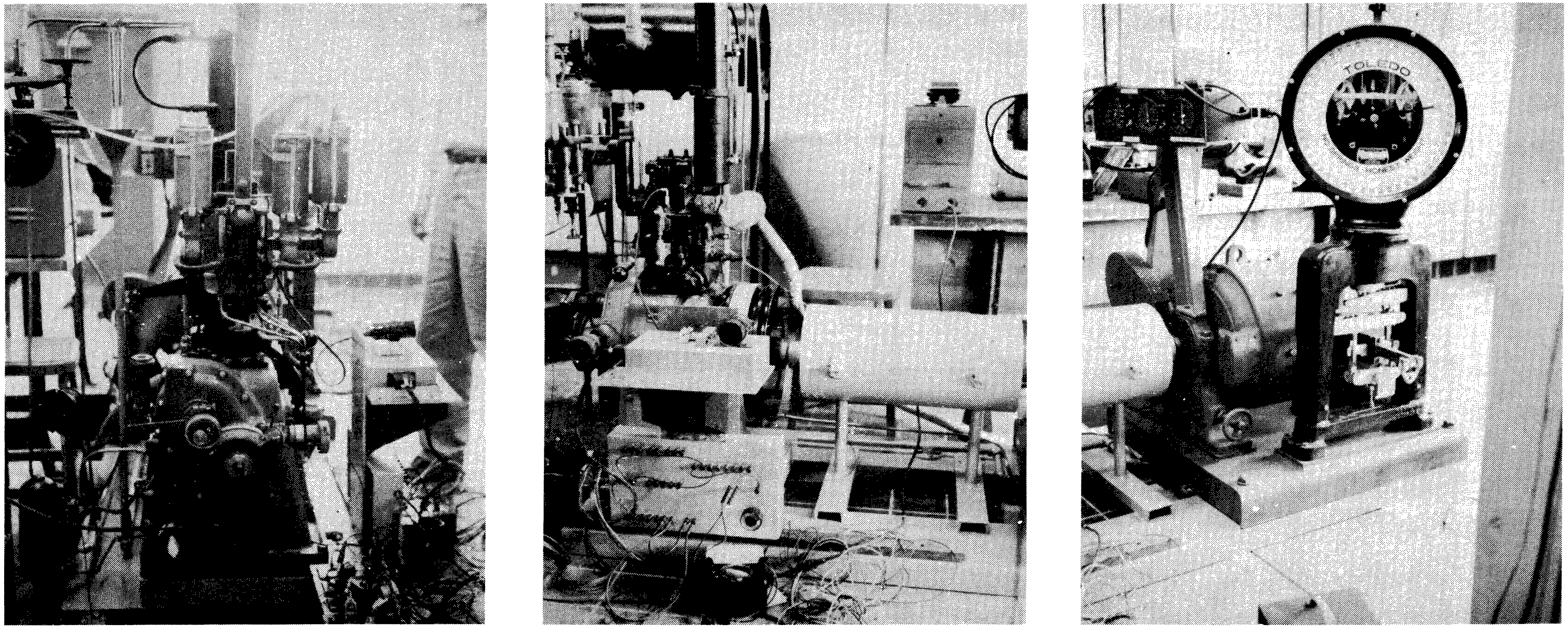
8.3 Equipment Data.

The test engine is a CFR model manufactured in June 1949. The serial number is 760135. The dynamometer is a dc shunt generator manufactured by the General Electric Co., Type number TLC - 2242, Serial number 2482929. The pressure sensor used to measure cylinder pressure is Model 2DC, Serial No. 59, manufactured by the Control Engineering Corporation.

8.4 Test Set Up

The CFR engine and dynamometer are shown in the photographs of Figure 8.1. A test panel, visible in Fig. 8.1b, was provided to accommodate chassis with the different ignition systems for making quick changes.

The circuit of the standard ignition system used for the engine tests is shown in Fig. 8.2. This circuit consists of a standard Auto-Lite spark coil and a voltage arrangement that provides continuous adjustment of the primary supply voltage from 0 to 12 volts. Terminals 1 through 7 provide dc voltages, in 2 volt increments, derived from storage batteries. Terminals 1 through 7 are on the test panel. Terminals A, B, and C are on the standard ignition chassis. Terminal C is connected to the negative end of the battery (terminal 1). Terminals A and B are connected to the appropriate terminals on the test panel with A going to the more positive point because of the electrolytic capacitor. V_{in} is the input voltage to the ignition system. The fine adjustment of V_{in} is accomplished by potentiometer R_1. The shunt load resistance R can be adjusted from 22,000 ohms to 10 megohms. This resistance simulates the effect of spark plug fouling.

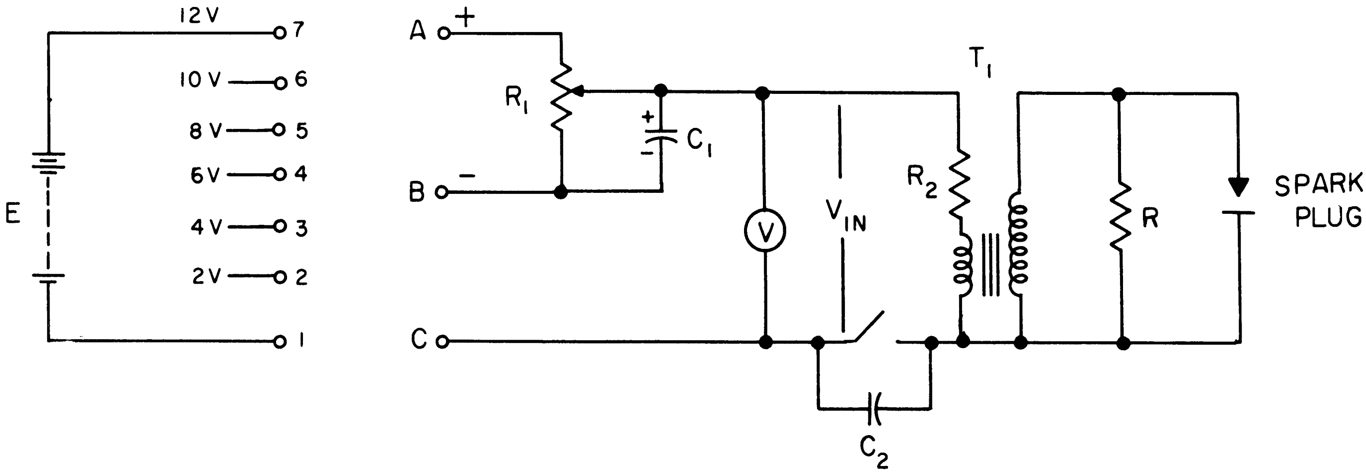


(a) FRONT END

(b) SIDE VIEW

(c) DYNAMOMETER

FIG. 8.1 CFR ENGINE TEST SETUP



E	2- 6 VOLT BATTERIES IN SERIES
R	5 - 22K 2W 9 - 100K 2W 10 - 1M 2W } ALL IN SERIES
R_1	2 Ω OHMITE POT
R_2	INCLUDED IN T_1
V	TRIPPLET 630-NA VOM METER
C_1	2000 μf 12 VOLTS
C_2	0.25 μf 600 VOLTS PAPER CONDENSER
T_1	AUTO-LITE 1496063 CZ 4001

FIG. 8.2 STANDARD 12 VOLT IGNITION SYSTEM

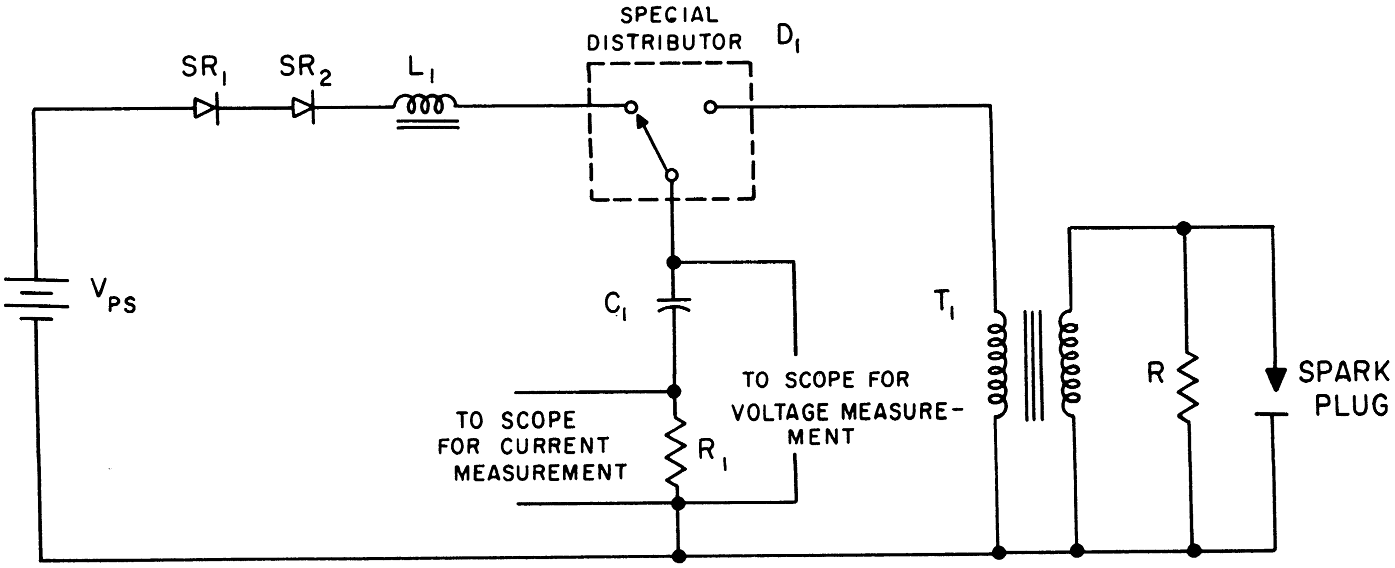
The capacitor discharge system circuit used in these tests is shown in Fig. 8.3. This system (designated type A) uses mechanical contacts for the storage capacitor switch. For this test, a special distributor was required. A standard CFR engine distributor was modified by Chrysler for this purpose. The modified distributor has two breaker point assemblies insulated from ground and connected as a single-pole double-throw switch. The contact material is tungsten. V_{PS}, the power supply voltage, is adjustable from 0 to 500 volts and has a current capacity of 250 ma.

8.5 Results of CFR Engine Tests

Evaluation tests on the standard ignition system are complete, but those on the capacitor discharge system are just getting under way. Therefore, no comparison can be made between these two systems. To illustrate the type of data that have been collected, a typical set of curves is presented. Using the procedure given in Section 8.2 for one compression ratio, one spark plug gap length, one fuel-air ratio, one speed, and one ignition system, the data collected is shown in Fig. 8.4. The curve V_2 is proportional to the input energy that must be supplied to the ignition system in order to start the engine when cranked at 600 rpm. In general, V_2 tended to increase for lean fuel air ratios in all tests conducted.

The curve V_3 is proportional to the minimum input energy to the ignition system that is necessary to sustain operation of the engine at 900 rpm and full throttle. The V_3 curve tends to increase at lower fuel-air ratios, and this was typical for all the tests.

L_4 is the plot of the dynamometer reading for full throttle at 900 rpm with the input voltage set equal to 1.2 V_3. Again, this curve is typical of the shape for all the tests run. L_4 tends to drop off as the fuel-air ratio is reduced. R_4 is the smallest resistance that can be placed in shunt with the high voltage side of the ignition coil without causing engine failure. Typically, R_4 is in excess of 10 megohms. R_5 is the same type of measurement as R_4 except that V_5 is equal to 2.0 V_3. No general statements can be drawn concerning the shape of the R_5 curve. The R_6 curve is a plot of the minimum shunt resistance that can be placed across the high voltage side of the ignition coil and still



V_{PS}	ADJUSTABLE POWER SUPPLY 0-500 VOLTS AT 250 MA
R	5-22K 2W 9-100K 2W 10-1M 2W ALL IN SERIES
R_1	0.1 Ω 1% NONINDUCTIVE (SHORT PIECE OF RESISTANCE)
C_1	1.0 μf 2000 VDC
L_1	0.2 HENRY 300 MA MODIFIED STANCOR C-2326
T_1	SPECIAL U OF M TRANSFORMER NO. 15 (SEE PAGE FOR MORE DATA
SR_1, SR_2	IN1S2, 0.5 AMP., 280 VOLTS PEAK INVERSE
D_1	SPECIAL DISTRIBUTOR. SINGLE POLE DOUBLE THROW SWITCH FLOATING FROM GROUND. CONTACT MATERIAL TUNGSTEN

FIG 8.3 CAPACITOR DISCHARGE SYSTEM, TYPE A

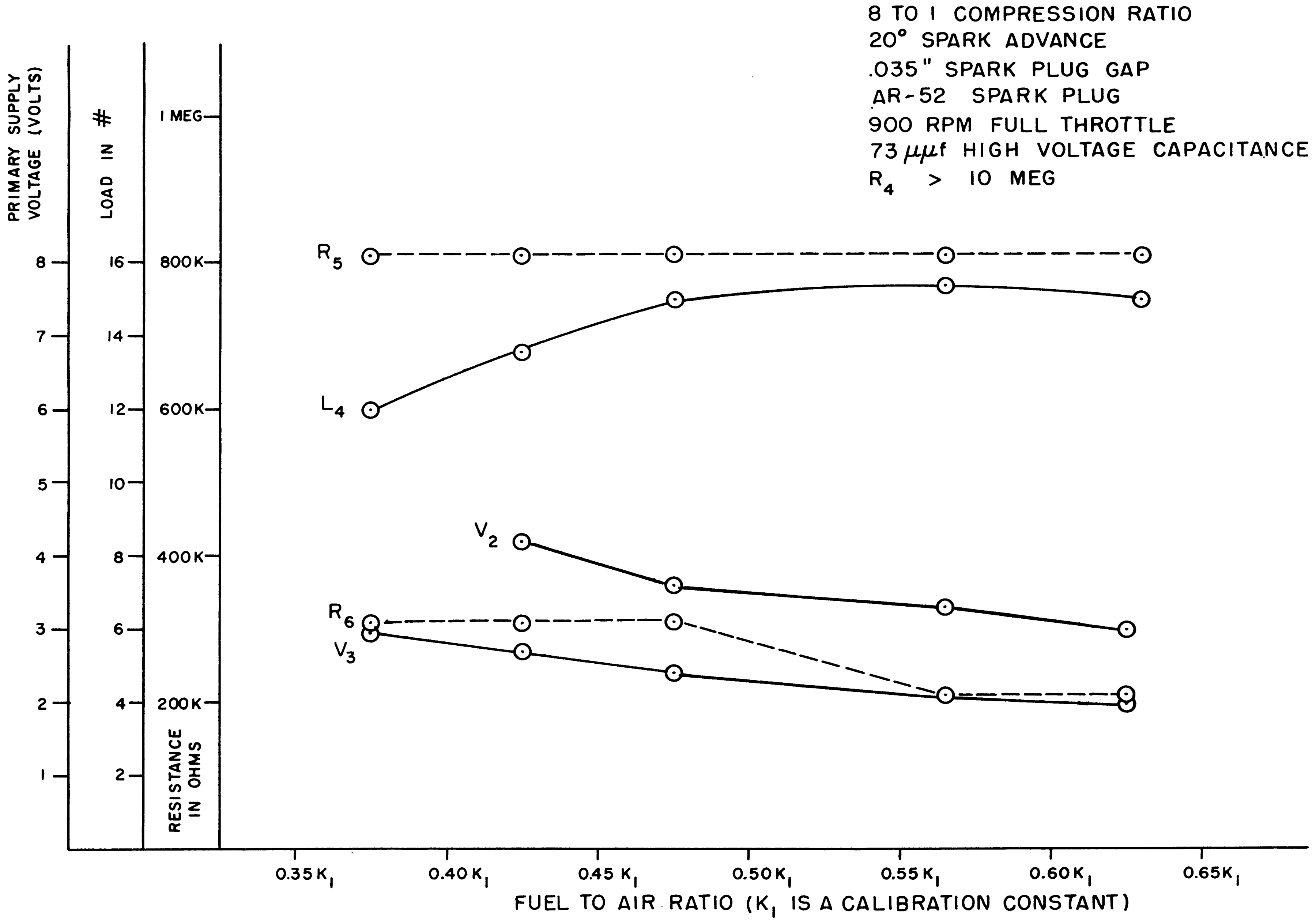


FIG 8.4 TYPICAL CURVES FOR STANDARD IGNITION SYSTEM
(SEE TEXT, SECTION 8.2, FOR DEFINITION OF R_4, R_5, R_6, V_2, V_3, L_4)

2370 A-G3-8 BM 5-3-56

sustain engine operation when the primary supply voltage is held constant at 12 volts. As with R_5, no general conclusion can be drawn concerning the shape of the resistance curve.

Two important results of the engine tests to date are as follows:

(1) Power output at full throttle was found to be independent of spark plug gap length, as indicated in Fig. 8.5. This differs from previously reported results, and bears further investigation. It was expected that the power output would improve as the gap length was increased, and this may occur at part-throttle. Unfortunately, this could no be checked at part-throttle on the CFR engine because of certain difficulties encountered with this engine.

(2) The input voltage which would just sustain engine operation (as a function of plug gap length) showed a minimum point at a certain gap setting. This is shown in Fig. 8.6 and was true for both standard and CD ignition systems. This minimum voltage can be understood on the basis of the requirements for stage one and stage two of the ignition process, as discussed in Section 4.

To the right of the minimum, where a larger sparking voltage is required for stage one, the input voltage is seen to increase with gap length as expected. To the left of the minimum, where the gap is small, the minimum energy for stage two begins to increase. This is caused by the greater heat-sink losses to the electrodes, and by the smaller interaction volume between the spark and the fuel mixture. Here the stage one requirement is more than satisfied, but the input voltage must be raised above the minimum to give the increased energy required for stage two.

At the minimum point, the input voltage is just adequate to furnish the electrical requirements for both stages of ignition. It is noted that when the two curves for lean mixture are compared, the minimum point falls at .03 inches for the standard ignition, and at .02 inches for the CD system. This is understandable, since these two systems are designed differently for the two stages of ignition.

2370 A-63-9 BM 5-3-56

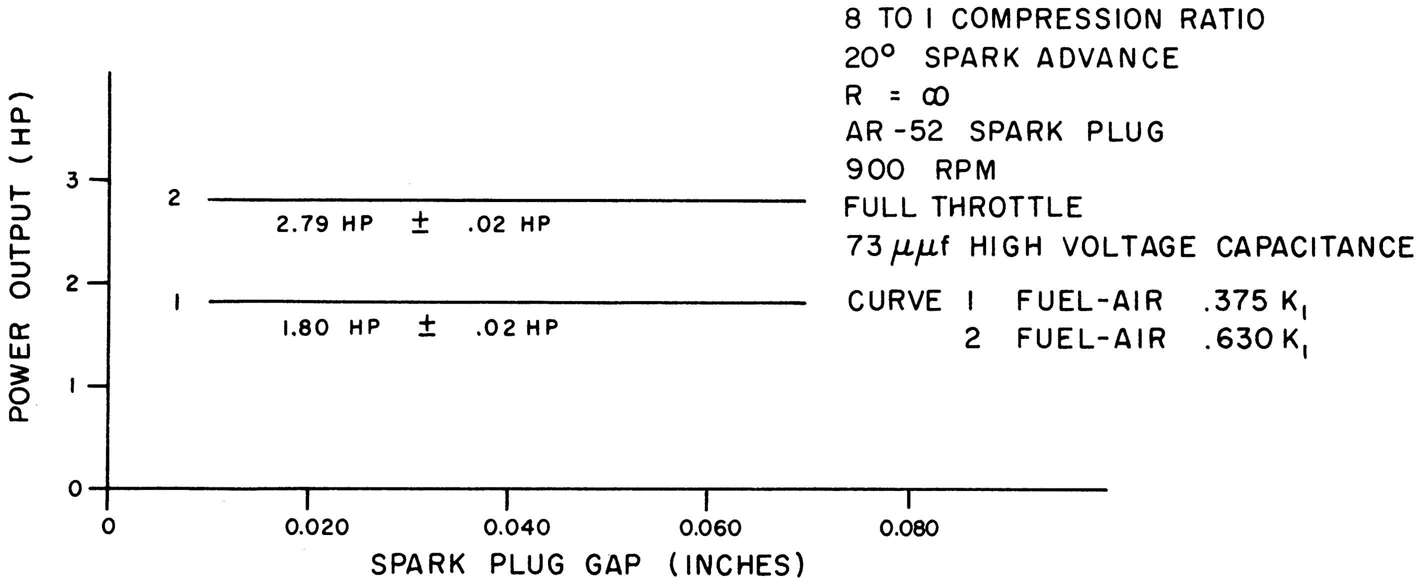
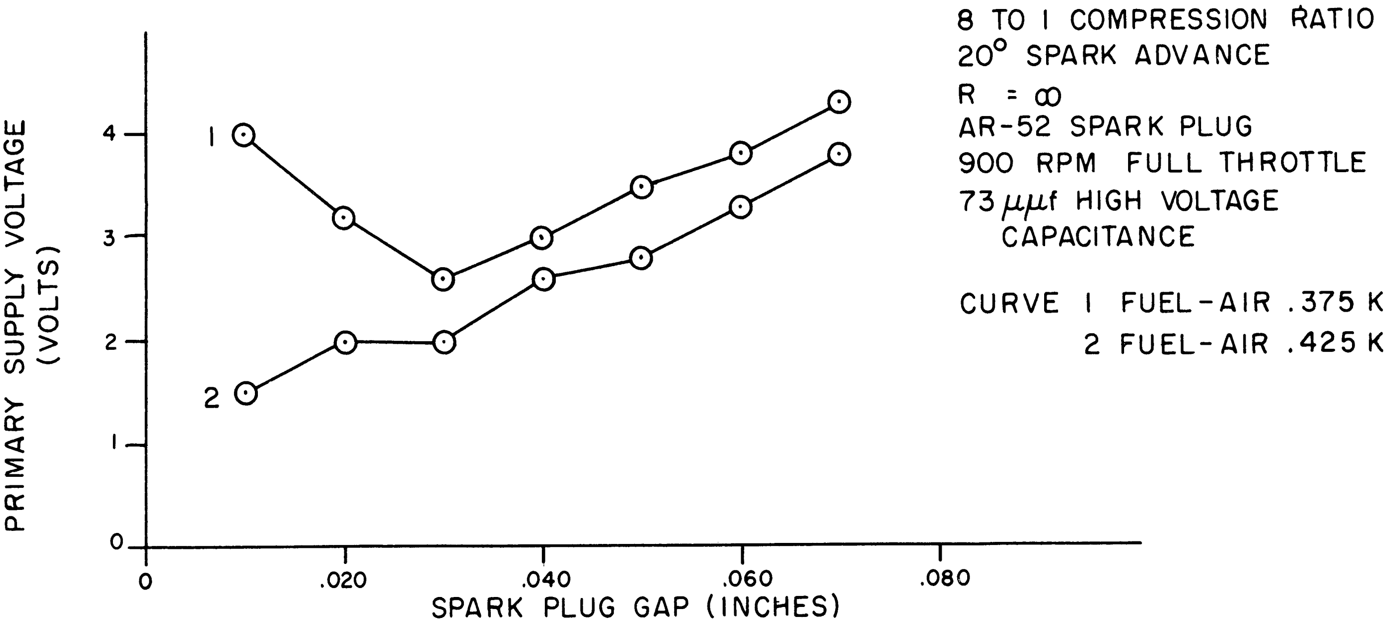
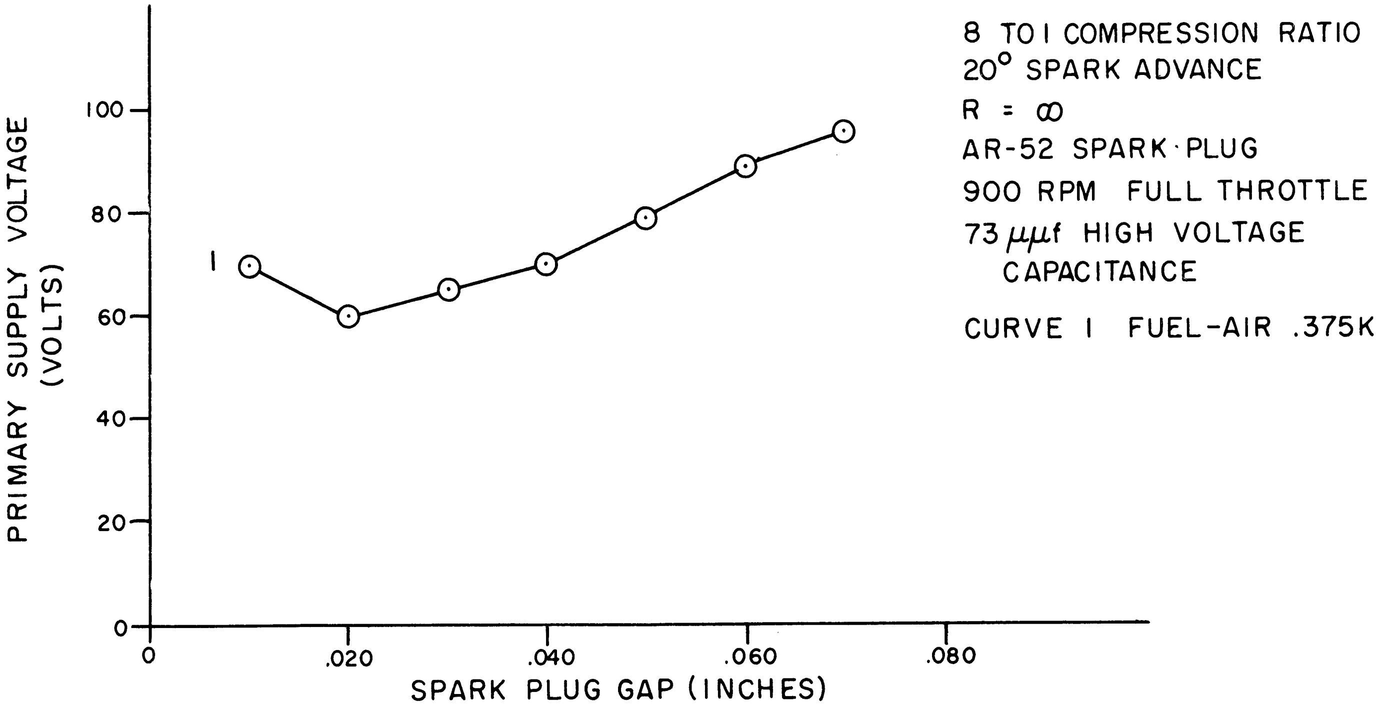


FIG. 8.5 CFR ENGINE POWER OUTPUT VS SPARK PLUG GAP FOR THE STANDARD IGNITION SYSTEM



(a) STANDARD IGNITION



(b) CAPACITOR DISCHARGE, TYPE A

FIG 8.6 PLOT OF THE MINIMUM PRIMARY SUPPLY VOLTAGE THAT WILL JUST SUSTAIN ENGINE OPERATION VS SPARK PLUG GAP.

When a richer fuel-air mixture is used, the minimum energy for stage two is reduced. For this reason, the minimum point for curve 2, Fig. 8.6a, has moved to the left. Although not apparent from the curve, the minimum probably occurs at about .01 inches.

9. DESIGN AND CONSTRUCTION OF PULSE TRANSFORMERS FOR CAPACITOR DISCHARGE SYSTEMS

9.1 Requirements for Automotive Use and Typical Transformer Specifications

The spark plug under certain conditions will require 20,000 volts for breakdown. To insure firing of the spark plug the ignition system should generate 30,000 volts with a shunt load of 200,000 ohms. Under open circuit conditions the ignition system voltage will then reach 40,000 volts, and, therefore, the transformer insulation should withstand this voltage.

The leakage inductance L should be low. A desirable value is 10 μh for a 137:1 transformer. To prevent a loss of output voltage due to magnetizing inductance drop, the value of L_m should be greater than 100 μh. A low leakage inductance and high magnetizing inductance are obtained by using a magnetic core. The core should have low losses up to 1 mc. Core materials that can be used are ferrites and powdered irons.

The amount of capacitance on the high voltage side of the ignition system determines the energy that must be put into the system to reach a given voltage. In order to keep this energy to a minimum, the capacitance should be made small. The wiring and plug capacitances are fixed so any reduction must come from the transformer. A realizable transformer capacitance is on the order of 25 μμfd.

The operation of the transformer in an automobile requires a moisture proof and mechanically rugged assembly. This can be accomplished with a good epoxy casting resin. The dielectric strength is high, good impregnation can be obtained, and the material is impervious to moisture. For experimental purposes, oil has been found to be most satisfactory for potting because of ease of construction and self healing of the dielectric after breakdown.

The following specifications are suitable for a pulse transformer to be used in a cold cathode gas switch circuit:

Turns Ratio, n	1:137
Secondary capacitance	25 μμf
Leakage inductance, L	10 μh
Magnetizing inductance, L_m	100 μh
Maximum voltage between layers	3000 volts

9.2 Practical Transformers

Fifteen transformers have been wound for the capacitor discharge system. Some of these were unsuccessful because of the potting technique used. All transformers were wound with No. 38 wire on the secondary and No. 22 wire on the primary. The resistance of a secondary with 2750 turns is about 700 ohms. The resistance of a 20 turn primary is about .06 ohm. The other materials used in construction are as follows:

Cores	Stackpole Cermag 7A Air
Insulation	Teflon Mylar
Potting Material	Air Oil Paraffin Castolite Scotchcast

Ferrite cores were used in the experimental transformers because the material was readily available in standard TV flyback transformers. The type of ferrite used was Cermag 7A made by the Stackpole Carbon Co. It has a saturation flux density of 0.25 webers/meter^2 at +30°C.

Calculations based on the capacitor discharge circuit of Fig. 6.5 show that a Cermag 7A core with a cross sectional area of 1 cm^2 and a 2750 turn secondary will saturate at 41,000 volts. "U" shaped cores with a cross sectional area of 2.05 cm^2 were used. These cores did not saturate in normal operation in a CD system. The linearity of an experimental transformer is shown in Fig. 9.1. These data were obtained from the circuit of Fig. 9.2. This figure shows the output of the same transformer coil with the core removed. Note that the reduction in output voltage is only on the order of 1/3. Therefore, it may be economically practical to use a ferrite slug or air instead of the closed ferrite core.

2370 A-G3-11 BM 5-3-56

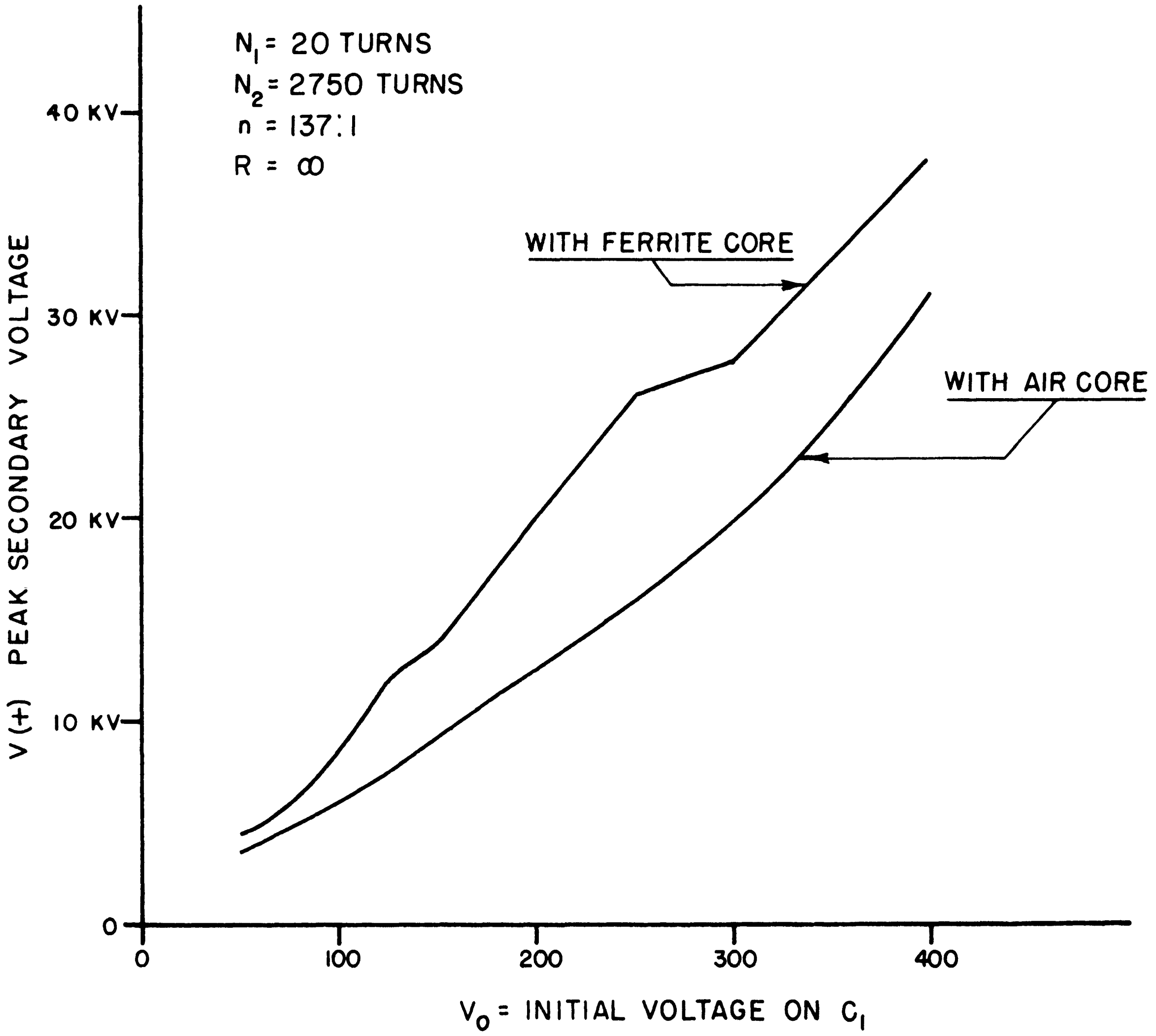
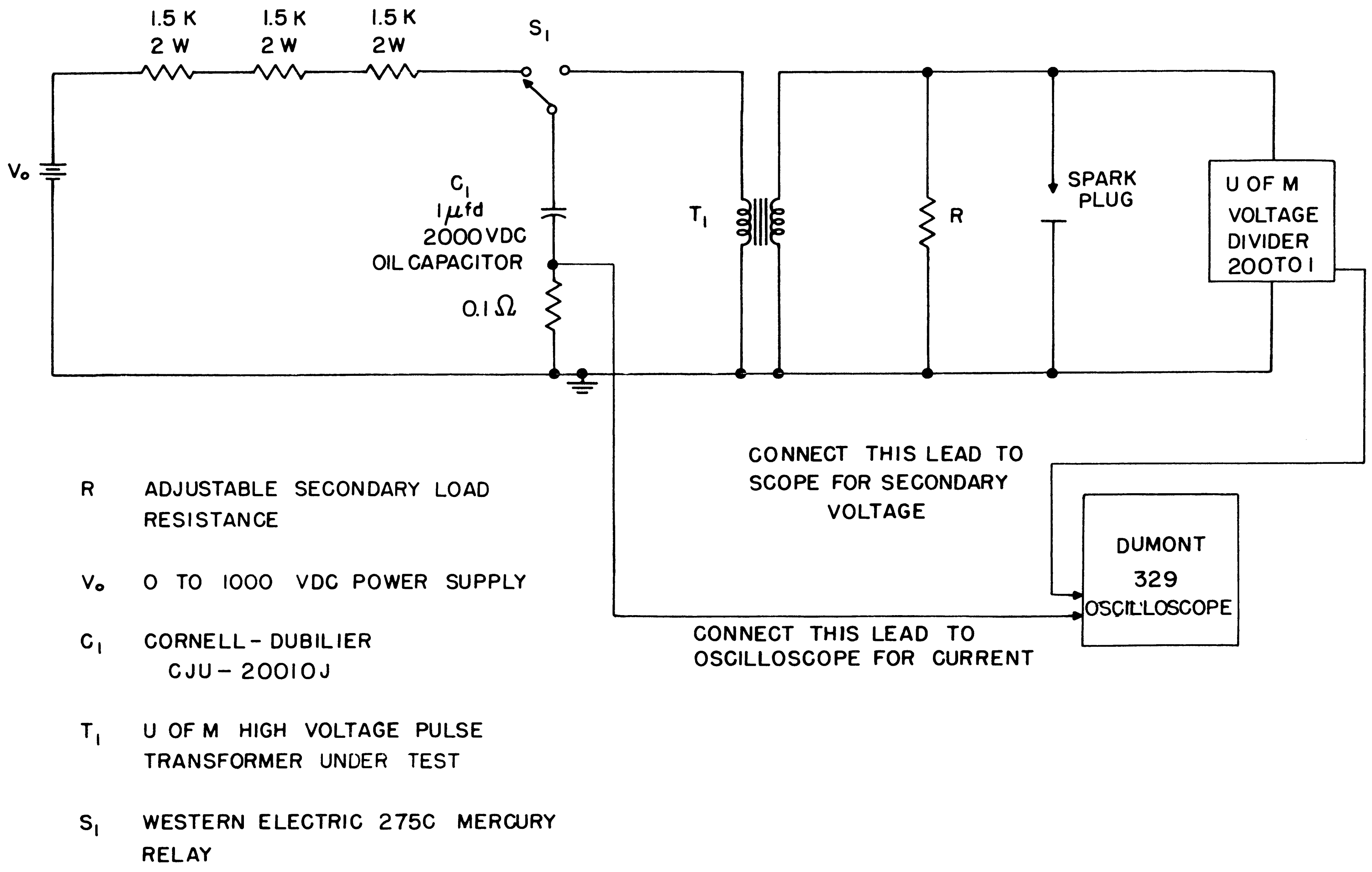


FIGURE 9.1 COMPARISON OF PEAK OPEN CIRCUIT SECONDARY VOLTAGE FOR TRANSFORMER WITH FERRITE CORE AND AIR CORE



R	ADJUSTABLE SECONDARY LOAD RESISTANCE
V_o	0 TO 1000 VDC POWER SUPPLY
C_1	CORNELL - DUBILIER CJU - 20010J
T_1	U OF M HIGH VOLTAGE PULSE TRANSFORMER UNDER TEST
S_1	WESTERN ELECTRIC 275C MERCURY RELAY

FIGURE 9.2 CIRCUIT USED TO STUDY THE LINEARITY OF THE U OF M PULSE TRANSFORMERS

2370 A-CT-11 MB 5-3-56

The experimental transformers were wound with 85 turns per layer on the secondary. This means that the peak voltage between layers could reach 2400 volts. Adequate insulation was obtained with Mylar and Teflon. Photographs of the unpotted transformer insulated with Mylar are shown in Fig. 9.3.

The best potting technique made use of oil and paraffin. The oil requires a container, whereas the paraffin does not. Trouble was encountered with the paraffin after a short period of use because of mechanical failure. Therefore, the greater number of experimental transformers were potted in oil. The oil used was Cenco HiVac 93050 No. 2. A photograph of an experimental transformer after potting is shown in Fig. 9.4.

Several unsuccessful attempts were made to pot the experimental transformer in a casting resin. These attempts failed due to cracks or air bubbles in the resin. Improved techniques and the use of vacuum impregnating equipment should eliminate these difficulties.

The characteristics of transformer No. 12 are as follows:

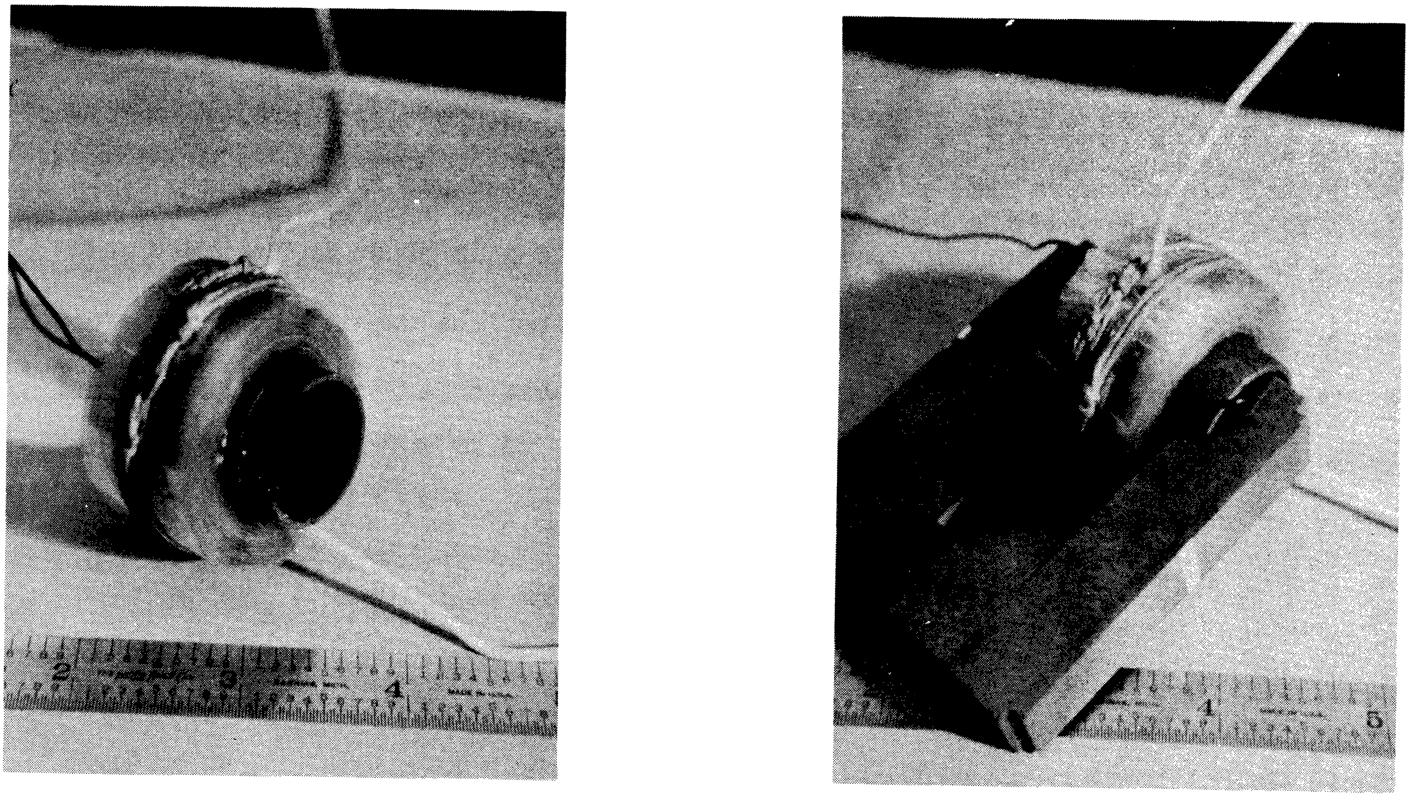
N_{pri}	20 turns
N_{sec}	2750 turns
n (turns ratio)	137
L (Primary leakage inductance)	6 μh
L_m (Magnetizing inductance)	2000 μh
C (Secondary Capacitance)	28 μμfd
Potted in	Cenco HiVac Oil
Core	Cermag 7A 2.05 cm^2 cross-sectional area.

10. POWER SUPPLY SYSTEMS

10.1 Introduction

The development of the CD ignition system, as discussed above, immediately dictated the need for a compatible companion power supply to provide the necessary dc power for the system. At a maximum engine speed of 6000 rpm, the CD system requires

2370 A-P3-26 JF 4-5-56



a. WITHOUT CORE

b. WITH FERRITE CORE

FIGURE 9.3 TYPICAL UNPOTTED PULSE TRANSFORMER. N_{PRI} = 20 TURNS. N_{SEC} = 2750 TURNS. INSULATION THREE LAYERS OF 1 MIL MYLAR.

2370 A-P3-29 JF 4-5-56

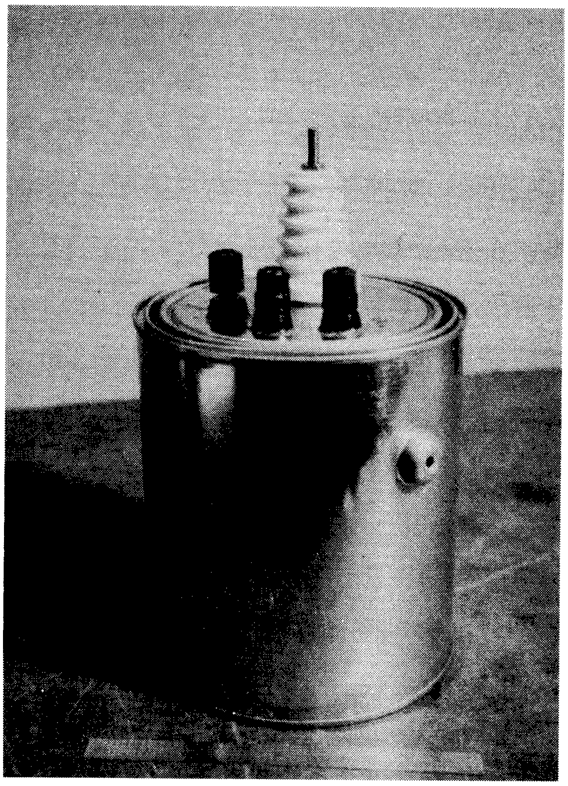


FIGURE 9.4 EXPERIMENTAL CAPACITOR DISCHARGE SYSTEM TRANSFORMER POTTED IN OIL.

approximately 25 watts if a mechanical switch is employed. This is the most efficient method of discharging the capacitor, although perhaps not the best. If one of the other switching means for a CD system is employed (see Section 6) the power required at any speed might increase by as much as a factor of two or three, depending on the efficiency of the particular switching method.

With these factors as a guide, the basic methods of power generation which appear to be suitable for automatic use are as follows:

1. Mechanical vibrator power system.
2. Motor-generator power system.
3. Transistor power converter system.

10.2 Mechanical Vibrator Power System

The mechanical vibrator has been used extensively as a source of B+ power in automotive radio and similar equipment. Recent improvements in contact design and construction have made the vibrator a rugged and reasonably long lived device. It is difficult, however, to evaluate its exact dependability and lifetime except by large-lot statistical test methods. Such a study has not as yet been undertaken by this project, but it is quite likely that pertinent information is available from various manufacturers, since there is considerable military interest in vibrators and their reliability.

From a cost standpoint, the vibrator system is unquestionably the most economical at the present time. Within the next three to five years, however, this situation is likely to change to the extent that the transistor power converter will be competitive with the vibrator system. Additional comments regarding cost and reliability are presented in later paragraphs of this section.

10.3 Motor-Generator Power System

The motor-generator or dynamotor system of power conversion utilizes a conventional dc drive motor coupled to a suitable dc generator. In practice, both the motor drive windings and the generator windings are often placed on the same rotating armature, with the motor commutator on one end of the rotating shaft and the generator commutator on the other end.

With proper maintenance of commutators and brushes, the motor generator system has proven to be a very dependable method of power conversion. The best evidence that can be cited is its universal use by both commercial and military aircraft.

To its disadvantage, the motor generator requires periodic and careful maintenance, has the poorest power conversion efficiency, and has the highest initial cost of the three systems under consideration.

10.4 Transistor Power Converter System

The transistor power converter system shares some of the desirable features of the two previous systems and, in addition, possesses some exclusive advantages of its own. These characteristics can be summarized as follows:

1. The transistor supply is compact and extremely rugged.
2. Efficiency of power conversion equals that of the vibrator supply.
3. The system is completely electronic, thus eliminating all moving parts and minimizing the need for maintenance.
4. When operated within its ratings, thousands of hours of satisfactory operation can be obtained from the system.

These advantages accrue because the transistor system is similar in operation to the vibrator power supply. The fundamental difference is the replacement of the vibrator by transistors which operate as repetitive electronic power switches.

The major disadvantage associated with this system at present is the high cost of transistors capable of controlling adequate amounts of power, particularly when subjected to the high ambient temperatures often encountered in automotive use. Although the above pertains specifically to germanium, the status of silicon transistors is similar. Compared with germanium, the silicon transistor is capable of operating at high temperatures with significantly less power derating, but the state of the art has not yet advanced to the point where silicon transistors with sufficient power capacity are commercially available. Fortunately, the improvements in transistor technology and prices which can confidently be expected in the next three to five years should alleviate the present situation considerably.

10.4.1 Description of the Transistor Power Converter Oscillator. The basic circuit configurations which utilize the power conversion characteristics of transistors are illustrated in Fig. 10.1.[1] Since maximum efficiency is obtained when one transistor is fully conducting while the other is completely cutoff, and vice versa, the circuits are arranged so that the transistors act as synchronized switches. They alternately conduct and are cutoff in turn, thereby transferring virtually the full power supply voltage across alternate sections of the transformer primary windings N_1. The switching action is controlled by suitable current derived from the feedback windings N_2. This switching action produces in the secondary winding, N_3, a square wave of voltage which can be rectified and filtered at any desired output voltage level.

A rectangular hysteresis loop transformer core material such as Deltamax[2] is necessary if the transition time between conduction and cutoff is to be kept short. The straight B-H curves for this material also allow maximum transistor current to flow during the conduction portion of its cycle. These characteristics contribute materially to the efficiency of the power conversion.

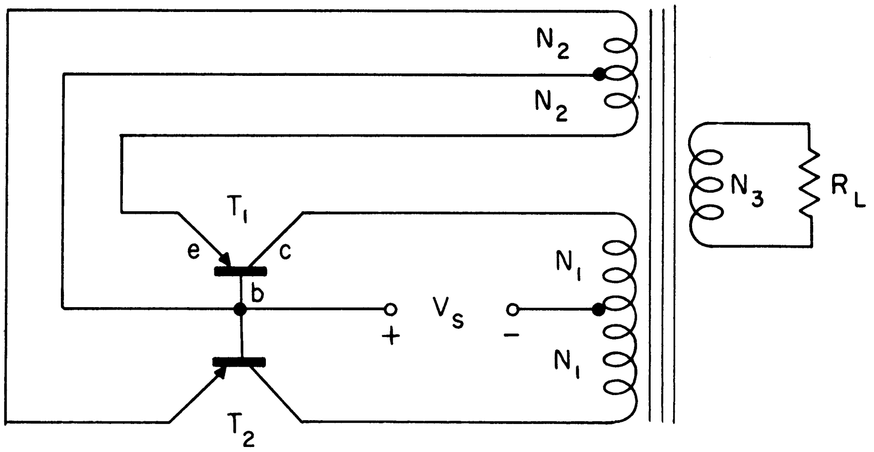
A qualitative description of the operation of the transistor oscillator for the common base configuration can be presented with the aid of Figs. 10.1, 10.2, and 10.3. It will be assumed that winding directions on the transformer are arranged so that the transformer core flux density approaches point A from point D (on Fig. 10.2) during the time that transistor TR_1 conducts. As the core approaches saturation at point A, the voltage induced in the driving or feedback winding, N_2, diminishes. Loss of driving voltage V_{e_1} immediately causes a decrease in emitter current I_{e_1} and a corresponding decrease in collector current I_{c_1}. The core flux density now begins to diminish and approach point B. The collapsing field applies a conducting bias via N_2 to the emitter circuit of the alternate transistor TR_2 which immediately begins to conduct and drive the

---

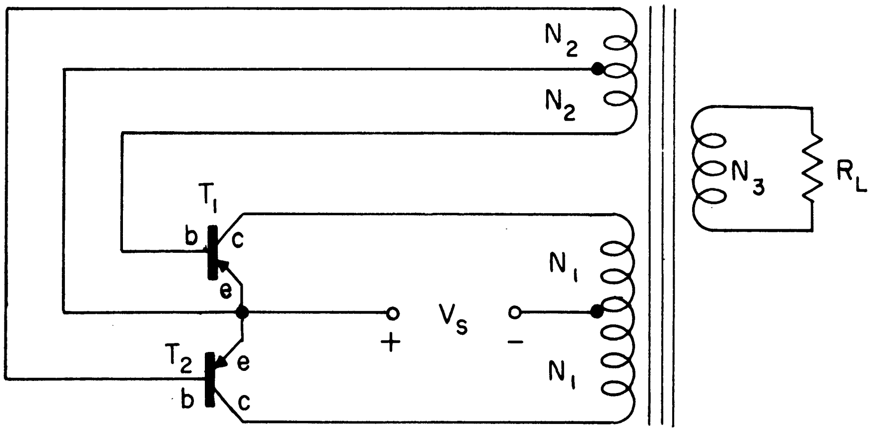
[1] See References 1, 2, 3, 6, 7, 8 and 9 in Appendix C.

[2] Manufactured by the Arnold Engineering Company, Marengo, Illinois.

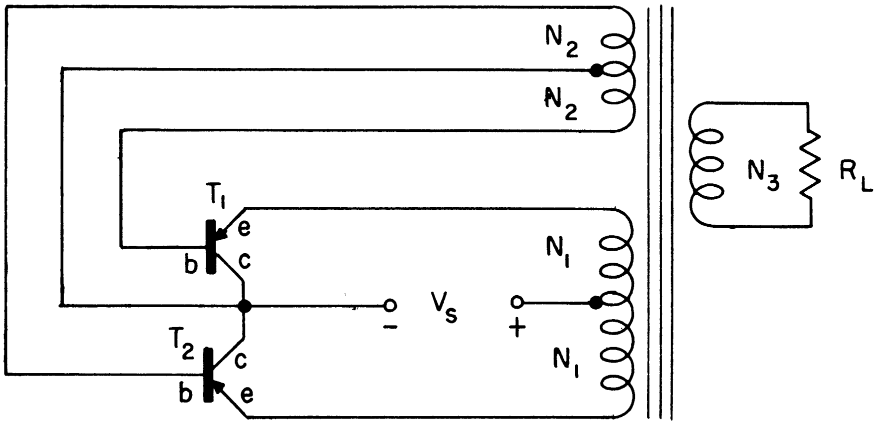
2370 A-CT-5 BM 4-3-56



COMMON BASE



COMMON EMITTER



COMMON COLLECTOR

FIG 10.1 TRANSISTOR POWER CONVERTER OSCILLATOR CIRCUITS

2370 A-S-I BM 4-3-56

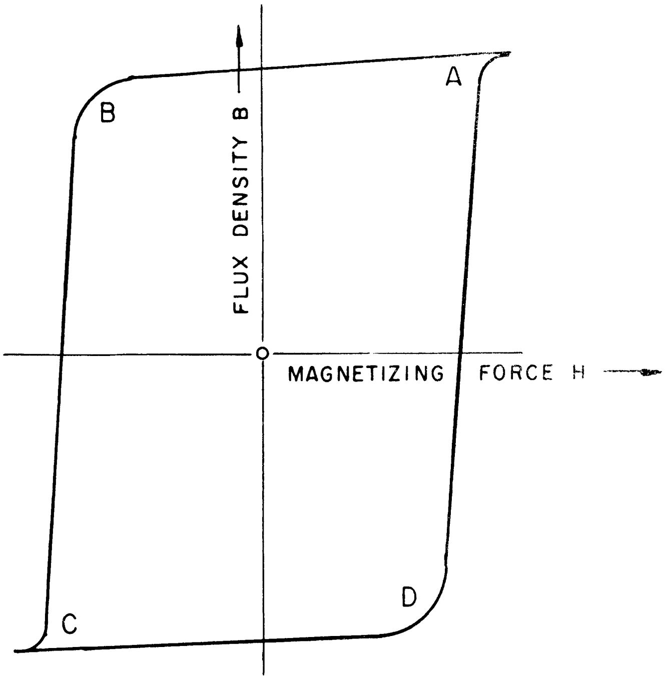


FIG 10.2 HYSTERESIS LOOP FOR SQUARE LOOP CORE MATERIAL

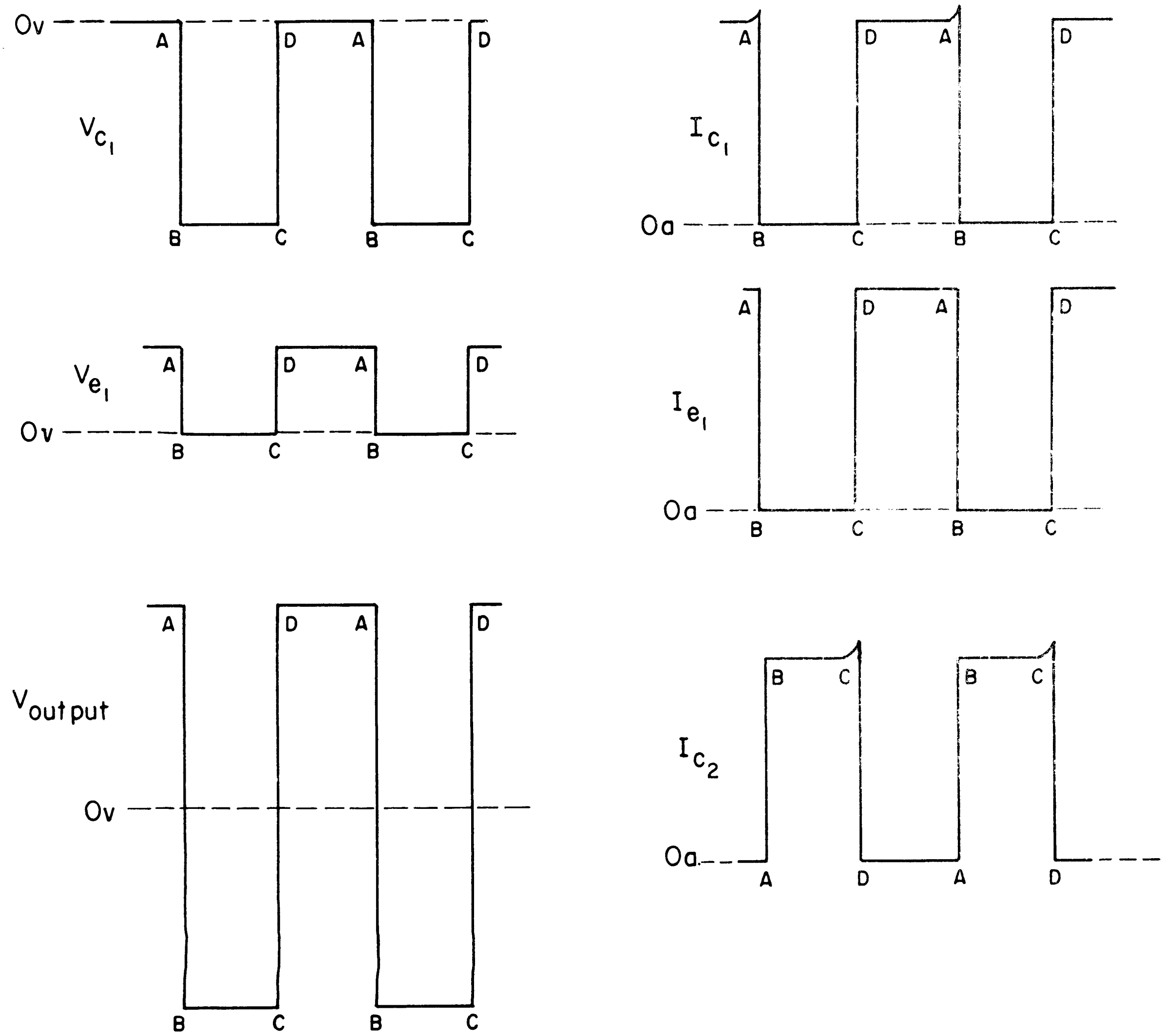


FIG 10.3 CURRENT AND VOLTAGE WAVEFORMS IN TRANSISTOR POWER CONVERTOR OSCILLATOR FOR COMMON BASE CONFIGURATION

core flux density from point B to point C. During this period of time the emitter of TR_1 is driven negative and therefore held at cutoff.

As the core approaches saturation in the opposite direction at point C, a sequence of events occur which are similar to those outlined at point A except that from C to D, TR_2 switches off and TR_1 switches on for its half cycle of conduction from D to A. This description neglects the effects of transformer leakage inductance, core hysteresis and transistor switching time, which are all important in practice but not essential for a basic understanding of the oscillation cycle.

10.4.2 Transistor Power Limitations. Consideration of the transistor voltage and current waveforms of Fig. 10.3 indicates that when either transistor is fully conducting, the only significant power dissipation within the transistor occurs in the emitter base region. Although collector current flows during conduction, the collector to base voltage is essentially zero. This is the most efficient operation which can be achieved with the transistor.

The transition period between full conduction and complete cutoff (AB and CD) cannot be neglected even though the time involved is quite short, because it is during this period that the collector to base voltage is increasing while collector current is still flowing. Transistion time is controlled principally by the shape of the hysteresis loop between segments AB and CD as shown on Fig. 10.2. Deltamax has an almost ideal B-H loop in this regard, and minimizes the time interval. Any curvature of the core B-H characteristics in regions AB and CD acts to round off the corners of the square wave oscillation and degrade the performance of the power oscillator.

10.4.3 Power Output Limitations of the Transistor Oscillator. The operating limitations which govern the use of transistors in switching service are illustrated in Fig. 10.4.[1] The dotted path from A to B represents the power dissipated at the collector during the transition from conduction to cutoff and vice versa. For a given ambient temperature, this defines the ultimate safe current in the collector circuit. Any

---

[1] See References 4, 5 and 9 in Appendix C.

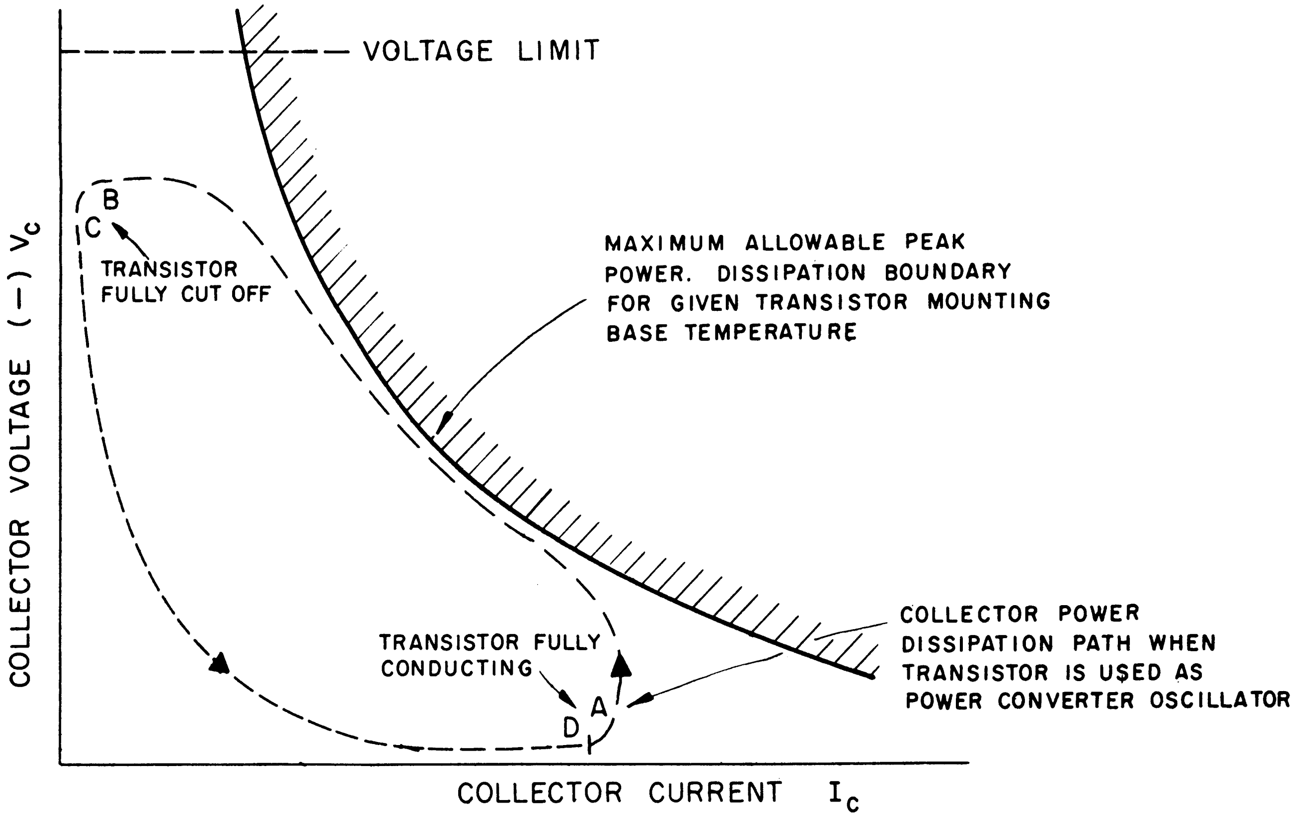


FIG. 10.4 POWER AND VOLTAGE LIMITATIONS FOR GROUNDED BASE TRANSISTOR

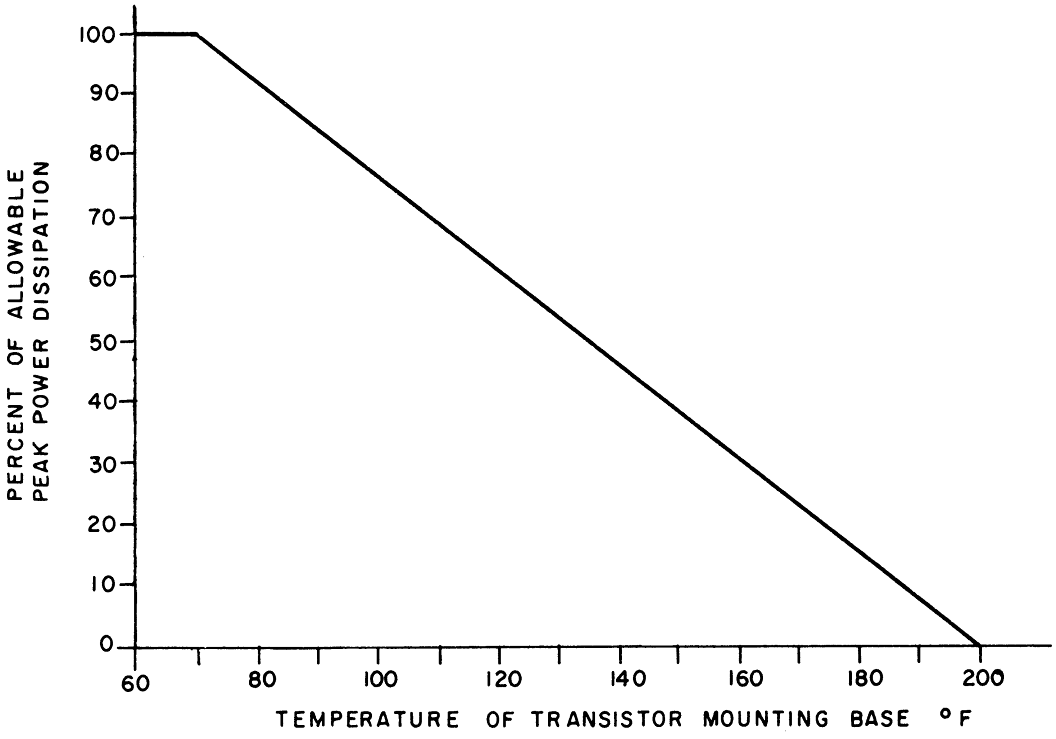


FIG. 10.5 TYPICAL GERMANIUM POWER TRANSISTOR DERATING CHART

combination of circumstances (such as load transients or load power factor variation) which causes the transition path AB to move to the right of the total peak power dissipation boundary for more than the time defined by the thermal time constant of the semiconductor junction will cause rapid transistor deterioration. Various power transistor investigators have reported that this time varies from about ten to fifty microseconds. This is so short that even a fuze in the collector circuit will not protect the transistor.

Figure 10.5 illustrates the peak power output derating necessary for a typical germanium power transistor. If it is assumed that the heat dissipator to which a transistor must be attached is at ambient temperature, the only methods presently available for improving transistor performance at elevated temperatures are: (1) improved design of the internal thermal characteristics of the semiconductor body, and (2) selection of a more suitable semiconductor material, such as silicon. Both methods are being actively investigated by the various manufacturers.

In spite of the difficulties just discussed, it is felt that the long term advantages outweigh the short term objections. For instance, component costs in the system can be reduced by using only one power transistor and replacing the other with a low power "core reset" transistor in applications where the load current is unidirectional.[1] This and other anticipated improvements make it desirable to continue the investigation in this field.

11. VOLTAGE DIVIDER DESIGN FOR HIGH VOLTAGES

In order to make accurate high voltage measurements and to investigate the high voltage waveshapes in ignition systems, a suitable voltage divider is required to reduce these voltages to values suitable for application to an oscilloscope. In the design three basic considerations are presented:

---

[1] See Reference 10 in Appendix C.

a) Frequency compensation

b) Compensation of distributed stray capacitance

c) Electric breakdown precautions

11.1 Basic Circuit

A frequency compensated voltage divider generally takes the form shown in Fig. 11.1. In this circuit, one of the capacitors, C_2 for example, is made variable.

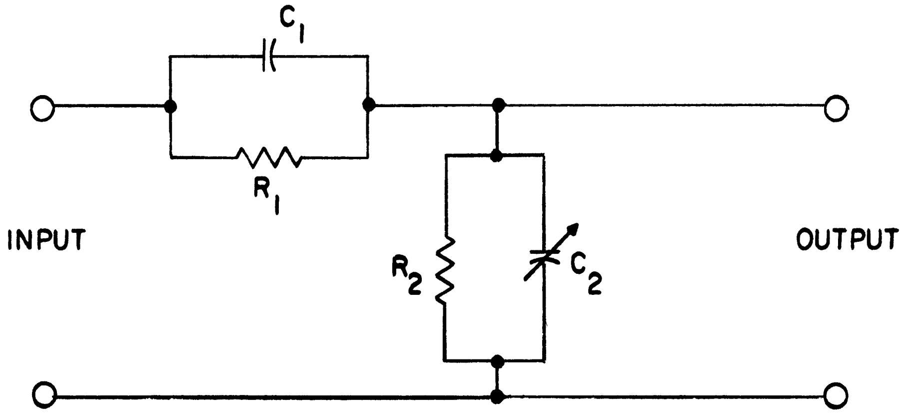


FIG 11.1 BASIC CIRCUIT

The output is connected to an oscilloscope having as input resistance R_3 and input capacitance (with cable)C_3. Correct frequency compensation is obtained when the capacitance adjustment gives $R_1C_1 = R_4C_4$. In this expression R_4 is the resistance of the parallel combination of resistor R_2 in the divider and the input resistance R_3 of the oscilloscope ($R_4 = R_2R_3/R_2+R_3$). C_4 is the total shunt capacitance including the divider output capacitance C_2, and the cable and input capacitance of the oscilloscope, C_3.

C_2 is adjusted by applying to the input of the divider a square wave with a half period of several R_1C_1 time constants, viewing the wave on the oscilloscope, and adjusting as in Fig. 11.2.

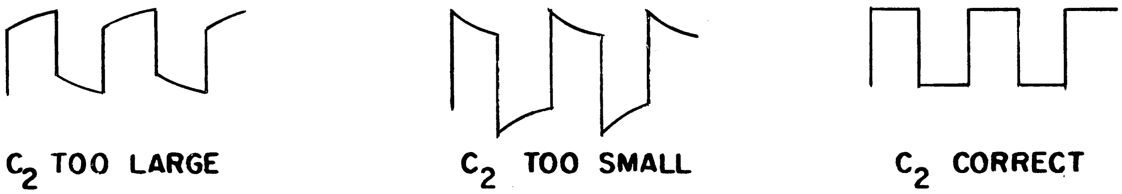


FIG 11.2 WAVEFORMS

11.2 Distributed Stray Capacitance

In high voltage dividers, the physical dimensions of R_1 are necessarily large. This gives rise to an appreciable stray capacitance distributed along the length of the resistor as indicated by C_s in Fig. 11.3. A typical example is a 200 to 1 divider having R_1 = 200 Meg and C_1 = 4 μμf. R_1 is a cylindrical resistor 4 inches long and 1/2 inch in diameter. When centrally located inside a metal enclosure 3-1/2 x 6 x 8 inches inside dimensions, the distributed stray capacitance C_{s1} is between 1 and 2 μμf. However, this has an adverse effect on the square wave response as indicated in Fig. 11.4. This is the response of the divider when a 120 cycle square wave is applied.

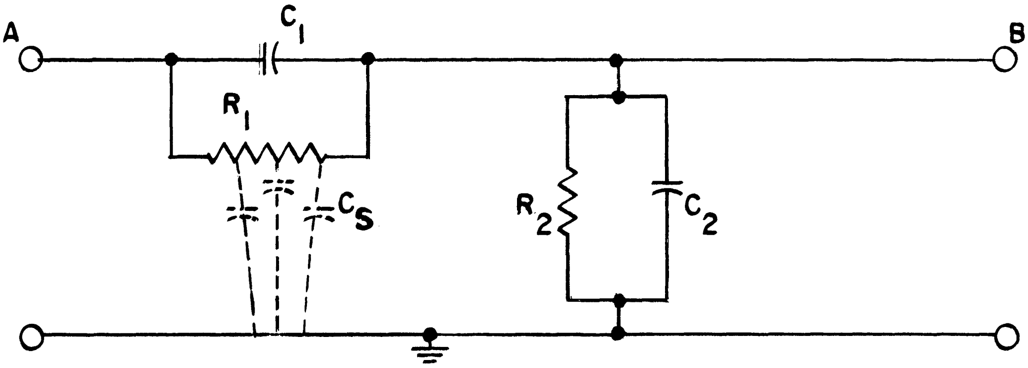


FIG 11.3 DIVIDER WITH DISTRIBUTED STRAY CAPACITANCE

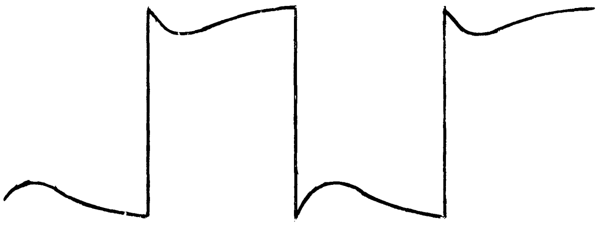


FIG 11.4 RESPONSE OF DIVIDER TO 120 cy SQUARE WAVE

In this case, C_2 was adjusted to give the required $R_1C_1 = R_4C_4$, but no adjustment of C_2 will produce a flat response.

The equivalent circuit is essentially a low pass filter shunted by a capacitance C_1 which passes the very high frequencies. The sinusoidal response is clearly equal at very high and very low frequencies, with a dip at some intermediate frequency. It is possible to add a synthetic distributed capacitance to compensate for this. The distributed capacitance added must be properly adjusted for exact compensation. It is added between the resistor R_1 and node B of the divider, as indicated in Fig. 11.5.

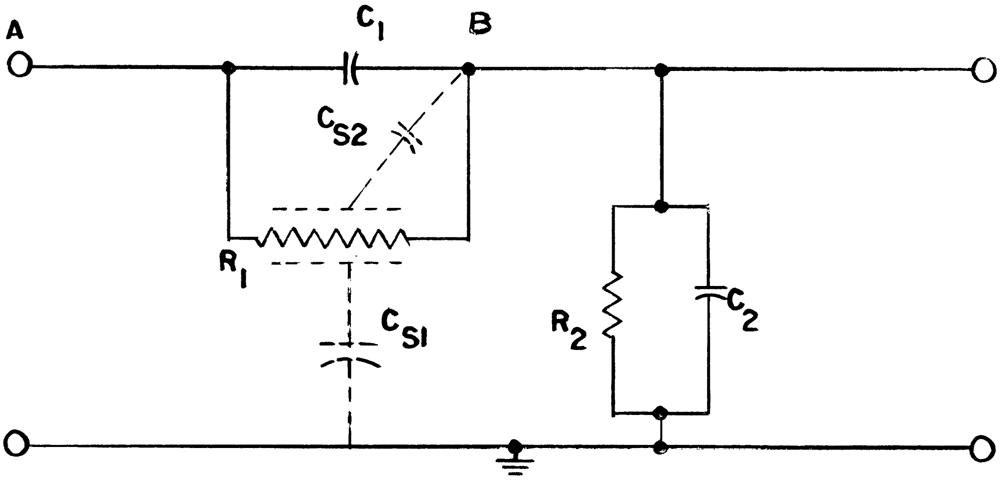


FIG 11.5 DIVIDER COMPENSATED FOR DISTRIBUTED STRAYS

The added stray capacitance C_{s2} may be realized by a small metal plate placed near R_1 and connected to B. Should voltage breakdown considerations prevent a close approach to R_1, the added structure must be redesigned with adequate insulation.

By making a theoretical treatment of the problem, it is possible to specify exactly the distribution of C_{s2} for exact compensation. However, the practical realization is accomplished readily by adjustment and testing as indicated in Fig. 11.6.

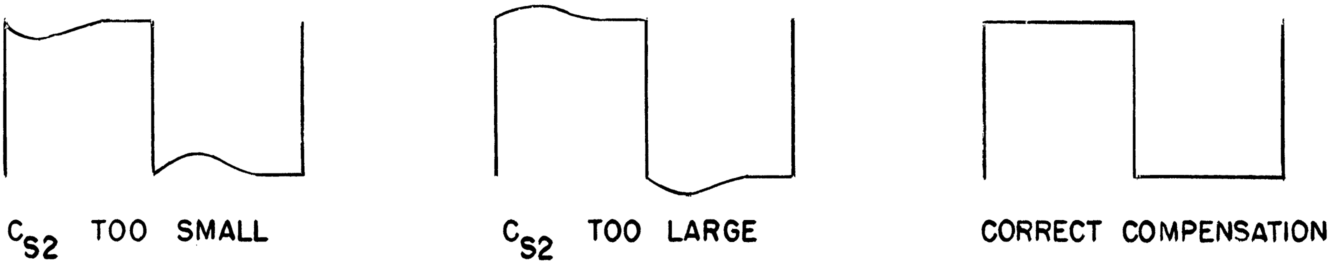


FIG 11.6 WAVEFORMS SHOWING RESPONSE OF VOLTAGE DIVIDER WITH COMPENSATION FOR DISTRIBUTED STRAYS

When the added distribured stray capacitance C_{s2} is correctly placed, it will exactly compensate the adverse stray C_{s1}. The sinusoidal frequency response will then be perfectly flat over the frequency range from dc to the upper frequency limit.

The upper frequency limit is determined by the shunt input capacitance of the divider, and its series inductance. The test lead inductance connecting the circuit to terminal A is generally the limiting element in the upper frequency limit, and should be kept short for high frequency work.

11.3 Electric Breakdown Precautions

The methods used to prevent corona and electric breakdown are (a) the use of smooth surfaces and corona rings on the high voltage terminal and (b) the use of materials to raise the dielectric constant adjoining high voltage parts, thus reducing the electric field.

The construction of a 200 to 1 divider is shown in Fig. 11.7. The 200 megohm resistor is covered with a polyethylene or polyvinyl jacket to prevent corona and surface leakage. The resistor is located inside a lucite tube, and mounted on the insulator. The insulator and the upper portion of the tube are filled with paraffin. A metal chassis 3-1/2 x 6 x 8 inches is used to shield the components.

A thin silver strip is painted on the surface of the lucite tube along one side only, and connected electrically to the output terminal by means of the metal bracket. A small area of the silver strip in the vicinity of the corona ring furnishes the capacitance C_1. The width of the strip is graduated, being somewhat wider near the bottom, to furnish the required distribution of compensating distributed capacitance C_{s2}. The distributed stray capacitance from the resistor to the chassis is illustrated by C_{s1}.

A 2 MΩ resistor is used for R_2. This resistance, in parallel with the 2 MΩ oscilloscope input resistance, gives the required 1 MΩ shunt resistance for 200:1 voltage division. The trimmer capacitor C_2 is adjustable from outside the case. The input impedance of the divider is 200 megohms shunted by 8 μμf.

2262 A-S4-119 JF 3-28-56

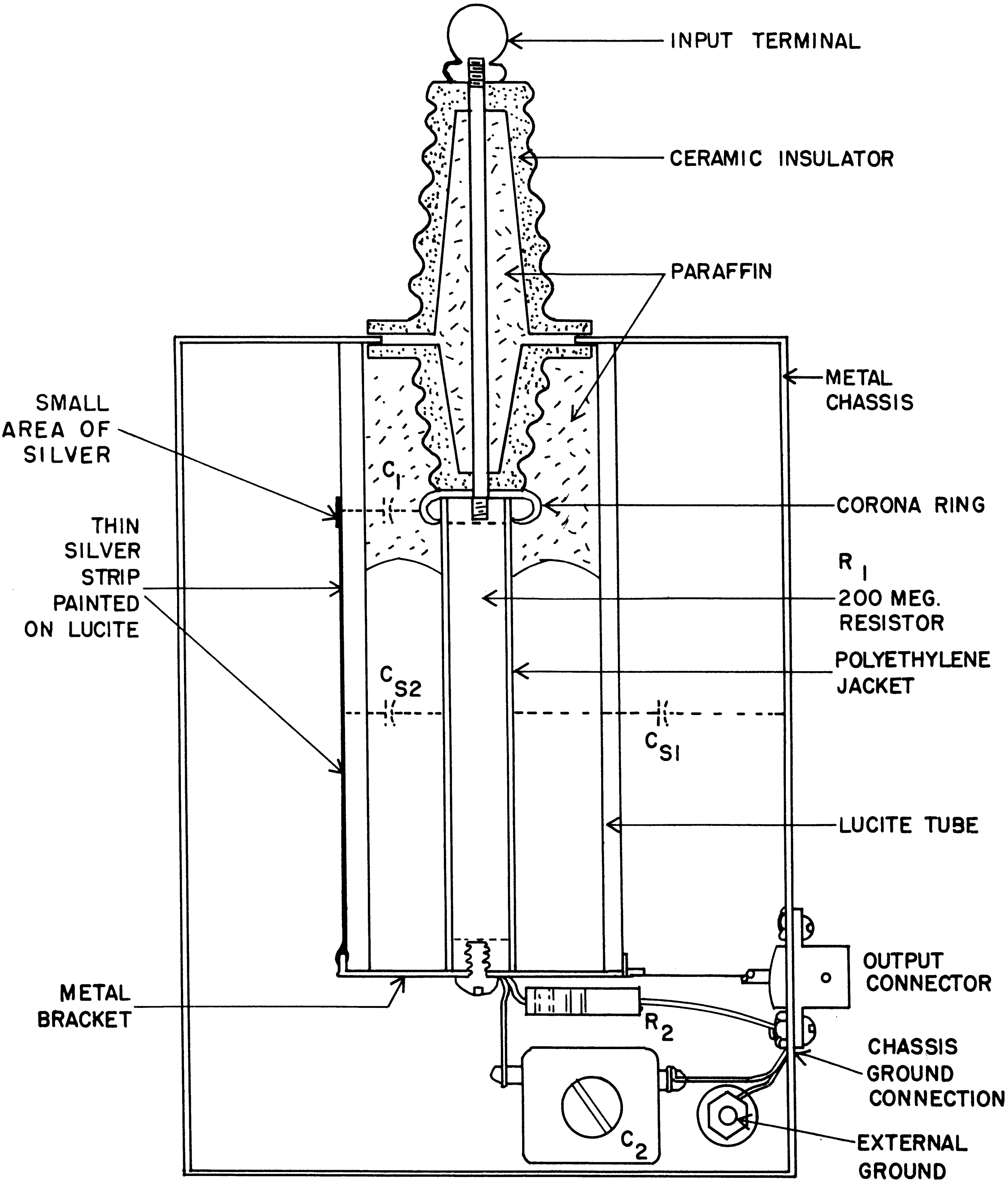


FIG. 11.7 CONSTRUCTION OF HIGH VOLTAGE DIVIDER

This divider construction permits operation up to 40 kilovolts without breakdown, and with a minimum of corona loss. It is desirable to use the same oscilloscope with a particular divider. In this way the compensating capacitor, C_2, does not require readjustment, and the voltage divider factor does not require rechecking with each use.

12. PIEZOELECTRIC VOLTAGE GENERATOR

Automotive ignition systems have, in the past, used either a magneto or a battery energized ignition coil as an energy source. A new system which is capable of generating the voltage required to fire a spark plug has recently been invented.[1] The voltage generator utilizes the piezoelectric effect of barium titanate to produce a voltage of sufficient amplitude to obtain reliable spark plug firing in small single cylinder gasoline engines.

To determine the feasibility of using a piezoelectric voltage generator in an automobile ignition system, simple experiments designed to measure the piezoelectric response of a barium titanate cylinder were carried out.

12.1 Hydraulic Ram Experiment

As shown in Fig. 12.1 the piezoelectric properties were determined by measuring the open circuit voltage resulting from the sudden release of a known peak force on a prepolarized barium titanate[2] cylinder 1" in diameter and 1" long. Silver electrodes were fired on the parallel faces of the cylinder and made contact with the brass shim stock leads. The force was applied to the specimen by means of a hydraulic ram. After building up a given pressure, the voltage across the specimen was brought to zero by a temporary short circuit. The valve of the hydraulic system was then opened, releasing

---

[1] J. R. Harkness, "Electric Ignition System for Internal Combustion Engines," U.S. Patent Office Pat. No. 2,649,488, issued Aug. 18, 1953.

[2] The pre-stressed barium titanate specimens were furnished by Mr. Wm. S. Parsons, President of Centralab Division, Globe-Union Inc., Milwaukee, Wis.

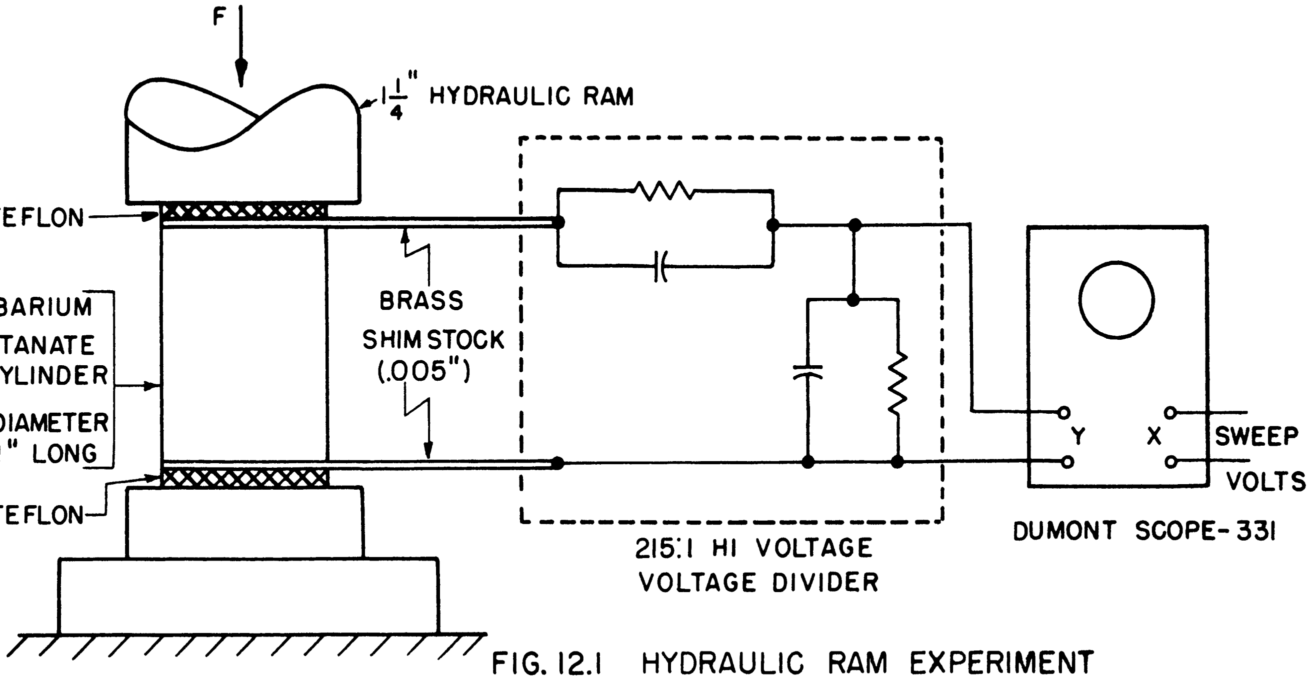


FIG. 12.1 HYDRAULIC RAM EXPERIMENT

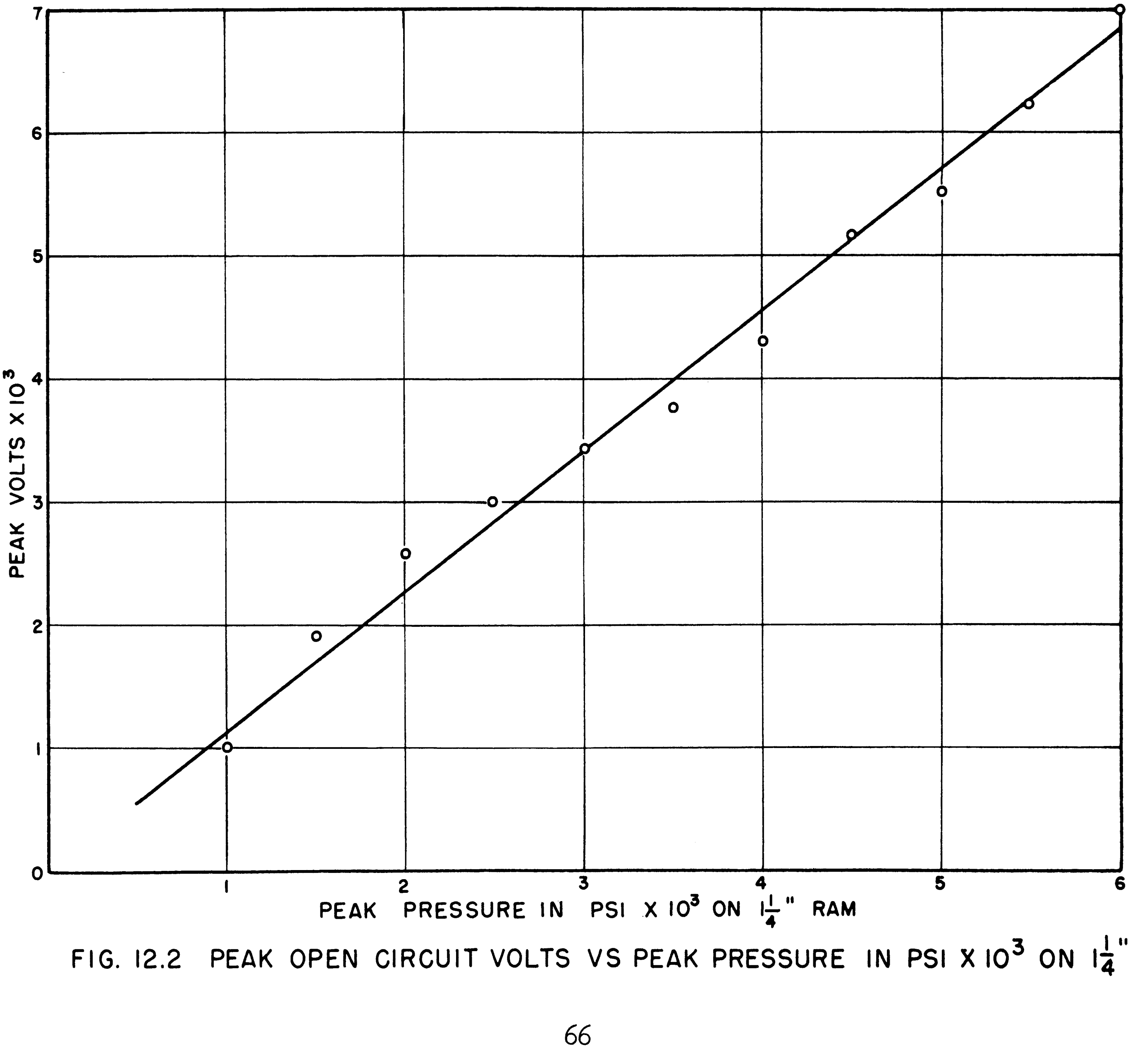


FIG. 12.2 PEAK OPEN CIRCUIT VOLTS VS PEAK PRESSURE IN PSI X 10^3 ON $1\frac{1}{4}$" RAM

the applied force in approximately 0.1 seconds. The peak open circuit voltage developed across the cylinder was measured by applying it to a voltage divider-scope combination as shown in Fig. 12.1. Figure 12.2 is a plot of peak open circuit voltage versus peak pressure (p.s.i. on 1-1/4" dia. ram) and indicates that the peak voltage generated is a linear function of the peak force. The teflon high voltage insulating pads served also to equalize the pressure applied to the specimen.

The average specimen pressure is obtained by multiplying the ram pressure by the ratio of ram to specimen areas, A_r/A_s. In this case $A_r/A_s = (1.25)^2 = 1.562$. The total force in pounds on the specimen is found by multiplying the ram pressure (in psi) by the ram area, A_r, (in square inches).

$$A_r = \pi/4 \ (1.25)^2 = 1.227 \text{ sq. in.}$$

At the highest pressure recorded (6000 psi, or 7360 lb. specimen force) no specimen damage was observed.

In a second experiment, the voltage divider and scope (in Fig. 12.1) was replaced by a laboratory spark gap with air at atmospheric pressure. For different spark gap spacings, the peak ram pressure which resulted in consistent firing of the gap was determined. Table 12.1 shows the results of these tests.

Spark Gap Spacing (inches)	Peak Pressure (psi on 1-1/4" ram necessary to fire gap)
1/16"	3000 psi
5/32"	3500 psi
1/4"	4000 psi

Table 12.1

12.2 Impact Experiment

As shown in Fig. 12.3, the hydraulic ram was replaced in the test setup by a drop-hammer. This allows a free-falling 7 lb brass slug to deliver a sharp impact to the specimen from various heights. In this case, the force and its duration are determined largely by the resiliency of the teflon pads; therefore, the peak voltage and its

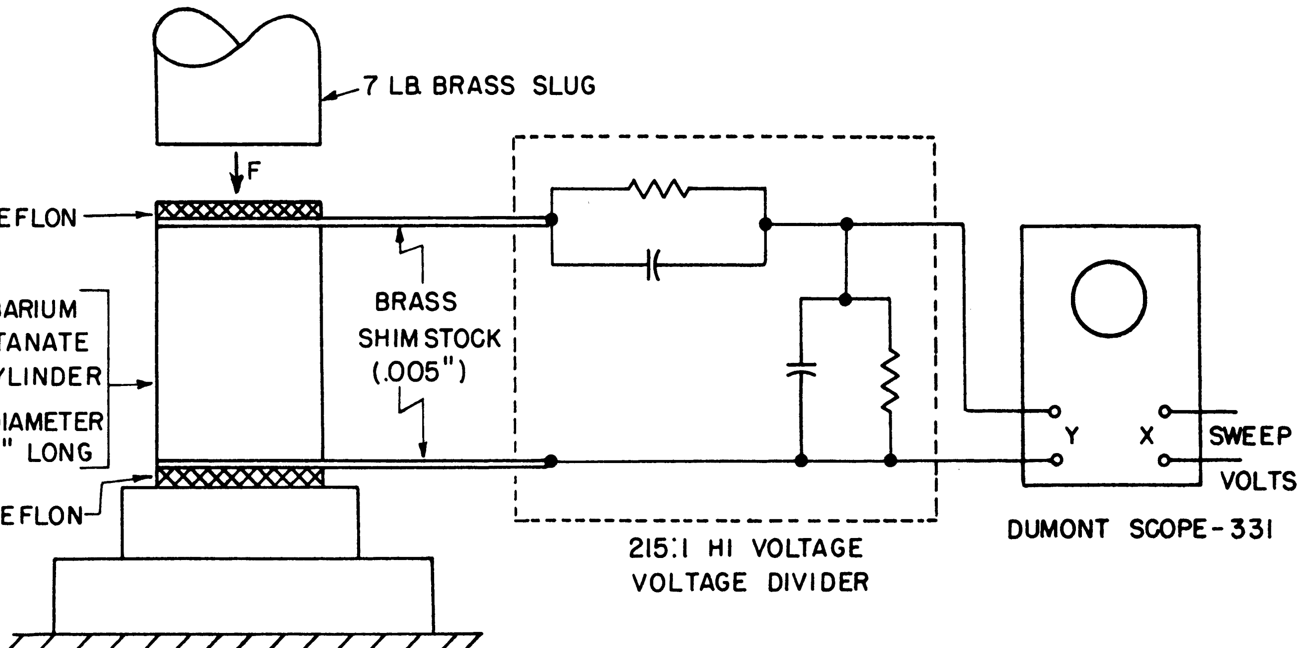


FIG. 12.3 IMPACT EXPERIMENT

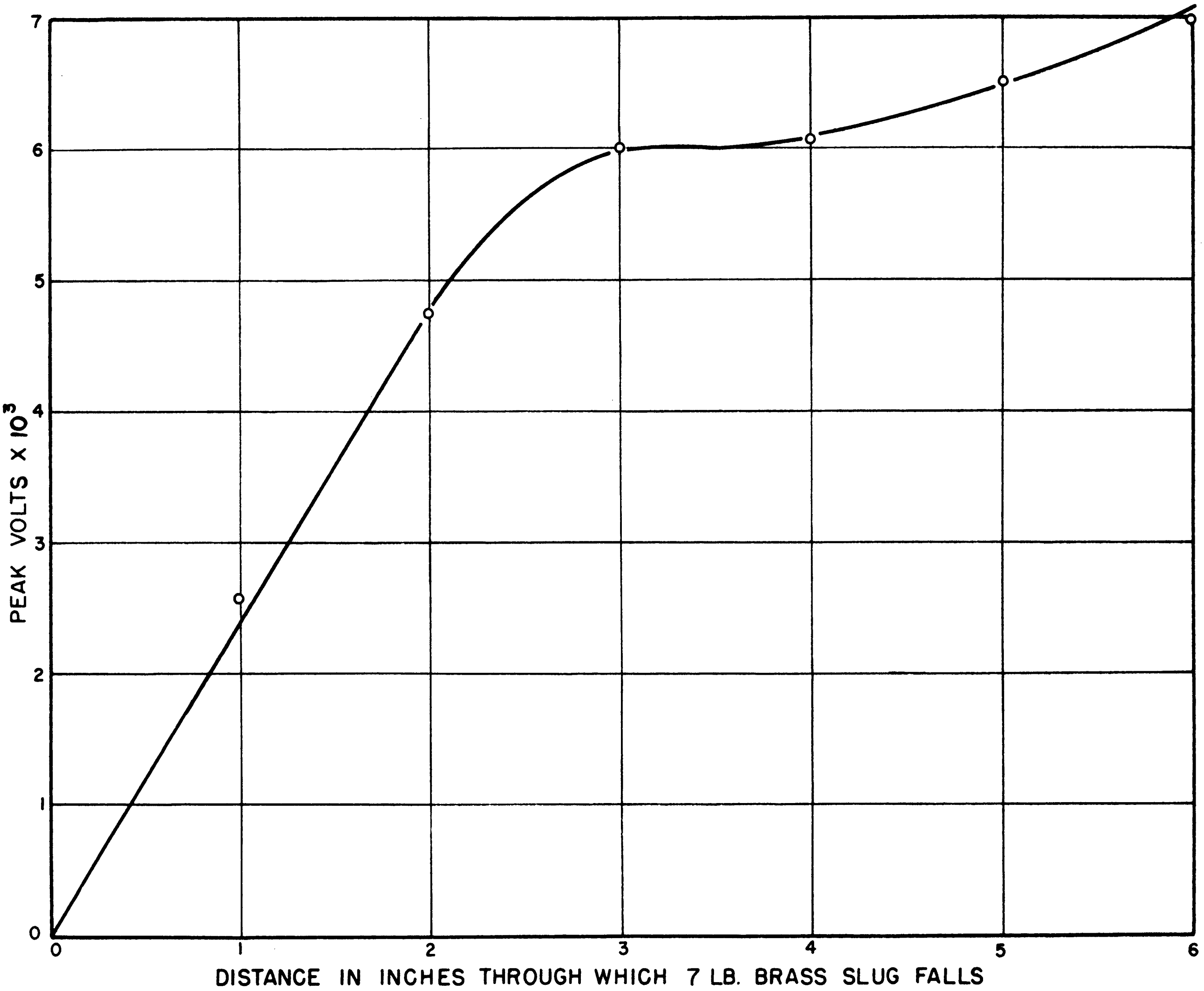


FIG. 12.4 PEAK OPEN CIRCUIT VOLTS VS DISTANCE THROUGH WHICH 7 LB BRASS SLUG FALLS

duration can be adjusted by proper design. In the impact tests, the voltage pulse duration was somewhat less than 2 milliseconds. The peak voltage is given by the curve in Fig. 12.4.

Using a spark gap as in the previous tests, the drop distance which would consistently fire the gap was determined. Results of these tests are given in Table 12.2.

Spark Gap Spacing in Inches	Distance in inches of free fall for 7 pound slug to fire gap
1/8	3.5
3/32	5
1/4	7

Table 12.2

12.3 Conclusions

As a primary power source for ignition in modern internal combustion engines, the piezoelectric voltage generator is not considered practical at the present time. In the use of the impact method, rather severe mechanical design problems arise. In addition, the impact noise is rather excessive.

When driven by the hydraulic method, such a generator may have other applications, as in triggering, or in future applications where transducers of this type are desired.

The specimens tested were rated by the supplier at an open circuit voltage of 30 KV peak with a force of 10^{10} dynes (11 tons), Under these conditions, the ceramic cylinder must be properly supported and the pressure equalized to prevent mechanical failure. No data are available at present on fatigue failure or operational lifetime of such units.

13. CONCLUSIONS

The capacitor discharge system shows considerable promise for automobile ignition. It appears reasonable to expect that a practical system design can be achieved in the near future using either mechanical contacts or a gas tube switch.

The success of the gas tube switch will depend upon redesign to obtain increased switch life. The success of the mechanical switching system will depend upon how well the bounce can be controlled. If the contact research is successful, mechanical contact switching may turn out to be the cheapest and most dependable switching means.

Power for the CD system can be furnished at present from a vibrator type power supply and later replaced by a transistor supply when the lowered cost of power transistors permits. Considerable success is anticipated for transistor power supplies because of the high efficiency obtainable.

The capacitor discharge system is superior to the standard ignition in its ability to fire fouled spark plugs and larger gaps under adverse engine conditions. To date, only one test has been run in which the fuel economy of a CD system was compared to that using a standard ignition. Although the results in this case were slightly in favor of the standard ignition, there are many reasons which indicate that the CD system can be modified to produce as good results on fuel economy as are presently enjoyed by the standard ignition.

14. PROPOSALS FOR FUTURE PROGRAM

14.1 Modification of CD System to Improve Fuel Economy

It is proposed to investigate the shape of spark pulse which will give best engine performance and fuel economy. With this information, it will then be possible to modify the CD system to approximate the required spark pulse shape without sacrificing the other advantages of the CD system.

14.2 Switching Means for the CD System

Research on triggered gaps and flash tubes will be extended to provide the best type of switch for the CD system.

14.3 Transistor Power Converter

A suitable transistor power supply will be developed which converts dc power at battery voltage to dc power at a voltage suitable for operation of the CD system.

14.4 Consulting Service

It is proposed that our technical personnel be placed at the disposal of the Chrysler Corporation for any type of electrical consulting service which may involve instrumentation, electronic design, or new product development.

APPENDIX A

DEFINITIONS OF SWITCH CHARACTERISTICS

Switch Characteristics

The following list of switch characteristics include all the variables that ar necessary for the design of the cold cathode gas switch.

1. Hold Off Voltage, E_{HO}

The hold off voltage is the minimum sustained DC voltage that does not produce conduction between the anode and cathode of the switch with no trigger applied. Two possibilities exist for the polarity of the voltage across the switch. Each of these possibilities must be considered in determining the hold off voltage.

2. Instantaneous Switch Voltage Drop, e_s

The instantaneous switch voltage drop is the voltage between the anode and cathode at any time, t. This voltage drop is a function of the age of the switch, the time following initial ionization and the current flowing through the switch.

3. Steady State Switch Voltage Drop, E_s

The steady state switch voltage drop is the voltage across the switch during conduction after sufficient time has elapsed to allow e_s to become independent of time with i_s constant. Thus, E_s is a function of the switch current but is not a function of t. A curve showing e_s as a function of t is helpful in clarifying this definition. See Figure B.1.

4. Deionization Time, T_D

The deionization time is the maximum time the switch must be off (i.e., no current flowing) before a voltage equal to E_s can be applied to the switch without causing the switch to ionize again. (Assuming no trigger).

2370 A-S3-6 MB 5-3-56

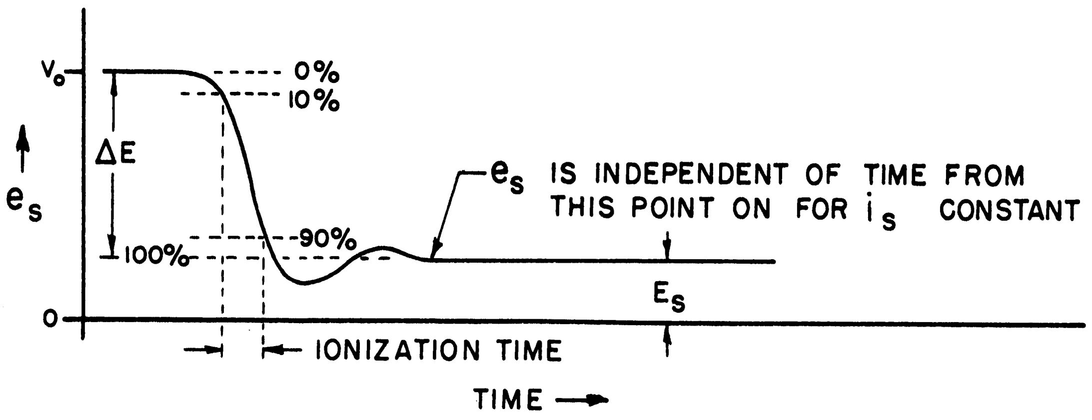


FIGURE A.1 INSTANTANEOUS SWITCH VOLTAGE DROP

5. Ionization Time, T_i

The switch ionization time is the time for the switch to change from 10% of ΔE to 90% of ΔE. Where E is the voltage drop across the switch prior to ionization, E_s is the steady state switch voltage drop and $\Delta E = E - E_s$. See Figure B.1 for a graphical illustration of this definition.

6. Instantaneous Switch Current, i_s

The instantaneous switch current is the current flowing through the switch at any time t. This current is a function of both the external circuit and the dynamic characteristics of the switch.

7. Peak Switch Current, I_{sp}

The peak switch current is the maximum value of i_s.

8. Trigger Voltage, E_T

The trigger voltage is the minimum voltage that must be applied to the trigger electrode to insure turning the switch on every time a trigger pulse is applied.

The trigger voltage is a function of the voltage between the cathode and anode of the switch before triggering and in general is not a straight line function (See Figure 6.15).

9. Dynamic Characteristics

The dynamic characteristics are the relationships of three variables: (1) the instantaneous switch voltage drop, e_s; (2) the instantaneous switch current, i_s, and (3) the time, t.

10. Photosensitivity

A cold cathode gas switch is considered to be photosensitive if the trigger voltage characteristic changes when the ambient light level is changed.

11. Switch Energy Loss, w_L

The energy loss of the switch is the number of joules dissipated as heat and radiated as light per single operation of the switch.

12. Switch Life, N_{SL}

The switch life N_{SL} is defined as the number of times that the switch can be turned on in a specified test circuit without the characteristics of the switch going beyond the limits defined by the following equations. The switch should be tested at 400 switch operations per second, representing top engine speed of 6000 rpm.

$$E_T = A(E_{TO})$$

$$E_S = B(E_{SO})$$

$$T_i = C(T_{io})$$

$$T_D = D(T_{DO})$$

where

E_{TO} is the nominal trigger voltage for a new switch.

E_{SO} is the nominal steady state switch drop for a new switch.

T_{io} is the nominal ionization time for a new switch.

T_{DO} is the nominal deionization time for a new switch.

The constants A, B, C, and D for these equations must be determined experimentally for each switch design. Experience will probably indicate that the first two expressions will be the inportant factors in determining the life of the switch.

APPENDIX B

COLD CATHODE GAS SWITCH CHARACTERISTICS

DEVICES	E_S	T_i	GAS	PRESSURE	ARC LENGTH	E_{HO}	N_{SL}
Amglo Switches "U"							
X1S1	60	4 μ sec	Xenon	210 mm	6 mm	1.1 KV	-
X2S1	50	4 μ sec	Xenon	150 mm	6 mm	1.1 KV	-
X3S1	50	5 μ sec	Xenon	90 mm	5.5 mm	0.8 KV	-
X4S1	60	5 μ sec	Xenon	50 mm	7.5 mm	0.65 KV	-
X1S2	-	-	Xenon	210 mm	6.5 mm	1.4 KV	-
X2S2	-	-	Xenon	150 mm	4.7 mm	0.8 KV	-
X3S2	-	-	Xenon	90 mm	5.2 mm	0.75 KV	+ 2.8 x
X4S2	-	-	Xenon	-*	6.5 mm	-	-
Sprague Switches							
FA-100	200	14 μ sec	Xenon	-	80 mm	2.0 KV	+ 3 x
FA-104	200	14 μ sec	Xenon	-	80 mm	2.0 KV	-
U of M Triggered Gap Switches							
Model 1	40	4 μ sec	Air	750 mm	0.25 mm	2.6 KV	-
Model 2	40	4 μ sec	Air	750 mm	0.25 mm	2.6 KV	-

\- Means that either the quantity is unknown or was not measured.

* This switch was supposed to have a gas pressure of 50 mm, but it had a hold off voltage in excess of 3 KV and therefore must actually have a considerably higher pressure.

\+ After this number of operations the triggering of the switch became erratic.

APPENDIX C

TRANSISTOR POWER SUPPLY REFERENCES

1. G. C. Uchrin and W. O. Taylor, "New Self-Excited Square-Wave Transistor Power Oscillator," Proc. I. R. E., Vol. 43, pp. 99; January, 1955.

2. G. C. Uchrin, "Transistor Power Converter Capable of 250 Watts DC Output," Proc. I.R.E., Vol. 42, pp. 261-262; February, 1956.

3. J. J. Ebers and J. L. Moll, "Large Signal Behavior of Junction Transistors," Proc. I. R. E., Vol. 42, pp. 1761-1772; December, 1954.

4. N. B. Saunder, "Designing Reliable Transistor Circuits," I and II, Electronic Design, March and April, 1955.

5. L. A. Griffith, "Power Transistor Temperature Rating," Electronic Design, June, 1955.

6. H. T. Mooers, "Design Procedures for Power Transistors," I, II, and II, Electronic Design, July, August and September, 1955.

7. G. H. Royer, "A Switching Transistor DC to AC Converter Having an Oputput Frequency Proportional to DC Input Voltage," AIEE Winter General Meeting, Paper No. 55-73, January 31, February 4, 1955.

8. R. R. Smyth, "Transistors as Power Conversion Devices," IRE-AIEE Conference on Transistor Circuits, University of Pennsylvania, February 18, 1955.

9. U. M. Thompson, "The Design of Transistor DC to DC Transformers for a High Degree of Reliability and Stability," 1956 Transistor Circuits Conference, sponsored by I.R.E., A.I.E.E., and the University of Pennsylvania, Philadelphia, Pa., February 16-17, 1956.

10. D. A. Paynter, "Single Power Transistor DC-DC Converter," 1956 Transistor Circuits Conference (See No. 9 above).

DISTRIBUTION LIST

No. of Copies	
15	Chrysler Corporation
1	Folsom, Richard G.
1	Attwood, Stephen S.
1	Boyd, Joseph A.
3	Orr, Lyman W.
1	Roberts, G. A.
1	Schulte, H. F., Jr.
1	Otterman, Joseph
1	Butler, T. W., Jr.
5	Electronic Defense Group

UNIVERSITY OF MICHIGAN
Department of Electrical Engineering

ERI Project 2370-2
Progress Report No. 1
May 1956

ERRATA SHEET

Page iii - Change List of Illustrations from page iv to read page v.

Page iii - Change Abstract from page vii to read page viii.

Page 23 - Line 28 - Change 400 miles to 250 miles.

Page 39 - Line 5 should read -- assemblies insulated from ground as in Fig. 6.2 and connected as a single-pole double-throw switch. The

Page 40 - In legend of Fig. 8.3 delete line 11.

Page 55 - Fig. 10.1 Change T_1 of each part of figure to read TR_1.

Page 55 - Fig. 10.1 Change T_2 of each part of figure to read TR_2.

Page 72 - Line 20 Change Fig. B.1 to read A.1

Page 74 - Line 4 Change Fig. B.1 to read A.1

Page 74 - Line 27 Add to end of sentence -- in a capacitor discharge circuit.

Page 77 - Reference No. 6 Change I, II, and II to read I, II, and III.

Page 78 - Distribution List -- Change last entry to read

4 Electronic Defense Group
Add: 1 Weir, Alexander, Jr.

L. W. Orr
May 23, 1956