Final Report

RESEARCH ON RELIABLE AND RADIATION INSENSITIVE PULSE-DRIVE SOURCES FOR ALL-MAGNETIC LOGIC SYSTEMS

Prepared for:

JET PROPULSION LABORATORIES
4800 OAK GROVE DRIVE
PASADENA, CALIFORNIA

CONTRACT 950104 UNDER NASw-6

By: *J. A. Baer, C. H. Heckler, Jr.*

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SRI Project No. 3729

Approved:

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CONTENTS

ILLUSTRATIONS

I INTRODUCTION

Spacecraft applications demand reliable operation of electronic equipment for extended periods of time. This electronic equipment must be lightweight and have high power-efficiency; it must operate with both high accelerating forces and zero gravity. In many instances operation is to be unaffected by irradiation of high energy particles.

For many years the single-path magnetic core, or toroid, has been widely used in digital electronic equipment; more recently multipath cores and schemes for their utilization for logic and memory have been developed and used. Integral to this digital magnetic equipment is a source of electrical power having as its output a repetitively occurring pulse of current. This pulse-drive source, or clock, is typically composed of semiconductors or electron tubes. For many applications these are satisfactory pulse drivers, but for spacecraft applications the use of electron tube and semi-conductor devices is a potential source of difficulty. Minimization or elimination of the use of these devices would be a significant step toward achieving reliable operation over extended periods of time.

This project is addressed to the task of minimizing and, hopefully, eliminating electron tube and semiconductor devices in a pulse generator for spacecraft applications. Such a driver should be suitable for use as the source of pulse power for digital magnetic equipment.

II SUMMARY AND CONCLUSIONS

In the course of this project we have found many potential means for suitable pulse generation. Feasibility has been demonstrated in some instances, while in others the ideas are in the embryo stage and will require additional investigation to determine their worth.

In one instance we have successfully developed a pulse generator and applied it to driving a large number of digital magnetic circuits. The method had been previously developed for radar applications; it takes an alternating current input (available in present-day spacecraft) and shapes it into a series of current pulses suitable for driving magnetic circuits.

Further, we have re-examined a class of devices known as "interrupters" that were the subject of extensive investigation in the early days of the electrical industry. These interrupters are a type of inverter, because their outputs contain ac components. Moreover, certain interrupters can convert direct current into unipolar pulses of current that should be suitable for driving magnetic circuits. Additional investigation of these interrupters seems warranted.

III SCOPE AND OBJECTIVE

A. General

The objective of this project is to devise and investigate unconventional means for the generation of pulses of electrical energy. These pulse drivers are to function as the source of clock power for digital magnetic logic systems, although no particular system application is to be fulfilled either in terms of hardware or in terms of driver specifications. The anticipated unmanned-spacecraft needs in two years as well as five years from now are to serve as guides in determining the environmental and operational requirements.

B. Driver Characteristics

The following general characteristics are deemed desirable for a pulse driver in this feasibility investigation:

1. Reliability

The paramount characteristic that is sought is that of reliability. Reliability in the absence and in the presence of radiation are both of concern in this project. Reliability in the absence of any radiation is of importance to near-future applications, with radiation effects becoming more important when the needs in the more distant future are considered. The radiation environment has not been defined for purposes of this project, but the best available information has been used.

In keeping with the reliability emphasis, the number of semiconductor devices required is to be minimized. In the proposal for this project, it was stated that semiconductors were not to be used. From the outset, however, JPL personnel have recognized that the magnitude of the driver problem is greatly increased by forbidding the use of semiconductors; further, they recognized that a driver using only a small number of semiconductors would effect a considerable stride in the right direction. Therefore, JPL stated that the use of a restricted number of semiconductors would be acceptable as an initial step in solving the pulse generation problem, while at the same time affirming that pulse generation without semiconductors would be more desirable. This statement is consistent with JPL's current approach to the logic system design in which magnetic cores are used in conjunction with a small number of semiconductors. The statement is also consistent with the current practice in the spacecraft power systems using transistorized inverters.

2. Non-Volatility

There are two aspects to this characteristic: one is related to reliability; the other is an operational characteristic. In the event that the power supplied to the pulse generator should fail for a time in such a way that the value of some parameter, e.g. voltage, lies outside the specified tolerance limits, it would be desirable to have the driver cease operation until such time as the power source is operating properly. This is nearly the same as specifying that the driver put out only good pulses. The other non-volatile aspect is that when the pulse generator is turned on and off by a command signal, only pulses of the proper phase (odd or even), amplitude, and shape are to be supplied by the pulse generator--(again, only good pulses are to be produced).

It is to be noted that this non-volatile characteristic of producing only good pulses is a requirement not imposed on pulse generators for other applications.

3. Weight

For obvious reasons it is desirable to have a spacecraft borne pulse generator weigh as little as possible.

4. Repetition Rate

The computation required aboard an unmanned spacecraft does not dictate a high repetition-rate for the clock source. For this reason speed is not emphasized. A repetition rate of a few kilocycles per second is quite adequate, and even 60 cps is of interest. Because of this slow repetition rate, and because some of the in-flight computations occur over a long period of time, it is desirable to be able to make ground checkout of the computation system at an accelerated rate.

This imposes the requirement that the pulse generator be operable at a higher repetition rate, say 80 kilocycles per second, for ground checkout purposes. It would be acceptable, however, to use an auxiliary pulse generator for this ground checkout if it is not feasible to operate the "in-flight" pulse generator at this high repetition rate.

5. Current Pulse

The current pulses required for magnetic logic systems have a time duration of the order of 2 to 10 μsec and a peak amplitude of the order of 0.5 to 5 amps. The peak voltage required is directly dependent upon the particular circuit under question.

Two outputs are necessary, each having the same or similar current pulses available, displaced in time one from the other (odd and even pulses).

6. Efficiency

Because of the problems present in obtaining power for the operation of equipment aboard a spacecraft, it is highly desirable that the means used for pulse generation be efficient. The minimum acceptable efficiency cannot be specified, but something of the order of 50% is probably reasonable.

7. Temperature

Although any driver in a spacecraft would be subjected to temperature changes, for the purposes of this feasibility investigation the problems relating to operating in temperature extremes can be ignored.

8. Acceleration Forces

The driver is to operate during the power phases of the flight as well as the non-powered phases; hence, operation in both high "g" and zero "g" conditions is necessary, as is operation in any orientation.

C. Specific Objectives

In order to give specific direction to the program and to provide a means of measuring our progress, we decided (in the second quarter) that several generation schemes, each having specifically defined characteristics, should be sought. It is intended that these "specifications" would match the changing needs of spacecraft in successive years. Our position is that the pulse driver problem can best be solved in several steps, that is to say, the pulse generator which will function satisfactorily for the spacecraft in operation today will probably not be satisfactory in two years, nor will one developed to be satisfactory in two years be satisfactory in five years. Moreover, even if one could jump directly to the five year solution, this might not be compatible with today's spacecraft. It therefore seemed prudent to lay a good foundation at the outset in anticipation of continued effort beyond this present contract, and to try to solve the problem in a step by step manner.

For these reasons we decided that four different specific objectives were pertinent to this technical program.

Objective (1) Design, construct, and test one laboratory model of a pulse generator that has the following capabilities:

- (a) Repetition-rate of 2.4 kc
- (b) 80-kc repetition-rate for ground checkout of system
- (c) Operable from 2.4-kc square wave and/or dc
- (d) Eight month lifetime in the absence of radiation
- (e) Potential ability to withstand an operating environment of -10°C to 65°C (with 120°C storage), 15 g acceleration, and a zero gravity field.

Objective (2) Show feasibility by means of a breadboard of a pulse generator having the following capabilities (with reduction to a laboratory model possible early in 1963):

- (a) Repetition-rate of 20 kc
- (b) 80-kc repetition-rate for ground checkout of system
- (c) Preferably operable with dc
- (d) Two-year lifetime in the absence of radiation

(e) Potential ability to withstand an operating environment of -10°C to + 65°C (with 120°C storage), 15 g acceleration, and a zero gravity field.

Objective (3) Acquire one (rational) idea for a pulse generator that is compatible with the advent of nuclear power, viz., mercury vapor turbine, magnetohydrodynamic generator,

Objective (4) Make a compilation of potentially useful concepts.

The specifications in Objectives (1) and (2) are rather arbitrary, but nevertheless useful. Temperature effects were singled out earlier as being of no particular importance for the purposes of this project; even so, we felt that some boundaries should be given. The 2.4 kc repetition was selected because a 2.4 kc square wave is currently available in the spacecraft, and this repetition-rate is within the general region of interest; the 20 kc repetition-rate is quite arbitrary. The laboratory model in (1) is one step closer to a practical solution than is the breadboard in (2). Radiation effects are ruled out of consideration in (1) and (2) but are implied in (3).

IV METHOD OF APPROACH

Aside from gaining knowledge about spacecraft problems, the first problem was to acquire some possible means of generating pulses within the constraints given. At the outset neither brute force nor novel techniques that might lead to a solution were apparent.

The proposal for this project indicated that a preliminary survey and evaluation of prospective means for achieving pulse generation would be made. This survey was successfully carried out on a continuing basis throughout the contract period. As time progressed, the emphasis has gradually shifted away from this survey effort to an evaluation of the ideas on hand.

Because of the initial dearth of ideas it was decided that "blue-sky" schemes must be looked upon with favor. Furthermore, an uninhibited approach was taken concerning the form of energy to be involved in any pulse generation idea; viz., mechanical, chemical, and heat energy as well as electrical energy, were considered appropriate forms.

The survey was effected by searching the literature and by seeking ideas from various SRI staff members to whom the problem at hand had been described. The evaluation was effected by reasoning and by laboratory investigations in light of the driver characteristics and the specific objectives given in Section III.

The literature search has two aspects: formal searching by the accepted library technique, and "day-by-day" searching of the literature by engineering personnel. This latter literature screening has led to most of the ideas that have been of interest to this project. The formal searching was of a limited nature and was begun late in the contract period; the results of this search have not been fully assimilated. The first formal search was made through ASTIA (at no direct charge to this project or to SRI). A second formal search has not been completed. The subject of this second search is "interrupters", an old name for a switching device that alternately connects and disconnects an electrical circuit to a dc source. The term per se was uncovered in the day-by-day searching. The Franklin Institute, the U. S. Department of Commerce, and the Library of Congress were contacted concerning this formal search; the search is being conducted by the Library of Congress.

The day-by-day searching covered many subjects, each of which is pertinent to the problem. In an activity such as this it is inevitable that many blind alleys will be followed, some to greater depth than others. In this project certain paths have been followed to the point that we can assert in some instances that a desirable method of pulse generation appears feasible; in other instances the results of the investigation are not conclusive and further work is warranted. The scope of this search can be described by listing some of the generic subjects which have been reviewed:

(1) Power sources
(2) Energy conversion
(3) Pulse generation
(4) Inverters (and converters)
(5) Oscillators
(6) Interrupters
(7) Commutators
(8) Contacts
(9) Switches
(10) Modulators
(11) Nonlinear magnetics
(12) Waveform shaping
(13) Radiation effects
(14) Reliability

It is evident that some of these terms overlap part of the area covered by another term.

Some of the above terms deserve closer examination. Energy conversion, i.e. changing radiation, chemical, atomic, thermal, etc., energy into electrical energy, is a problem that has been receiving widespread study for space applications. As part of the survey conducted during this project the energy conversion work has been partially monitored. There are several reasons for this monitoring, one of which is our attempt to consider pulse generation as an integral part of the spacecraft power system rather than as an isolated problem. It seems reasonable that a systems approach, while admittedly more difficult, is the most practical approach. Not only must any pulse-drive source be compatible with the energy sources available on the spacecraft, but also it is desirable to minimize the number of energy transformations that are required, and thereby increase over-all efficiency. An example of this latter might be the use of mechanical motion in pulse generation when such motion is available, viz., when a mercury vapor turbine is a part of the spacecraft power system. An additional reason for this monitoring is that in the search for the so-called "unconventional" energy converters, the researchers might uncover a phenomenon which would convert some form of energy directly into ac or unipolarity pulses of electrical energy rather than dc. Such a phenomenon might not be of direct interest to those in the energy conversion field, but it is conceivable that it would be of interest to this project. The anomalous ac generation that has been observed in cesium cells might be in this category.

The subject of inverters is pertinent to this work in keeping with the systems approach. In the power systems where electrical energy in the form of dc is the result of an energy conversion step, this dc must at some stage be changed to ac (or unipolarity pulses). The inverter should be as reliable as the pulse generator itself.

In interrupters, dc can be changed directly to pulse energy without first being changed to alternating-current energy. These devices might be considered a special class of inverters; they are described in detail later in this report.

The last generic subjects to be expanded are nonlinear magnetics and modulators. Since the pulse generator is to be used as a driver for a magnetic logic system, the use of magnetic circuitry in the pulse generator could result in reliability in the generator of the same order as that of the logic system itself. For this reason it was intended from the outset to explore the possibility of pulse generation using nonlinear magnetics. The subject modulator is appropriate since certain types of modulators produce pulses. (The Melville pulse compression network, described below, was developed as a modulator for radar system; it uses nonlinear magnetic devices).

This survey has resulted in a greater number of plausible pulse-generation schemes than expected. Some of these schemes are applicable to long range objectives and some to short range objectives of this program. Some ideas are quite nebulous and some are quite specific. Several ideas that have received the most attention will be described in the sections of the report that follow.

V SPECIFIC INVESTIGATIONS

A. Introduction

Of the many ideas that were given at least brief examinations, we have given greatest attention to the Melville pulse compression network, mercury interrupters, and the Wehnelt interrupters; these are described in the following sections of the report. The Melville network was the first to come to our attention, and has been investigated to the point that it has been successfully applied as a driver for magnetic logic in another SRI project. The Melville network makes use of square loop magnetic cores and is applicable to Objective (1) in Sec. III.

The mercury and Wehnelt interrupters, although discovered to be the subjects of considerable work in the late 1800's, were not developed as pulse generators to the same degree that the Melville network has been. We have conducted some tests on breadboard versions of these interrupters, and have investigated their principles of operation to the point that we can affirm that further work in this direction is warranted.

B. Melville Pulse Compression Network

1. Background

An area of interest expressed in the proposal for this project is that of applying non-linear magnetic phenomena to the generation of pulses. Since we are searching for means of generation that are compatible with all-magnetic (and other magnetic type) logic systems, the possibility of using devices that belong to the same generic family as the logic devices is a natural point to consider. In inquiring into the function that non-linear magnetic devices can perform we asked the question, "Can these devices be used to change direct current to alternating current?". Although square loop magnetic cores are active transducers in magnetic logic systems that are supplied with pulses of current, intuitively it seemed to us that they were not active transducers in the inverter sense. Our intuition is confirmed in a paper by R. J. Duffin[1],*

*References are grouped at the end of the report.

who demonstrated that "...system whose primary resistors are quasi-linear cannot convert direct current to alternating current. ....arbitrary magnetic coupling is permitted... This coupling may result from ferromagnetic material with arbitrary hysteresis." This means that when the prime power source is dc, an inverter of some type, in addition to the non-linear magnetic devices, must be in the circuit. The non-linear magnetic devices can be used only in the wave-shaping function; this is the case in the Melville network.

The family tree for this network has its roots in magnetic-type harmonic generators use in carrier telephone systems in the 1930's[2]. These "coil pulsers" comprise what we would now call a one-stage, shunt-type, bi-cycle mode, Melville network. Apparently the series-type network and the cascading of several stages were conceived by W. S. Melville[3] in Great Britain.

Following Melville's publication of his work, considerable investigation of this circuit has taken place in this country largely under government sponsorship. Our first knowledge of the circuit came from a government report.[4] This report and others cover many aspects of the circuit, having in view its application to radar modulators (see Bibliography). Subsequent to the time we started our investigation of this network for our problem, we learned that its application to magnetic circuits has been considered by the Sandia Corporation and possibly by Ampex Computer Products Co.

2. The Idealized Network -- Approximate Theory

No contributions to the theory of circuit operation were made as a part of this project; however, it seemed desirable to collect together some of the various contributions and present them in this brief manner.

The terminal characteristics of the Melville network are

(1) An input consisting of an alternating voltage and possibly a direct voltage, and

(2) An output consisting of pulses of voltage across a resistance. There is no dc component in the output.

Figure 1 shows the time relation between the input voltage and output voltage. In this instance a sinusoidal voltage input is illustrated; other alternating voltage waveforms can be used,[5] e.g., a square wave. In the bi-cycle mode the first output pulse occurs at approximately π/ω after the beginning of the input sine wave; in the uni-cycle mode the first pulse occurs at approximately $2\pi/\omega$ after the beginning. Note that in the steady state condition there is no dc component in the output for the uni-cycle mode.

Before looking at the entire network we shall consider the circuit shown in Fig. 2a to understand the compression principle. In this circuit

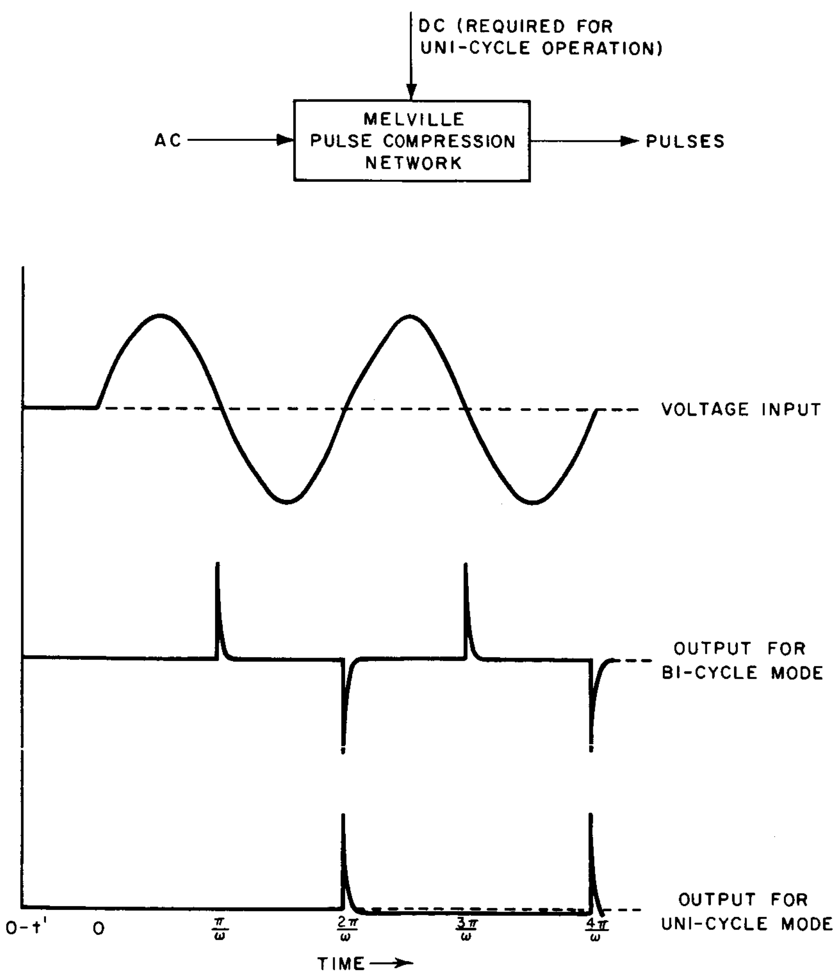


FIG. 1 INPUT AND OUTPUT VOLTAGE, MELVILLE NETWORK

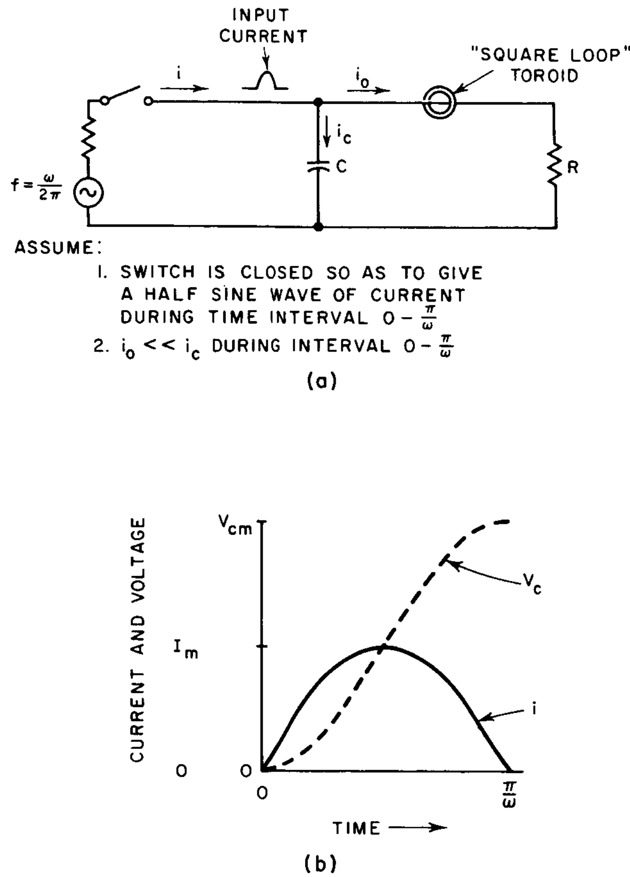


FIG. 2 CHARGING AND SWITCHING INTERVAL

the switch is closed during the time interval $0-\pi/\omega$ and is opened at all other times. During this time interval, a half sine wave of current I sin ωt flows from the generator. This current is virtually the same as the current i_c during this interval since $i_o \ll i_c$. The voltage across the capacitor during the interval is

$$v_c \cong 1/C \int i \, dt = V_{cm} (1 - \cos \omega t) \quad ;$$

where V_{cm} is $I/\omega C$.

The input current waveform and the capacitor voltage waveform during this interval are shown in Fig. 2b. Now we turn our attention to the current i_o during this same time interval. Although this current is small compared to i_c, it is just great enough to cause the core to switch. The core is assumed to be saturated in the counterclockwise direction before the switch is closed. When i_o begins to flow, the core begins to switch toward the saturation state in which the flux is all in the clockwise direction. This saturation state is reached just at the time π/ω, the time that the switch is opened. At this instant the circuit shown in Fig. 2a can be redrawn as shown in Fig. 3. The toroid has been replaced by a coil having an inductance equal to the saturation inductance of the toroid. The voltage on the capacitor has the value V_{cm} and will

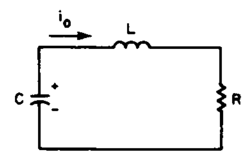


FIG. 3 CIRCUIT FOR DISCHARGE INTERVAL

be discharged through the inductance and resistance. If the circuit parameters are selected to effect critical damping, then the current i_o during this interval will have only positive values and will have a rise time (from) zero to peak of

$$T_p = \sqrt{LC} \quad .$$

We can define the pulse width of this critical damped waveform as

$$T_w = \pi\sqrt{LC} = \pi T_p$$

(Note that this pulse width corresponds to the interval of a half sine wave for an LC circuit having no resistance.)

Now let us return to waveform shown in Fig. 2b. We note that the area under the capacitor voltage waveform is $(\pi/2)V_{cm}$ volt seconds. This volt-time integral is of course equal to the volt-time integral across the toroid and resistor in series. The voltage across the toroid during this charging and switching interval is much greater than the voltage across the resistor. For the toroid to switch from one saturation state to another as described, the flux-turn product N $(\Delta\Phi)$ of the toroid must be equal to $(\pi/2)\ V_{cm}$.

Denoting the time interval π/ω by T_c, we can write

$$T_c/T_w = \frac{(2/V_{cm})\ N\ (\Delta\Phi)}{\pi\sqrt{LC}} \quad .$$

This defines the compression ratio for this circuit; ratios of 3 to 30 are typical. The capacitor current waveform shown in Fig. 4 illustrates the compression that has been achieved. Note that the toroid parameters that affect the compression ratio are $N(\Delta\Phi)$ and $\sqrt{L}$; their ratio is independent of the number of turns, N. Also note that the output current

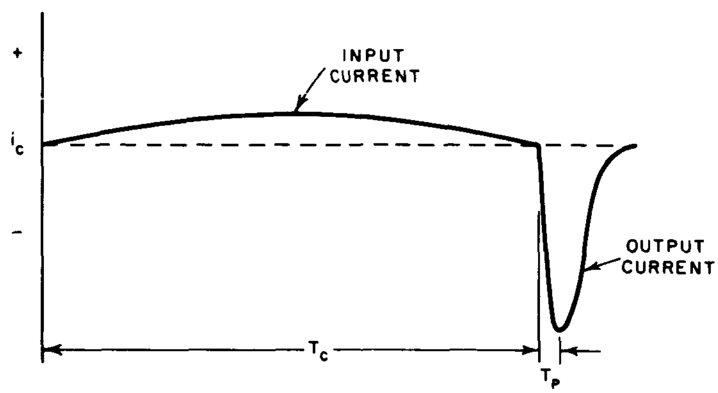
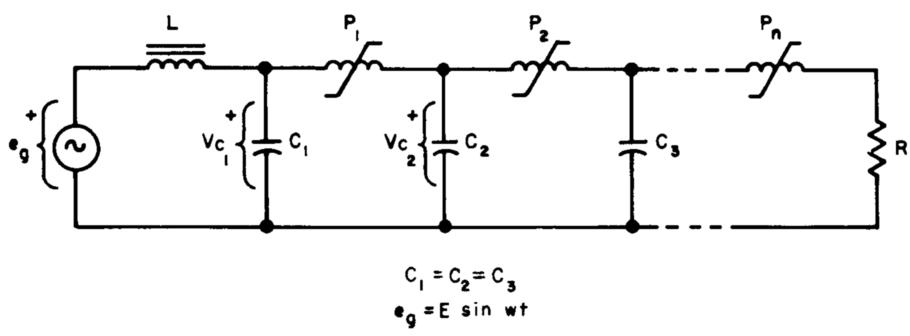


FIG. 4 CAPACITOR CURRENT

pulse occurs after the toroid has completed its switching. The output current drives the toroid far into the saturation region; the magnetomotive force applied at this time may be 1000 times that required to switch the toroid.

Fig. 5 shows the entire network for the series circuit, bi-cycle mode. The square loop toroids are indicated by P_1, P_2, and P_n. These have been termed "pulsactors" and "thyractors" in the literature. The term pulsactor is used here. A pulsactor is usually a toroid made from metal tape, such as Deltamax*. The element designated "L" is a linear inductor.

Circuit operation can be understood by dividing the circuit into three sections and applying the compression principle described above.



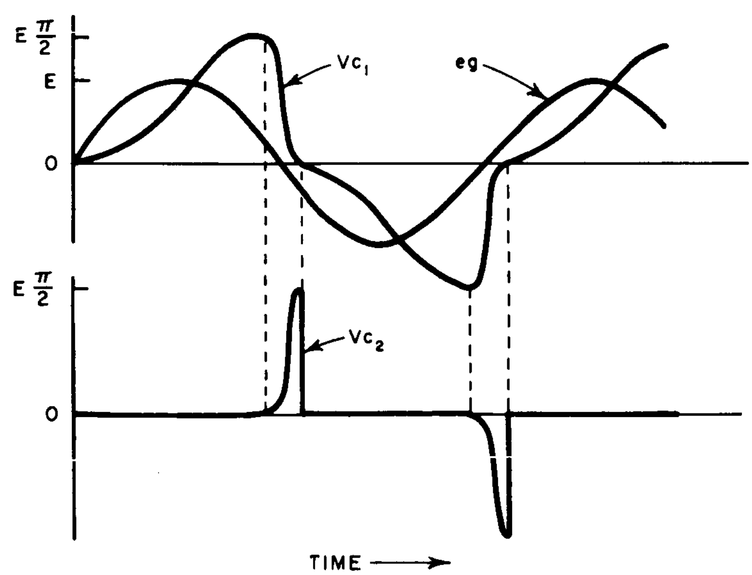


FIG. 5 SERIES CIRCUIT, BI-CYCLE MODE

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* T. M. Arnold Engineering Co.

The output section consists of the load resistance R, the pulsactor P_n, and the capacitor C_n. The intermediate section consists of all the elements between the output section and P_1; the input section consists of the generator, L, C_1 and P_1. One cycle of operation will be explained for the three sections of the circuit, beginning with the input section.

Assume that all pulsactors are initially magnetized to their maximum residual flux density condition; pulsactor current flowing from left to right in Fig. 5 will be in the direction to cause switching. The series resonant frequency of the elements L and C_1 is to be the same as the frequency of the generator voltage (this is not necessarily desirable in a practical circuit)[6]. Assume that the generator voltage is initially at zero and that it then starts to go positive in a sinusoidal manner. As before, when the volt-time product across the capacitor C_1 equals the flux-turn product of the pulsactor, the pulsactor will saturate. This is designed to occur at (or near) the time when the input voltage goes to zero. The pulsactor, then, has switched flux from one remanent state to the other saturation region (not remanance yet) during one half cycle of the input voltage.

The capacitor C_1 now tries to discharge. One discharge path is through the linear inductor L, and the other is through the nonlinear inductance of the pulsactor P_1 in its saturation region. The discharge takes place primarily through P_1 into C_2. The inductance of P_1 when saturated is much smaller than that of the coil L, so practically all of the charge can leave the capacitor through P_1 before the amount through L has had time to build up to any appreciable value. Likewise the generator voltage has not had time to change appreciably. During the discharge of C_1, P_2 is in a high impedance condition, i.e., it is switching from one remanent state toward the other, so the discharge current flows mainly into the capacitor C_2. This operation is quite similar to that described in the hypothetical circuit above, and the current into the capacitor C_1 has been compressed by the discharge of C_1. When the discharge is completed, P_1, is at remanence.

It was stated above that during the charging of C_1 there is a small amount of current going through P_1, that is, the current necessary to cause P_1 to switch. This current has many paths into which it divides after leaving P_1; most of it flows through the remaining pulsactors and the load resistance. This current in the remaining pulsactors is in the direction which, at this time, would tend to switch them. Assuming that the core materials and geometry are the same for all of the pulsactors, and that the number of turns on each pulsactor is less than the number on its neighbor to the left, this current will have too small an amplitude to bring any pulsactor except P_1 up to its switching threshold. When the material and/or geometry are not the same for all pulsactors, then the effect of this current must be considered. The fact that pulsactors have a threshold value of current for switching is ignored in the usual design procedures.[7]

Referring again to Fig. 5, we have traced the operation of the input section from the time that V_{C1} was initially zero, increased up to $E\pi/2$, and then decreased again to zero. We now turn our attention to the intermediate section of the network. This section may consist of several pulsactor-capacitors combinations; each combination is referred to as a stage. (The input section of the network has one stage.) When C_1 is discharging into C_2, the current waveform is a half sine wave. This is the same waveform that was used in charging the capacitor in the hypothetical circuit, so this part of the operating cycle has been explained. In the practical circuit, however, there is no physical switch to open after C_2 has been charged. After C_2 is charged, it will attempt to discharge through P_1 and through P_2. Current to the left through P_1 is now in the direction to cause it to switch while current through P_2 will flow in the direction which will cause it to be driven further into the saturation region. The current is, therefore, steered into P_2 and C_3. The discharge of C_1 and of C_2 takes place, ideally, in a lossless circuit rather than a critically damped hypothetical circuit. Assuming a lossless network and no current flow to the left through the pulsactor, all of the charge on one capacitor is transferred to the next capacitor. Figure 5 illustrates this lossless transfer in that the peak voltage value is the same on both C_1 and C_2; the capacitance value of the capacitors is made equal to effect this complete charge transfer.[8]

The transfer of charge from one capacitor to the next continues to progress in the circuit from left to right until the output stage is reached. This stage is critically damped as was the hypothetical circuit, so (ideally) all the energy stored in the last capacitor is delivered to the load resistor.

Since the transfer of charge down the line takes place in a short time interval, the generator voltage does not have time to increase negatively to any appreciable extent. As an approximation, we can consider the negative half-cycle of operation to begin with no currents in the circuit, except that which is an immediate consequence of the generator voltage. The pulsactors are all in the opposite remanent state from that which they were in for the positive half-cycle, so the operation proceeds as before (except for polarities).

The discussion of the Melville network operation so far has dealt only with the series circuit in the bi-cycle mode. This mode is characterized by two output pulses per input cycle, one pulse positive and one negative with respect to the common connection. The uni-cycle mode, on the other hand, is characterized by one output pulse per input cycle, with a small current amplitude of opposite polarity occurring throughout the interpulse period. There is no dc component in the output. Figure 6 shows the series type circuit for the uni-cycle mode. The only topological difference here is the addition of the dc bias windings. There are means of eliminating the bias, under certain conditions, for all pulsactors except P_1.[8,9] For our purposes it will be sufficient to consider the case where all pulsactors have a bias winding.

In Fig. 6 the cores are initially saturated, as indicated by the bias windings. The first half-cycle of operation is seen to be approximately the same as it is for the bi-cycle mode. However, at the end of this first half-cycle, P_1 does not saturate. The pulsactor is designed to saturate just as the voltage across C_1 passes through zero, so the pulsactor starts switching in the other direction at this time. By the time the input sine wave has completed its second half-cycle the pulsactor again saturates. This time the voltage across the pulsactor and C_1 is a negative maximum, so the saturation permits C_1 to begin its

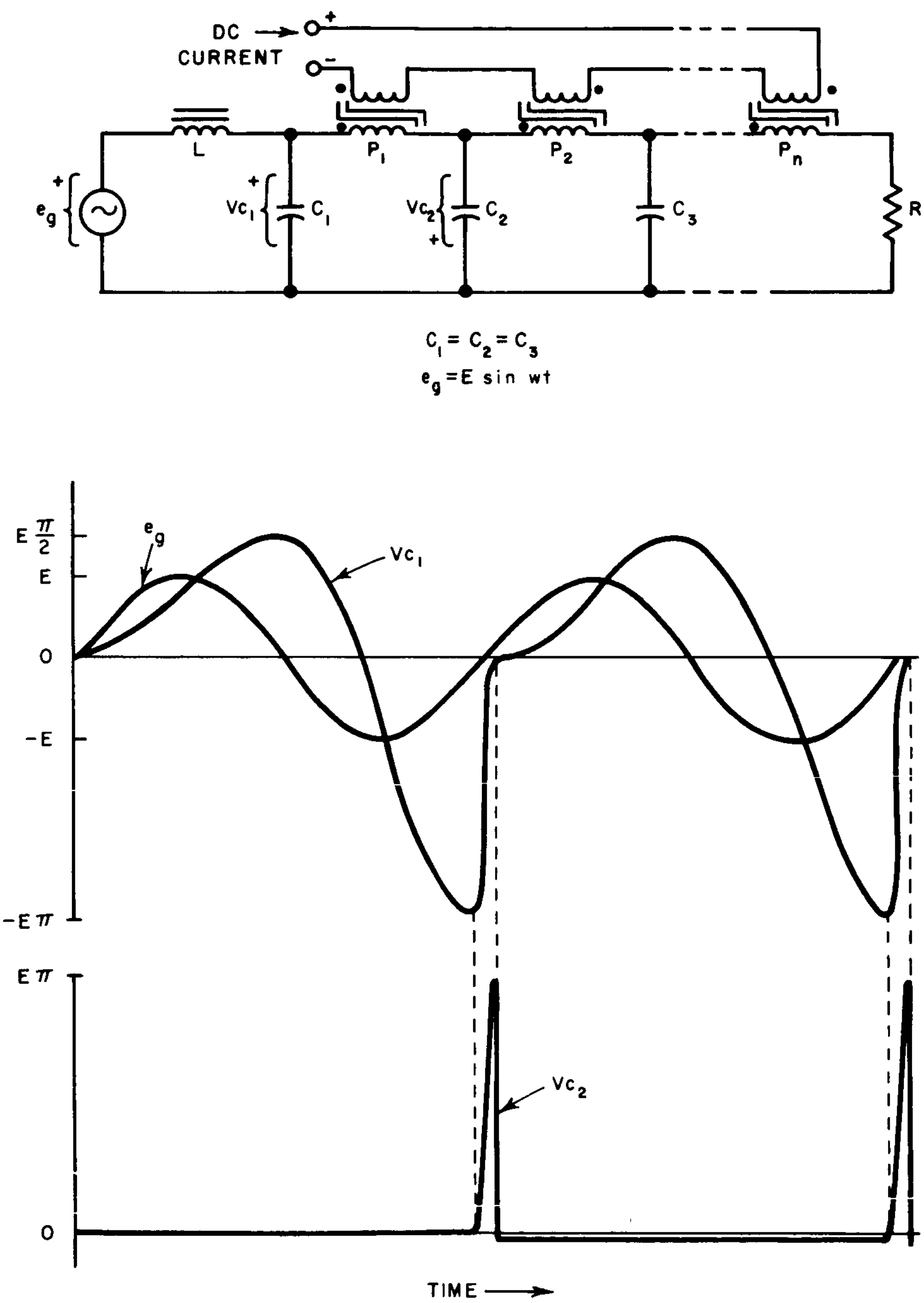

FIG. 6 SERIES CIRCUIT, UNI-CYCLE MODE

discharge into C_2. When this discharge is completed, the pulsactor P_1 is in the same state as it was for the start of the first half-cycle; current in the bias winding tends to maintain the core in this state. This dc current in the bias winding of P_1 can be looked upon as being required to oppose the core switching up until the time that the capacitor voltage waveform passes through zero, and then aiding the switching until P_1 saturates; actually, the situation is more complicated than this.[7,8,9]

While C_1 discharges through the saturation inductance of P_1 into C_2, the pulsactor P_2 is switching as in the bi-cycle mode. After P_2 has saturated and C_2 has discharged into C_3, the current in the bias winding returns the flux in P_2 to its original state. This is indicated in Fig. 6 by the low amplitude negative voltage across C_2. Here again, as in the resetting of P_1, the resetting of P_2 is more complicated than has been indicated.[7,8,9]

The successive discharge of the capacitors progresses down the line as in the bi-cycle mode except for the resetting of the pulsactors. The pulsactors are all returned to their initial state by the bias currents, so that the network is ready to repeat the cycle.

The remaining operation to be described in this first order explanation of the Melville network is that associated with the shunt circuit. The bi-cycle mode circuit is shown in Fig. 7. The initial condition required of the pulsactors is that they be saturated in alternate directions as one proceeds down the line. Current downward in the circuit branch containing P_1 will tend to switch it; current upward in the

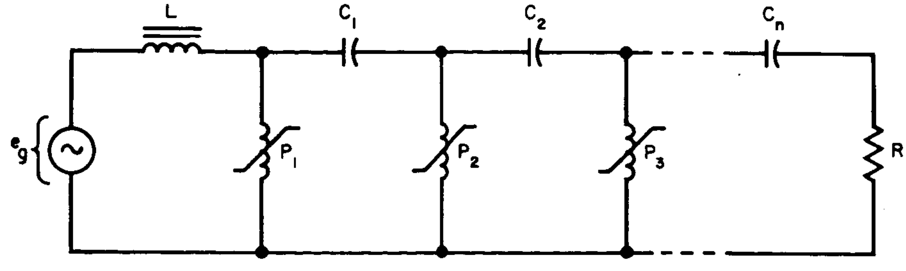

FIG. 7 SHUNT CIRCUIT, BI-CYCLE MODE

branch containing P_2 will tend to switch it, etc.. The charge path for C_1 is from the generator through L and the saturation inductance of P_2. P_1 is essentially in parallel with C_1 during the time C_1 is charging and P_1 is switching, as is true for the series circuit. When P_1 saturates, C_1 discharges through the saturation inductance of P_1 and P_3 into C_2. The saturation inductance of P_1 is much greater than that of P_3. The process travels down the line in a manner similar to the series circuit.

There are several differences [4,9] between the series and shunt type circuits that will not be described here. A notable difference that will be mentioned is that of using the pulsactors as transformers. This can be done in the shunt type circuit by replacing the two terminal pulsactor with a four terminal pulsactor with two windings. The voltage level can be changed between stages in this way; this can be of considerable practical importance.

3. Application to Magnetic Circuits

There are several questions we can ask regarding the application of the pulse compression network to magnetic circuits. Some of these questions have been answered during the course of this project; others remain to be answered in the future.

To answer a few of these questions, to test a design procedure given in Quarterly Progress Report 2,[10] and to become familiar with practical circuit problems, a 2.4-kc Melville circuit was designed. The required output voltage and current were found to be compatible with practical circuit-components so a breadboard circuit was constructed. From the breadboard it was then determined that it is possible to obtain the output waveform shown idealized in Fig. 1 for the uni-cycle mode of operation. The significant point of this test is that the current in the negative direction in the interpulse period need not be composed of pulses but can be essentially a constant value. This means it might be possible to eliminate diodes in the output circuit of a driver and yet obtain, in effect, unipolarity output pulses. If the interpulse current amplitude is sufficiently small, the threshold inherent in magnetic circuits would permit the circuits to respond essentially as they do to truly unipolar pulses. Additionally, direct current of the proper magnitude could conceivably be added to the load from the dc source to effect unipolar pulses. It was also determined that current pulses that are quite similar in shape to that which is typically used for magnetic core circuits of the MAD-resistance type[11] can be obtained. This was effected by using 4-79 Mo-Permalloy* tape for the core material in the pulsactor in the output stage. Deltamax cores in this same circuit gave a different shaped output waveform but it was one which seemed to be satisfactory for MAD-R circuits. The nonlinear inductance characteristic of the pulsactor is responsible for this variation in waveform.

Because of a need for the practical realization of a reliable clock-pulse generator that arose on another project in the Computer Techniques Laboratory, additional application work was done. This project is titled "Design and Instrumentation of Error-Correcting Codes" and is supported by Rome Air Development Center, under Contract AF 30 (602)-2327. An encoder/decoder comprising about 500 multi-aperture devices was to be designed and constructed; it appeared that the Melville circuit could be used advantageously in this system. The practical application of the Melville circuit to such a specific need as this is outside the scope of this project with JPL. Consequently, it was decided that this application of the Melville circuit should properly be done with the funds available from Contract AF 30(602)-2327. This course of action was pursued and a pulse generator has been designed and constructed and is operating as a part of the encoder/decoder system.

The results of this endeavor have been of benefit to JPL as well as RADC. The uncovering and initial evaluation of the Melville circuit, supported by JPL, has been justified to the extent that it has led to a practical pulse generator in a specific application.

The basic circuit of this bi-cycle mode pulse generator is shown in Fig. 8. The encoder/decoder realization requires two input transformers

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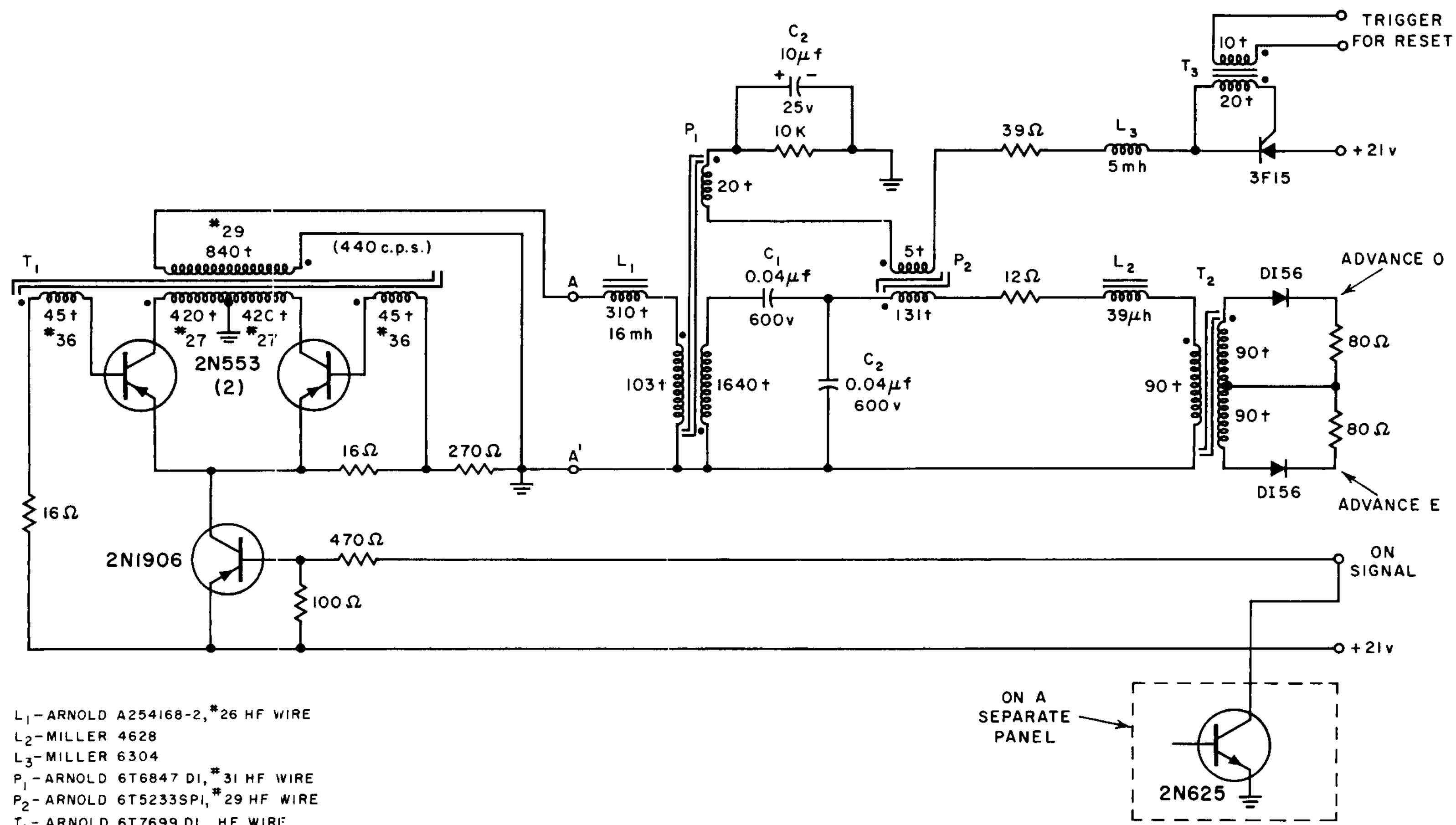
* T. M. Arnold Engineering Co.



L_1-ARNOLD A254168-2, #26 HF WIRE
L_2-MILLER 4628
L_3-MILLER 6304
P_1-ARNOLD 6T6847 DI, #31 HF WIRE
P_2-ARNOLD 6T5233SPI, #29 HF WIRE
T_1-ARNOLD 6T7699 DI, HF WIRE
T_2-ARNOLD 6T5515 DI, #29 HF WIRE
T_3-TMI 180TI

FIG. 8 PULSE GENERATOR

like T_1 and two Melville circuits like the one shown, although a single circuit could have been used as far as the Melville circuit *per se* is concerned. The primaries of the two T_1 transformers are connected in parallel to the collectors of the 2N553 transistors. The secondaries of each T_1 transformer go to a separate Melville circuit. The transistors and T_1 form an inverter that converts the dc source into a 400-cps square-wave source.

The output of *each* Melville circuit is, approximately, a critically-damped current pulse having a peak amplitude of 4 amperes. The rise time of this pulse is about 1.7 μsec. The peak power output is 1.7 kw. On the basis of calculations made using oscillograms of the current and voltage waveforms, the approximate average-power was found to be: 6 watts output, 8 watts into the Melville circuit (terminals A to A') and 13-1/2 watts into the transistor inverter (for each Melville circuit). The efficiency of the Melville circuit is 75 percent and that of the inverter 60 percent. These efficiencies could have been increased, but this was not necessary for this application.

Two pulse compression stages are present in the circuit; the two pulsactors are designated P_1 and P_2. The decision to use two stages was a rather arbitrary one; the availability of the cores employed was the main reason for selecting two stages. The first stage is the shunt type circuit and the second is a series type. The first pulsactor functions as a transformer in addition to its role in the compression process. The voltage step-up was divided between T_1 and P_1 as was convenient for practical reasons (viz., inside diameter of toroid and wire size.). The main function of the inductor L_2 is to simulate the inductance inherent in the load. This inductance limits the effective compression of the last stage. The compression of the last stage, including the inductance of L_2, is 7, while the compression of the first stage is 30. The transformer T_2 and the two diodes in the secondary circuit convert the bipolar output of the bi-cycle circuit into two unipolar pulses. In addition to this function, the primary of T_2 in effect filters out of the load circuit the 400-cps charging current for C_1. The maximum amplitude of current in the load during the interpulse period from all causes is less than 20 milliamperes.

Now we turn our attention to the control circuitry. The operation of the encoder/decoder requires that the generation of current pulses begin when an appropriate command signal is given; this generation is to continue until a stop command is given. These functions are accomplished by the control circuitry associated with the 2N1906 transistor and the 3F15 silicon-controlled-rectifier, as follows.

The schematic diagram indicates that two input signals are received from the logic circuitry. The On Signal saturates the 2N1906 transistor, thereby applying +21 volts to the positive terminal of the inverter, making it operative. When the On Signal is removed, the 2N1906 is turned off and the output from the inverter goes to zero. The removal of the On Signal occurs during the period of time that the Advance E pulse is present at the output of the pulse generator. This means that the cycle for generating the Advance O pulse has begun and that T_1 and P_1 are in the process of being switched when the positive input voltage is removed from the inverter. For this reason, unless corrective measures are taken, when the On Signal is received and the positive voltage is reapplied to the inverter, the first output pulse (Advance O) will have a smaller amplitude than the pulses that follow. The preset circuit associated with the silicon-controlled-rectifier corrects this situation by putting T_1 and P_1 in their appropriate saturated states immediately after the last Advance E pulse occurs.

The operation just described effects the nonvolatile turn on and off that is one desirable characteristic of a pulse generator for this project. By combining semiconductors with the Melville circuit this characteristic has been achieved.

It is to be observed that the semiconductors required in this pulse generator do not have difficult tasks to perform. The specifications that the circuit operation imposes on the semiconductors are not critical; the silicon-controlled-rectifier and the transistor types were selected on the basis that they were readily available and performed satisfactorily.

C. The Wehnelt Interrupters

1. Historical Developments

The need for a device to interrupt current periodically and automatically--an interrupter--dates from the discovery of magnetic induction by Joseph Henry and Michael Faraday in 1831. Faraday, in his experiments, plunged a platinum wire into a cup of mercury alternately to make and break the electric circuit. The widespread investigation which followed the discovery of magnetic induction and the later use of this phenomenon as a tool for other investigations resulted in the development of the interrupter into its many forms. These interrupters were mainly mechanical devices, however, there were two classes which are of interest to this project: those devices which use mercury--described in a following section--and the electrolytic class of interrupters.

The original form of the electrolytic interrupter as reported by A. Wehnelt[12] consisted of two dissimilar sized electrodes immersed in an electrolyte and connected through an inductance to a voltage supply as shown in Fig. 9. The small area electrode, (anode) was made of

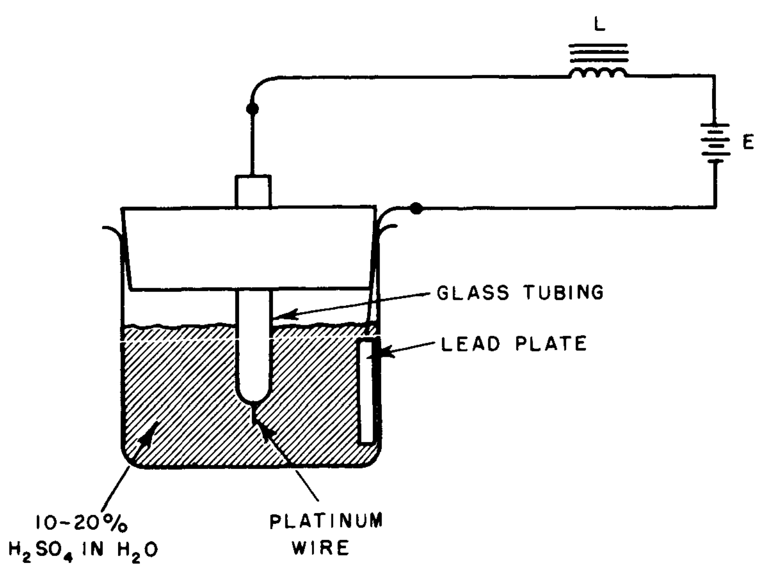


FIG. 9 WEHNELT INTERRUPTER

platinum wire, the large area electrode, (cathode,) was made of lead. When connected in a circuit having suitable inductance and a supply voltage between 12 and 110 volts, electric arcing occurred around the anode, a noise of variable pitch was emitted, and the current through the cell was rapidly and periodically interrupted. Wehnelt demonstrated that the interruptions produced were complete and that the time rate of change of current was greater than with the mechanical break commonly employed. With this interrupter, he obtained a spark length between the secondary terminals of an induction coil greater than with a mechanical break--even though he used a lower supply voltage. He also found the frequency of the interruptions to be a function of the surface area of the platinum anode, the value of the supply voltage, and the value of the inductance; the value of the current was found to be a function of the surface area of the anode and the value of the supply voltage. By varying these three variables, Wehnelt reported interrupting currents as large as six amperes average value, and at rates from a few interruptions per second up to 1700 interruptions per second.

The Wehnelt interrupter is based upon the "luminous electrode" phenomenon discovered and reported by Fizeau and Foucault[13] in 1844. Thirty seven years later Slouginoff[14] reported investigating the luminous glow appearing at the anode by means of a rotating mirror and found it to be intermittent. Koch and Wullner[15] studied this phenomenon in 1892 and established with the aid of a telephone that the current was intermittent. Wehnelt's contribution, then, was in demonstrating the completeness of the current interruptions and the effectiveness of this type of interrupter for use with magnetic induction coils.

The first theory of the operation of this device was one of resonance, principally because Wehnelt reported that inductance was required in order for the device to operate and that the voltage across the cell was greater than the supply voltage. This theory was shown to be in error by Blondel,[16] who in one of the early analytic applications of his oscillograph found the current to have an exponential rise with a rapid fall to zero. The voltage across the cell consisted of large spikes at the time of the fall of the current.

Tesla[17] and Humphreys[18] reported that the electrolyte could be replaced by a conducting liquid and the device would still operate as an interrupter. Caldwell[19] and Wehnelt[20] also showed that the small platinum anode could be replaced with a small aperture. In this latter device--which became known as the Caldwell interrupter--the conducting liquid was divided into two volumes, each insulated from the other everywhere except at a small aperture in the insulating surface (Figs. 10 and 11). Electrical connections were made by immersing electrodes in each volume. The interruptions were produced by the action of the current on the liquid conductor through the small aperture. The luminous glow then occurred in or around the aperture. Caldwell found that an external inductance was not necessary for operation but did improve the regularity of the breaks.

The theory proposed to explain the operation of this form of interrupter by Caldwell[19] and Simon[21] was one of Joule heating and vaporization of the water due to the very high current density through the aperture. Klupathy[22] found that the Joule heat was insufficient to vaporize the water and suggested that the necessary heat must come from the Peltier phenomenon that occurs at the surface of the platinum anode and the electrolyte, and that this accounted for the polar property of the Wehnelt interrupter i.e., that it would not operate with the small area electrode connected to the negative terminal of the supply voltage.

By the end of 1899 the unique characteristics and the apparent simplicity of the Wehnelt interrupter had attracted the interest and curiosity of many of the leading scientists of the day, especially those using an induction coil for the production of high voltages for the study of electric discharges in gasses and x-rays (which only four years before, in 1895, had been discovered by Roentgen). In fact, it was available commercially by this time, from the German firm of Siemens & Halske.

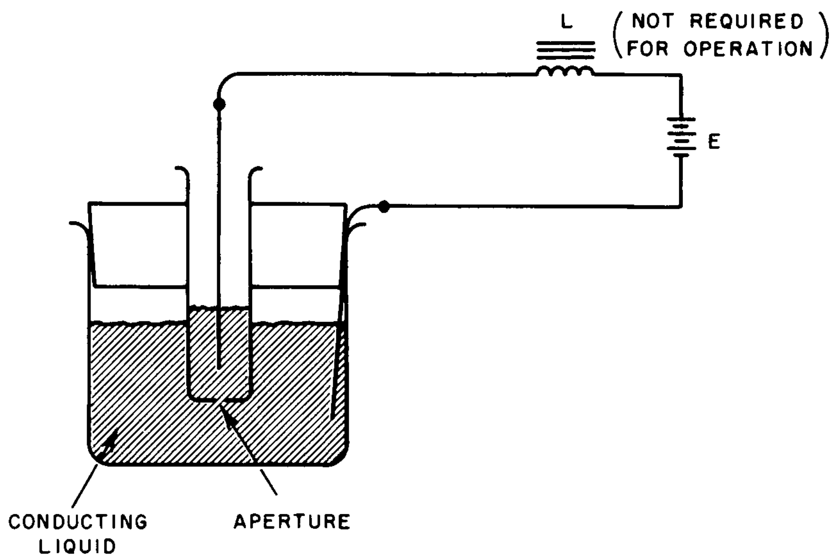


FIG. 10 CALDWELL TEST TUBE INTERRUPTER

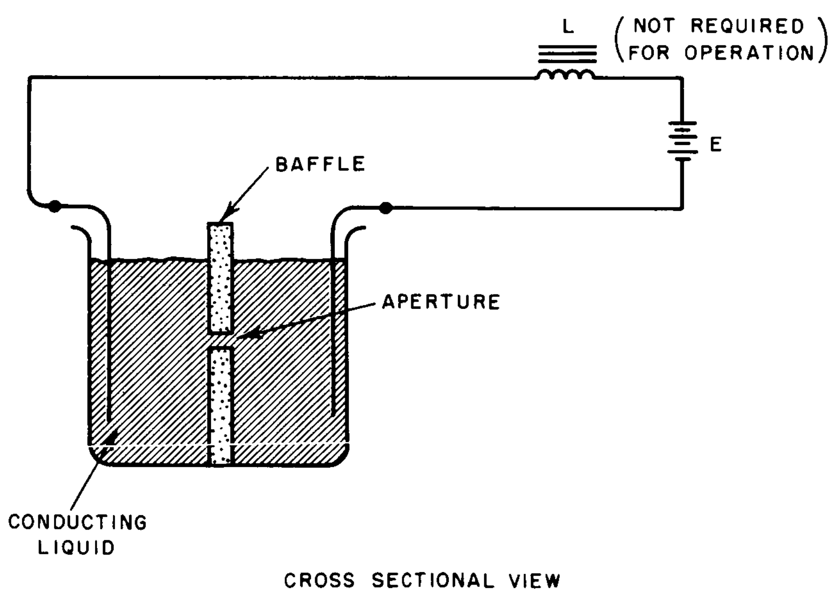


FIG. 11 CALDWELL PARTITION INTERRUPTER

In 1907 Northrup[23] presented a detailed analysis of the forces on the interior of a conductor and showed both experimentally and analytically the effect of these forces acting upon a liquid conductor. The effect had originally been directed to his attention by a friend, Carl Hering, who had given to it the name "pinch" phenomenon. Hering also suggested that this was the action which produced the operation of the Caldwell interrupter. In the same year Bary[24] proposed the theory of electromagnetic constriction (this is the same phenomenon for which Hering had coined the term "pinch" phenomenon) to explain the operation of the Caldwell interrupter. In 1909 Bary[25] expanded his analysis to explain all the various types of liquid interrupters, both electrolytic and conducting liquid. Bary's analysis was not exhaustive and did not treat quantitatively the operation of these devices.

By 1910, ten years after its introduction, the Wehnelt interrupter (or one of its evolved forms) was found in most scientific laboratories, even though the theory of its operation was not known quantitatively. The investigation of the literature on the Wehnelt interrupter has not been completed at this writing. There is no contemporary literature on this device; this has necessitated the tracing of its development during the period it was in common use.

2. Laboratory Experiments

A Wehnelt electrolytic interrupter was built for laboratory experimentation to help resolve some of the conflicting reports uncovered in the older literature and to become acquainted with the problems and peculiarities involved in the operation of such a device. In addition, it was felt that observation of the current and voltage waveforms with modern instrumentation might uncover some facts heretofore unknown or unreported, expecially in the absence of current literature on the subject.

A Wehnelt cell was constructed as follows: a half litre beaker was 3/4 filled with a 20% solution of sulphuric acid. A sheet of lead about 2" x 3" was immersed in the electrolyte and positioned against the outer wall of the beaker to form the negative electrode of the cell. The anode was formed by inserting a length of 0.010 in. diameter platinum wire into a 5" section of an 0.011 in. diameter glass capillary tube so that it extended approximately 3/8" beyond one end; the excess wire extended from the opposite end. The glass capillary tube was then inserted through a hole in a rubber stopper which in turn was placed on top of the beaker, the length of the capillary tube was adjusted so that the 3/8" of platinum wire was at a depth of approximately 1/2 the level of the solution (Fig. 9). The inductors used in the experiments were made from 3 in. diameter Western Electric toroids* of permalloy powder. Inductors of several values were made, the largest of which was approximately 10 mh; larger values were obtained by connecting these units in series. The device was made to function by using a 10 mh inductance in series with the Wehnelt cell and a variable voltage source adjusted above 14 volts with the platinum wire electrode connected to the positive terminal. A pale purpde illumination surrounded the platinum electrode at this time and a whistling sound was clearly audible. The current wave form was periodically reduced to zero, from which point it would increase in a manner determined by the electric circuit parameters to a limited value, at which time it would rapidly reduce again to zero, the time required for the current to decrease from its maximum value to zero being a small fraction of the required time for the current to go from its minimum to maximum value. Increasing the supply voltage caused the intensity of the luminous glow to increase, the pitch of the audible note to rise, and the frequency of the interruptions to increase. The peak value of the current was also found to increase with the frequency of the interruptions. A further increase beyond a critical voltage caused the interruptions to stop, the current was then reduced to a low steady value.

The permalloy toroids used in these experiments differed from the inductors used by the early experimenters in that they had low losses and that they were saturable. This latter means that the measured value of 10 mh was correct only for low values of current; as the current increased the inductance decreased. In effect this was a saturable reactor connected to a Wehnelt interrupter. By this means it is possible to

* Western Electric 637627

effect a certain amount of control over the current waveform. Experimentally, close approximations to a sawtooth waveform were obtained, as were waveforms where the current increased gradually at first, until the inductor saturated, and then more rapidly, producing a spike. The peak value of the current during these tests varied between 15 and 25 amps as the frequency varied from a few cycles per second to just under 1 kc.

When an additional inductance was inserted in series with the original 10 mh inductance and the supply voltage maintained at the same value, the frequency of the interruptions decreased. Decreasing the inductance from the original 10 mh value increased the frequency of the interruptions under the same condition of constant supply voltage. However, it was found that there was a minimum value of inductance, approximately 5 mh, required to be in the circuit for the interrupter to operate. Under the conditions of insufficient inductance, where the Wehnelt cell does not function as an interrupter, it was found that nonsynchronized pulses of low amplitude were generated and superimposed on the direct current. These pulses were triangular in shape and varied in duration from between 0.5 to 25.0 depending upon the circuit parameters and the value of the applied voltage. Under certain conditions high frequency oscillations were superimposed upon the current pulse. Frequencies as high as 20 mc were observed. It is significant to note that nowhere in the literature was mention made of this mode of operation; indeed, one would expect this to be the case due to the limited instrumentation available to early experimenters who investigated this device.

D. The Mercury Interrupters

1. Historical Development

The succession of developments that preceded the discovery of the Wehnelt interrupter led to the development of the mercury jet interrupter in 1898. In this device, two diametrically opposing jets of mercury were rotated so that for a portion of each revolution they impinged upon two plates. When an external circuit was connected, through these two plates, the current could flow only when the jets were impinging upon them. The mercury was immersed in oil, alcohol or coal gas to prevent the formation of a scum from the oxidation of the contaminants in the mercury. A variation of this device, known as the mercury turbine interrupter, consisted of a jet directed at the rim of a rotating toothed wheel. The mercury jet, alternately impinging upon the teeth and passing through the space between teeth and impinging on the target plate, produced rapid interruptions of current. With these devices, up to 150 interruptions per second were produced. The mercury jet commutator has been in use in one form or another[25-36] up to the present date and is available on the commercial market today under the trade name Delta Switch.*

The two most significant developments from the point of view of this investigation were the zero gravity[33] mercury jet interrupter and the mercury-to-mercury break[32] type of interrupter. In the former, the design is such that the interrupter functions in any position and is therefore unaffected by the presence or absence of a gravitational field. In the second type, the rotating mercury jet does not impinge upon a plate; instead the jet impinges upon another mercury jet that makes contact with the plate (but is insulated from the main body of mercury). In this manner a mercury to mercury make and break of the electrical circuit is obtained. The contamination produced by the arc between the mercury and a metal electrode as in the other forms, is thereby eliminated.

Hartman[37] states that in 1918 he designed an electromagnetic pump for a mercury jet rectifier employing the principle of the interaction of a current through a liquid conductor and an orthogonal magnetic field. Since the advent of the nuclear reactor there has been considerable literature[38] on the application of the electromagnetic pump for pumping liquid metals.

2. New Developments

The principle of the interaction of current through a liquid conductor with an orthogonal magnetic field has been applied on this

*T.M. Advanced Technology Laboratory Division of American Standards project to the generation of current pulses from a direct current source. We conceived several two terminal devices having the property that the action of the current flowing through the liquid conductor and interacting with the orthogonal magnetic field interrupted the current thereby generating the current pulse.

Figure 12 shows one such device. Here alternate layers of a conducting liquid and an insulating liquid fill an insulated tube. Electrodes are inserted through the walls of the insulated tubing so they are flush with the inside wall. They are so positioned that each layer of the conducting liquid passes between them providing a current path normal to the magnetic field. By making the insulated tube a closed

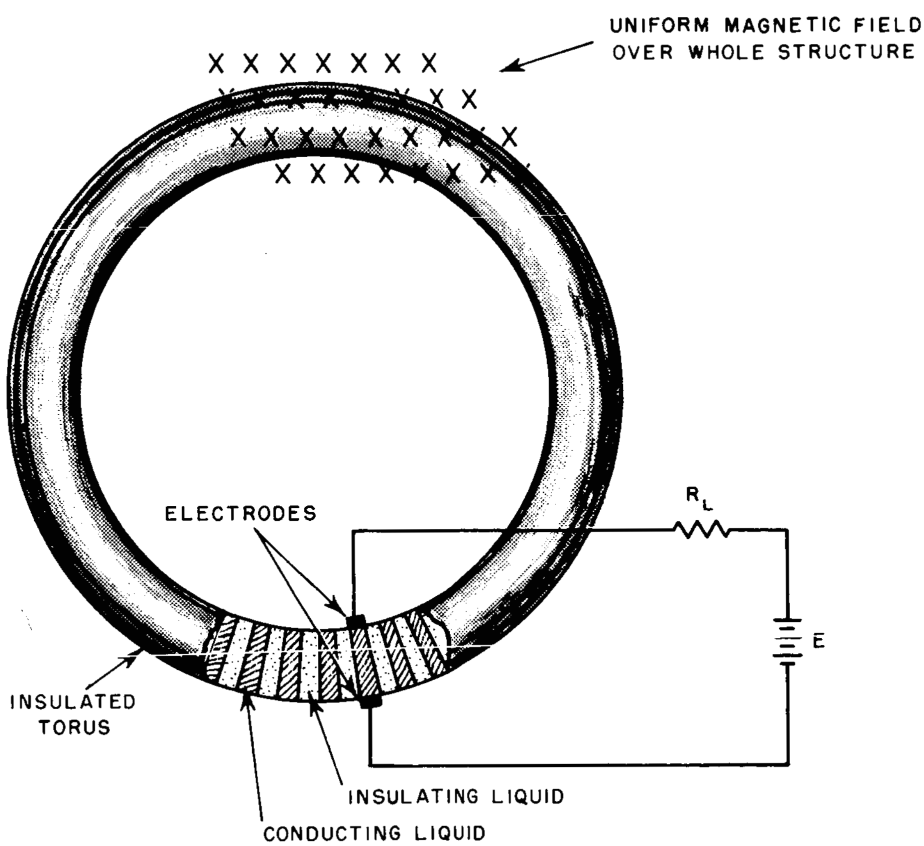


FIG. 12 ALTERNATE LAYER LIQUID CONDUCTOR, LIQUID INSULATOR INTERRUPTER

ring and placing it in a magnetic field, the magnetic field is easily made normal to both the direction in which the current passes through the tube and the plane of the closed ring. The force of interaction between the current and the magnetic field will cause the liquid to be set in motion, which in turn will break the electrical connection. The momentum of the liquid will carry the liquid to where the next conducting liquid segment will make contact with the two electrodes where an additional momentum will be added to the liquid. The liquid will reach a final velocity such that the momentum gained on the passage of the conducting liquid between the electrodes is just equalled by the loss in momentum during the time interval when the insulating liquid traverses the electrodes. An experimental model of this device has not been constructed, time being devoted instead to other more simply constructed devices. A preliminary analysis indicates that such a device will work; however, in order to achieve the extremely long lifetimes that are of interest to this investigation, it would be necessary to use a different solution to the contact interface problem as contamination and wear produced by the arcing between a liquid conductor and the solid electrode would limit lifetime.

A second device of this class is shown in Fig. 13. In this device, a drop of mercury is placed between two concentric conductors insulated

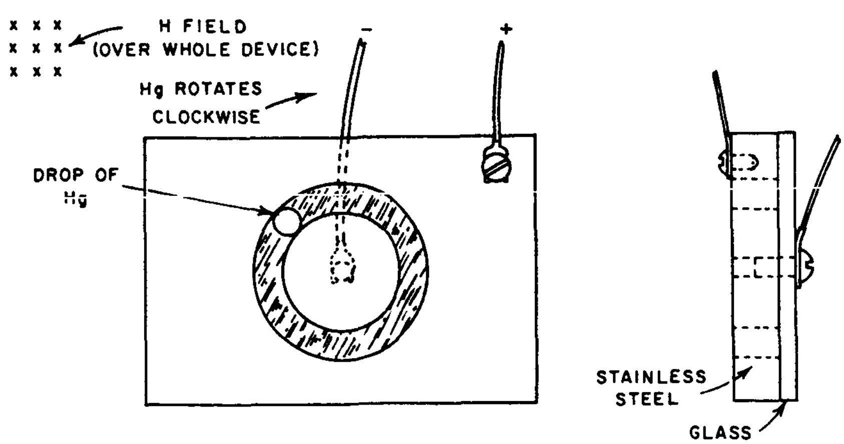


FIG. 13 ROTATING DROP MERCURY INTERRUPTER

from each other and enclosed at the top and bottom, thereby forming a closed track in which the drop is free to rotate. An external magnetic field is applied normal to the plane of the cylindrical track and the two electrodes are connected to the terminals of a voltage supply. The geometry of this device is such that the current always passes from the one conductor through the mercury to the other in a radial direction. The resultant force produced by the interaction of this current and the normal magnetic field is always tangential. It was expected that this tangential force would cause the drop to rotate around the track, and in a manner analogous to the above device produce current interruptions by segmenting the outer conductor. This, in fact, did not happen. The frictional forces were unexpectedly high. A more detailed discussion of this device will be found under Laboratory Experiments.

A third device was conceived using the same principles. It is shown in Fig. 14. This device consists of a cylindrical conductor which is

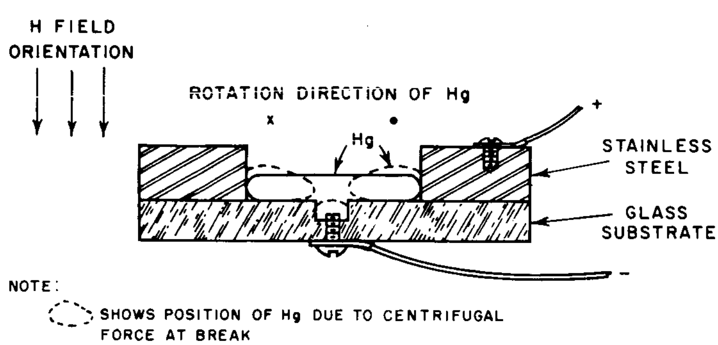


FIG. 14 VORTEXING MERCURY INTERRUPTER

closed top and bottom with an insulating material. There is a well in the bottom insulating plate located on the same axis as the cylindrical conductor. The bottom of this well is closed with a second metal conductor. The mercury is poured into the structure, filling the well in the bottom insulator plate and covering this bottom plate so that contact is made with the cylinder wall at all points. This device is placed in an external magnetic field parallel to the axial direction of the cylindrical conductor. When the two electrodes are connected to the terminals of the voltage supply, current flows radially from (or to) the center of the structure. The interaction of this current and the orthogonal magnetic field is in such a direction as to cause the mercury pool to rotate. As the angular velocity of this pool increases, the centrifugal force pushes the mercury against the cylindrical conductor. At a critical velocity there is insufficient mercury in the center of the structure to maintain contact with the mercury in the well, thereby interrupting the current. The arcing that takes place upon the break occurs between two mercury surfaces. The only material vaporized by this arc is mercury. This vapor, in a closed system, is condensed back into the main pool of mercury. There is no contamination produced by this arcing and the device is inherently a long lived one.

A variation of this device, based on the experiments of Plateau,[39] has been conceived to work in a zero gravity environment. Plateau showed in his experiments that a liquid in a gravitationless environment will assume a spherical shape by virtue of its surface tension. Further, he showed that when this sphere is rotated, at a critical angular velocity a portion of the liquid will be separated from the main body at the equatorial region due to the action of centrifugal force; however, surface tension will maintain it in a toroidal form coaxial with the main spherical body. By replacing the conductor at the bottom of the well and the well in the bottom insulating plate with an axial conductor extending between the top and bottom insulating plates, we expect that a mercury-to-mercury break can be made to work in a zero gravity environment.

During the course of this investigation, the problems associated with using a solid metal for one or more of the contacts made it apparent that by using a liquid metal element such as mercury or galium for both contact surfaces the action of the arcing upon contact make and break could only change this element to a vapor, which in a closed system would condense back into the main body of the liquid. In this manner lifetimes equaling or exceeding the theoretical lifetime of semiconductors should be obtainable.

The following device was conceived as a result of a search for a method to achieve this type of a break while using only the current which is being interrupted to produce the effect. The device is shown in Fig. 15. Here a 1 inch long capillary tube of 0.010 in. diameter filled with mercury provides an electric circuit between two reservoirs

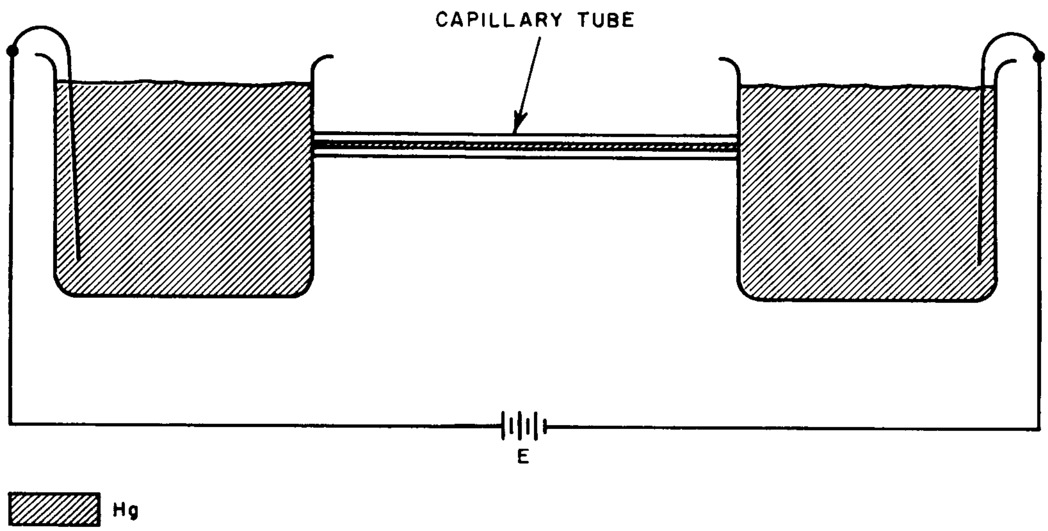


FIG. 15 MERCURY CAPILLARY INTERRUPTER

of mercury. Connection to the power supply is made by electrodes immersed in the two mercury pools. Calculations considering only first order effects show that the Joule heat should vaporize the mercury column and thus break the current. Condensation of the vapor so formed would then remake this circuit. An experimental device of this nature was constructed and it did work with surprising results. (These results will be reported under experiments below). However, later investigation of the Wehnelt interrupter uncovered the papers of Northrup[23] and Bary[25] which advanced the theory that the "pinch" phenomena produced the interruptions of current in the case of the electrolytic interrupters. Subsequent first order calculations showed the "pinch" phenomena to be of the proper order of magnitude to produce the results originally thought to be derived from Joule heating. It appears likely that with both effects being of the proper order of magnitude to cause interruptions, the interruptions are due to or are a function of both effects. A more detailed analysis coupled with additional experiments will be required to resolve this problem.

3. Laboratory Experiments

The first experiment was performed to verify the correctness of the analysis and illustrate the magnitude of the force produced by the interaction of a current through a liquid conductor and an orthogonal magnetic field. In this experiment a column of mercury was placed between two electrodes spaced about an inch and a half apart. In order to make the cross section of the mercury small compared to its length, it was placed in a gutter formed by a vertical surface and a gently inclined surface having a slope of about 5%. This structure was placed in a normal magnetic field of three to five kilogauss and its two terminals were connected to the terminals of a power supply. With only a small current flowing through the mercury no effect was observed. As the current increased, the mercury filament moved up the gently inclining plane with the maximum displacement at the center. With a further increase of current, the displacement of the bow-shaped filament increased until it ruptured, interrupting the current, and the mercury then rolled back down the inclined surface to the gutter. The time required for this process decreased with increasing current. This experiment established that it was possible to rupture a filament of mercury by the interaction between a current of under ten amperes and a magnetic field of 3,000 gauss.

A second experiment was performed to determine if a drop of mercury could be continuously rotated about a circular path by the interaction of these forces. The structure used in this experiment is shown in Fig. 13, and has been described in the preceding section. In this experiment, it was expected that the interaction of the radial current and the orthogonal magnetic field which everywhere produces a tangential force on the mercury drop would cause a steady rotation of the drop. This was not the case, however; the drop moved in a very erratic manner. For small values of current the drop would not move or else would move only a short distance and then stop. With increased current the drop suddenly moved from its rest position, rapidly accelerated, flattened against the outside wall of the track due to the action of centrifugal force, and the current was thereby interrupted. With the current interrupted, the mercury drop decelerated, the surface tension caused it to reform into spherical form and remake contact with the inner wall. The current was then re-established and the process was repeated. The metal walls of the track had been made of non-magnetic stainless steel, which normally is not wetted by mercury, so that the adhesive forces would not be present to restrain the mercury drop from moving. The arcing removed the absorbed monomolecular gas layer from the surface of the stainless steel and allowed certain portions to become wetted by the mercury. This increased the erratic movement of the drop in the circular track, due to the increased mechanical resistance that occurred at these points. An additional effect found during this experiment was that small droplets of mercury were formed and adhered to the various surfaces of the track and would not coalesce. These droplets were formed by the combination of the violent action of the mercury drop in its erratic movement around the track and the arcing between the inner cylinder wall and the mercury drop. This effect was reduced by operating in an inert atmosphere. Microscopic examination of the surface of the inner electrode showed that the surface was pitted by the action of the arcing. This indicates that such a device would have a limited lifetime due to the progressive wear of the conductor surface and the resultant contamination of the mercury by this material. For this reason, further work with this structure was discontinued, even though current interruptions were obtainable in this manner.

The next series of experiments were again concerned with interrupting the current, this time by using mercury-to-mercury contact, while still utilizing the interaction of the current through the mercury and the orthogonal magnetic field. The device used in these experiments is shown in Fig. 14, and was described in the preceding section. In this device, the mercury break was achieved by making electrical connection to the center of the mercury pool through the well of mercury, the bottom of which made contact with a metal electrode. The current passing the length of the mercury column in the well experienced no displacement force due to the external magnetic field as it moved parallel with it. Forces on the radial current, however, did impart a motion to the mercury pool; centrifugal force pushed the mercury away from the center and caused the mercury to rupture at the top of the well, thereby interrupting the current. In the operation of this device, two modes of operation were observed. In the first, the rupture was complete and was observable through a glass cover over the top of the device. In the second mode of operation, the rupture between the mercury pool and the top of the well occurred without rupturing the surface of the mercury pool. The frequency of the interruptions in the latter mode of operation was greater, but less stable. The frequency of interruptions obtainable with the dimensions of this experimental device ranged from a few interruptions per second to a few hundred interruptions per second. The zero gravity version of this device, based upon the experiments of Plateau,[39] was not experimentally investigated, due to the lack of facilities. The principle employed in this device appears very promising for the eventual development of a very long lived, highly reliable current interrupter. Additional work would be required to achieve this goal, especially in the area of dimensional resonance.

The final experiments using mercury to produce current interruptions did not employ an external magnetic field. This device is shown in Fig. 15. The principles involved in the operation of this device are unclear at this time. As originally conceived, the Joule heating of the mercury, by the passage of the current through it, would cause it to vaporize at one point, thereby interrupting the current. The subsequent searching of the literature in connection with the Wehnelt interrupter revealed that the "pinch" phenomenon could possibly effect such a rupture. First order calculations have shown that for this experimental device each phenomenon alone is of sufficient order of magnitude to produce the results obtained. The current interruptions produced by this device were very sharp and relatively stable. With this experimental device the frequency of interruptions obtained were around four hundred cycles per second. The waveform was generally a square wave; both the frequency and the symmetry of the waveform were dependent upon the value of the current through the device. This device appears very promising, inasmuch as the current is interrupted by the rupturing of the mercury and therefore no contaminating products are formed. Such a device can be expected to have a very long lifetime. The lack of an external magnetic field requirement is an additional advantage for space application.

In the investigations described above, mercury was used as the liquid conductor. This was done for convenience. It should be noted that other liquid conductors such as gallium, sodium or potassium could be employed to advantage in certain cases.

E. Further Work

The Melville pulse compression network itself is inherently reliable and radiation insensitive. Future work would be aimed at the elimination of the associated semiconductors in the output and input, thus improving the reliability and radiation tolerance of the driver as a whole. The use of the uni-cycle mode of operation should be further investigated to eliminate the diodes in the output. To eliminate the transistors in the input, the Wehnelt and mercury interrupters should be considered. These interrupters are potentially capable of being pulse generators *per se* and are also capable of performing the inverting function for the Melville network. Perhaps as an intermediate step, a tunnel diode inverter[40] should be tried, since these semi-conductors are less sensitive to radiation than transistors.

In the Wehnelt interrupter, and in the mercury types which involve the change from a liquid state to a gaseous state, there is a need for better understanding of principles of operation. A better understanding must be achieved before we can fully assess these devices and determine the bounds within which they must operate, and can firmly establish their reliability and long life. Having established the principle of operation of these "change of state" devices, the use of various liquids and electrodes might add a powerful design parameter to be exploited. The geometry and size of an interrupter and its operating characteristics would be intimately related to the properties of the liquid and electrodes used. Another design dimension to be examined is the effect of external circuit components on operation.

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