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74APB502

IMPROVED SETBACK GENERATOR

FINAL REPORT

G. L. Sullivan

J. E. Suminsby

R. T. Ziemba

December 1973

Prepared for

PICATINNY ARSENAL

Ammunition Development and Engineering Directorate

Fuze Development and Engineering Division

Dover, New Jersey 07801

Contract No. DAAA21-73-C-0474

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GENERAL ELECTRIC COMPANY

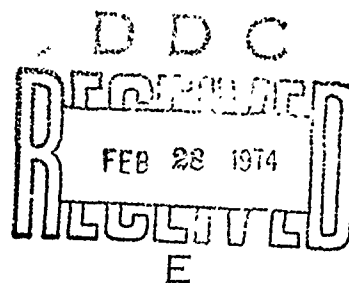
Armament Systems Department

Burlington, Vermont

and

Aerospace Instrument and Control Systems Department

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FOREWORD

This report summarizes the work performed by the General Electric Company under Contract No. DAAA21-73-C-0474 for the Ammunition Directorate at Picatinny Arsenal, Dover, New Jersey. The period of the contract was from April 1973 through December 1973.

The scope of this contract effort involved the design, fabrication and test of a high energy Setback Generator and its associated energy storage module, developed for use as a power source for artillery ammunition fuzes.

The generator hardware demonstrated at the conclusion of this program has been shown to meet all design requirements imposed by the contract. In addition, significant growth capability has been identified in the design to allow for its miniaturization in any subsequent programs which could utilize such a device.

Twenty (20) generators and energy storage modules in two design configurations were delivered to Picatinny Arsenal at the conclusion of this program. These units will undergo laboratory and flight testing at the Picatinny facility to further identify the features and capability of the design.

The General Electric Company gratefully acknowledges the efforts of Mr. Peter J. Weldon of Picatinny Arsenal who, in addition to serving as Program Contract Officer, also provided valuable technical advice and consultation throughout the program. We wish also to acknowledge the efforts of Mr. Henry Hagedorn, Jr. of Picatinny Arsenal for his participation as test coordinator on this program. Finally, we acknowledge a contribution of services provided by Picatinny Arsenal in rail gun testing of prototype hardware at a contractor facility.

This technical report contains neither classified nor company proprietary information.

ABSTRACT

This technical report summarizes the design, development and test of a setback generator and its associated energy storage module. The generator, measuring 1.5 inches in diameter and 1.2 inches in height, has produced over one million ergs of energy in laboratory tests. This energy is stored on a capacitor bank (energy storage module) to serve as a power source for an artillery fuze. The contract specifies a minimum energy requirement of 675,000 ergs.

The setback generator developed on this program provides a unique feature in that it extracts energy from a magnetic field through a reverse saturation cycle. An important result of this feature is that the low magnetic forces between the core and its housing allowed the core assembly to release at very low acceleration input levels. This makes a generator of this design particularly attractive for use in rocket and mortar fuze applications. Laboratory and field tests have demonstrated that the generator of this general design can produce nearly 400,000 ergs in a 30g setback environment.

Test units which were fabricated were evaluated under both laboratory and gun launch environments. The results of these tests confirmed the output predicted from analytical studies to be consistent with those results demonstrated in the laboratory, but greater than those demonstrated in ballistic firings. The inconsistency is expected to be resolved following ballistic tests on the 20 deliverable units under this contract.

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INTRCDUCTION

The major goal of this program was to design, develop and evaluate a setback generator and an energy storage module capable of producing enough energy to operate an electronic time fuze for 200 seconds. Such a fuze would require a minimum of 675,000 ergs of energy stored at a maximum potential of 15 volts.

The generator designed for this application contained a unique magnetic circuit which maximized conversion of the mechanical energy into the device. The energy generated was then stored upon capacitors which were selected for their insensitivity to the gun launch environment of an artillery fuze.

This final report summarizes the concept, design, analysis and evaluation of generators and storage modules developed to satisfy the requirements of this contract. Although an extensive amount of laboratory testing was conducted during the design phase of this effort, only three sample units were tested thus limiting the ballistics test data. The results of the ballistics tests, it was found, did not correlate well with the results obtained in the laboratory, nor those predicted through analysis. Additional ballistic testing will be necessary to correctly ascertain the reason for this discrepancy.

SECTION I

PROGRAM OBJECTIVES

The principal objective of this program was to design and demonstrate a setback generator suitable for use as a power source for a 200-second electronic time fuze. More specifically, the generator was to exhibit the following physical and functional characteristics:

Functional

1. Provide at least 675,000 ergs of energy into capacitors at 15 volts (600 microfarads at 15 volts). The capacitors are considered to be part of the generator.
2. Have a voltage rise time of less than 5 milliseconds.

Physical

1. The setback generator shall operate over a temperature range of -40°F to $+145^{\circ}\text{F}$.
2. It shall operate satisfactorily over a range of setback forces from 3,000 to 30,000 g's.
3. It shall operate satisfactorily over a range of spin velocities of 2,000 to 35,000 rpm.
4. The dimensions are not to exceed $1\frac{1}{2}$ inches in diameter and $1\frac{1}{4}$ inches in length, not including capacitors. The dimensions of the volume required for the capacitors are not to exceed $\frac{3}{4}$ inch by $1\frac{1}{4}$ inch by 1 inch.

Guidance

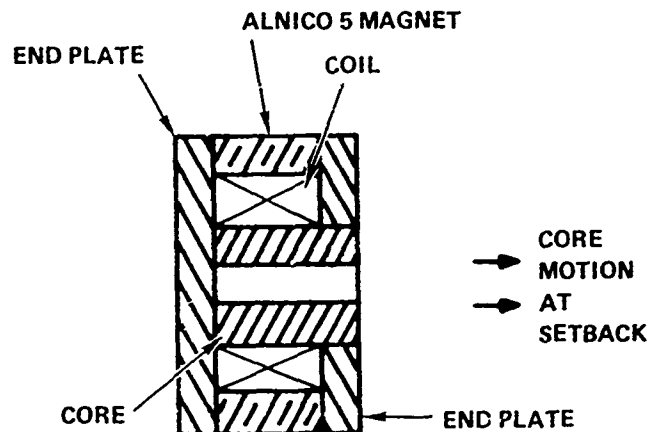
1. Consider the use of a latching mechanism and shorting switch to prevent inadvertent movement of the generator core and/or generator output in storage and transit.

At the conclusion of this program, 20 setback generators and their associated energy storage modules were to be delivered to Picatinny Arsenal for test and evaluation. .

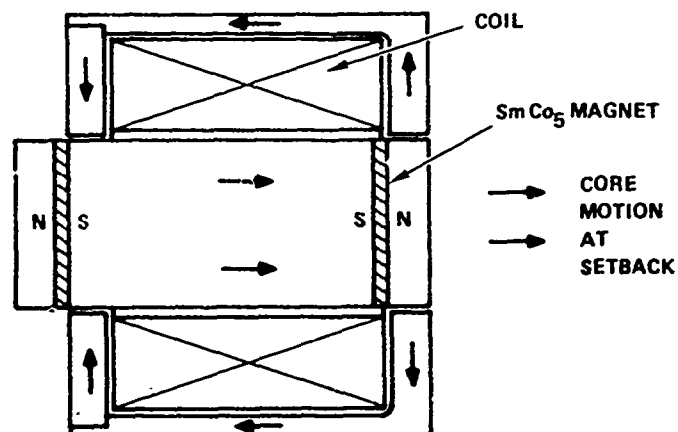
SECTION II
TECHNICAL APPROACH

A. GENERATOR CONCEPT DEVELOPMENT

Previous setback generators have been configured as shown in the sketch below.



The energy available from this configuration is limited by the large volume occupied by the magnet (which, in turn, limits the coil volume) and by the fact that the flux change seen by the coil during setback cannot exceed the initial core flux. In order to circumvent these limitations a unique two magnet design was conceived as sketched below.



In this design, two small disk-shaped, high-energy magnets are attached to the moving element. Magnet polarities are opposing. In the armed position shown, the right-hand magnet produces core flux of one polarity while the left hand magnet is air-circuited and expends most of its μmf producing leakage flux outside of the unit. At setback, the core moves to the opposite position in which the left-hand magnet produces flux of reverse polarity through the core while the right-hand magnet becomes air-circuited. The use of two oppositely-polarized magnets doubles the flux change seen by the coil which, in turn, doubles the volt second integral. Additionally, the outside cylinder can have a much thinner cross-section than the magnet used in that position in the previous generator design. This allows more space for increased core size and coil impedance optimization, resulting in further increase in output energy.

Because this design requires that the magnets operate between air-circuit and essentially closed-circuit conditions, it is necessary to use a material which, in addition to having a high value of residual induction, does not lose its flux-producing capability when exposed to air knockdown.

Samarium cobalt (SmCo_5), a rare earth magnet material, has exceptional capabilities in this regard. This material has unique B/H properties as can be seen by referring to Figure 1. The solid line represents the properties of SmCo_5 . A dashed line representing the B/H curve for ALNICO 9, the highest energy conventional material available, has been added for comparison purposes. Also shown are approximate closed-circuit and air-circuit load lines.

When an air-exposed magnet is closed-circuited, it operates on a minor loop which is nearly parallel to the upper portion of the major B/H curve. As can be seen, the SmCo_5 magnet returns to essentially its original point of the B/H curve after air knockdown whereas the flux output from the ALNICO 9 has been reduced nearly 70 percent.

While SmCo_5 is a relatively new material, its outstanding characteristics make it ideal for this setback generator design approach. It is

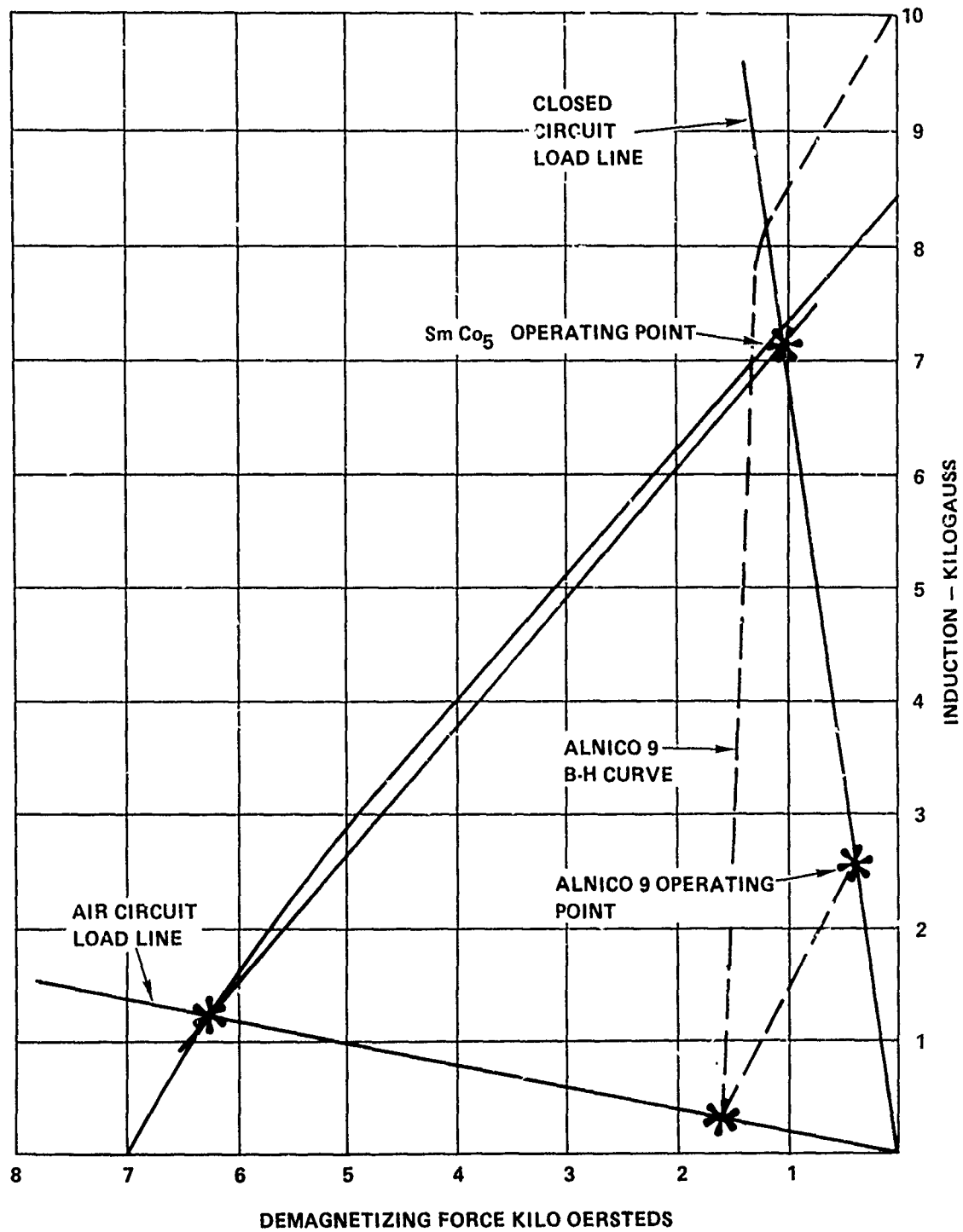


Figure 1. Comparison of Properties - Samarium Cobalt and ALNICO9

now available from three major suppliers. For these reasons it has been selected for use in this application.

B. PRELIMINARY EFFORT

Prior to contract award, sufficient work had been done to demonstrate the feasibility of the two-magnet concept. A prototype unit was built using available conventional magnet material. Tests on this unit confirmed the basic theory.

In addition, a detailed analysis was performed by Dr. Erick Manteuffel (General Electric Aerospace Control Department consultant). This analysis provided confidence that a 675,000 erg (15 volts into 600 μ fd) unit in a package less than 1.5 inch diameter by 1 inch was feasible.

C. CONTRACT REQUIREMENTS

The contract work statement called for a minimum energy requirement of 675,000 ergs (15 volts on 600 microfarads). A maximum size was also specified. One approach would have been to design for 675,000 ergs minimizing size and weight. Since this would have required a knowledge of design parameters not available at the outset of the program, the only feasible course was to maximize the energy output from a maximum size unit. This would assure that contract requirements would be met while, in a parallel effort, an analytical model of the generator was being developed and verified. An adequate model would then permit varied design requirements to be met in a single design iteration.

SECTION III

GENERATOR DESIGN

A. DRAWINGS

Figure 2 is a photograph of the final design configuration of the setback generators delivered under this contract. Detail drawings covering this configuration are reproduced in Appendix C. It is suggested that the reader refer to these drawings during the discussions on design details which follow.

B. MAGNET DESIGN

The magnet design has only two mechanical parameters; thickness and diameter. The thickness of the magnet disk has a basic limitat'on; i.e., it cannot exceed half the distance allowed for setback motion. However, a further practical limitation exists, in that, in order to assure that the motion of the magnet assembly is smooth and uninterrupted, it is desirable for the magnet thickness to be slightly less than the thickness of the generator end plates. In early prototypes an end plate thickness of 0.100 inch resulted in the selecting of a magnet thickness of 0.080 inch. Because the magnetic circuit (at start and finish of setback) has no definable air gap, this thickness is adequate. When end plate thickness was later increased to avoid saturation, the original magnet thickness was retained.

Selection of magnet diameter poses a problem of optimization. Since core flux increases with the square of the magnet diameter, maximum diameter is desirable. However, increased diameter reduces winding space and requires either fewer turns or finer, higher resistance wire. As will be shown later, winding resistance can be, at least in certain configurations, one of the major factors in limiting output. Since

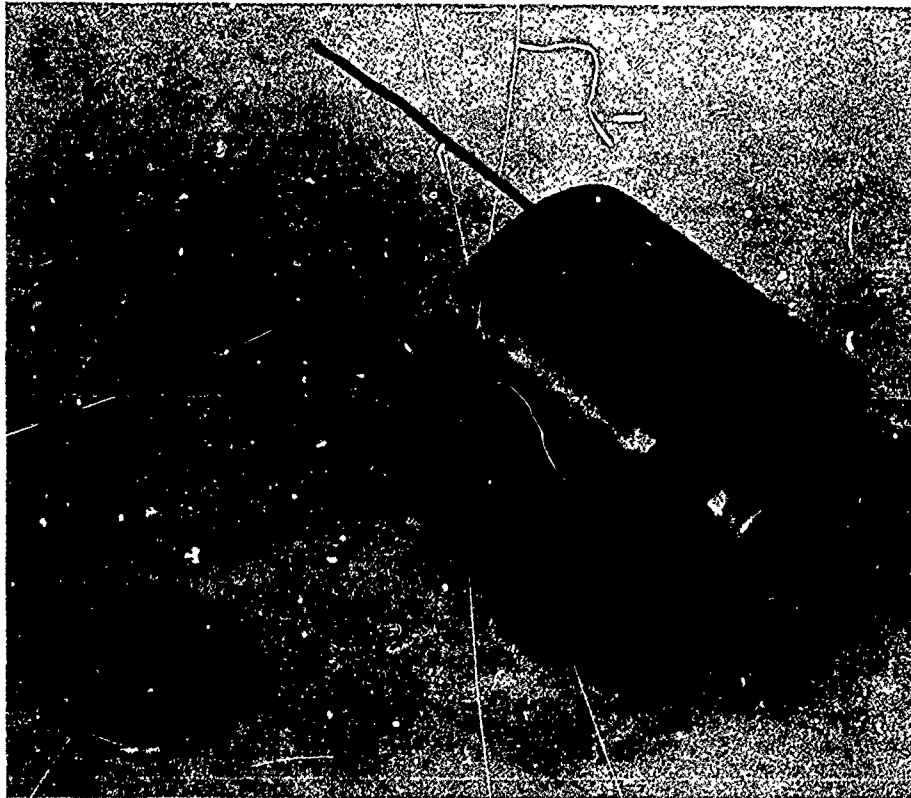


Figure 2. Final Design Configuration of Setback Generator

mathematical relationships relating coil parameters with output were not available during the design stage, selection of magnet diameter was somewhat arbitrary. A diameter of 0.75 inch was finally selected.

With these dimensions maximum flux densities in the various parts of the magnetic circuit are as follows (leakages neglected):

	<u>Area (cm²)</u>	<u>B(gauss)</u>	<u>B(gauss)</u>
Magnet (and Core)	2.86	6000	8000
Air Gap (Ring I.D.)	1.90	9050	12050
Cup (Return Path)	1.82	9450	12550

The 6000 gauss magnet flux density is closest to what can be expected from production magnet material as will be demonstrated later. With this condition all parts of the magnetic circuit are well below the saturation limit of low carbon steel (approximately 15,000 gauss).

The average air gap between core and end ring I.D. is .0015 inches. However, since the attractive force between the core and end ring forces the core to solid contact (i.e., zero air gap) against one side, the average air gap has considerably less effect than might be expected. This was verified by tests on a unit with an end ring I.D. enlarged to give about .0065 average gap. Resulting flux reduction was only 10%.

Attachment of the magnets and end pieces to the core developed into a major problem and severely limited the amount of test data obtainable from laboratory drop tests. Two types of failures occurred. One type was a clean separation of the magnet from either the core or the end cap. In the second type of failure the magnet fractured or separated internally with portions of the magnet adhering to both mating surfaces. Failure invariably occurred in the upper magnet within the core assembly. Various adhesives were tried without complete success. While this failure mode may be a greater problem during repeated lab tests than in one-shot firings, better attachment techniques of the magnet may be required. Sample magnet assemblies with one magnet held in place with a screw through its center have been built but not evaluated extensively during the course of this program.

C. FRAME AND COIL ASSEMBLY

The present frame design consists of a single-piece cup and an end ring which is held in place by rolling over the edge of the cup. In production it is expected that this assembly would utilize two end rings permitting the main shell to be made from drawn tubing.

The coil is wound on a fiber glass coil form. Using a fixture designed for that purpose, it is centered inside the frame and held in place by an epoxy potting compound. Such centering and potting may not be necessary in a production design but was included in these prototype units because of uncertainty as to the deformation effect of high acceleration on the coil.

D. COIL TURNS

Because of the time required to develop a realistic mathematical model of the setback generator in the firing environment, selection of the number of coil turns was based upon extrapolated drop test results. Further guidance was expected from rail gun tests on 54 and 210 turn preliminary design units. Although results from these tests were not conclusive (as will be discussed later), low output from the 54 turn units resulted in a decision to increase the number of turns to 132. Ten of the units supplied at the conclusion of this contract had this number and ten had 210 turns. It is anticipated that firing tests on these units will provide clearer evidence of the optimum coil configuration.

E. SAFING DESIGN

The safing method originally proposed was a shear plate spot-welded to the lower end of the frame. However, after further consideration, this approach was rejected in favor of a simple shear pin between the core and frame. The advantage of the shear pin lies in its flexibility, particularly in these prototype units. The shear pin need not be added until actual firing, allowing preliminary tests to be readily conducted. Moreover the shear pin release point is considerably more predictable and repeatable.

Since the work statement requires generator function with an acceleration as low as 3000 g's, shear action must always occur at a lesser value to assure operation. Although handling shock environment is not defined, it was assumed that these inputs would be less than 1000 g's. Several sample shear pins of 0.0465 inch diameter drill rod were made and tested statically. Breaking force varied from 175 to 200 pounds. With a 2.8 ounce core weight, these results are equivalent to an average release acceleration of 1085 g's.

Although somewhat greater release acceleration would be desirable, a larger diameter shear pin was not practical due to limited end plate thickness. Some consideration was given to using two shear pins. However, because of hole alignment problems, it was felt that two pins would, at least in some cases, release in series rather than in parallel, producing no net gain.

F. GENERATOR COST DATA

In generating a cost estimate for the setback generator, several assumptions with respect to future design changes were made. These were as follows:

1. The present single-piece cup would be replaced by a section of tubing and rolled-on end rings.
2. Flat head screws would be required on both ends of the core assembly to provide better magnet retention during setback. Small clearance holes would be cast into magnet disks.
3. Magnetization would be accomplished after assembly and grind operations were completed.
4. Potting of the coil inside cup would be eliminated.

With these assumptions a preliminary estimate of setback generator cost has been completed. A breakdown of the resulting cost is given in Table 1. These figures are based on a production rate of 100,000 units per year. Equipment cost associated with this estimate is approximately \$75,000, primarily for automatic winding machines and a screw machine for automatic production of the core cylinder.

Most of the material cost is in the magnets for which the best price quoted to date is \$1.97 each. Since samarium cobalt manufacturing technology is still being developed, there is potential for significant cost reduction in this area. Additional and significant cost savings could result if mischmetal cobalt magnets were substituted for the higher priced samarium cobalt magnets in the generator design. The reason is the lower cost of the mischmetal. Whereas samarium (a rare-earth metal) is presently selling for about \$60/lb., mischmetal is only about \$6/lb. This cost reduction, it should be pointed out however, can only be realized at the expense of a magnet energy loss of up to 1/3 that of the samarium cobalt magnets.

This cost estimate has not been predicated on the use of specially-designed, highly-automatic equipment. Providing proper funding were available, such equipment could result in further price reduction.

TABLE I
SET BACK GENERATOR COST DATA^{1.}

<u>Material</u>	<u>Unit Cost</u> ^{2.}
Magnets (2) \$1.97 each	\$3.94
Wire	.07
Metal Parts	.26
Coil Form	<u>.11</u>
Total	\$4.38

<u>Labor</u>	<u>Man Minutes</u>
Machining	5.0 Min.
Assembly	7.4 Min.
Test	<u>0.9 Min.</u>
Total	13.3 Min.

Notes:

1. Estimate based upon a 100,000 unit buy.
2. Purchased price less adders.

SECTION IV

TEST AND EVALUATION

A. FLUX MEASUREMENTS

Flux measurements were made on a number of different generators including magnets from three separate sources. The generator volt second output, when the magnet assembly was pushed through, was measured using a Magnemetrics Model MF-1 Fluxmeter. The instrument scale is calibrated so that maxwell-turns can be read directly. The gauss level produced in the coil by each magnet can then be calculated since coil turns and magnet area are known. Results of these are shown in Table 2.

The values obtained (see Table 2) show a wide range in magnet strength depending upon source and lot. The GE (Schenectady) first lot magnets demonstrate what can be produced under laboratory conditions. These magnets have a residual induction (B_r) in excess of 9500 gauss which may not be obtainable in production quantities. The Raytheon and Spectra-Flux magnets must be considered more typical of the present state-of-the-art of cost-effective samarium cobalt material.

In the laboratory test data to be presented in the following sections, results have been ratioed to a common gauss level of 5300 in order that variations due to other parameter changes can be seen more clearly.

TABLE 2

FLUX OUTPUT

<u>VENDOR</u>	<u>COIL NO.</u>	<u>MAGNET NO.</u>	<u>GAUSS</u>
GE (Schenectady) First Lot	B1A	B1A	6960
	C1A	B1A	6970
	B2A	B2A	6560
	C1A	B2A	6860
	C1A	C1A	6970
	C2B	C1A	6680
	Average GE First Lot =		6830
GE (Schenectady) Second Lot	C1A	A	5920
	C1A	B	5960
	C1A	C	5970
	Average GE Second Lot =		5950
Raytheon	P3	P6	5400
	P4	P7	5250
	P5	P8	5550
	Average Raytheon =		5400
Spectra-Flux	P6	P9	5600
	P7	P10	5500
	P13	P11	5400
	P14	P12	5500
	P15	P13	5600
	P17	P15	5350
	P18	P16	5300
	Average Spectra-Flux =		5460

B. LABORATORY TEST SETUP

It was recognized early in the program that proper evaluation of the design samples would require something more scientific than a hammer blow to cause function of the generators. Initial effort was directed toward duplication of a scaled-down version of a typical artillery shell acceleration profile. It was soon realized, however, that while standard shock machines could be set up for ramp deceleration, this test equipment would be awkward to utilize if many and varied tests were to be performed.

An alternative setup was devised using a pipe-guided drop weight (see Figure 3). The unit to be tested is inserted into a support fixture with the magnet assembly as shown. A drive plug was placed on top of the generator coil assembly to better distribute the force of the drop weight. The generator frame and coil move during this test rather than the magnet assembly. This approach minimizes the possibility of damage to the magnets by avoiding a direct blow to the core from the drop weight.

With this setup the core moves through the coil at constant velocity. This velocity and the corresponding core travel time can be calculated as follows:

Let m = mass of drop weight (0.8 lbs)

v_i = velocity of drop weight at instant of impact

v_f = velocity of drop weight immediately after impact

M = combined mass of drive plug and generator housing

(0.79 + 0.33 = 1.12 lbs)

V = velocity of combined mass after impact

LAB TEST FIXTURE

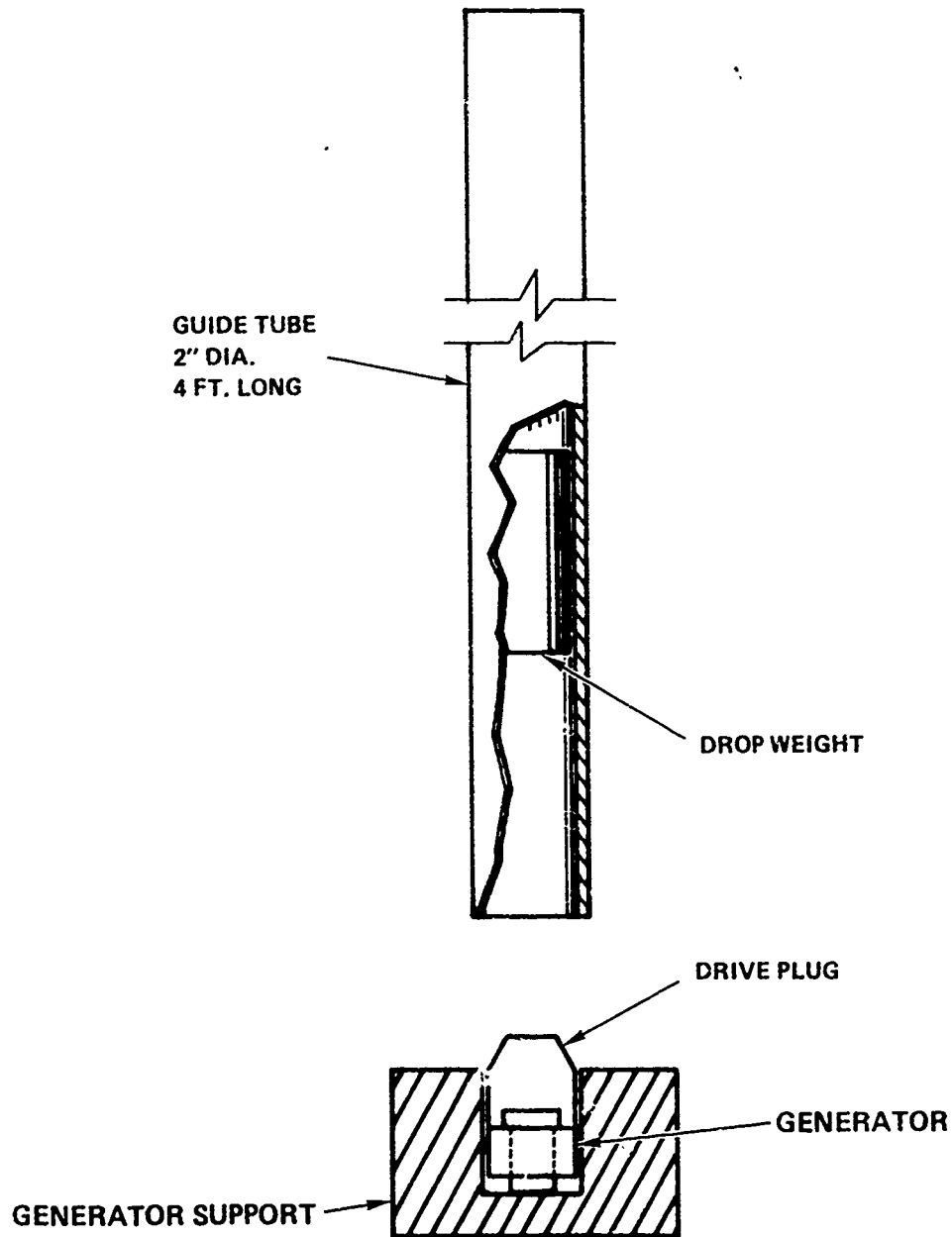


Figure 3. Test Setup using Pipe-Guided Drop Weight

Then $mv_i = mv_f + MV$ (Conservation of Momentum)

and $\frac{1}{2} mv_i^2 = \frac{1}{2} mv_f^2 + \frac{1}{2} MV^2$ (Conservation of Energy)

(Lossless collision assumed)

$$v_f = v_i - \frac{MV}{m}$$

Substituting

$$mv_i^2 = m \left(v_i - \frac{MV}{m} \right)^2 + MV^2$$

$$mv_i^2 = mv_i^2 - 2MV v_i + \frac{M^2 V^2}{m} + MV^2$$

which simplifies to

$$V = \frac{2v_i}{\left(\frac{M}{m} + 1\right)}$$

but since $v_i = \sqrt{2gh}$

where h is the drop height

and g is the acceleration of gravity

$$\text{then } V = \frac{2 \sqrt{2gh}}{\left(\frac{M}{m} + 1\right)}$$

Substituting known values

$$\begin{aligned} V &= \frac{2 \sqrt{2 \times 32.2 \times h}}{\left(\frac{1.12}{0.8} + 1\right)} \\ &= 6.66 \sqrt{h} \text{ feet/second} \end{aligned}$$

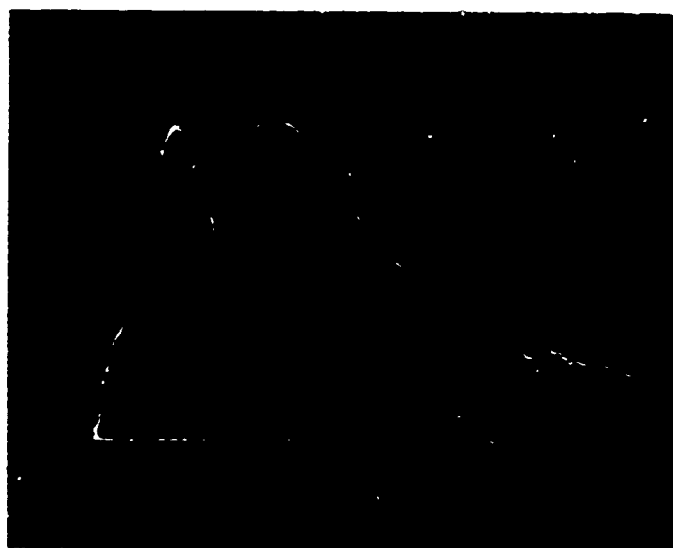
Let T_c = Core transit time

$$\text{then } T_c = \frac{0.2}{12 \times 6.66 \sqrt{h}} = \frac{2.5}{\sqrt{h}} \text{ milliseconds}$$

To verify this analysis, oscilloscope photographs were taken of open-circuit generator output for three different drop heights (see Figure 4). Calculated transit time compares very favorably with transit time measured from these photographs (Transit time was taken as twice the time between start and peak). Results (T_c in milliseconds) are tabulated below.

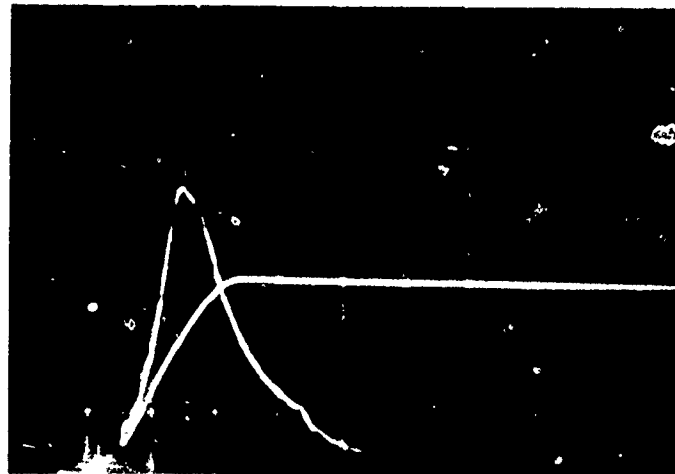
<u>h.</u>	<u>Calculated T_c</u>	<u>Measured T_c</u>
5 feet	1.12	1.2
1.25 feet	2.24	2.4
4 inches	4.33	4.4

The measured values are probably best to use since consideration of energy loss during impact would result in longer transit time. These values were used in later analyses.

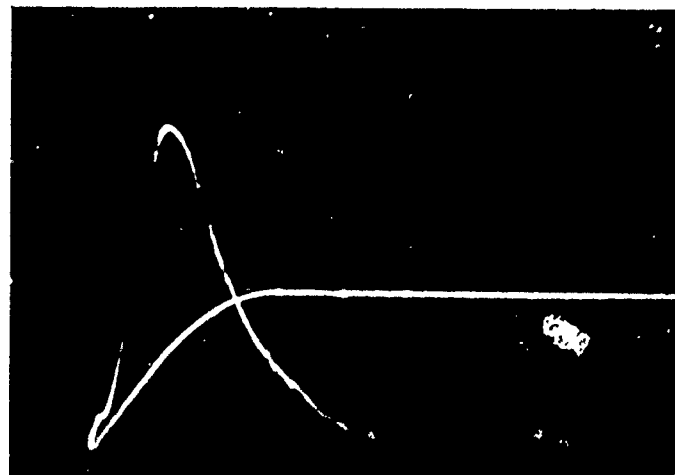


5' Drop
10 V/Div
0.5msec/Div
and
0.2msec/Div

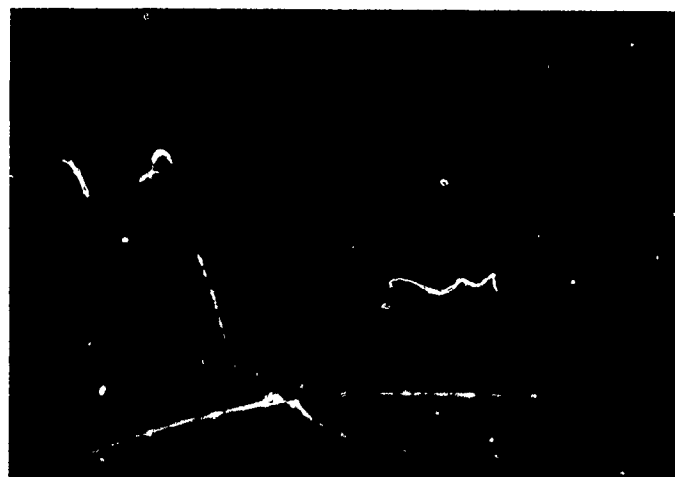
Figure 4. Open-Circuit Generator Output for Three Different Drop Heights (sheet 1 of 2)



4" Drop
4 V/Div
2msec/Div



1½' Drop
5 V/Div
1msec/Div



5' Drop
10 V/Div
0.5msec/Div

Figure 4. Open-Circuit Generator Output for Three Different Drop Heights (sheet 2 of 2)

C. LABORATORY TEST RESULTS

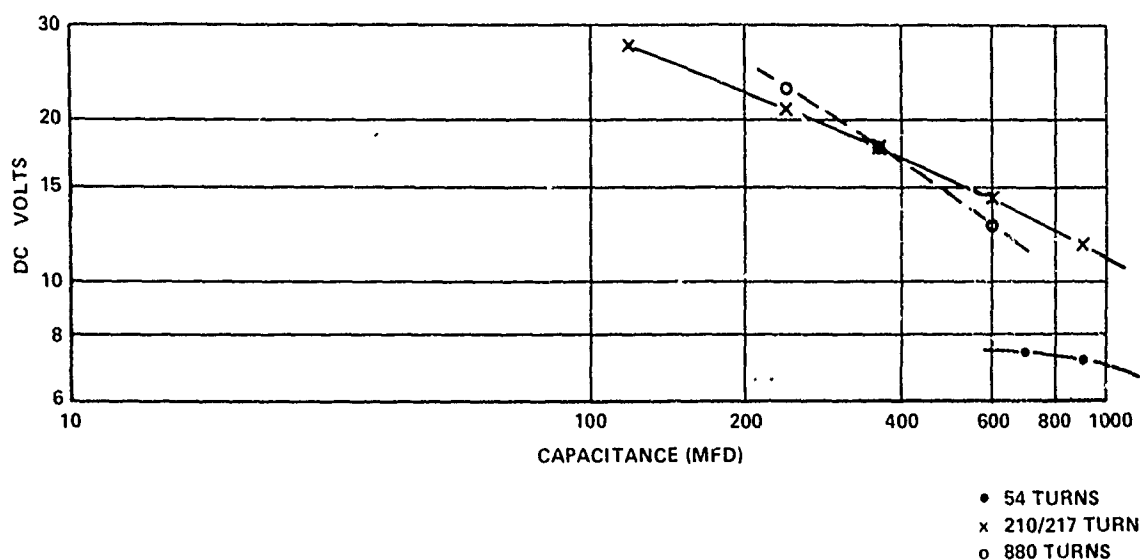
Although the drop test setup provides a constant velocity (rather than accelerating) core motion, the transit time with a 5-foot drop is only about 2:1 greater than that expected during actual firing. (This condition is illustrated in section V, D of this report.) This test technique should, therefore, be a source of much useful data in comparing the performance of various generator configurations. Unfortunately, however, data gathering was frequently interrupted by separation of a magnet from the core assembly. Although in some cases the assembly could be repaired by recementing, this often resulted in lower flux density, thereby making test results less comparable.

Except for a special test discussed later, Table 3 summarizes the data obtained in the drop test setup. Not indicated in the table is the fact that most data points are actually the average value of from two to five repeated tests.

In interpreting this data, plots of DC volts versus capacitance on log-log paper were found convenient. For comparison purposes all output voltages have been ratioed to a common flux density of 5300 gauss before plotting. Figures 5a and 5b are plots of three different coil turns taken at 1.25-foot and 5-foot drop heights, respectively. These two heights are equivalent to a 2:1 difference in core transit time; i.e., from 2.4 millisecond to 1.2 millisecond.

Despite the limited data points available, these plots show the basic difference between low turn and high turn units. The output of the 54 turn unit (which has low source impedance relative to the capacitive loads used) remains roughly constant as capacitance is increased. In effect, the capacitor load is charging up to nearly peak generated voltage. Since halving the transit time nearly doubles the generator output (increased losses prevent full doubling), a substantial increase in generator output occurs at the higher drop height.

A



B

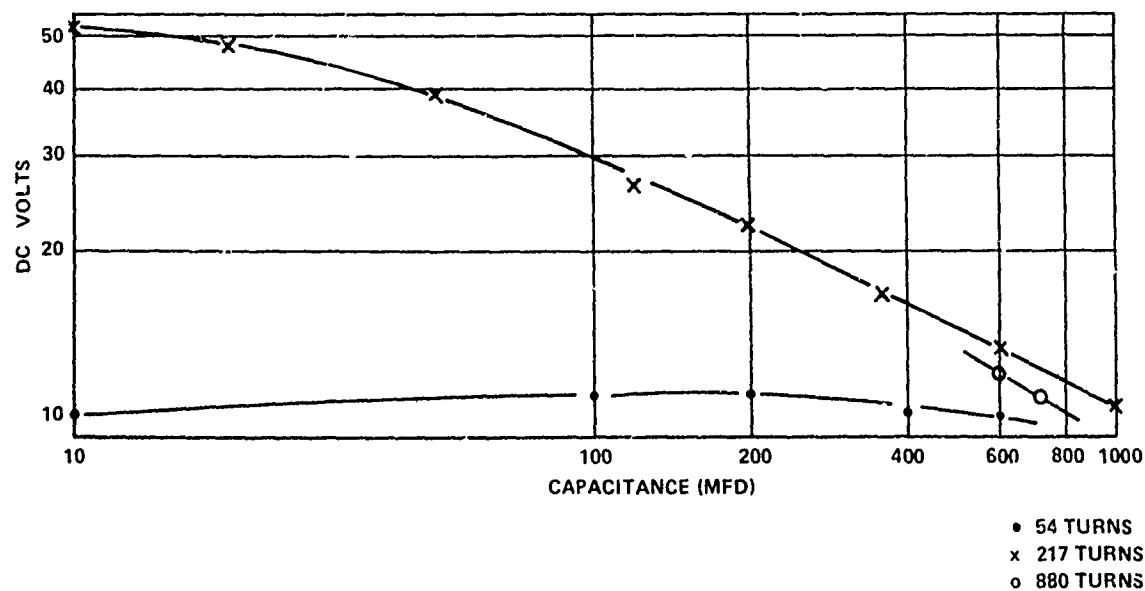


Figure 5. Plots of Three Different Coil Turns taken at 1.25-foot and 5-foot Drop Heights

On the other hand, the 210 and 880 turn units, though having higher generated voltages, also have substantially higher internal impedance. This impedance limits the current into the capacitor load and results in a reduction in voltage as capacitance is increased. In other words, the higher turn units (for the transit times shown) act like current sources while the lower turn unit is more like a voltage source.

Also worthy of note is the slight reduction in output voltage of the higher turn units as core transit time is decreased. If the transit time is reduced further, the output of the 54 turn unit should continue to increase while output from higher turn units decreases. Thus, for very short transit times, higher output would be obtained from the lower turn unit (at least with loads above 600 microfarads).

Figure 6 demonstrates the need for maintaining adequate winding space to keep winding resistance down. This data, taken on the laboratory drop test setup at a 5-foot drop height, shows that, for this particular coil configuration, doubling the winding resistance will reduce output voltage over 15 percent.

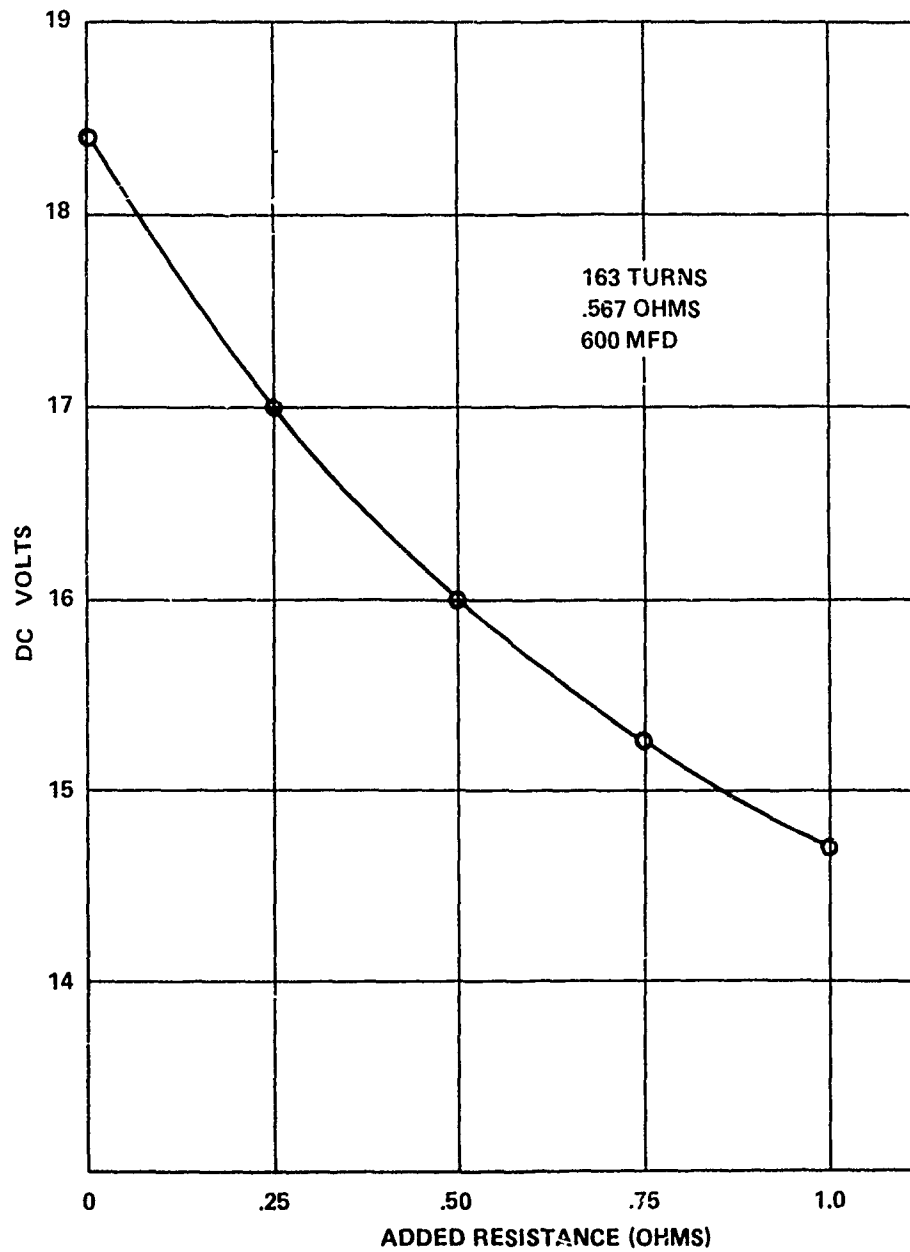


Figure 6. Output Voltage versus Added Resistance

TABLE 3
LABORATORY DROP TEST DATA

TEST DATE	COIL		MAGNET		C	1.25-FT. OUTPUT	5-FT. OUTPUT
	NO.	TURNS	NO.	GAUSS			
9/19	B2B	55	B	5580	600	-	12.7
	B2B	55	B	5580	840	-	11.6
9/19	B2A	55	B2A	6560	600	-	11.9
	B2A	55	B2A	6560	742	-	11.2
	B2A	55	B2A	6560	742	-	11.3
9/12	B2A	55	B2A	6560	10	-	12.3
	B2A	55	B2A	6560	100	-	13.2
	B2A	55	B2A	6560	200	-	13.4
	B2A	55	B2A	6560	400	-	12.4
	B2A	55	B2A	6560	600	-	12.2
11/16	P8	54	P5	5200	600	7.8	-
11/19	D2	54	D1	5900	600	6.6	9.0
11/21	P8	54	P5	5100	600	7.1	9.9
	P8	54	P5	5100	900	6.9	-
	P8	54	P5	5100	1200	6.3	-
11/21	P8	54	P4	5250	600	7.4	10.0
9/12	B1A	219	B1A	6960	600	-	19.5
9/19	C1A	210	C1A	6970	600	-	19.1
9/19	C1A	210	C	5970	600	-	13.5
9/21	C1A	210	A	5920	600	-	13.6
10/4	D1	217	D1	5300	10	-	52.2
	D1	217	D1	5300	120	-	26.5
	D1	217	D1	5300	200	-	22.2
	D1	217	D1	5300	600	-	13.2
10/5	D1	217	D1	5300	20	-	48.1
	D1	217	D1	5300	50	-	38.2
	D1	217	D1	5300	300	-	16.7
	D1	217	D1	5300	1000	-	10.2

TABLE 3
LABORATORY DROP TEST DATA - Continued

<u>TEST DATE</u>	<u>COIL NO.</u>	<u>TURNS</u>	<u>MAGNET NO.</u>	<u>GAUSS</u>	<u>C</u>	<u>1.25-FT OUTPUT</u>	<u>5-FT. OUTPUT</u>
11/16	P4	210	P5	5200	600	14.0	-
11/16	P4	210	P4	5350	120	27.7	-
	P4	210	P4	5350	240	21.3	-
	P4	210	P4	5350	360	18.0	-
	P4	210	P4	5350	600	14.6	-
	P4	210	P4	5350	900	11.9	-
11/19	P4	210	P4	5350	600	14.7	-
11/19	P4	210	P5	5150	600	14.1	-
11/19	D1	217	D1	5300	600	12.9	13.4
9/24	C2B	880	C1A	5800	600	-	13.1
9/24	C2B	880	C	5330	600	-	11.7
	C2B	880	C	5330	720	-	10.6
11/11	P1	880	P1	5400	240	22.5	-
	P1	880	P1	5400	360	17.5	-
11/11	P2	880	P2	5600	240	24.1	-
	P2	880	P2	5600	360	18.8	-
	P2	880	P2	5600	600	15.4	-

D. RAIL GUN TEST

1. Energy Storage Modules

Three prototype generators and their associated energy storage modules were forwarded to Picatinny Arsenal for "rail gun" tests during the latter part of this program. Upon receipt of these units it was determined that the energy storage modules contained voids within the potting material in the vicinity of the circuit board. X-ray inspection of these units at General Electric (see Figure 7) later confirmed this condition.

As a safeguard against possible failure of these units in a gun launch environment, it was decided to fabricate three new energy storage modules to replace those considered marginal. These new units were subsequently forwarded to Picatinny Arsenal to replace the defective units.

An X-ray of these units (Figure 8) showed no evidence of voids within the potting compound.

Electrically, the energy storage modules consisted of six 150 microfarad capacitors connected in parallel (900 microfarads total) and a 1N5059 rectifying diode. These components were mounted on a printed circuit board and potted in Emerson Cumings type 2057 epoxy.

2. Generators

Three generators were supplied for these tests in two electrical designs. All three were identical in physical design with the exception of the coil configuration. Coils within two of the units were 54 turns of No. 15 wire and the other unit had a coil of 220 turns of No. 21 wire. Data on these three units prior to firing is shown in Table 4. Voltage decay measurements were performed on all capacitor modules both prior to, and following, potting of the units into the test hardware. Note that the voltage decay characteristics of all units were similar.

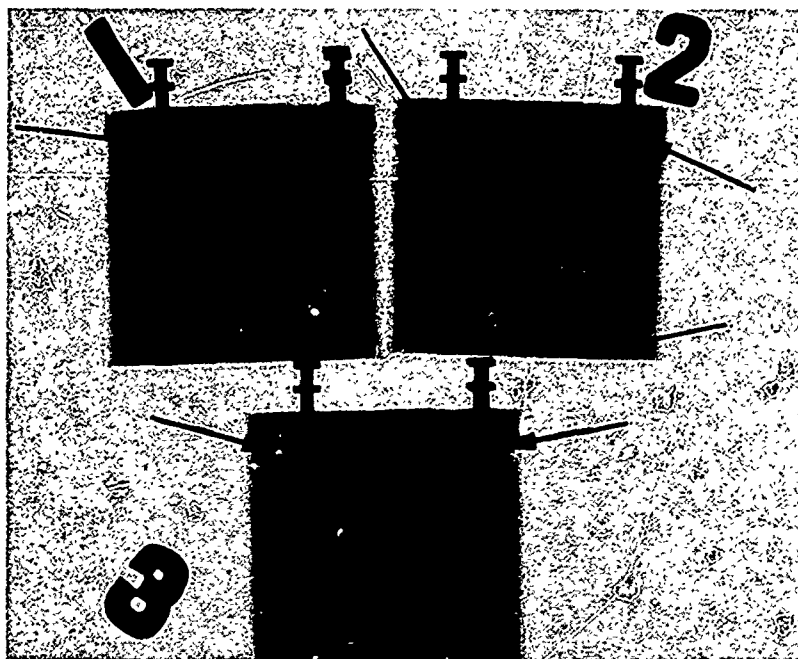


Figure 7. Energy Storage Modules Containing Voids within the Potting Material

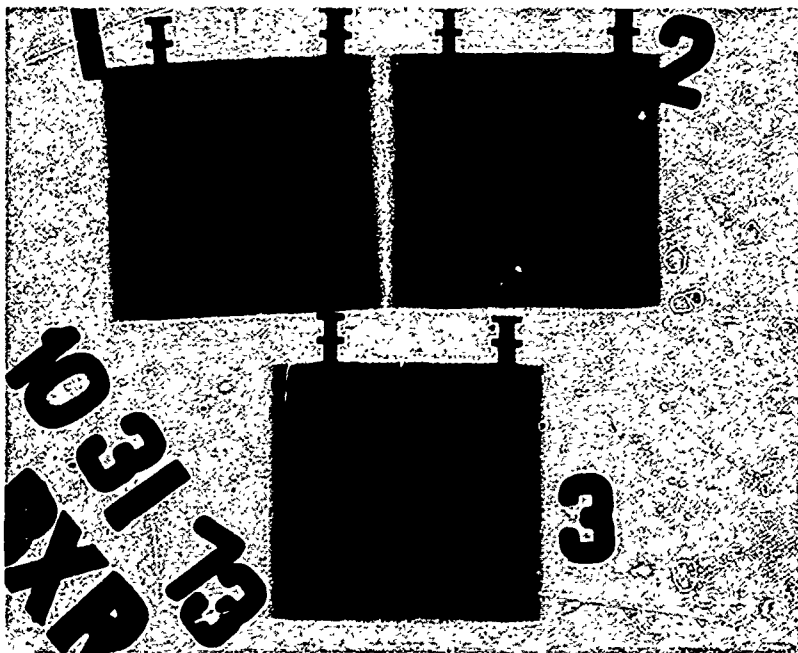


Figure 8. Energy Storage Modules Containing No Voids within the Potting Material

The test fixture into which the generator hardware was installed is shown in the drawing of Figure 9. These units were, in turn, installed in 155-mm test rounds in a manner shown in Figure 10. Note that generators numbers 1 and 3 were assembled with one shear pin each, designed to release the magnet assembly at about a 1000 g acceleration load. Generator No. 2 had two shear pins within the unit which should have caused the magnet assembly to release at about 2000 g's.

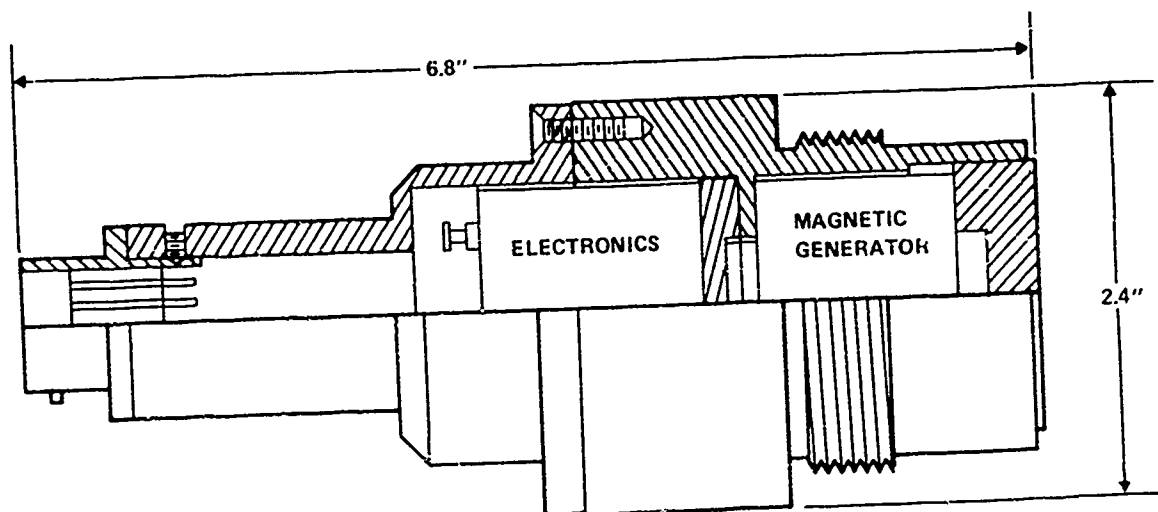
The test projectiles were fired from a 155-mm weapon into a "soft recovery" water trough which slowed the projectile to a stop in about 100 feet of travel. At this point, the projectile was removed from the water trough, opened up, and the voltage on the capacitor bank was measured.

Data from Figures 11, 12 and 13 show that the voltage on unit No. 1 (5 minutes after firing) was 12.5 volts. Unit No. 2 had a voltage of 3.18 volts (11 minutes after firing) and unit No. 3 had a voltage of 6.6 volts (5 minutes after firing). These voltage levels, extrapolated back to the voltage at the time of firing, showed unit No. 1 to have been 13.4 volts (808,000 ergs), unit No. 2 was 4.1 volts (75,600 ergs) and unit No. 3, 7.2 volts (233,000 ergs). These values were arrived at after having tested the decay characteristics of the capacitor banks after firing at two voltage levels for each unit. Table 5 shows the results of these tests. This technique assured a reasonable degree of accuracy in predicting the "start" voltage for each of the generators under test.

3. Post Flight Inspection

After all of the electrical tests had been completed on the three generator test units, the hardware was cut open for visual inspection.

It was noted that the magnets on each unit were severely damaged. It could not be determined from inspection when the damage to these magnets had occurred during the test cycle. It is suspected, however, that the damage occurred at peak projectile setback within the gun tube sometime after



FIJZE TEST UNIT

Figure 9. Generator Hardware Installed in Test Fixture

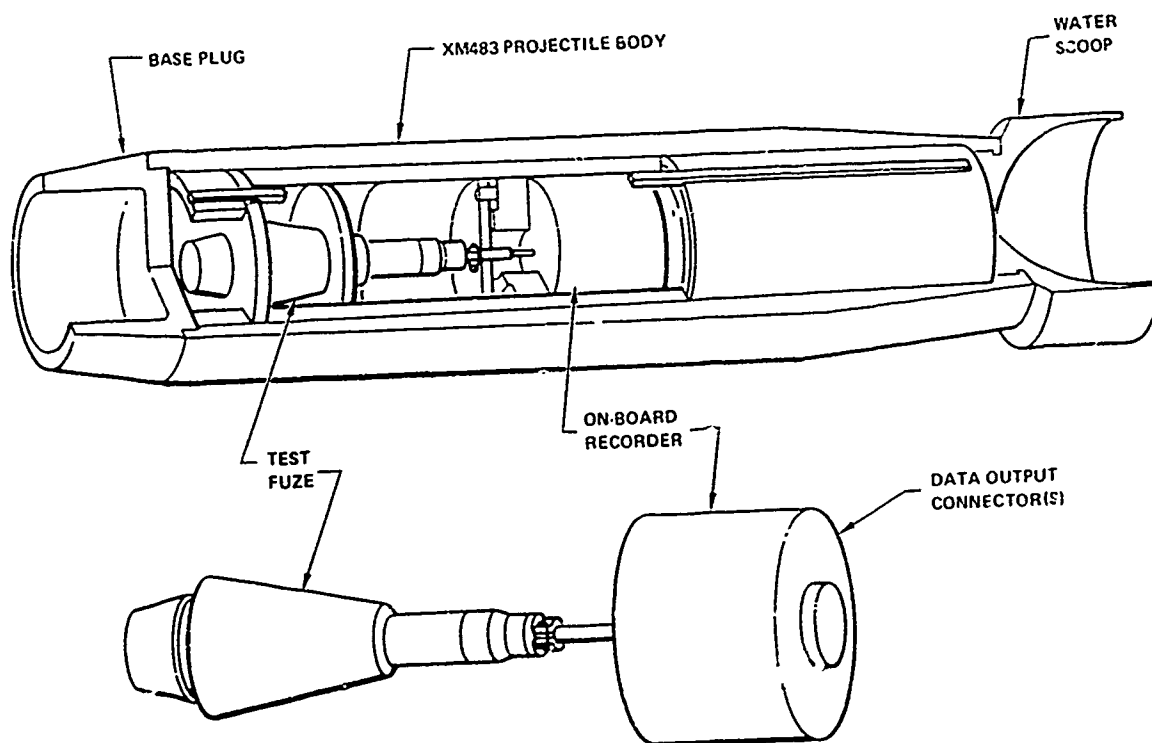


Figure 10. Ballistic Rail Gun Projectile/Carrier

VOLTAGE DECAY OF 900 μ f STORAGE MODULE NO 1

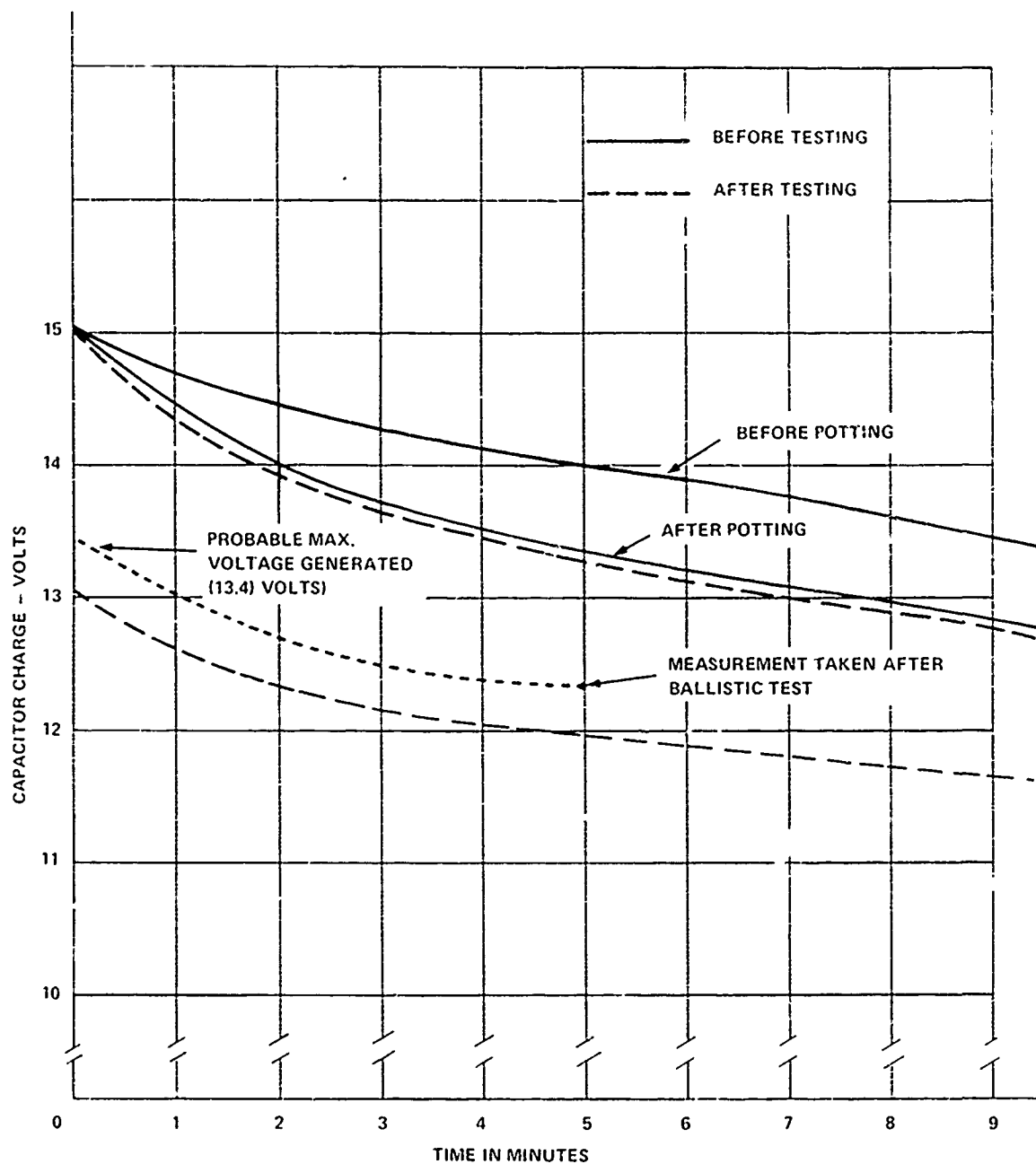


Figure 11. Voltage Decay of 900 μ f Storage Module Number 1

VOLTAGE DECAY OF 900 μ f STORAGE MODULE NO. 2

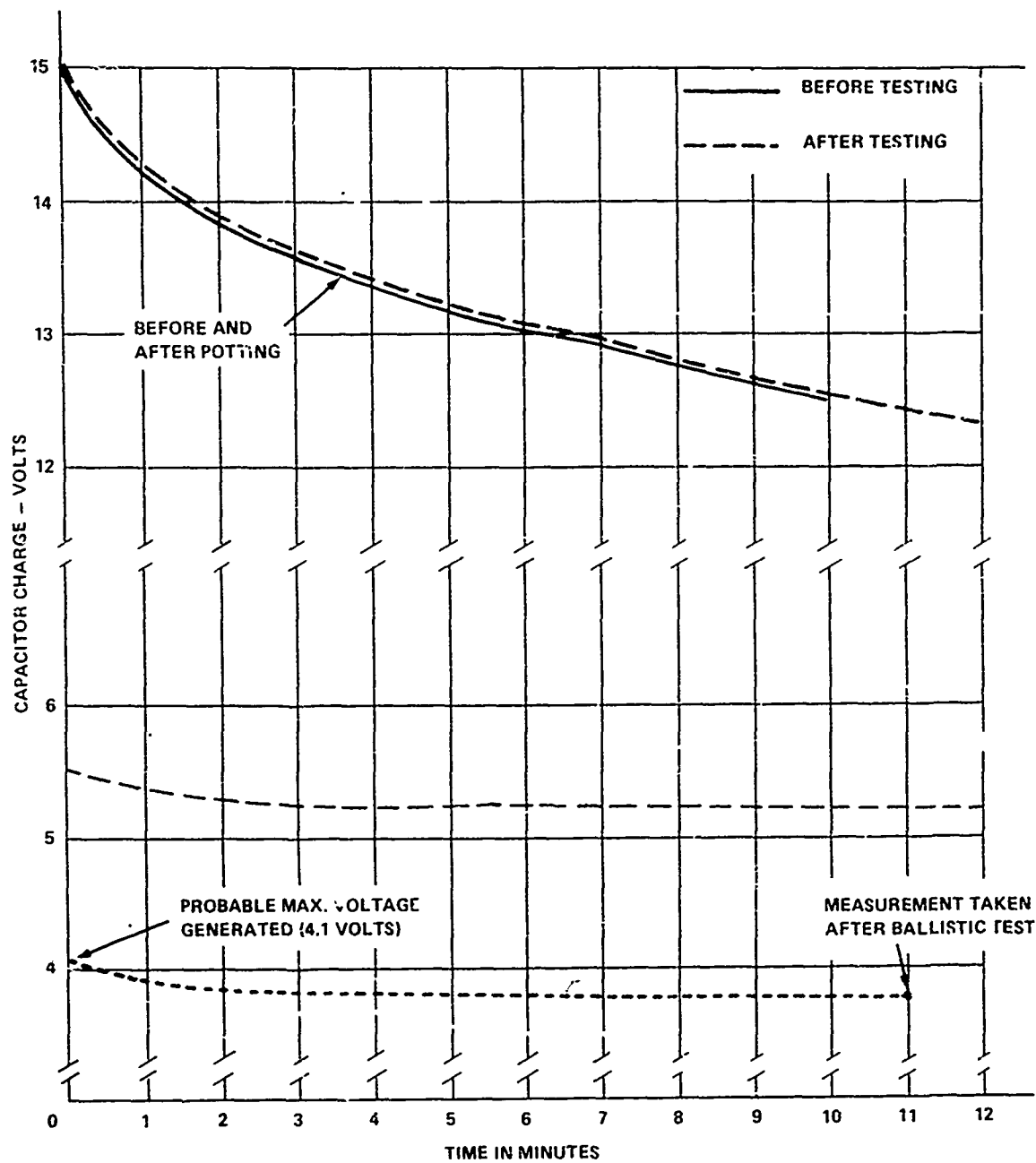


Figure 12. Voltage Decay of 900 μ f Storage Module Number 2

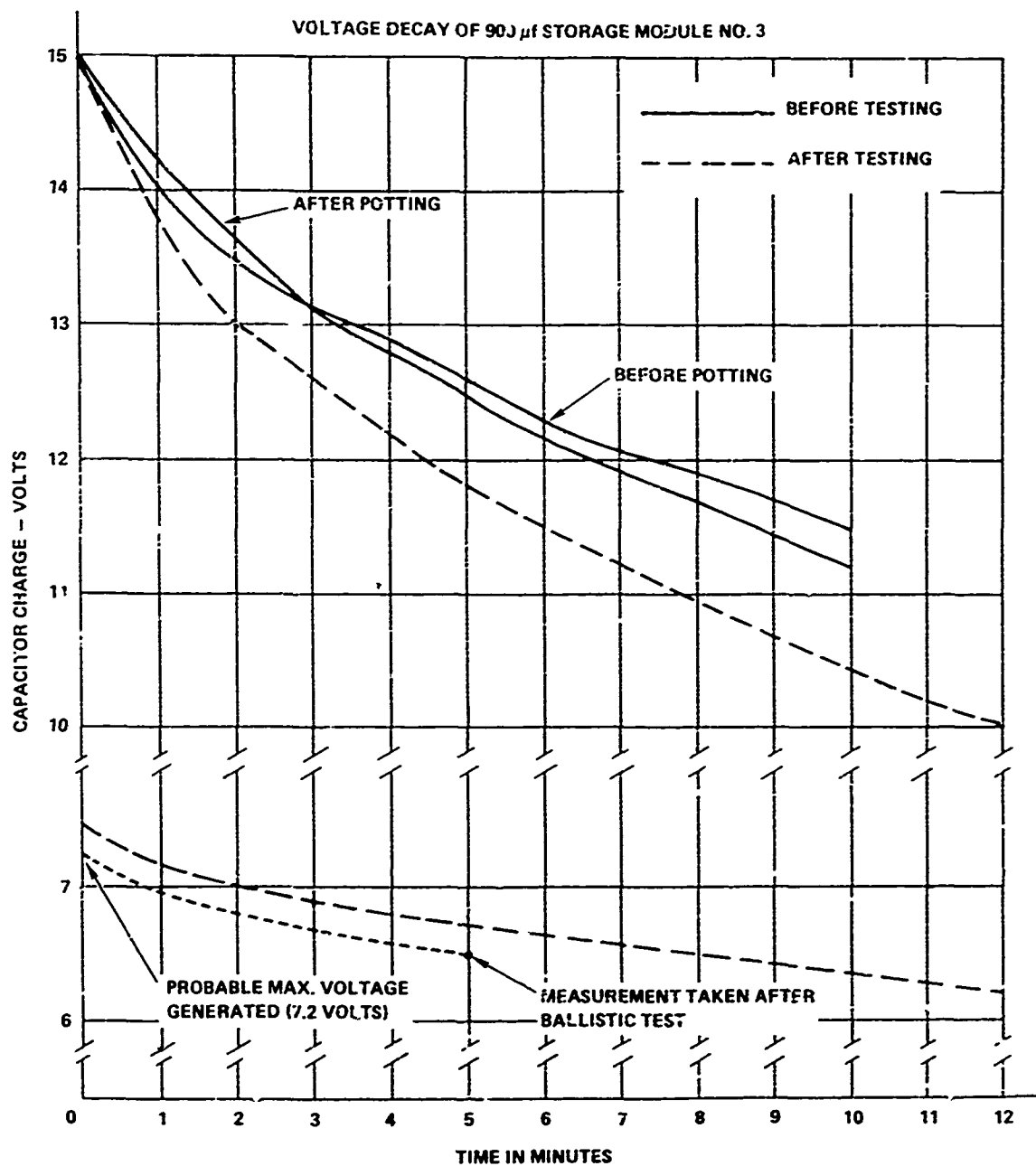


Figure 13. Voltage Decay of 900 μ f Storage Module Number 3

the generator would have performed its function. In this case, failure of the magnets would not influence voltage produced by the generators.

4. Conclusions

1. The output of generator No. 1 (220 turn unit) met performance requirements. However, generators Numbers 2 and 3 (54 turn units) produced outputs below the level anticipated.
2. The energy storage modules survived the shock environment and did not leak off the charge.
3. The test technique, though it did not allow for a measurement of peak voltage at projectile setback, provided a degree of test versatility not available in other test vehicles.

A number of possible causes, for the less than expected performance on two of these generators, have been identified. The more probable of these are listed below:

1. The shear pin under shock conditions may have released much sooner than anticipated by static measurements resulting in reduced velocity of the core through the coil and consequently reduced generator output.
2. The test projectiles may not have provided a realistic presentation of a normal acceleration profile during the first millisecond after "first motion".
3. Dislodging of the forward magnet on the generator assembly during the early phase of projectile setback could have caused reduction in the amount of reverse flux resulting in lower output voltage.

More sophisticated testing techniques will be required on the 20 deliverable units to identify the exact cause of the malfunction for two of the three prototype units tested to date.

TABLE 4
DATA ON FUZE TEST UNITS

UNIT NUMBER	1		2		3		
GENERATOR NUMBER	B1A		B2A		B2B		
TYPE	#21 AWG 220 TURNS		#15 AWG 54 TURNS		#15 AWG 54 TURNS		
# SHEAR PINS	1		2		1		
ELECTRONICS MODULE NO.	1		2		3		
TYPE	900 μ f - No Zener 15 volts		900 μ f - No Zener 15 volts		900 μ f - No Zener 15 volts		
VOLTAGE DECAY MEASUREMENTS (VOLTS)	TIME (MIN)	BEFORE POTTING	AFTER POTTING	BEFORE POTTING	AFTER POTTING	BEFORE POTTING	AFTER POTTING
	0	15	15	15	15	15	15
	1	14.7	14.3	14.2	14.3	14.0	14.2
	2	14.5	14.0	13.8	13.9	13.5	13.7
	3	14.3	13.8	13.5	13.6	13.2	13.2
	4	14.2	13.5	13.3	13.4	12.9	12.8
	5	14.0	13.4	13.1	13.2	12.6	12.5
	6	13.9	13.2	13.0	13.0	12.3	12.0
	7	13.7	13.1	12.8	12.8	12.1	11.9
	8	13.6	13.0	12.7	12.7	11.9	11.7
	9	13.5	12.8	12.6	12.5	11.7	11.4
	10	13.3	12.7	12.4	12.4	11.5	11.2

RESISTANCE MEASUREMENTS

Case to Pin H	∞	∞	∞
Case to Pin G	∞	∞	∞
Case to Pins A & E	∞	∞	∞

FUZE WEIGHTS (ounces)	28.5	28.7	28.6
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FINAL TEST PROCEDURE

- Before Firing - Press METER to determine charge on capacitors
 - Press DISCHARGE (Meter must read 0)
 - Press CHARGE
 - Press and Hold METER - indicator should be off scale and after a few seconds should begin dropping
 - Press DISCHARGE (Meter MUST read 0)

- After Firing - Connect hi-input impedance voltmeter to either red wire (+) and black wire (-) from connector or violet jack (+) and black jack (-) on test box.
 - Mate connector with fuze and measure voltage

TABLE 5

TEST MEASUREMENTS OF FUZE TEST UNITS AFTER FIRING AT HONEYWELL

MODULE NUMBER	1		2		3		
CHARGE REMAINING IN CAPS SINCE TEST ON 11/8	0.70 VOLTS		0.39 VOLTS		0.003 VOLTS		
CHARGE CHARACTERISTICS FROM POWER SUPPLY	OK DISCONTINUOUS		OK DISCONTINUOUS		OK DISCONTINUOUS		
VOLTAGE DECAY MEASUREMENTS (VOLTS)	MIN	TEST 1	TEST 2	TEST 1	TEST 2	TEST 1	TEST 2
	0	15.0	13.0	15.0	5.5	15.0	7.5
	1	14.3	12.5	14.2	5.35	13.8	7.15
	2	14.0	12.4	13.8	5.30	13.0	7.05
	3	13.7	12.2	13.6	5.30	12.6	6.95
	4	13.5	12.1	13.4	5.78	12.2	6.82
	5	13.4	12.0	13.2	5.28	11.8	6.75
	6	13.3	11.9	13.0	5.26	11.5	6.65
	7	13.1	11.8	12.9	5.25	11.2	6.58
	8	13.0	11.7	12.8	5.24	10.9	6.50
	9	12.9	11.7	12.6	5.23	10.7	6.42
	10	12.8	11.6	12.5	5.22	10.4	6.35
	11	12.7	11.6	12.4	5.21	10.2	6.28
	12	12.5	11.5	12.3	5.20	10.0	6.21
DIODE CONDITION	OK		OK		OK		
Resistance Forward X1K	4.6		4.6		4.6		
Resistance Reverse X1K	∞		∞		∞		

E. LOW G BALLISTICS TESTS

The General Electric Company is concurrently developing, under a separate contract with Picatinny Arsenal (DAAA21-73-C-0764), a Remote Set Fuze for 2.75" Rockets. These fuzes are presently battery powered. Preliminary laboratory testing of setback generators under the current program, however, suggested that they might provide sufficient output within a low g rocket launch environment to allow for their use in rocket fuzing applications. On this basis, the General Electric Company initiated an in-house funded program to evaluate a setback generator specifically designed to operate in this low g environment.

Picatinny Arsenal offered to provide the range facilities (Camp Edwards, Massachusetts) and its support personnel to evaluate this hardware.

Three test units were fabricated for test. Figure 2 shows the generator and Figure 14 the energy storage module (300 mfd's). The units were assembled within plumbing hardware which was used to assure parts recovery. Figure 15 shows this hardware. The unit under test was attached to a live 2.75" rocket with the generator output hardwired to a remote recorder. Figure 16 shows such a test vehicle prior to launch.

The rockets were launched from a fixed tube positioned a few hundred feet in front of a sand pile with data being recorded over a flexible cable connected to the hardware under test. Figure 17 shows the launcher and impact area. Upon firing, the output of the generator was transmitted over the cable to a recorder in a bunker located a safe distance from the launch site. Since the cable remained connected to the rocket head throughout the short trajectory, data was recorded to rocket impact with the sand bank where the rocket imbedded and the motor burned out. The rocket and its test hardware were then extracted from the sand bank for subsequent bench tests.

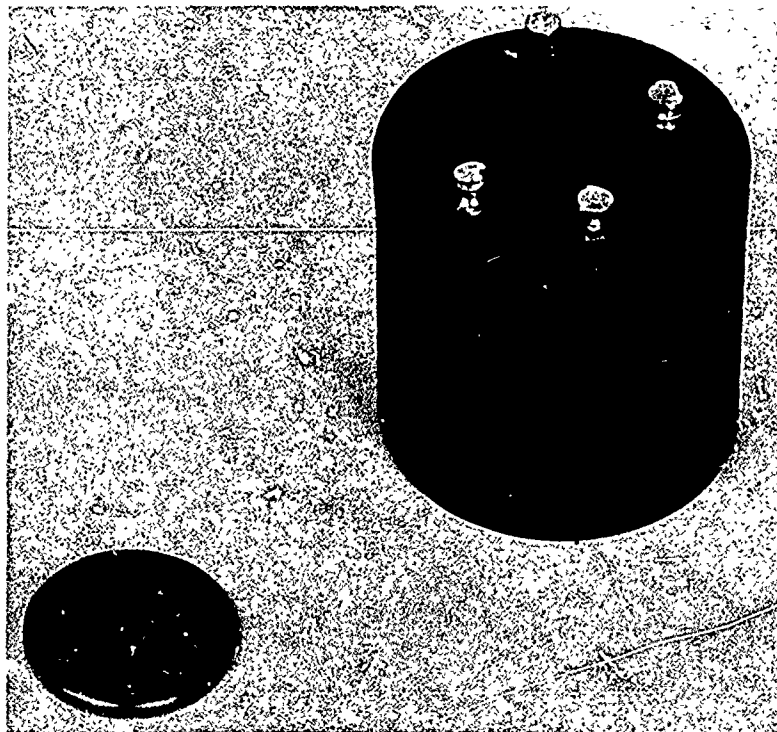


Figure 14. Energy Storage Module

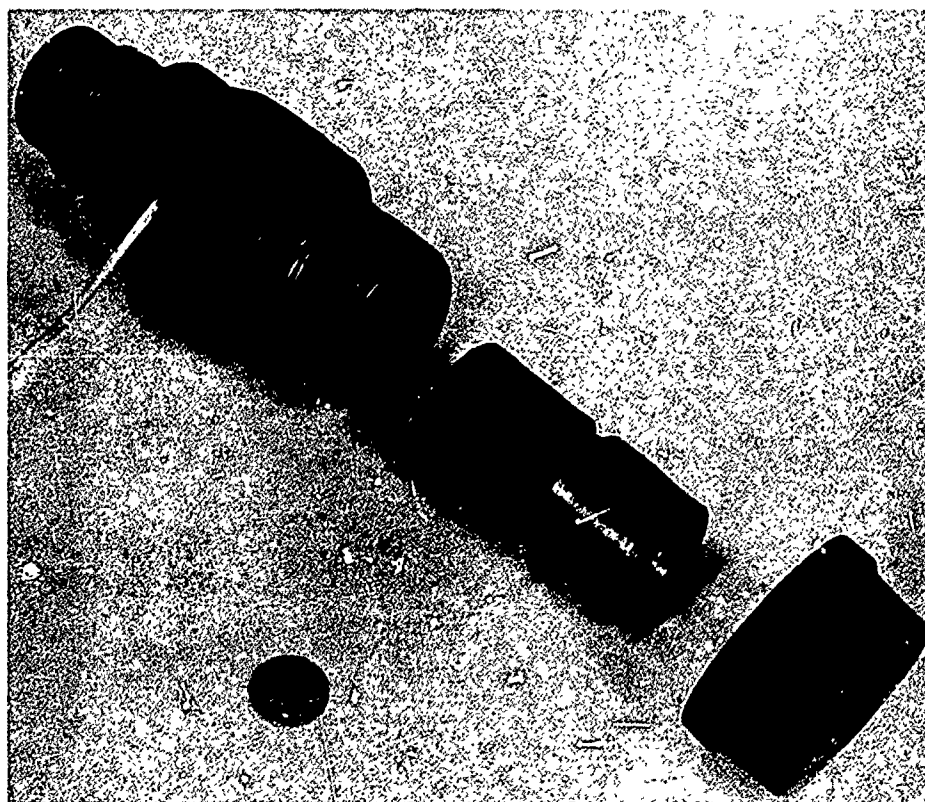


Figure 15. Test Hardware Assembly

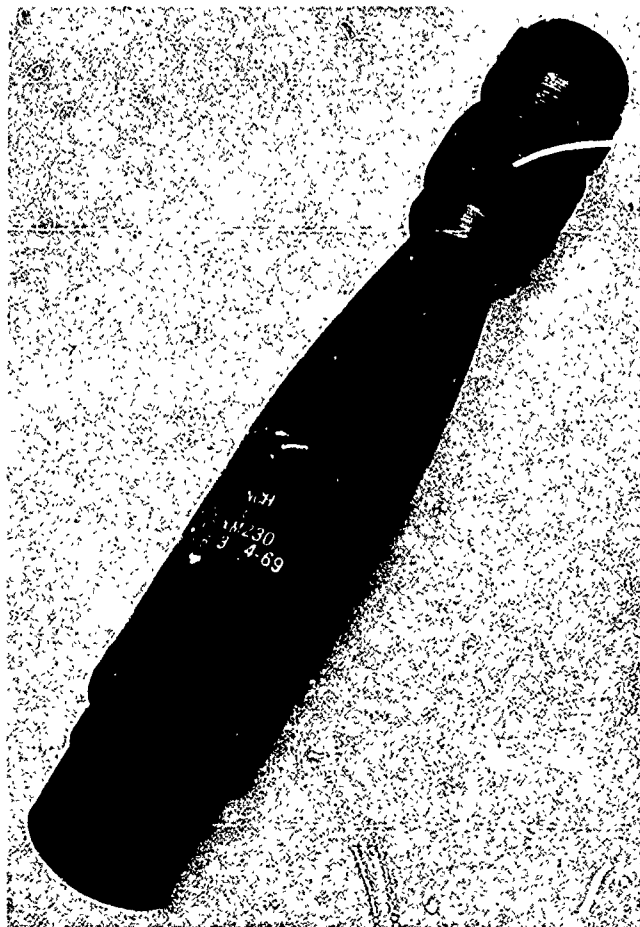


Figure 16. Test Vehicle

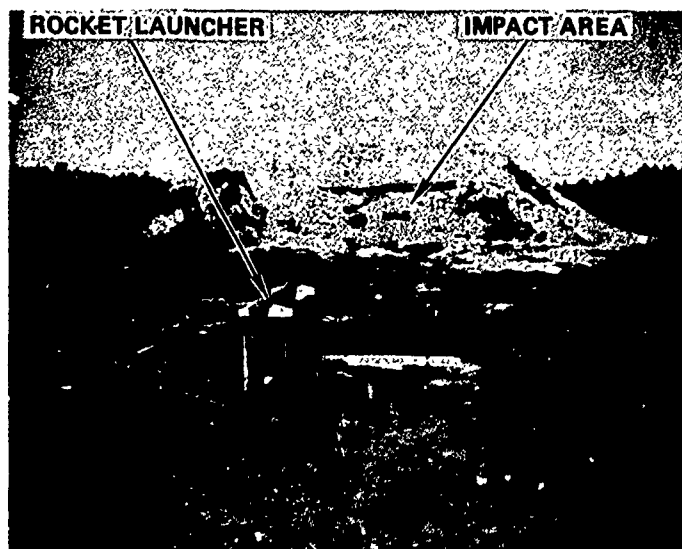


Figure 17. Rocket Test Sight

A typical data trace shown in Figure 18 reveals the time of rocket ignition, rocket first motion, and the voltage impressed upon the 300 microfarad capacitor storage bank by the generator. Note that the voltage rose very abruptly to about 16 volts. This represents approximately 385,000 ergs of stored energy, enough to power a remote set rocket fuze electronics for a few seconds. Minor changes in the fuze electronics could extend this time period significantly. A summary of the test data obtained during the course of these tests is shown in Table 6.

F. CONCLUSIONS

There is conclusive evidence to support the position that a setback generator, of proper design, could serve as a power source for Remote Set Fuzes on 2.75" rockets. Further, it was demonstrated that the energy available from such a generator is sufficient so as to require only minor modification to the existing electronics to allow for its use in this application.

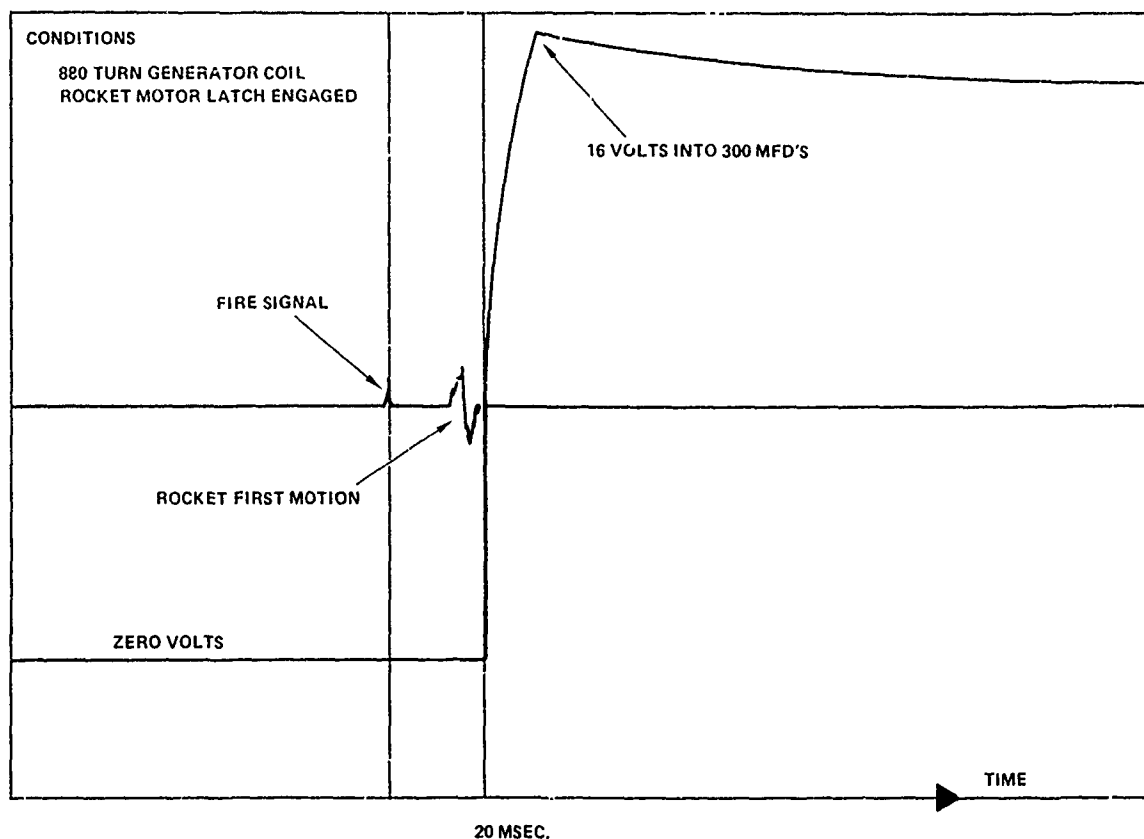


Figure 18. Setback Generator Voltage Profile

TABLE 6

SETBACK GENERATOR TEST RESULTS

TEST NO.	GENERATOR COIL (TURNS)	SETBACK WEIGHT (0.224 LB)	MOTOR LATCHED	ACTION TIME (msec)	TIME TO PEAK		STORED VOLTAGE	STORED ENERGY (ergs)	REMARKS
					VOLTAGE (msec)	VOLTAGE (msec)			
1	220	Yes	Yes	20	40	11.4	195,000	-	
2	880	Yes	Yes	18	30	16.2	391,000	-	
3	880	No	Yes	15	62	11.2	188,000		Step function in recorded voltage rise was traced to magnet separation at launch.
4	880	Yes	No	20	35	10.4	162,000	-	
5	880	Yes	Yes	20	-	-	-		Following recovery, generator wires were found to have broken off (presumably at launch) causing loss of output.
6	880	No	Yes	-	-	15.6	365,000		Hardware, refurbished from a previous shot, produced only a short period of sustained voltage across the capacitor bank before shorting to ground.

Notes:

1. Rocket motors - MK40
2. Motor temperature - 70°F
3. Blanks in the above table indicate loss of recorded data.
4. Action time is the period between the fire signal and rocket first motion.

SECTION V

GENERATOR ANALYSIS SUMMARY

A. OUTPUT VOLTAGE (SIMPLE GENERATOR MODEL)

Effort toward developing a mathematical expression for generator output was initially based upon the assumption of a cosinusoidal distribution of flux, versus position, during core motion. This assumption was supported by a flux versus position plot made from test data on an early generator which, at first inspection, appeared to reasonably conform to the expected cosinusoidal distribution. For constant velocity core motion this assumption resulted in a generated open-circuit voltage corresponding to a half-sine wave. The magnitude of this voltage could be calculated from measurable or known values of core area, flux density, number of coil turns and core transit time.

Using a simple RLC model, the equations controlling output voltage were generated and a computer program set up. However, values for R and L had to be determined before results could be obtained. This was not a simple task since the value for R had to include core losses and the variation of inductance with flux density and frequency had to be determined. While this work was underway, a series of open-circuit voltage oscilloscope photographs were taken which revealed substantial discrepancies between measured and calculated voltages and transit times. These discrepancies resulted in a review of our earlier assumptions. As a result, it was decided that the following changes were necessary to properly describe the generator action:

1. Provide a better curve fit than the previously assumed cosinusoidal flux versus core position distribution.
2. Modify the simple RLC model to include the effect of leakage flux.

B. OPEN CIRCUIT VOLTAGE (LAB TEST ENVIRONMENT)

Figure A-1 of Appendix A illustrates the measured relationship between flux linkages and core position. Also shown is a plot representing the slope, or rate of change of flux linkages with distance traveled, which is closely approximated by an isosceles triangle. With constant velocity motion, such as is developed during laboratory drop tests, rate of change of flux linkages with time, or generated voltage, will also be triangular. Relationships describing the triangular wave shape and relating it to a periodic function are derived in Section I of Appendix A, and the peak value of the generated voltage is computed for a 5-foot laboratory drop test of a setback generator having 217 turns and 5300 gauss peak flux density. This peak voltage is more than twice as large as the measured open circuit voltage for these conditions. This provides clear evidence that a simple series R,L equivalent circuit, which would require that open circuit output voltage be equal to generated voltage, is not adequate to describe the operation of the device.

In Section II of Appendix A, a realistic equivalent circuit is developed using conventional transformer theory, and parameter values are determined using open circuit test measurements.

Section III consists of an open circuit voltage analysis based on this equivalent circuit, and includes calculations of open circuit voltage versus time for the 217 turn unit when subjected to the 5-foot drop test. These results are plotted in Figure A-2 along with calculated generated voltage. Superimposed on this plot is the measured open circuit voltage obtained by scaling from an open circuit voltage oscilloscope photograph, included in this report as Figure 4.

Calculated and test results are in substantial agreement, giving confidence that the equivalent circuit and its specific parameters are suitable for use in prediction of capacitor voltage.

The most notable difference between the calculated and the measured open circuit voltage wave is in the time for reaching the peak voltage. The calculated waveform shows the open circuit voltage peak to lag the generated voltage peak, while the measured waveform indicates a lead. It is believed that this lead may have been caused by one or both of the following conditions not considered in the analysis:

1. Dissymmetry of the magnetic structure, such as different strengths for the magnets at each end of the core, causing the flux to go through zero before the core reached the center of its travel.
2. Decreasing relative velocity during transit caused by frictional and magnetic forces, causing the core to reach the center of its travel at less than half the transit time.

C. OUTPUT VOLTAGE PREDICTION (LAB TEST ENVIRONMENT)

Section IV of Appendix A consists of an output voltage analysis, and includes calculation of the voltage developed across a 600 microfarad capacitor by a 217 turn setback generator when subjected to the 5-foot laboratory drop test. The calculated time for achieving maximum capacitor voltage of 1.17 msec beyond completion of travel agrees very well with that measured in test (see oscilloscope photograph, Figure 4) but the predicted capacitor voltage of 21.51 volts is about 50 percent higher than that illustrated in the same photograph. The discrepancy is not necessarily this large, however, because measurements on other 217 turn units earlier in the program gave more typically 18 volts during the same test. With 18 volts as a reference, the prediction is about 20 percent high. Therefore, the equivalent circuit and the measured parameters are considered sufficiently close for predictions relative to the effect of variations in turns, core velocity, and load capacitance.

Although the phenomenon involved in charging the capacitor is a transient one, once the transient response has been calculated for one set of conditions, certain qualitative predictions may be made relative to moderate variations of these conditions by investigating the effect on the frequency response transfer function. This transfer function is:

$$E_o (S) = \frac{E_g (S)}{L_o C (S^2 + \frac{R_o}{L_o} S + \frac{1}{L_o C_o})}$$

Let $S = j\omega$, where ω is the angular frequency of the periodic generated voltage function.

For the 5-foot drop test, $\omega = 2\pi (400) = 2513$ rad/sec.

$$b_o = \text{undamped natural frequency} = \frac{1}{\sqrt{L_o C_o}}$$

= 741.49 rad/sec for the 217 turn unit charging a 600 mfd capacitor

Because ω exceeds b_0 , operation is beyond the break point frequency, resulting in an amplification of the denominator as ω is increased. This amplification exceeds the first power of ω .

The numerator, $E_g(S)$, increases in direct proportion to velocity, and is, therefore, amplified by the first power of ω .

Combining these two effects indicates that the output of the 217 turn setback generator will decrease as the core speed is increased. Conversely, the output will increase as the core speed is decreased, as long as ω remains substantially above b_0 . This relationship is borne out by inspection of the log-log plots for the 5-foot drop test and the 1.25-foot drop test, where the 1.25-foot drop test results in reduction of ω by a factor of 2 to 1.

Results from the plots for a 217 turn unit supplying 600 mfd are:

5-foot drop: 13.2 volts
1.25-foot drop: 14.5 volts

For operation well above the natural frequency, the denominator $L_0 C (S^2 + \frac{R_0}{L_0} S + \frac{1}{L_0 C_0})$ can be approximated by $L_0 C S^2$, and therefore will increase in proportion to capacitance. For operation well below the natural frequency, the denominator can be approximated by $\frac{C}{C_0}$, and therefore will not be affected. For intermediate conditions, the denominator will be amplified by less than the first power of C . This relationship is readily apparent by inspection of the log-log plots where the attenuation with increasing capacitance approaches proportionally with C for the 880 turn unit which, because of its high inductance, produces a low natural frequency, and approaches unity for the 54 turn, high natural frequency unit.

Relationship of output voltage with turns is more complex because of the substantial effect that turns has on natural frequency. L_0 increases with the square of the turns causing the natural frequency to decrease in proportion to the turns. The denominator approximations mentioned above do apply, however, but careful attention must be given to the relationship between operating frequency and natural frequency.

For high frequency operation, the denominator approximation of $L_0 C S^2$ indicates that the denominator will increase in proportion to the square of the turns. The numerator will increase in proportion to the turns, causing the output voltage to decrease in proportion to the turns. For low frequency operation, the denominator approximation of $\frac{C}{C_0}$ indicates that the denominator will be unaffected, resulting in the output voltage increasing in proportion to turns. The log-log plots support this in that the 54 turn, high natural frequency unit produced more output into 600 microfarads during the 5-foot drop than during the 1.25-foot drop, while the 217 turn and 880 turn units produced less.

Because the transit time is shorter (operating frequency higher) by a factor of approximately two for the artillery shell application as compared with the 5-foot drop, a further attenuation can be expected with the higher turn units, while a further amplification would be expected with the 54 turn unit. The optimum design will be one where neither attenuation nor amplification will result for small changes around the operating frequency. For this reason, 10 of the 20 units are being furnished with 132 turns which would appear to be closer to the optimum than either the 54 turn or the 217 turn units. The remaining 10 units are being furnished with 210 turns, which is representative of the design configuration for which the greatest amount of test data is available.

D. PROJECTION TO FIRING ENVIRONMENT

Data from velocity curves for a 105-mm (high acceleration) and a 106-mm (low acceleration) projectile is interpreted in Appendix B to arrive at acceleration, breakaway time, and core transit time for 1000 g and 3000 g safing. Also included is a calculation of the relative velocity developed between setback generator core and housing at the end of core travel with a safing level of 1000 g. This velocity is 67.19 ft/sec for the 105-mm projectile, and 47.15 ft/sec for the 106-mm projectile. If the assumption is made that the acceleration remains constant for this short interval, the velocity curve then becomes a simple ramp function. Average velocities and transit times based on this assumption are:

1. 105-mm Projectile

$$v_m = 67.19 \text{ ft/sec}$$

$$v_a = \frac{v_m}{2} = \frac{67.19}{2} (12) = 403.14 \text{ in/sec.}$$

$$t_t = \text{transit time}$$

$$S_t = \text{transit distance} = 0.2 \text{ in.}$$

$$t_t = \frac{S_t}{v_a} = \frac{0.2}{403.14} (10^3) = 0.496 \text{ msec}$$

2. 106-mm Projectile

$$v_m = 47.15 \text{ ft/sec}$$

$$v_a = \frac{47.15}{2} (12) = 282.9 \text{ in/sec.}$$

$$t_t = \frac{0.2}{282.9} (10^3) = 0.707 \text{ msec}$$

For discussion purposes, the averages of the above two sets of values will be considered as representative of the firing environment.

These averages are:

$$v_a = 343 \text{ in.}$$

$$t_t = 0.6 \text{ msec}$$

Corresponding values for the 5-foot laboratory drop test environment considered in the analysis of Appendix A are:

$$v = \text{const.} = 160 \text{ in/sec}$$

$$t_t = 1.25 \text{ msec}$$

Therefore the nominal firing environment provides double the average velocity and, conversely, half the transit time or double the angular frequency. All three conditions are synonymous.

If the velocity were constant and therefore equal to the average value presented above, then, because of the further increased operating frequency, the low natural frequency 217 turn unit analyzed in Appendix A would produce a smaller output voltage during the firing environment than during the drop test environment. The reasoning to support this is presented in the preceding section. Another qualitative explanation for the decrease in output is that the volt-time integral would be unchanged, yet the time base would be decreased by a factor of 2. Therefore, a low natural frequency circuit could not respond as effectively.

The ramp nature of the velocity tends to improve the output for a low natural frequency circuit. Although the peak voltage will be the same as for a constant velocity equal to the average velocity of the ramp, and will still occur at the midpoint of travel, a generated voltage near the peak value will be maintained until about 60 percent of travel, and 2/3 of the volt-time integral will occur during the last half of travel. This situation will tend to restore much of the output lost by the increase in operating frequency. Better results, however, can be anticipated with the 132 turn units which will provide a 59 percent higher natural frequency (compared with the 210 turn delivered units) resulting in faster response to overcome the attenuating influence of the higher operating frequency.

SECTION VI

ENERGY STORAGE MODULE

Energy is produced from a setback generator in the form of a narrow electrical pulse which must be stored for subsequent distribution to electronic circuits within the fuze during its flight. The mechanism used to store this energy is a capacitor of sufficient size to allow the storage of this energy at a voltage which will not cause damage to the electronic circuits. This level for CMOS circuitry is about 15 volts. A zener diode is sometimes connected across the capacitor bank to assure that this level is not exceeded. It also serves to protect the capacitors against a voltage breakdown condition.

The voltage from the generator is applied to the capacitor bank through a rectifier which also serves to isolate the generator from the energy storage module. Figure 19 is a schematic diagram of the energy storage module.

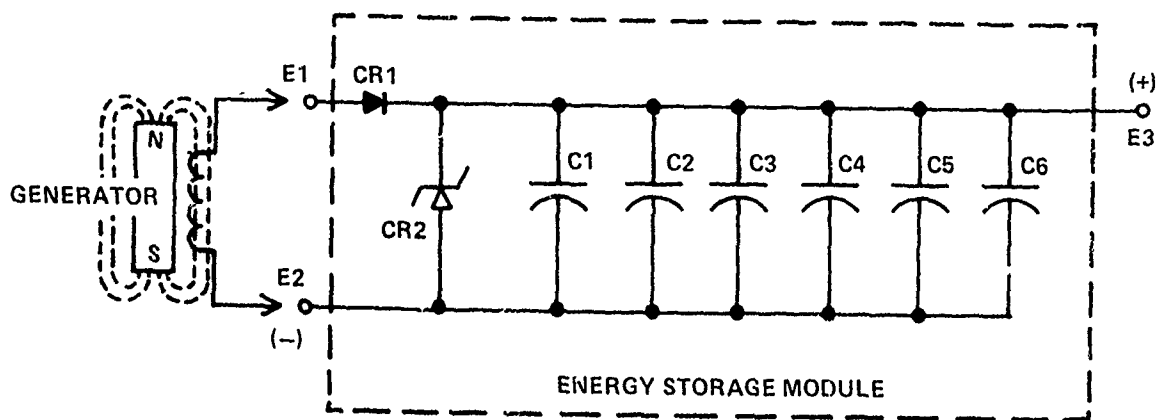


Figure 19. Schematic Diagram of Energy Storage Module

To assure structural integrity of the energy storage module under conditions of projectile setback, the components which make up the module are encapsulated in a hard epoxy. A photograph of a module prior to potting is shown in Figure 20. The photograph also shows a potted module and the mold assembly used to encapsulate the electrical components.

The physical dimensions of the energy storage module are presently excessive when the actual volume of the tantalum slugs within these capacitors is considered. The X-ray photograph in Figure 8 clearly points this out. The use of these capacitors and the general physical configuration of the module are primarily for expedience in this program since only limited resources were available to develop an acceptable package.

Technical discussions held with capacitor vendors have confirmed the belief that a special capacitor module could be developed which would meet the necessary environmental requirements and be packaged with a volume equal to about 1/4 that of the present energy storage module. It was further suggested that the development of such a package would involve only modest development costs.



Figure 20. Energy Store Module - Before and After Potting

A. CAPACITOR EVALUATION

The key element in the successful design of the setback generator power source is the ability of the energy module (capacitor bank) to properly store the energy produced by the generator and maintain the level of that energy through the shock induced into the capacitors during projectile setback. The susceptibility of capacitors to fail to maintain their charge within this high g environment was observed during the course of related contract work in which setback generators of an earlier design were employed.

During the course of this contract effort (and concurrent with Picatinny Arsenal contract DAAA21-73-C-0292, "Remote Settable Fuze Information Link" which also included a task relating to capacitor evaluation) a laboratory investigation into the failure mechanism of tantalum capacitors was undertaken. The scope of this investigation included an evaluation of both dry, wet slug, and electrolytic foil capacitors.

The data presented below combines the results of capacitor tests performed in support of investigations on both programs. It should be noted that the laboratory test technique employed was nearly identical in studies conducted on both contracts.

1. Laboratory Tests

A laboratory investigation into the failure mechanism of tantalum and electrolytic capacitors within a high g shock environment was undertaken during the course of this contract. Both "solid" and "wet slug" tantalum capacitors were investigated.

The fixture used to induce shock into the capacitors was a small air-driven jack hammer operated from shop air. A photograph of the test device is shown in Figure 21. It is capable of inducing $\pm 20,000$ g shock impulses into a test specimen at a rate of 50 impulses per second. Figure 22 shows an individual induced shock pulse. The multiple shock pattern is primarily the result of transducer ringing. Test cycles used for this evaluation consisted of the following:

1. Charge potted capacitor to +15 volts, remove supply and record voltage decay (leakage) for 50 seconds.
2. Repeat same as above except that the test specimen is shocked during the 50-second decay period.
3. Following shock test, recharge capacitor to +15 volts and record voltage decay (leakage) for 50 seconds. This cycle was repeated for identical capacitors in two perpendicular mounting planes.

2. Results

Tantalum and foil electrolytic capacitors were subjected to shock tests as described above. These included solid, wet slug, and foil capacitors from six different vendors (General Electric, Kemet, Tansitor, Sprague, MECPO, and IEC). Test results from this evaluation confirmed similar findings by Picatinny Arsenal which indicated that the Kemet "bullet" capacitors (type 7246HB and 7249HD) repeatedly survived the shock environment without evidence of electrical degradation.

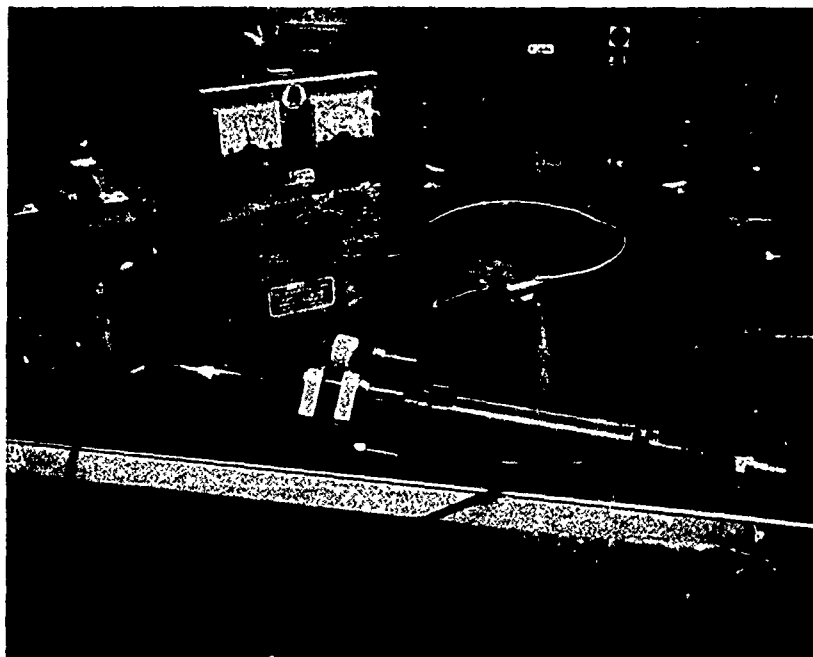


Figure 21. Air Hammer Shock Fixture

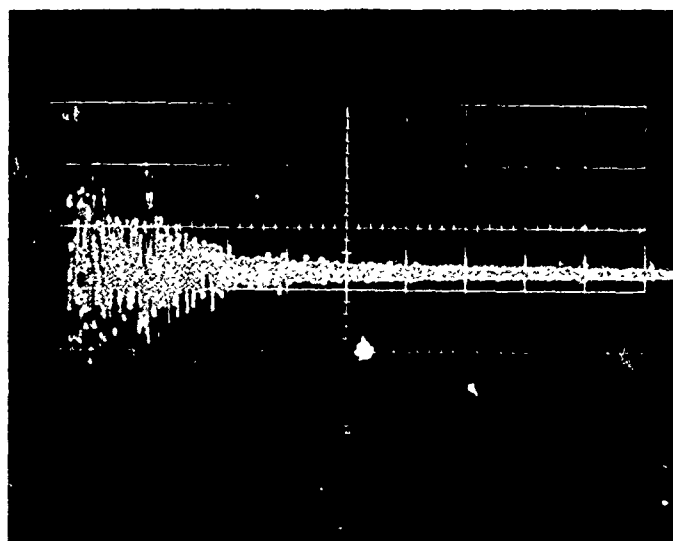


Figure 22. Shock Pulse

In addition, however, a wet slug capacitor manufactured by Tansitor (47 μ fd @ 15V) also showed evidence of acceptable performance within the induced shock environment. Of the five units of this type tested, all were unaffected by the shock environment. One of the units, however, showed moderate leakage prior to the shock test and was rejected. Testing of a larger sample may show this capacitor type to be an acceptable substitute for the Kemet units.

Figures 23 through 29 compare the results of typical wet slug tantalum and foil electrolytic capacitors with that of an acceptable solid core tantalum capacitor.

Table 7 summarizes the results of some 65 test runs performed on 17 capacitor types. On the basis of this test data and other test data compiled at Picatinny Arsenal, the Kemet "bullet" capacitors were selected for use as the energy store for all fuze hardware fabricated and delivered in this program. Ten energy storage modules which were delivered at the conclusion of this program contained six 100 μ fd, 20 volt Kemet capacitors. Another 10 modules delivered were fabricated using six 150 μ fd, 15 volt Kemet capacitors.

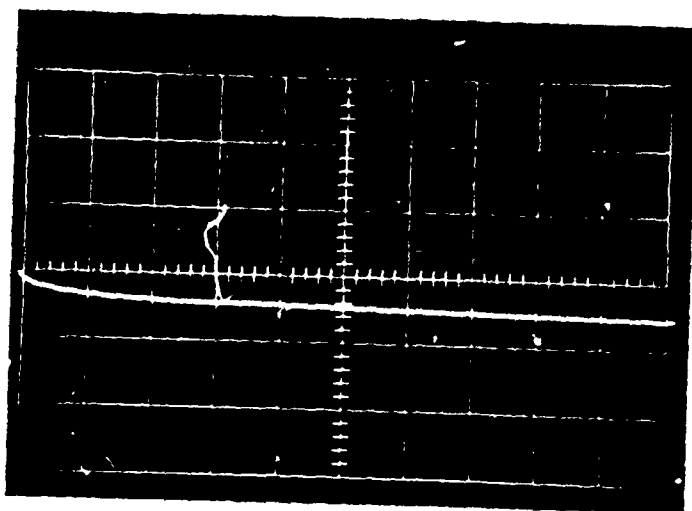


Figure 23. Electrolytic Foil Capacitor prior to Shock

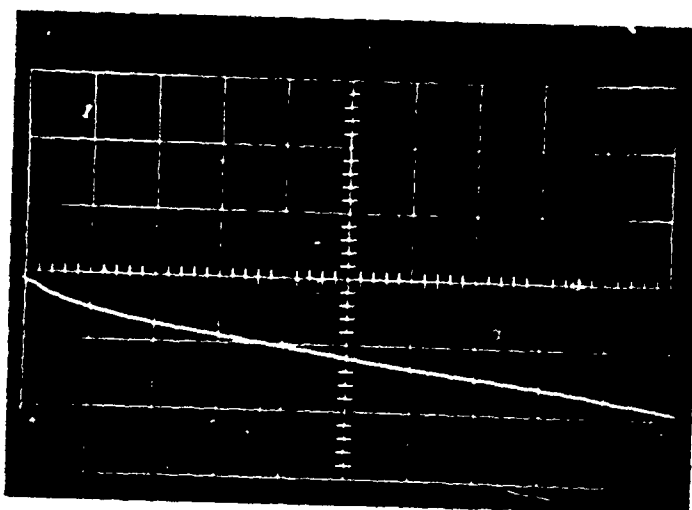


Figure 24. Electrolytic Foil Capacitor during Shock

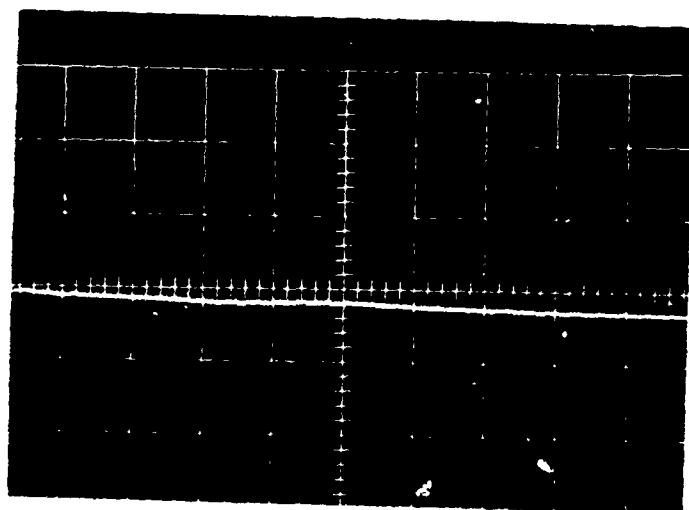


Figure 25. Typical Wet Slug Capacitor Leakage prior to Shock

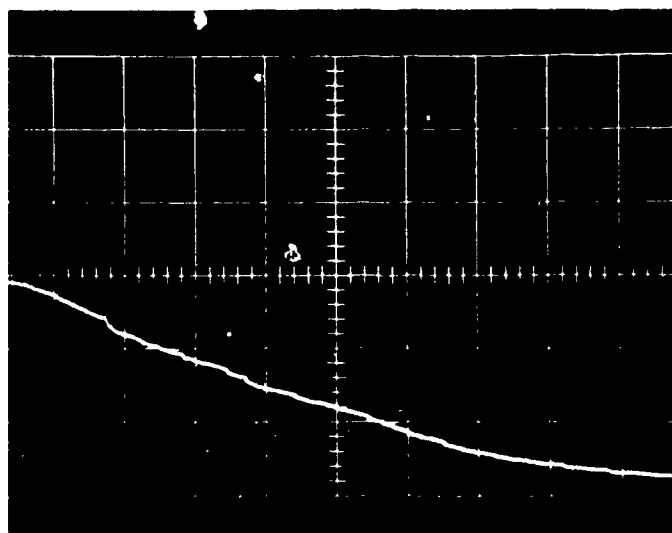


Figure 26. Typical Wet Slug Capacitor Leakage during Shock

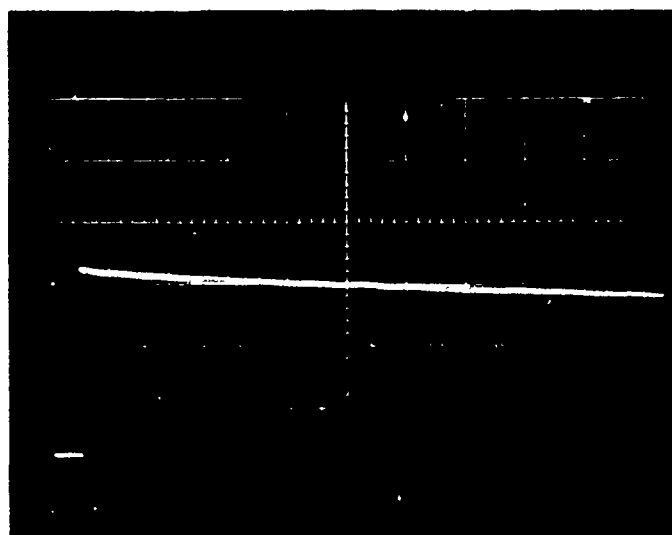


Figure 27. T310 Kemet Capacitor Leakage prior to Shock

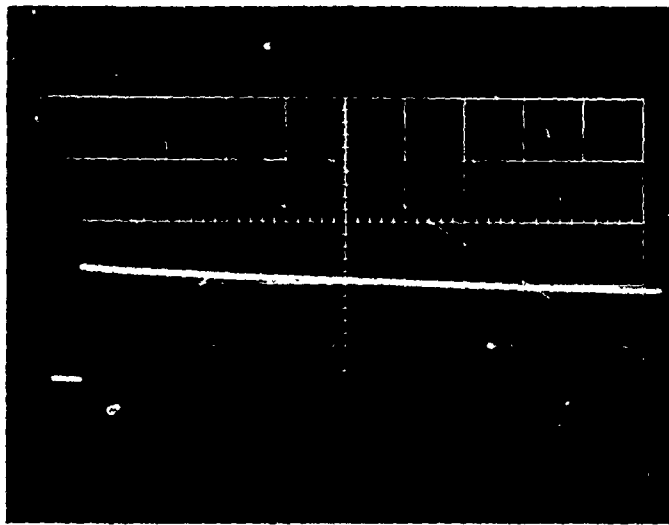


Figure 28. T310 Kemet Capacitor Leakage during Shock

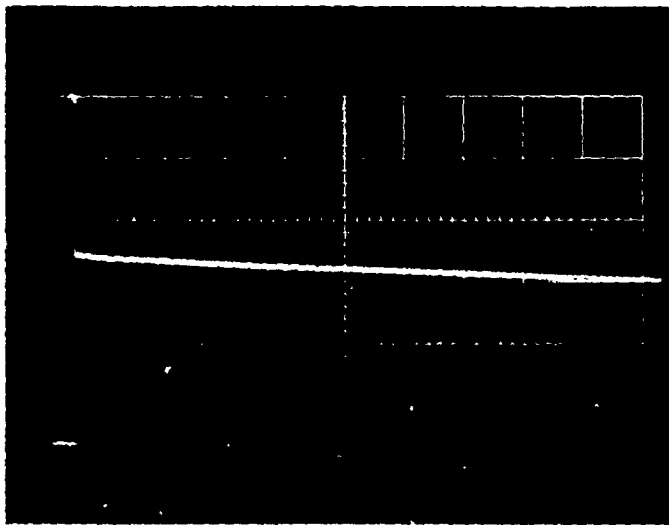


Figure 29. T310 Kemet Capacitor Leakage following Shock

TABLE 7
CAPACITOR TEST DATA SUMMARY

<u>Type</u>	<u>Vendor</u>	<u>Part No.</u>	<u>Test No.</u>	<u>Remarks</u>
Wet slug	Sprague	150D 100 μ fd @ 20V.	1	Failed - Breakdown to 8 volts after 5 sec. of shock
			2	Acceptable
			3	Failed - Breakdown of 10 volts after 20 sec. of shock
Solid	Sprague	162D 22 μ fd @ 15V.	1	Marginal - Excessive leakage
			2	Marginal - Excessive leakage
			3	Marginal - Excessive leakage
Solid	Sprague	198D 22 μ fd @ 15V.	1	Marginal - Significant leakage rate before, during and after shock
			2	Marginal - Significant leakage rate before, during and after shock
Solid	Kemet	K 100 100 μ fd @ 20V.	1	Failed - Breakdown to 3 volts due to potting stresses
			2	Failed - Shorted as purchased
			3	Acceptable
Solid	Sprague	196D 120 μ fd @ 15 V.	1	Acceptable
			2	Acceptable
			3	Failed - Breakdown to 3 volts due to potting stresses

TABLE 7

CAPACITOR TEST DATA SUMMARY -- continued

<u>Type</u>	<u>Vendor</u>	<u>Part No.</u>	<u>Test No.</u>	<u>Remarks</u>
Solid	Sprague	196D 47 μ fd @ 20V.	1	Failed - Breakdown to 13 volts after 2 sec. of shock
			2	Failed - High leakage induced by shock
			3	Failed - Breakdown to 4 volts due to potting stresses
Wet slug	General Electric	69F2441G8 620 μ fd @ 30V.	1	Failed - High leakage due to shock
			2	Failed - High leakage due to shock
			3	Failed - High leakage due to shock
Solid	Kemet (Union Carbide)	T-310 47 μ fd @ 20V.	1	Acceptable
			2	Acceptable
			3	Acceptable
Solid	Kemet	T-310 47 μ fd @ 15 V.	1	Acceptable
			2	Acceptable
			3	Acceptable
Wet slug	General Electric	69F2336G8 510 μ fd @ 25 V.	1	Failed - Excessive leakage due to shock
			2	Failed - Excessive leakage due to shock
			3	Failed - Excessive leakage due to shock
Wet slug	Tansitor	W100-15C2M1 100 μ fd @ 15 V.	1	Failed - Excessive leakage due to shock
			2	Failed - Moderate leakage due to shock
			3	Failed - Excessive leakage prior to shock
			4	Failed - Excessive leakage following shock

TABLE 7

CAPACITOR TEST DATA SUMMARY - continued

<u>Type</u>	<u>Vendor</u>	<u>Part No.</u>	<u>Test No.</u>	<u>Remarks</u>
Wet slug	Tansitor	S47-15C3M1 47 μ fd @ 15 V.	1 2 3 4 5	Acceptable Marginal - Moderate leakage prior to shock Acceptable Acceptable Acceptable
Solid	Kemet (Union Carbide)	T-310 150 μ fd @ 15 V.	1 2 3 4 5 6	Acceptable Acceptable Acceptable Acceptable Acceptable Acceptable
Electrolytic Foil	IEC Corp.	Series PCV 500 μ fd @ 16 V.	1 2	Failed - Moderate leakage due to shock Failed - Moderate leakage due to shock
Electrolytic Foil	IEC Corp.	Series TAD 500 μ fd @ 16 V.	1 2	Failed - Excessive leakage due to shock Failed - Excessive leakage due to shock
Electrolytic Foil	MEPCO Electra Corp.	3LC-0009-21 500 μ fd @ 16 V.	1 2 3 4 5 6	Failed - Excessive leakage due to shock Failed - Excessive leakage due to shock Failed - Excessive leakage due to shock Failed - Excessive leakage due to shock Failed - Excessive leakage due to shock Failed - Moderate leakage due to shock

TABLE 7

CAPACITOR TEST DATA SUMMARY - continued

<u>Type</u>	<u>Vendor</u>	<u>Part No.</u>	<u>Test No.</u>	<u>Remarks</u>
Electrolytic Foil	MEPCO Electra Corp.	680 μ fd @ 16 V.	1	Failed - Excessive leakage due to shock
			2	Failed - Excessive leakage due to shock
			3	Failed - Moderate leakage due to shock
			4	Failed - Shorted due to shock
			5	Failed - Excessive leakage due to shock
Electrolytic Foil	MEPCO Electra Corp.	3LO-0009-W 1500 μ fd @ 16 V.		Failed - Excessive leakage due to shock
			1	Failed - Moderate leakage due to shock
			2	Failed - Moderate leakage due to shock
			3	Failed - Excessive leakage due to shock
			4	Failed - Moderate leakage due to shock
			5	Failed - Moderate leakage due to shock

SECTION VII
DELIVERABLE HARDWARE

A. ENERGY STORAGE MODULES

Prior to shipping the 20 energy storage modules to Picatinny Arsenal, a capacitor leakage test was conducted on each of the potted units. This test was performed by first charging each module to its maximum operating voltage (+15 or +20 volts depending upon the group being evaluated) and monitoring the residual voltage on each unit at 15 minute increments over a period of two hours.

The results of these tests are shown in Tables 8 and 9. Note that even the most leaking module (600 μ fd) retained over 54 percent of its initial voltage at the end of the first 15 minute period. The best module showed a voltage decay of only 20.5 percent over the same period.

Following the leakage tests the units were x-rayed for evidence of potting flaws. No significant voids within the potting material were found as can be seen from the x-ray photograph in Figure 8.

TABLE 8
CAPACITOR LEAKAGE TEST DATA
(900 mfd. Modules)

UNIT NO.	T _O	TIME								Voltage
		+15 min.	+30 min.	+45 min.	+60 min.	+75 min.	+90 min.	+105 min.	+120 min.	
1	15.01	11.99	11.52	11.17	10.90	10.64	10.41	10.19	9.97	
2	15.01	11.60	11.00	10.56	10.24	9.93	9.68	9.45	9.22	
3	15.01	11.59	10.83	10.25	9.82	9.40	9.06	8.75	8.44	
4	15.01	11.39	10.54	9.88	9.39	8.93	8.53	8.19	7.84	
5	15.01	11.33	10.26	9.44	8.83	8.27	7.81	7.41	7.02	
6	15.01	11.77	11.33	11.00	10.74	10.50	10.29	10.09	9.88	
7	15.01	10.71	9.53	8.68	8.05	7.48	7.01	6.61	6.21	
8	15.01	10.23	8.73	7.66	6.90	6.21	5.66	5.20	4.76	
9	15.01	11.99	11.42	10.97	10.62	10.27	9.97	9.70	9.40	
10	15.01	11.62	10.87	10.29	9.84	9.40	9.03	8.70	8.35	

TABLE 9
CAPACITOR LEAKAGE TEST DATA
(600 mfd. Modules)

UNIT NO.	T _o	TIME								Voltage
		15 min.	30 min.	45 min.	60 min.	75 min.	90 min.	105 min.	120 min.	
1	20.0	13.58	11.80	10.55	9.66	8.91	8.35	7.88	7.41	
2	20.0	14.01	12.62	11.70	11.06	10.53	10.14	9.81	9.48	
3	20.0	15.91	14.84	14.05	13.48	12.99	12.61	12.29	11.97	
4	20.0	14.13	12.75	11.83	11.21	10.69	10.31	9.99	9.67	
5	20.0	13.71	12.22	11.22	10.53	9.95	9.52	9.16	8.79	
6	20.0	11.66	10.21	9.27	8.63	8.10	7.71	7.38	7.05	
7	20.0	13.08	11.71	10.83	10.24	9.75	9.40	9.10	8.80	
8	20.0	11.28	9.93	9.09	8.54	8.08	7.75	7.48	7.20	
9	20.0	10.96	9.31	8.21	7.47	6.86	6.41	6.04	5.67	
10	20.0	13.84	12.52	11.66	11.08	10.60	10.25	9.96	9.67	

B. GENERATOR UNITS

All generator units passed a 200 volt hipot test between winding and frame.

Maximum flux density was measured on all units with the following results.

<u>SERIAL NO.</u>	<u>NO. OF TURNS</u>	<u>CORE GAUSS</u>
G1-1	132	5200
G1-2	132	5300
G1-3	132	5400
G1-4	132	5000
G1-5	132	5400
G1-6	132	5550
G1-7	132	5400
G1-8	132	5550
G1-9	132	5100
G1-10	132	5100
G2-1	210	5400
G2-2	210	5250
G2-3	210	5550
G2-4	210	5600
G2-5	210	5500
G2-6	210	5400
G2-7	210	5500
G2-8	210	5600
G2-9	210	5600
G2-10	210	5350

SECTION VIII

CONCLUSIONS AND RECOMMENDATIONS

The primary objectives of this design effort have been met and demonstration hardware has been delivered for customer evaluation.

In the course of providing workable hardware and a mathematical model of the generator design, a number of areas have been identified as requiring more experimental and analytical study. These areas are described below. It is recommended that this additional effort be undertaken in a follow-on effort designed to provide this much needed information.

A. CONCLUSION

This program has successfully accomplished the following tasks:

1. Completed design drawings of a high energy setback generator.
2. Produced 20 units suitable for firing tests.
3. Developed a mathematical solution for output voltage.
4. Devised a test setup for evaluation of effect of parameter variation.
5. Demonstrated in excess of 800,000 ergs in a firing environment.
6. Demonstrated in excess of 1,000,000 ergs in a laboratory environment.

B. RECOMMENDATIONS

If the United States Army decides that the setback generator has a role in future fusing programs, it is recommended that additional development effort be expended in the following areas:

1. Design refinements to include:
 - a. Dimensional changes for higher output.
 - b. Improved means of magnet attachment to assure survivability.
 - c. Investigation of customer designed capacitor module for increased storage density.
 - d. Cost reduction.
2. Gathering of additional drop test data with studies of the variation in output as a function of parameters such as:
 - a. Capacitance
 - b. Drop height (core velocity)
 - c. Number of turns
 - d. Resistance
3. Refinement of mathematical model:
 - a. Obtain more accurate flux plot data.
 - b. Increase accuracy of loss measurements.
 - c. Devise computer program and obtain solutions thereto.
 - d. Compare results with drop test data.
4. Extend analysis to include firing environment:
 - a. Interpret firing test results.
 - b. Obtain more information on projectile acceleration profile.
 - c. Generate computer solutions of optimum coil configuration in various firing environments.

APPENDIX A

SETBACK GENERATOR ANALYSIS

I. Determination of Flux and Generated Voltage Waveforms

Measurements were made of flux linkage change while moving the core from its initial position to its final position in increasing increments. Because of the design symmetry of the magnetic circuit, the flux linkage traversed from a positive λ_m at the initial position to a negative λ_m at the final position. Therefore, the maximum flux linkages at the initial position were $\lambda_m = \frac{(\Delta\lambda)_{\max}}{2}$. The measured data for each point was then subtracted from λ_m and the difference was divided by λ_m to obtain per unit flux linkages λ_u . Similarly, the displacement for each point was divided by the displacement S_m between the initial and the final positions to obtain per unit travel S_u . This data is plotted in Figure A-1 and a smooth curve is fitted. Data extracted from the curve showing λ_u for 0.05 increments of S_u is tabulated, along with calculated values for the negative of the slope at each point.

In spite of the cosine-like appearance of the λ_u curve, the slope curve appears somewhat triangular, rather than sinusoidal. For simplicity, a conventional triangular function having similar area has been substituted. The equations for this function are:

A. For $0 \leq S_u < 0.5$

$$-\frac{d\lambda_u}{dS_u} = \frac{4}{0.5} S_u = 8S_u \quad (1)$$

$$\text{Giving } d\lambda_u = -8S_u dS_u$$

$$\lambda_u = -4S_u^2 + K_1$$

$$1 = 0 + K_1, \text{ or } K_1 = 1$$

$$\lambda_u = 1 - 4S_u^2 \quad (2)$$

B. For $0.5 < S_u < 1.0$

$$-\frac{d\lambda_u}{dS_u} = \frac{-4}{0.5} (S_u - 1) = 8 - 8S_u \quad (3)$$

$$\text{Giving } d\lambda_u = 8S_u dS_u - 8dS_u$$

$$\lambda_u = 4S_u^2 - 8S_u + K_2$$

$$-1 = 4 - 8 + K_2, \text{ or } K_2 = 3$$

$$\lambda_u = 4S_u^2 - 8S_u + 3 \quad (4)$$

Substitution of $S_u = 0.25$ into equation (2) and $S_u = 0.75$ into equation (4) gives $\lambda_u = 0.75$ and -0.75 respectively, compared to ± 0.76 from the curve, and ± 0.707 if a cosine function had been used to define λ_u vs. S_u .

Generated voltage E_g may now be calculated for any assumed core velocity profile. E_g is the theoretical voltage developed by the rate of change of total flux linkages. The open circuit voltage is less than E_g because of flux leakage and core losses.

$$\begin{aligned} E_g &= -\frac{d\lambda}{dt} \times 10^{-8} \\ &= -\frac{d\lambda}{dS} \left(\frac{dS}{dt}\right) \times 10^{-8} \end{aligned}$$

$$\lambda_u = \frac{\lambda}{\lambda_m}$$

$$S_u = \frac{S}{S_m}$$

$$\frac{d\lambda}{dS} = \frac{\lambda_m}{S_m} \frac{d\lambda_u}{dS_u}$$

$$E_g = - \frac{\lambda_m}{S_m} \frac{d\lambda_u}{dS_u} \left(\frac{dS}{dt} \right) \times 10^{-8}$$

C. For $0 < S_u < 0.5$

$$- \frac{d\lambda_u}{dS_u} = 8S_u = 8 \frac{S}{S_m}$$

$$E_g = \frac{\lambda_m}{S_m} \left(\frac{8S}{S_m} \right) \frac{dS}{dt} \times 10^{-8}$$

$$= \frac{8\lambda_m}{S_m} \times 10^{-8} \vee \frac{S}{S_m}$$

$$\text{But } \lambda_m = NAB_m$$

$$E_g = \frac{8NAB_m}{S_m} \times 10^{-8} \vee \frac{S}{S_m}$$

$$\text{Let } \frac{8NAB_m}{S_m} \times 10^{-8} = C_1$$

$$\text{Then } E_g = C_1 \vee \frac{S}{S_m}$$

(5)

D. For $0.5 \leq S_u < 1.0$

$$-\frac{d\lambda}{dS_u} = 8 - 8S_u = 8 - 8\frac{S}{S_m}$$

$$E_g = \frac{\lambda_m}{S_m} \left(8 - 8\frac{S}{S_m} \right) \frac{dS}{dt} \times 10^{-8}$$

$$= \frac{8\lambda_m}{S_m} \times 10^{-8} \vee \left(1 - \frac{S}{S_m} \right)$$

$$E_g = \frac{8NAB_m}{S_m} \times 10^{-8} \cdot \left(1 - \frac{S}{S_m} \right)$$

$$E_g = C_1 \vee \left(1 - \frac{S}{S_m} \right) \quad (6)$$

For a typical setback generator subjected to laboratory drop tests for data accumulation, the physical constants were:

$$N = 217 \text{ turns}$$

$$d = \text{Core diameter} = \frac{3}{4} \text{ inch}$$

$$B_m = 5300 \text{ gauss}$$

$$S_m = 0.2 \text{ in.}$$

$$A = \frac{\pi}{4} d^2 = \frac{\pi}{4} \left(\frac{3}{4} \right)^2 (2.54)^2 = 2.85 \text{ cm}^2$$

Using the above units,

$$C_1 = \frac{8NAB_m}{S_m} \times 10^{-8} \text{ volt seconds/inch}$$

$$C_1 = \frac{8(217)(2.85)(5300)}{0.2} \times 10^{-8} = 1.31 \text{ volt seconds/inch}$$

For a constant velocity motion, typical of the laboratory drop tests:

$$S = vt$$

$$S_m = vt_m, \text{ where } t_m = \text{total transit time}$$

Then, from equation (5):

$$Eg_1 = C_1 v \frac{S}{S_m} = C_1 v \left(\frac{vt}{vt_m} \right) = C_1 v \frac{t}{t_m}$$

And, from equation (6):

$$Eg_2 = C_1 v \left(1 - \frac{S}{S_m} \right) = C_1 v \left(1 - \frac{vt}{vt_m} \right) = C_1 v \left(1 - \frac{t}{t_m} \right)$$

The triangular generated voltage wave ($Eg_1 + Eg_2$) may be considered as one half-cycle of a periodic function having a period $T = 2t_m$ sec.

$$\text{Then } Eg_1 = C_1 v \left(\frac{2t}{T} \right)$$

$$Eg_2 = C_1 v \left(1 - \frac{2t}{T} \right)$$

$$\text{Let } f = \frac{1}{T} \text{ Hz}$$

$$Eg_1 = C_1 v (2 f t)$$

$$Eg_2 = C_1 v (1 - 2 f t)$$

$$\text{Let } \omega = 2\pi f \text{ rad/sec}$$

$$Eg_1 = C_1 v \left(\frac{\omega}{\pi} t \right) \quad 0 \leq t \leq \frac{t_m}{2} \quad (7)$$

$$Eg_2 = C_1 v \left(1 - \frac{\omega}{\pi} t \right) \quad \frac{t_m}{2} \leq t \leq t_m \quad (8)$$

For the laboratory drop test from a 5-foot height, measured t_m was 1.2 msec.

To facilitate computation, a value of $t_m = 1.25$ msec will be used.

Then $T = 2t_m = 2.5$ msec.

$$f = \frac{10^3}{2.5} = 400 \text{ Hz}$$

$$\omega = 2\pi (400) = 2513 \text{ rad/sec.}$$

$$v = \frac{S_m}{t_m} = \frac{0.2}{1.25} = 10^3 = 160 \text{ in/sec.}$$

$$\begin{aligned} E_{g1} &= C_1 v \left(\frac{\omega t}{r} \right) = 1.31 (160) \left(\frac{\omega t}{r} \right) \\ &= 209.6 \left(\frac{\omega t}{r} \right) \end{aligned}$$

$$\text{For } E_{g1} = E_{gm}, t = \frac{t_m}{2}$$

$$\text{Then } \omega t = \frac{\omega t_m}{2} = \frac{\pi}{2}$$

$$\text{Therefore } E_{gr} = 209.6 \left(\frac{1}{2} \right) = \underline{104.8 \text{ volts}}$$

Generated voltage E_g in volts versus periodic function angle ωt in radians, is plotted in Figure A-2. Note that this type curve is applicable only for constant velocity motion of the core. Changes in turns and test velocity will alter only the magnitude of E_{gm} .

II. Determination of the Equivalent Circuit

A setback generator was constructed with two independent 100 turn windings and tested as a 1 to 1 transformer at 60 Hz and 400 Hz using conventional open circuit measurement techniques supplemented by one additional measurement. Primary excitation at each frequency was set so that the induced secondary voltage corresponded with the flux density excursion provided by normal setback motion of the core ($B_m = \pm 6140$ gauss for the unit tested). The 400 Hz measurements produced approximately 350 watts power dissipation, resulting in overheating, excessive distortion of waveform, and lack of repeatability of data. Therefore, calculations will be made using only the 60 Hz data. The d-c resistance of each winding was measured as 0.43 ohm.

The following measurements were recorded at 60 Hz:

$E_p = 7.1$ volts = excitation voltage, primary

$I_p = 7.3$ amps = primary current

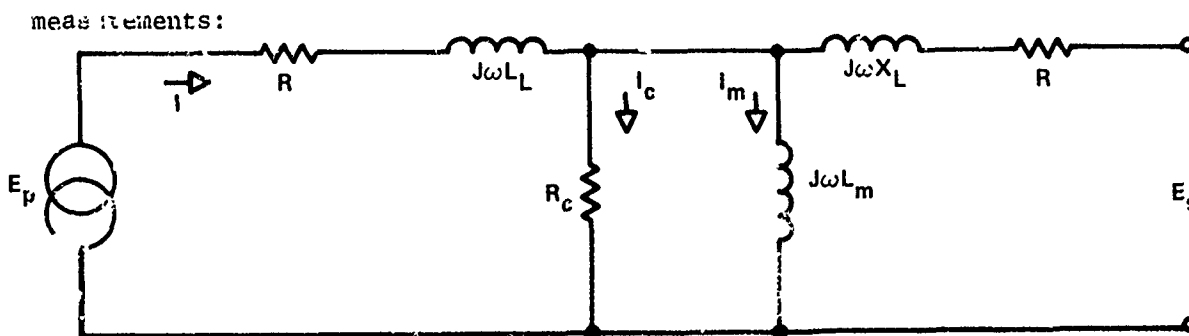
$P_p = 32.5$ watts = primary power

$E_s = 5.0$ volts = induced voltage, secondary

$P_c = 9.5$ watts = core loss power (wattmeter connected to I_p and E_s)

$E_p - E_s = 3.9$ volts = voltage drop across series impedance

The following equivalent circuit was assumed for the transformer



$$P_C = \frac{E_S^2}{R_C}$$

$$R_C = \frac{E_S^2}{P_C} = \frac{(5.0)^2}{9.5} = 2.63 \text{ ohms}$$

$$P_P - P_C = I_P^2 R$$

$$R = \frac{P_P - P_C}{I_P^2} = \frac{32.5 - 9.5}{(7.3)^2} = \frac{23}{(7.3)^2} = 0.43 \text{ ohm}$$

It may be noted that the above computed value of R is equal to the measured d-c resistance.

$$I_P^2 = I_C^2 + I_M^2$$

$$I_M^2 = I_P^2 - I_C^2$$

$$I_C = \frac{E_S}{R_C}$$

$$I_M^2 = I_P^2 - \left(\frac{E_S}{R_C}\right)^2 = (7.3)^2 - \left(\frac{5.0}{2.63}\right)^2 = 53.29 - 3.61$$

$$I_M^2 = 49.68$$

$$I_M = 7.05 \text{ ams}$$

$$X_M = \frac{E_S}{I_M} = \frac{5.0}{7.05} = 0.71 \text{ ohms}$$

$$L_M = \frac{X_M}{\omega} = \frac{0.71}{2\pi(60)} = 1.88 \times 10^{-3} \text{ hy}$$

$$\sqrt{R^2 + X_L^2} = \frac{E_P - E_S}{I_P}$$

$$X_L^2 = \left(\frac{E_P - E_S}{I_P}\right)^2 - R^2 = \left(\frac{3.9}{7.3}\right)^2 - (0.43)^2 = 0.29 - 0.18$$

$$X_L^2 = 0.11$$

$$X_L = 0.33 \text{ ohms}$$

$$L_L = \frac{X_L}{\omega} = \frac{0.33}{2\pi(60)} = 0.88 \times 10^{-3} \text{ hy}$$

Because of the two independent windings, the parameters for the unit tested were not typical of those for a conventional unit. For example, using the same wire size, 217 turns could normally be fitted. Because R is essentially the d-c resistance, its value will increase in proportion to the number of turns until the coil form is filled. All other values will increase in proportion to the square of the turns. However, once the coil form has been filled, if turns are changed by changing wire size while keeping the space filled, R will also change by the square of the turns.

Ratioing for a 217 turn unit gives:

$$R = 0.43 (2.17) = 0.93 \text{ ohm}$$

$$L_L = 0.88 (2.17)^2 = 4.14 \text{ mhy}$$

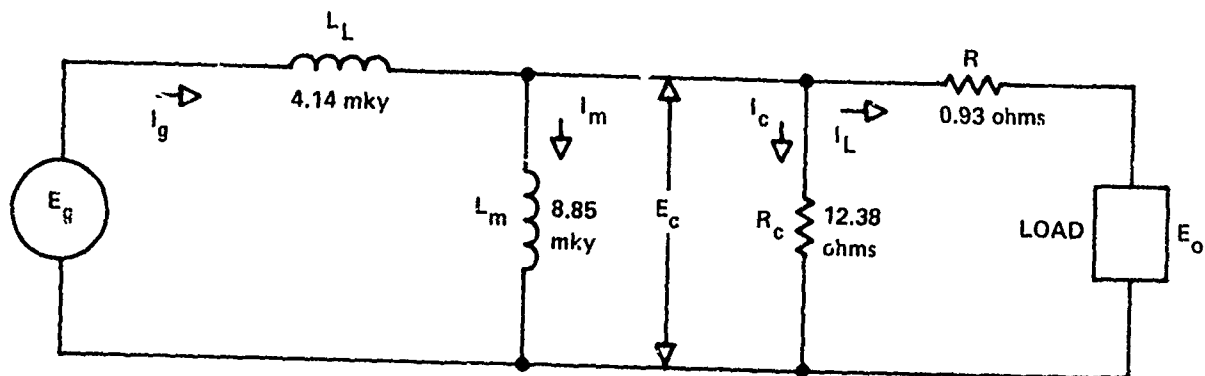
$$R_C = 2.63 (2.17)^2 = 12.38 \text{ ohms}$$

$$L_M = 1.88 (2.17)^2 = 8.85 \text{ mhy}$$

The equivalent circuit for operation by mechanical setback differs somewhat from the one analyzed above. For example, there is no "primary side" series resistance voltage drop, and no "secondary side" leakage inductance voltage drop. The rate of change of total flux linkages E_g

supplies the rate of change of magnetizing flux linkages E_c , through the voltage drop E_L , representing the rate of change of leakage flux linkages. Drains on E_c include the magnetizing current and the core loss current. The output voltage to a connected load is supplied from E_c through a series resistance voltage drop E_R .

The equivalent circuit for a 217 turn setback generator appears below.



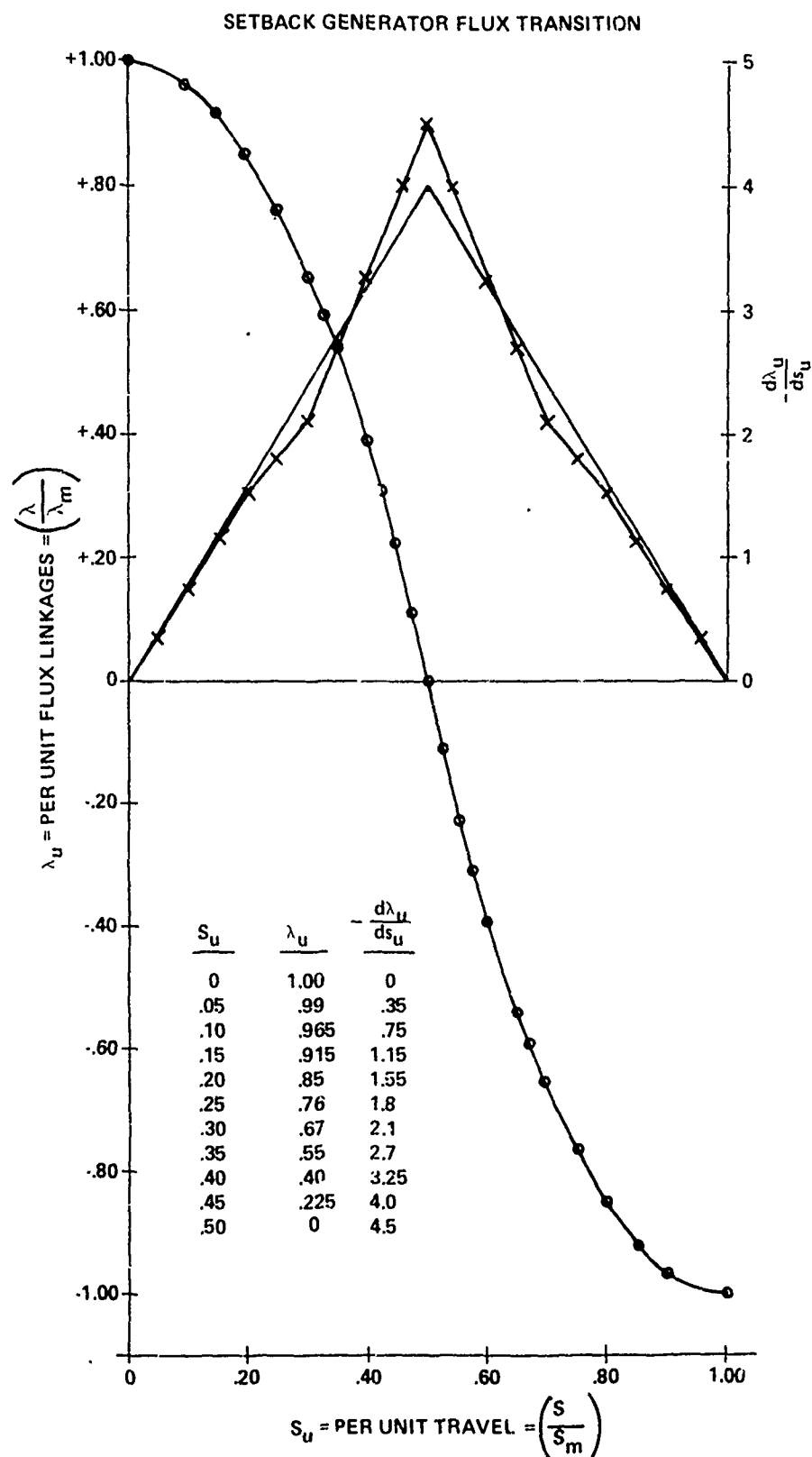
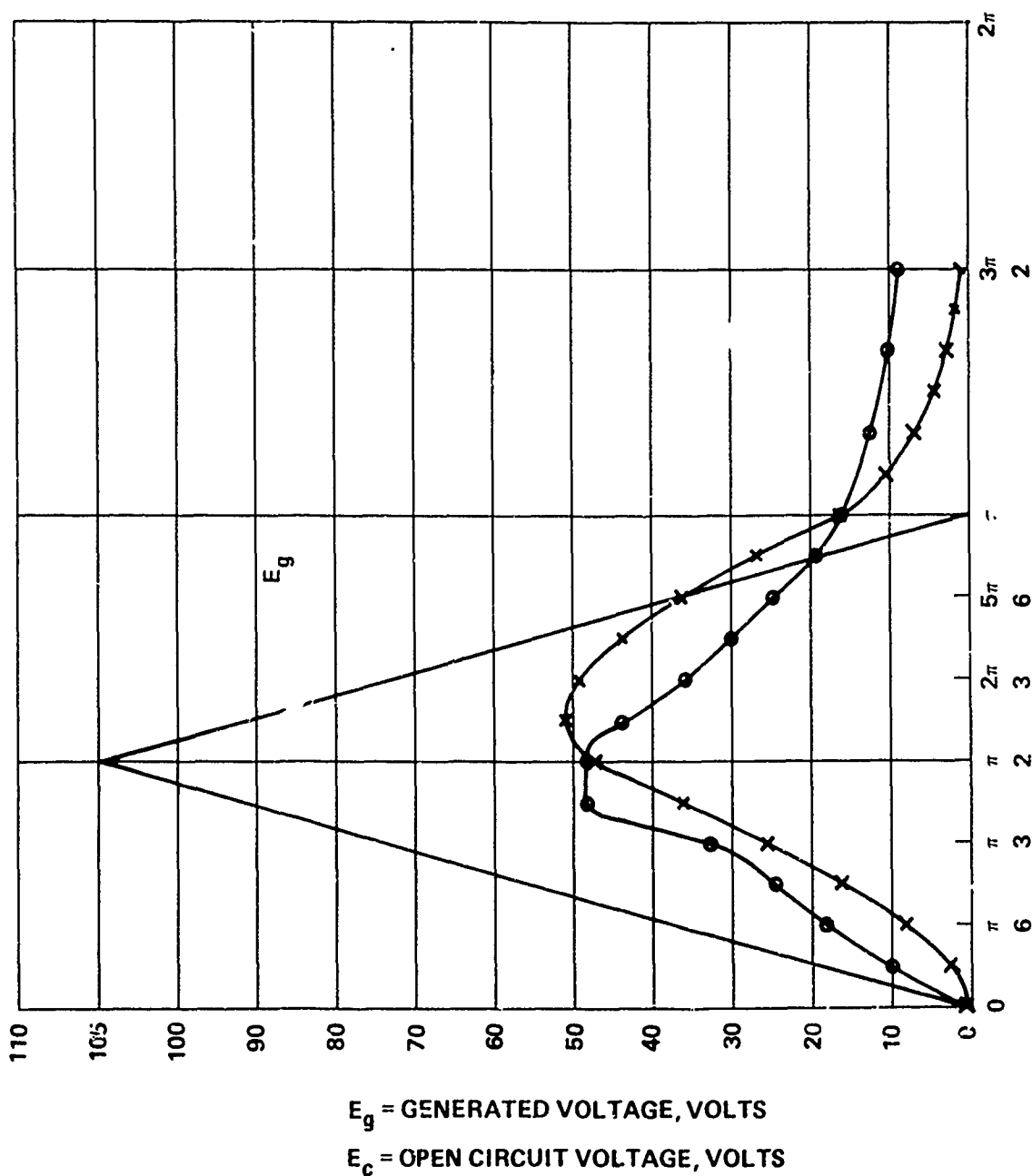


Figure A-1. Setback Generator Flux Transition

SETBACK GENERATOR VOLTAGE RELATIONSHIPS

○ CALCULATED E_c

x CALCULATED E_c



Wt = PERIODIC FUNCTION ANGLE, RADIONS

Figure A-2. Setback Generator Voltage Relationships

III. DERIVATION OF OPEN CIRCUIT VOLTAGE FUNCTIONS

$$E_g = L_L \frac{dI_g}{dt} + R_c I_c$$

$$I_g = I_m + I_c$$

$$E_g = L_L \frac{dI_m}{dt} + L_L \frac{dI_c}{dt} + R_c I_c$$

$$L_m \frac{dI_m}{dt} = R_c I_c$$

$$\frac{dI_m}{dt} = \frac{R_c}{L_m} I_c$$

$$E_g = L_L \left(\frac{R_c}{L_m} I_c \right) + L_L \frac{dI_c}{dt} + R_c I_c$$

$$= L_L \frac{dI_c}{dt} + R_c \left(1 + \frac{L_L}{L_m} \right) I_c$$

$$L_L [s I_c(s) - I_c(0^+)] + R_c \left(1 + \frac{L_L}{L_m} \right) I_c(s) = E_g(s)$$

$$I_c(s) \left[L_L s + R_c \left(1 + \frac{L_L}{L_m} \right) \right] = E_g(s) + L_L I_c(0^+)$$

$$I_c(s) = \frac{\frac{1}{L_L} E_g(s)}{s + \frac{R_c}{L_L} \left(1 + \frac{L_L}{L_m} \right)} + \frac{I_c(0^+)}{s + \frac{R_c}{L_L} \left(1 + \frac{L_L}{L_m} \right)}$$

$$\text{Let } \frac{R_c}{L_L} \left(1 + \frac{L_L}{L_m} \right) = \alpha$$

$$I_c(s) = \frac{\frac{1}{L_L} E_g(s)}{s + \alpha} + \frac{I_c(0^+)}{s + \alpha} \quad (9)$$

A. For first interval, $0 \leq t \leq \frac{t_m}{2}$,
or $0 \leq \omega t \leq \frac{\pi}{2}$

$$I_c(0^+) = I_{c1}(0^+) = 0$$

$$E_g = E_{g1} = C_1 v \left(\frac{\omega t}{\pi} \right)$$

$$E_{g1}(s) = C_1 v \left(\frac{\omega}{\pi} \right) \frac{1}{s^2}$$

$$I_c(s) = I_{c1}(s) = \frac{\frac{1}{L_L} E_{g1}(s)}{s + \alpha}$$

$$I_{c1}(s) = \frac{C_1 v \left(\frac{\omega}{\pi} \right) \left(\frac{1}{L_L} \right)}{s^2 (s + \alpha)}$$

$$I_{c1} = \frac{C_1 v \left(\frac{\omega}{\pi} \right) \left(\frac{1}{L_L} \right)}{\alpha^2} \left[e^{-\alpha t} + \alpha t - 1 \right]$$

$$E_{c1} = I_{c1} R_c = \frac{C_1 v \left(\frac{\omega}{\pi} \right) \left(\frac{R_c}{L_L} \right)}{\alpha^2} \left[e^{-\alpha t} + \alpha t - 1 \right]$$

$$\text{But } t = \frac{\omega t}{\omega}$$

$$E_{c1} = \frac{C_1 v \left(\frac{\omega}{\pi} \right) \left(\frac{R_c}{L_L} \right)}{\alpha^2} \left[e^{-\frac{\alpha}{\omega} (\omega t)} + \frac{\alpha}{\omega} (\omega t) - 1 \right]$$

For 217 turns and 400 Hz :

$$C_1 V = 209.6 \text{ volts}$$

$$\frac{\omega}{\pi} = 2f = 2(400) = 800 \text{ sec}^{-1}$$

$$\frac{R_c}{L_L} = \frac{12.38}{4.14 \times 10^{-3}} = 2990 \text{ sec}^{-1}$$

$$\alpha = \frac{R_c}{L_L} \left(1 + \frac{L_L}{L_m}\right) = 2990 \left(1 + \frac{4.14}{8.85}\right)$$

$$\alpha = 2990(1.468) = 4389 \text{ sec}^{-1}$$

$$\frac{\alpha}{\omega} = \frac{4389}{2\pi(400)} = 1.7463$$

$$\alpha^2 = (4389)^2 = 19.263 \times 10^6 \text{ sec}^{-2}$$

$$\frac{C_1 V \left(\frac{\omega}{\pi}\right) \left(\frac{R_c}{L_L}\right)}{\alpha^2} = \frac{209.6 \left[\frac{2\pi(400)}{\pi}\right] (2990)}{19.263 \times 10^6}$$

$$= 26.03 \text{ volts}$$

$$E_{c1} = 26.03 \left(e^{-1.7463\omega t} + 1.7463\omega t - 1 \right)$$

$$\text{Let } E_{c1} = 26.03 \left(e^{-A\omega t} + A\omega t - 1 \right)$$

$$= 26.03 \text{ B}$$

Results for the first interval are:

ωt rad.	$A\omega t$	$e^{-A\omega t}$	B	E_{cl} volts
0	0	1	0	0
$\frac{\pi}{12}$	.4572	.6331	.0903	2.35
$\frac{\pi}{6}$	.9144	.4008	.3152	8.20
$\frac{\pi}{4}$	1.3715	.2537	.6252	16.27
$\frac{\pi}{3}$	1.8287	.1606	.9893	25.75
$\frac{5\pi}{12}$	2.2859	.1017	1.3876	36.12
$\frac{\pi}{2}$	2.7431	.0644	1.8075	47.05

B. For second interval, $\frac{t_m}{2} \leq t \leq t_m$,

$$\text{or } \frac{\pi}{2} \leq \omega t \leq \pi$$

Replace t by t_2 , where $t_2 = 0$ at the beginning of the interval. Then the interval becomes $0 \leq t_2 \leq \frac{t_m}{2}$, or $0 \leq \omega t_2 \leq \frac{\pi}{2}$.

$$t_2 = t - \frac{t_m}{2}$$

$$\omega t_2 = \omega t - \frac{\omega t_m}{2} = \omega t - \frac{\pi}{2}$$

$$\omega t = \omega t_2 + \frac{\pi}{2}$$

$$I_c(0^+) = I_{c2}(0^+) = I_{c1}(\omega t = \frac{\pi}{2}) = \frac{E_{c1}(\omega t = \frac{\pi}{2})}{R_c}$$

$$I_{c2}(0^+) = \frac{47.05}{12.38} = 3.80 \text{ amps}$$

$$E_g = E_{g2} = C_1 V \left(1 - \frac{\omega t}{\pi}\right) = C_1 V \left(1 - \frac{\omega t_2}{\pi} - \frac{1}{2}\right)$$

$$E_{g2} = C_1 V \left(\frac{1}{2} - \frac{\omega t_2}{\pi}\right) = \frac{C_1 V}{2} - C_1 V \left(\frac{\omega t_2}{\pi}\right)$$

$$E_{g2}(s) = \frac{C_1 V}{2} \left(\frac{1}{s}\right) - C_1 V \left(\frac{\omega}{\pi}\right) \left(\frac{1}{s^2}\right)$$

$$I_c(s) = I_{c2}(s) = \frac{1}{L} \frac{E_{g2}(s)}{s + \alpha} + \frac{I_{c2}(0^+)}{s + \alpha}$$

$$I_{c2}(s) = \frac{C_1 V \left(\frac{1}{2}\right) \left(\frac{1}{L}\right)}{s(s + \alpha)} - \frac{C_1 V \left(\frac{\omega}{\pi}\right) \left(\frac{1}{L}\right)}{s^2(s + \alpha)} + \frac{I_{c2}(0^+)}{s + \alpha}$$

$$I_{c2} = \frac{C_1 V \left(\frac{1}{2}\right) \left(\frac{1}{L}\right)}{\alpha} \left[1 - e^{-\alpha t_2}\right] + I_{c2}(0^+) e^{-\alpha t_2} - \frac{C_1 V \left(\frac{\omega}{\pi}\right) \left(\frac{1}{L}\right)}{\alpha^2} \left[e^{-\alpha t_2} + \alpha t_2 - 1\right]$$

$$E_{c2} = I_{c2} R_c = \frac{C_1 V \left(\frac{1}{2}\right) \left(\frac{R_c}{L}\right)}{\alpha} \left[1 - e^{-\alpha t_2}\right] + E_{c2}(0^+) e^{-\alpha t_2} - \frac{C_1 V \left(\frac{\omega}{\pi}\right) \left(\frac{R_c}{L}\right)}{\alpha^2} \left[e^{-\alpha t_2} + \alpha t_2 - 1\right]$$

$$E_{c2} = \frac{C_1 V \left(\frac{1}{2}\right) \left(\frac{R_c}{L}\right)}{\alpha} \left[1 - e^{-\frac{\alpha}{\omega}(\omega t_2)}\right] + E_{c2}(0^+) e^{-\frac{\alpha}{\omega}(\omega t_2)} - \frac{C_1 V \left(\frac{\omega}{\pi}\right) \left(\frac{R_c}{L}\right)}{\alpha^2} \left[e^{-\frac{\alpha}{\omega}(\omega t_2)} + \frac{\alpha}{\omega}(\omega t_2) - 1\right]$$

Note that the final term above is the negative of the total expression for E_c during the first interval.

$$\frac{C_1 V(\frac{1}{2})(\frac{R_c}{L})}{\Delta} = \frac{209.6(\frac{1}{2})(2990)}{4839} = 64.76 \text{ volts}$$

$$E_{c2}(0^+) = 47.05 \text{ volts}$$

$$E_{c2} = 64.76 \left(1 - e^{-1.7463 \omega t_2} \right) + 47.05 e^{-1.7463 \omega t_2} - 26.03 \left(e^{-1.7463 \omega t_2} + 1.7463 \omega t_2 - 1 \right)$$

$$\text{Let } E_{c2} = 64.76 \left(1 - e^{-A \omega t_2} \right) + 47.05 e^{-A \omega t_2} - 26.03 \left(e^{-A \omega t_2} + A \omega t_2 - 1 \right)$$

$$= E_{c2A} + E_{c2B} - E_{c2C}$$

Results for the second interval are:

wt rad.	ωt_z rad.	$A\omega t_z$	$e^{-A\omega t_z}$	E_{c2B} Volts	$1-e^{-A\omega t_z}$	E_{c2A} Volts	E_{c2C} Volts	E_{c2} Volts
$\frac{\pi}{2}$	0	0	1	47.05	0	0	0	47.05
$\frac{\pi}{12}$	$\frac{\pi}{12}$	.4572	.6331	29.79	.3669	23.76	2.35	51.20
$\frac{3\pi}{3}$	$\frac{\pi}{6}$	.9144	.4008	18.86	.5992	38.80	8.20	49.46
$\frac{3\pi}{4}$	$\frac{\pi}{4}$	1.3715	.2537	11.94	.7463	48.33	16.27	44.00
$\frac{5\pi}{6}$	$\frac{\pi}{3}$	1.8287	.1606	7.56	.8394	54.36	25.75	36.17
$\frac{11\pi}{12}$	$\frac{5\pi}{12}$	2.2859	.1017	4.78	.8983	58.17	36.12	26.83
π	$\frac{\pi}{2}$	2.7431	.0644	3.03	.9356	60.59	47.05	16.57

C. For third interval, $t_m \leq t \leq \infty$,
or $\pi \leq \omega t \leq \infty$

Replace t by t_3 , where $t_3 = 0$ at the beginning of the interval. Then the interval becomes $0 \leq t_3 \leq \infty$, or $0 \leq \omega t_3 \leq \infty$.

$$t_3 = t - t_m$$

$$\omega t_3 = \omega t - \omega t_m = \omega t - \pi$$

$$\omega t_3 = (\omega t_2 + \frac{\pi}{2}) - \pi = \omega t_2 - \frac{\pi}{2}$$

$$I_c(0^+) = I_{c3}(0^+) = I_{c2}(\omega t_2 = \frac{\pi}{2}) = \frac{E_{c2}(\omega t_2 = \frac{\pi}{2})}{R_c}$$

$$I_{c3}(0^+) = \frac{16.57}{12.38} = 1.34 \text{ amps}$$

$$E_g = E_{g3} = 0$$

$$I_c(s) = I_{c3}(s) = \frac{I_{c3}(0^+)}{s + \alpha}$$

$$I_{c3} = I_{c3}(0^+) e^{-\alpha t_3}$$

$$E_{c3} = I_{c3} R_c = E_{c3}(0^+) e^{-\alpha t_3} = E_{c3}(0^+) e^{-\frac{\alpha}{\omega}(\omega t_3)}$$

$$E_{c3} = 16.57 e^{-1.7463 \omega t_3} = 16.57 e^{-A \omega t_3}$$

Results for the third interval are:

ωt rad.	ωt_3 rad.	$A \omega t_3$	$e^{-A \omega t_3}$	E_{c3} volts
π	0	0	1	16.57
$\frac{13\pi}{12}$	$\frac{\pi}{12}$	.4572	.6331	10.49
$\frac{7\pi}{6}$	$\frac{\pi}{6}$	.9144	.4008	6.64
$\frac{5\pi}{4}$	$\frac{\pi}{4}$	1.3715	.2537	4.20
$\frac{4\pi}{3}$	$\frac{\pi}{3}$	1.8287	.1606	2.66
$\frac{17\pi}{12}$	$\frac{5\pi}{12}$	2.2859	.1017	1.69
$\frac{3\pi}{2}$	$\frac{\pi}{2}$	2.7431	.0644	1.07

Calculated open circuit voltage E_c for the three intervals is plotted in Figure A-2. Superimposed on this plot is the measured open circuit voltage obtained by scaling from an open circuit voltage oscilloscope photograph, Figure . Data was taken from that trace having a 0.2 msec per division time base.

IV, DERIVATION OF OUTPUT VOLTAGE FUNCTIONS

The output circuit consists of a capacitor charged through a diode. Maximum capacitor voltage is achieved when the load current I_L goes to zero causing the diode to block. For simplification, electrical characteristics of the diode will be neglected during the analysis, however, a diode voltage drop of 0.7 volts will be subtracted from the calculated final capacitor voltage.

$$E_g = L_L \frac{dI_g}{dt} + RI_L + \frac{1}{C} \int I_L dt$$

$$I_g = I_m + I_c + I_L$$

$$E_g = L_L \frac{dI_m}{dt} + L_L \frac{dI_c}{dt} + L_L \frac{dI_L}{dt} + RI_L + \frac{1}{C} \int I_L dt$$

$$L_m \frac{dI_m}{dt} = R_c I_c = RI_L + \frac{1}{C} \int I_L dt$$

$$\frac{dI_m}{dt} = \frac{R}{L_m} I_L + \frac{1}{L_m C} \int I_L dt$$

$$I_c = \frac{R}{R_c} I_L + \frac{1}{R_c C} \int I_L dt$$

$$\frac{dI_c}{dt} = \frac{R}{R_c} \frac{dI_L}{dt} + \frac{1}{R_c C} I_L$$

$$E_g = L_L \left(\frac{R}{L_m} \right) I_L + L_L \left(\frac{1}{L_m C} \right) \int I_L dt + L_L \left(\frac{R}{R_c} \right) \frac{dI_L}{dt}$$

$$+ L_L \left(\frac{1}{R_c C} \right) I_L + L_L \frac{dI_L}{dt} + R I_L + \frac{1}{C} \int I_L dt$$

$$E_g = R \left[1 + \frac{L_L}{L_m} + \frac{L_L}{R} \left(\frac{1}{R_c C} \right) \right] I_L + L_L \left(1 + \frac{R}{R_c} \right) \frac{dI_L}{dt}$$

$$+ \frac{1}{C} \left(1 + \frac{L_L}{L_m} \right) \int I_L dt$$

$$\text{Let } R_0 = R \left[1 + \frac{L_L}{L_m} + \frac{L_L}{R} \left(\frac{1}{R_c C} \right) \right]$$

$$L_0 = L_L \left(1 + \frac{R}{R_c} \right)$$

$$\frac{1}{C_0} = \frac{1}{C} \left(1 + \frac{L_L}{L_m} \right)$$

$$E_g = R_0 I_L + L_0 \frac{dI_L}{dt} + \frac{1}{C_0} \int I_L dt$$

$$E_g(s) = R_0 I_L(s) + L_0 [s I_L(s) - I_L(0^+)]$$

$$+ \frac{1}{C_0} \left[\frac{I_L(s)}{s} + \frac{I_L^{-1}(0^+)}{s} \right]$$

Let $I_{L0} = I_L(0^+) = \text{initial load current}$

$V_{C0} = \frac{1}{C} I_L^{-1}(0^+) = \text{initial capacitor voltage}$

$$E_g(s) = (L_0 s + R_0 + \frac{1}{C_0 s}) I_L(s) - L_0 I_{L0} + \frac{C}{C_0} \frac{V_{C0}}{s}$$

$$(L_0 s + R_0 + \frac{1}{C_0 s}) I_L(s) = E_g(s) + L_0 I_{L0} - \frac{C}{C_0} \frac{V_{C0}}{s}$$

$$\frac{L_0}{s} (s^2 + \frac{R_0}{L_0} s + \frac{1}{L_0 C_0}) I_L(s) = E_g(s) + L_0 I_{L0} - \frac{C}{C_0} \frac{V_{C0}}{s}$$

$$(s^2 + \frac{R_0}{L_0} s + \frac{1}{L_0 C_0}) I_L(s) = \frac{s E_g(s)}{L_0} + s I_{L0} - \frac{C V_{C0}}{L_0 C_0}$$

$$I_L(s) = \frac{E_g(s)}{L_0 (s^2 + \frac{R_0}{L_0} s + \frac{1}{L_0 C_0})} + \frac{s I_{L0}}{s^2 + \frac{R_0}{L_0} s + \frac{1}{L_0 C_0}} - \frac{C V_{C0}}{L_0 C_0 (s^2 + \frac{R_0}{L_0} s + \frac{1}{L_0 C_0})} \quad (10)$$

$$E_0(s) = \mathcal{L} \left[\frac{1}{C} \int I_L dt \right] = \frac{1}{C} \left[\frac{I_L(s)}{s} + \frac{I_L^{-1}(0^+)}{s} \right] \\ = \frac{I_L(s)}{C s} + \frac{V_{C0}}{s}$$

$$E_0(s) = \frac{E_g(s)}{L_0 C (s^2 + \frac{R_0}{L_0} s + \frac{1}{L_0 C_0})} + \frac{I_{L0}}{C (s^2 + \frac{R_0}{L_0} s + \frac{1}{L_0 C_0})} - \frac{V_{C0}}{L_0 C_0 s (s^2 + \frac{R_0}{L_0} s + \frac{1}{L_0 C_0})} + \frac{V_{C0}}{s} \quad (11)$$

Assume an underdamped circuit (in keeping with the desire to maximize the capacitor voltage). Therefore,

$$\begin{aligned} \text{Let } s^2 + \frac{R_0}{L_0} s + \frac{1}{L_0 C_0} &= (s+a)^2 + b^2 \\ &= s^2 + 2as + (a^2 + b^2) \\ &= s^2 + 2\delta b_0 s + b_0^2 \end{aligned}$$

Then $\delta = \frac{a}{b_0} = \text{damping factor}$

$b_0 = \frac{1}{\sqrt{L_0 C_0}} = \text{undamped natural frequency}$

$$a = \frac{R_0}{2L_0}$$

$$b_0^2 = a^2 + b^2$$

$$b = \sqrt{b_0^2 - a^2} = \left[\frac{1}{L_0 C_0} - \left(\frac{R_0}{2L_0} \right)^2 \right]^{\frac{1}{2}} = \text{resonant frequency}$$

$$\begin{aligned} I_L(s) &= \frac{s E_g(s)}{L_0 [(s+a)^2 + b^2]} + \frac{s I_{L_0}}{(s+a)^2 + b^2} \\ &\quad - \frac{C V_{C_0}}{L_0 C_0 [(s+a)^2 + b^2]} \end{aligned} \tag{12}$$

$$E_o(s) = \frac{E_g(s)}{L_o C [(s+a)^2 + b^2]} + \frac{I_{L_o}}{C [(s+a)^2 + b^2]} - \frac{V_{co}}{L_o C_o s [(s+a)^2 + b^2]} + \frac{V_{co}}{s} \quad (13)$$

Let $(s+a)^2 + b^2$ be represented by D .

$$I_L(s) = \frac{s(\frac{1}{L_o})E_g(s)}{D} + \frac{s I_{L_o}}{D} - \frac{\frac{C V_{co}}{L_o C_o}}{D}$$

$$E_o(s) = \frac{(\frac{1}{L_o C})E_g(s)}{D} + \frac{\frac{I_{L_o}}{C}}{D} - \frac{\frac{V_{co}}{L_o C_o}}{s D} + \frac{V_{co}}{s}$$

A For first interval, $0 \leq t \leq \frac{t_m}{2}$,
or $0 \leq \omega t \leq \frac{\pi}{2}$

$$I_{L_o} = I_{L_1}(0^+) = 0$$

$$V_{co} = \frac{1}{C} I_{L_1}^{-1}(0^+) = 0$$

$$E_g = E_{g_1} = C_1 v\left(\frac{\omega t}{\pi}\right)$$

$$E_{g_1}(s) = C_1 v\left(\frac{\omega}{\pi}\right) \left(\frac{1}{s^2}\right)$$

$$I_L(s) = I_{L_1}(s) = \frac{s(\frac{1}{L_o})E_{g_1}(s)}{D}$$

$$I_{L_1}(s) = \frac{C_1 V(\frac{\omega}{\pi})(\frac{1}{L_0})}{s D}$$

$$E_0(s) = E_{01}(s) = \frac{(\frac{1}{L_0 C}) E_{g1}(s)}{D}$$

$$E_{01}(s) = \frac{C_1 V(\frac{\omega}{\pi})(\frac{1}{L_0 C})}{s^2 D}$$

$$I_{L_1} = C_1 V(\frac{\omega}{\pi})(\frac{1}{L_0}) \left[\frac{1}{b_0^2} - \frac{e^{-at} \sin(bt + \psi_1)}{b b_0} \right]$$

$$\text{Where } \psi_1 = \tan^{-1} \frac{b}{a}$$

$$E_{01} = C_1 V(\frac{\omega}{\pi})(\frac{1}{L_0 C}) \left[\frac{1}{b_0^2} \left(t - \frac{2a}{b_0^2} \right) + \frac{e^{-at} \sin(bt + \psi_2)}{b b_0^2} \right]$$

$$\text{Where } \psi_2 = 2 \tan^{-1} \frac{b}{a}$$

For 217 turns and 400 Hz, and
with $C = 600 \mu\text{fd}$:

$$R_0 = R \left[1 + \frac{L_L}{L_m} + \frac{L_L}{R} \left(\frac{1}{R_0 C} \right) \right]$$

$$= 0.93 \left[1 + \frac{4.14}{8.85} + \frac{4.14 \times 10^{-3}}{0.93} \left(\frac{1}{12.38 \times 600 \times 10^{-6}} \right) \right]$$

$$= 0.93 (1 + 0.468 + 0.599) = 0.93 (2.067)$$

$$R_0 = 1.92 \text{ ohms}$$

$$L_0 = L_L \left(1 + \frac{R}{R_c} \right)$$

$$= 4.14 \left(1 + \frac{0.93}{12.38} \right) = 4.14 (1 + 0.075)$$

$$L_0 = 4.45 \text{ mhy}$$

$$\frac{1}{C_0} = \frac{1}{C} \left(1 + \frac{L_L}{L_m} \right) = \frac{1}{C} (1.468)$$

$$C_0 = \frac{C}{1.468} = \frac{600}{1.468} = 408.72 \mu\text{fd}$$

$$C_1 V \left(\frac{\omega}{\pi} \right) \left(\frac{1}{L_0} \right) = 209.6 \left[\frac{2\pi(400)}{\pi} \right] \left(\frac{1}{4.45 \times 10^{-3}} \right)$$

$$= 37.68 \times 10^6 \text{ amps/sec}^2$$

$$\frac{1}{b_0^2} = L_0 C_0 = 4.45 \times 10^{-3} (408.72 \times 10^{-6})$$

$$= 1.82 \times 10^{-6} \text{ sec}^2$$

$$b_0^2 = \frac{10^6}{1.82} = 549,812 \text{ sec}^{-2}$$

$$a = \frac{R_0}{2L_0} = \frac{1.92}{2(4.45)10^{-3}} = 215.73 \text{ sec}^{-1}$$

$$a^2 = (215.73)^2 = 46,539 \text{ sec}^{-2}$$

$$b^2 = b_0^2 - a^2 = 549,812 - 46,539 = 503,273 \text{ sec}^{-2}$$

$$b = \sqrt{503,273} = 709.42 \text{ sec}^{-1}$$

$$b_0 = \sqrt{549,812} = 741.49 \text{ sec}^{-1}$$

$$\frac{1}{bb_0} = \frac{10^{-6}}{0.70942(0.74149)} = 1.90 \times 10^{-6} \text{ sec}^2$$

$$\begin{aligned} I_{L1} &= 37.68 \times 10^6 \left[1.82 \times 10^{-6} - 1.90 \times 10^{-6} e^{-at} \sin(bt + \psi_1) \right] \\ &= 37.68 \left\{ 1.82 - 1.90 e^{-\frac{a}{\omega}(wt)} \sin\left(\frac{b}{\omega}(wt) + \psi_1\right) \right\} \end{aligned}$$

$$\frac{a}{\omega} = \frac{215.73}{2\pi(400)} = 0.08584$$

$$\frac{b}{\omega} = \frac{709.42}{2\pi(400)} = 0.28227$$

$$\psi_1 = \tan^{-1} \frac{b}{a} = \tan^{-1} \frac{709.42}{215.73} = \tan^{-1} 3.2885$$

$$\psi_1 = 73.09^\circ = 1.2755 \text{ rad.}$$

At end of first interval, $I_{L1} = I_{L1}\left(\frac{\pi}{2}\right)$

$$\frac{b}{\omega}(wt) = 0.28227\left(\frac{\pi}{2}\right) = 0.4434 \text{ rad.}$$

$$\frac{b}{\omega}(wt) + \psi_1 = 0.4434 + 1.2755 = 1.7189 \text{ rad}$$

$$= 98.49^\circ$$

$$\sin \left[\frac{b}{\omega}(wt) + \psi_1 \right] = \sin 98.49^\circ = 0.9890$$

$$\frac{a}{\omega}(wt) = 0.08584 \left(\frac{\pi}{2} \right) = 0.1348 \text{ rad}$$

$$e^{-\frac{a}{\omega}(wt)} = e^{-0.1348} = 0.8739$$

$$I_L \left(\frac{\pi}{2} \right) = 37.68 [1.82 - 1.90 (0.8739) (0.9890)]$$

$$= 37.68 (1.82 - 1.64) = 37.68 (0.18)$$

$$I_L \left(\frac{\pi}{2} \right) = 6.78 \text{ amps}$$

$$C_1 V \left(\frac{\psi}{\pi} \right) \left(\frac{1}{L_0 C} \right) = \frac{37.68 \times 10^6}{600 \times 10^6} = 62.8 \times 10^9 \text{ volts/sec}^3$$

$$\frac{2a}{b^2} = 2(215.73)(1.82 \times 10^{-6}) = 785.3 \times 10^{-6} \text{ sec}$$

$$\frac{1}{bb_0^2} = \frac{1.82 \times 10^{-6}}{709.42} = 2.566 \times 10^{-9} \text{ sec}^3$$

$$E_{01} = 62.8 \times 10^9 \left[1.82 \times 10^{-6} (t - 785.3 \times 10^{-6}) \right. \\ \left. + 2.566 \times 10^{-9} e^{-at} \sin(bt + \psi_2) \right]$$

$$E_{o1} = 62.8 \left[1820 (t - 0.7853 \times 10^{-3}) + 2.566 e^{-\frac{a}{\omega}(\omega t)} \sin\left(\frac{b}{\omega}(\omega t) + \psi_2\right) \right]$$

At end of first interval, $E_{o1} = E_{o1}(\frac{\pi}{2})$

$$t = \frac{\omega t}{\omega} = \frac{\pi}{2(2\pi)(400)} = \frac{1}{1600} = 0.625 \times 10^{-3} \text{ sec.}$$

$$\begin{aligned} \psi_2 &= 2 \tan^{-1} \frac{b}{a} = 2(73.09^\circ) = 146.18^\circ \\ &= 2.5511 \text{ rad} \end{aligned}$$

$$\begin{aligned} \frac{b}{\omega}(\omega t) + \psi_2 &= 0.4434 + 2.5511 = 2.9945 \text{ rad.} \\ &= 171.59^\circ \end{aligned}$$

$$\sin\left[\frac{b}{\omega}(\omega t) + \psi_2\right] = \sin 171.59^\circ = 0.1463$$

$$\begin{aligned} E_{o1}\left(\frac{\pi}{2}\right) &= 62.8 \left[1820 (0.625 - 0.7853) 10^{-3} \right. \\ &\quad \left. + 2.566 (0.8739)(0.1463) \right] \end{aligned}$$

$$= 62.8 [1.82(-0.1603) + 0.3281]$$

$$= 62.8 (0.3281 - 0.2917) = 62.8 (0.0364)$$

$$E_{o1}\left(\frac{\pi}{2}\right) = 2.29 \text{ volts}$$

B. For second interval, $\frac{t_m}{2} \leq t \leq t_m$,
or $\frac{\pi}{2} \leq \omega t \leq \pi$.

Replace t by t_2 , as in section III, where
 $t_2 = t - \frac{t_m}{2}$, or $\omega t_2 = \omega t - \frac{\pi}{2}$

$$I_{L0} = I_{L2}(0^+) = I_{L1}(\omega t = \frac{\pi}{2}) = 6.78 \text{ amps}$$

$$V_{C0} = E_{02}(0^+) = E_{01}(\omega t = \frac{\pi}{2}) = 2.29 \text{ volts}$$

$$E_g = E_{g2} = \frac{C_1 V}{2} - C_1 V \left(\frac{\omega t_2}{\pi} \right) = \frac{C_1 V}{2} - E_{g1} \Big]_{t_2}$$

Where $E_{g1} \Big]_{t_2}$ represents E_{g1} as a
function of t_2 .

$$E_{g2}(s) = \frac{C_1 V}{2} \left(\frac{1}{s} \right) - E_{g1}(s) \Big]_{t_2}$$

$$I_L(s) = I_{L2}(s) = \frac{s \left(\frac{1}{L_0} \right) E_g(s)}{D} + \frac{s I_{L0}}{D} - \frac{\frac{C V_{C0}}{L_0 C_0}}{D}$$

$$I_{L2}(s) = \frac{\frac{C_1 V}{2} \left(\frac{1}{s} \right) \left(\frac{1}{L_0} \right)}{D} - \frac{s \left(\frac{1}{L_0} \right) E_{g1}(s)}{D} \Big]_{t_2} \\ + \frac{s I_{L0}}{D} - \frac{\frac{C V_{C0}}{L_0 C_0}}{D}$$

$$I_{L2}(s) = \frac{\left[C_1 V \left(\frac{1}{2} \right) \left(\frac{1}{L_0} \right) - \frac{C V_0}{L_0 C_0} \right]}{D} + \frac{S I_{L0}}{D} - \frac{S \left(\frac{1}{L_0} \right) E_{q1}(s)}{D} \Big|_{t_2}$$

$$I_{L2} = \left[C_1 V \left(\frac{1}{2} \right) \left(\frac{1}{L_0} \right) - \frac{C V_0}{L_0 C_0} \right] \left(\frac{1}{b} e^{-at_2} \sin bt_2 \right) + I_{L0} \left[\frac{b_0}{b} e^{-at_2} \sin (bt_2 + \psi_3) \right] - I_{L1} \Big|_{t_2}$$

Where $I_{L1} \Big|_{t_2}$ represents I_{L1} as a function of t_2 .

$$C_1 V \left(\frac{1}{2} \right) \left(\frac{1}{L_0} \right) = 209.6 \left(\frac{1}{2} \right) \left(\frac{1}{4.45 \times 10^{-3}} \right) = 23,551 \text{ amps/sec.}$$

$$\frac{C V_0}{L_0 C_0} = \frac{600 \times 10^{-6} (2.29)}{4.45 \times 10^{-3} (408.72 \times 10^{-6})} = 755 \text{ amps/sec.}$$

$$\left[C_1 V \left(\frac{1}{2} \right) \left(\frac{1}{L_0} \right) - \frac{C V_0}{L_0 C_0} \right] \left(\frac{1}{b} \right) = \frac{23,551 - 755}{709.42} = \frac{22796}{709.42} = 32.13 \text{ amps}$$

$$I_{L0} \left(\frac{b_0}{b} \right) = \frac{6.78 (741.49)}{709.42} = 7.09 \text{ amps}$$

$$\psi_3 = \tan^{-1} \left(\frac{b}{-a} \right) = \tan^{-1} \left(\frac{3.2885}{-1} \right) = 180^\circ - 73.09^\circ = 106.91^\circ = 1.8658 \text{ rad.}$$

$$I_{L2} = 32.13 e^{-\frac{a}{\omega}(wt_2)} \sin \frac{b}{\omega}(wt_2) + 7.09 e^{-\frac{a}{\omega}(wt_2)} \sin \left[\frac{b}{\omega}(wt_2) + \psi_3 \right] - I_{L1} \Big]_{t_2}$$

At end of second interval, $I_{L2} = I_{L2}(wt_2 = \frac{\pi}{2})$

$$e^{-\frac{a}{\omega}(wt_2)} = 0.8739$$

$$\frac{b}{\omega}(wt_2) = 0.4434 \text{ rad} = 25.41^\circ$$

$$\sin \frac{b}{\omega}(wt_2) = \sin 25.41^\circ = 0.4291$$

$$\begin{aligned} \frac{b}{\omega}(wt_2) + \psi_3 &= 0.4434 + 1.8658 = 2.3093 \text{ rad} \\ &= 132.32^\circ \end{aligned}$$

$$\sin \left[\frac{b}{\omega}(wt_2) + \psi_3 \right] = \sin 132.32^\circ = 0.7394$$

$$I_{L1} \Big]_{t_2} = I_{L1} \left(\frac{\pi}{2} \right) = 6.78 \text{ amps}$$

$$\begin{aligned} I_{L2}(wt_2 = \frac{\pi}{2}) &= 32.13(0.8739)(0.4291) \\ &\quad + 7.09(0.8739)(0.7394) - 6.78 \end{aligned}$$

$$I_{L2}(wt_2 = \frac{\pi}{2}) = 12.05 + 4.58 - 6.78 = 9.85 \text{ amps}$$

$$E_o(s) = E_{o2}(s) = \frac{\left(\frac{1}{L_o C}\right) E_g(s)}{D} + \frac{\frac{I_{L_o}}{C}}{D} \\ - \frac{\frac{V_{co}}{L_o C_o}}{SD} + \frac{V_{co}}{S}$$

$$E_{o2}(s) = \frac{C_1 v\left(\frac{1}{2}\right)\left(\frac{1}{L_o C}\right)}{SD} - \frac{\left(\frac{1}{L_o C}\right) E_{g1}(s)}{D} \Big]_{t_2} \\ + \frac{\frac{I_{L_o}}{C}}{D} - \frac{\frac{V_{co}}{L_o C_o}}{SD} + \frac{V_{co}}{S}$$

$$E_{o2}(s) = \frac{\left[C_1 v\left(\frac{1}{2}\right)\left(\frac{1}{L_o C}\right) - \frac{V_{co}}{L_o C_o}\right]}{SD} + \frac{\frac{I_{L_o}}{C}}{D} + \frac{V_{co}}{S} \\ - \frac{\left(\frac{1}{L_o C}\right) E_{g1}(s)}{D} \Big]_{t_2}$$

$$E_{o2} = \left[C_1 v\left(\frac{1}{2}\right)\left(\frac{1}{L_o C}\right) - \frac{V_{co}}{L_o C_o} \right] \left[\frac{1}{b^2} - \frac{e^{-at_2} \sin(bt_2 + \psi_1)}{b b_o} \right] \\ + \frac{I_{L_o}}{C} \left(\frac{1}{b} e^{-at_2} \sin bt_2 \right) + V_{co} - E_{o1} \Big]_{t_2}$$

where $E_{o1} \Big]_{t_2}$ represents E_{o1} as a function of t_2 .

$$C_1 v\left(\frac{1}{2}\right)\left(\frac{1}{L_o C}\right) = \frac{23,551}{600 \times 10^{-6}} = 39.252 \times 10^6 \text{ volts/sec}^2$$

$$\frac{V_{co}}{L_0 C_0} = \frac{755}{600 \times 10^{-6}} = 1.258 \times 10^6 \text{ volts} / \text{sec}^2$$

$$\left[C_1 V \left(\frac{1}{2} \right) \left(\frac{1}{L_0 C_0} \right) - \frac{V_{co}}{L_0 C_0} \right] = (39.252 - 1.258) 10^6 \\ = 38.00 \times 10^6 \text{ volts} / \text{sec}^2$$

$$\frac{I_{L0}}{C} \left(\frac{1}{b} \right) = \frac{6.78}{600 \times 10^{-6}} \left(\frac{1}{709.42} \right) = 15.93 \text{ volts}$$

$$E_{02} = 38.00 \times 10^6 \left[1.82 \times 10^{-6} - 1.90 \times 10^{-6} e^{-at_2} \sin(bt_2 + \psi_1) \right] \\ + 15.93 e^{-at_2} \sin bt_2 + V_{co} - E_{01} \Big]_{t_2}$$

$$E_{02} = 38.00 \left[1.82 - 1.90 e^{-\frac{a}{\omega}(wt_2)} \sin \left(\frac{b}{\omega}(wt_2) + \psi_1 \right) \right] \\ + 15.93 e^{-\frac{a}{\omega}(wt_2)} \sin \frac{b}{\omega}(wt_2) + V_{co} - E_{01} \Big]_{t_2}$$

At end of second interval, $E_{02} = E_{02}(wt_2 = \frac{\pi}{2})$

$$\text{Then } E_{01} \Big]_{t_2} = V_{co}$$

$$E_{02}(wt_2 = \frac{\pi}{2}) = 38.00 \left[1.82 - 1.90(0.8739)(0.9890) \right] \\ + 15.93(0.8739)(0.4291) \\ = 38.00(1.82 - 1.64) + 5.97$$

$$E_{02}(wt_2 = \frac{\pi}{2}) = 38.00(0.18) + 5.97 = 6.84 + 5.97$$

$$E_{02}(\omega t_2 = \frac{\pi}{2}) = 12.81 \text{ volts}$$

C. For third interval, $t_m \leq t \leq \infty$,
or $\pi \leq \omega t \leq \infty$.

Replace t by t_3 , as in Section III, where

$$t_3 = t - t_m, \text{ or } \omega t_3 = \omega t - \pi$$

$$I_{L0} = I_{L3}(0^+) = I_{L2}(\omega t_2 = \frac{\pi}{2}) = 9.85 \text{ amps}$$

$$V_{C0} = E_{03}(0^+) = E_{02}(\omega t_2 = \frac{\pi}{2}) = 12.81 \text{ volts}$$

$$E_g = E_{g3} = 0$$

$$I_L(s) = I_{L3}(s) = \frac{SI_{L0}}{D} - \frac{\frac{CV_{C0}}{L_0 C_0}}{D}$$

$$I_{L3} = I_{L0} \left[\frac{b_0}{b} e^{-at_3} \sin(bt_3 + \psi_3) \right] \\ - \frac{CV_{C0}}{L_0 C_0} \left(\frac{1}{b} e^{-at_3} \sin bt_3 \right)$$

$$I_{L0} \left(\frac{b_0}{b} \right) = \frac{9.85(741.49)}{709.42} = 10.30 \text{ amps}$$

$$\frac{CV_{C0}}{L_0 C_0} \left(\frac{1}{b} \right) = \frac{600 \times 10^{-6} (12.81)}{4.45 \times 10^{-3} (408.72 \times 10^6) (709.42)} \\ = 5.96 \text{ amps}$$

$$I_{L3} = 10.3 e^{-at_3} \sin(bt_3 + \psi_3) - 5.96 e^{-at_3} \sin bt_3$$

For maximum E_{03} , $I_{L3} = 0$

$$\text{Then } 10.3 \sin(bt_3 + \psi_3) = 5.96 \sin bt_3$$

$$\sin bt_3 \cos \psi_3 + \cos bt_3 \sin \psi_3 = \frac{5.96}{10.3} \sin bt_3$$

$$\psi_3 = 106.91^\circ$$

$$-0.2909 \sin bt_3 + 0.9568 \cos bt_3 = 0.5786 \sin bt_3$$

$$0.9568 \cos bt_3 = 0.8695 \sin bt_3$$

$$\tan bt_3 = \frac{0.9568}{0.8695} = 1.1004$$

$$bt_3 = 47.73^\circ = 0.8331 \text{ rad.}$$

$$t_3 = \frac{0.8331}{b} = \frac{0.8331}{709.42} = 1.1743 \times 10^{-3} \text{ sec.}$$

$$E_0(s) = E_{03}(s) = \frac{\frac{I_{L0}}{C}}{D} - \frac{\frac{V_{C0}}{L_0 C_0}}{SD} + \frac{V_{C0}}{S}$$

$$E_{03} = \frac{I_{L0}}{C} \left(\frac{1}{b} e^{-at_3} \sin(bt_3 + \psi_1) \right) - \frac{V_{C0}}{L_0 C_0} \left[\frac{1}{b^2} - \frac{e^{-at_3} \sin(bt_3 + \psi_1)}{b b_0} \right] + V_{C0}$$

$$\text{But } \frac{V_{c0}}{L_0 C_0} \left(\frac{1}{b_0^2} \right) = V_{c0}$$

$$E_{03} = \frac{I_{L0}}{C} \left(\frac{1}{b} e^{-at_3} \sin bt_3 \right) + \frac{V_{c0}}{L_0 C_0} \left[\frac{e^{-at_3} \sin(bt_3 + \psi_1)}{bb_0} \right]$$

$$\frac{I_{L0}}{C} \left(\frac{1}{b} \right) = \frac{9.85}{600 \times 10^{-6} (709.42)} = 23.14 \text{ volts}$$

$$\frac{V_{c0}}{L_0 C_0} = \frac{12.81}{4.45 \times 10^{-3} (408.72 \times 10^6)} = 7.043 \times 10^6 \text{ volts/sec}^2$$

$$E_{03} = 23.14 e^{-at_3} \sin bt_3 + 7.043 \times 10^6 (1.90 \times 10^{-6}) e^{-at_3} \sin(bt_3 + \psi_1)$$

$$E_{03} = 23.14 e^{-at_3} \sin bt_3 + 13.38 e^{-at_3} \sin(bt_3 + \psi_1)$$

For maximum E_{03} :

$$at_3 = 215.73 (1.1743 \times 10^{-3}) = 0.2533 \text{ rad}$$

$$e^{-at_3} = 0.7762$$

$$bt_3 = 47.73^\circ$$

$$\sin bt_3 = 0.7400$$

$$bt_3 + \psi_1 = 0.8331 + 1.2755 = 2.1086 \text{ rad} \\ = 120.82^\circ$$

$$\sin(bt_3 + \psi_1) = 0.8588$$

$$E_{o3} \Big]_{\max} = 23.14 (0.7762)(0.7400) \\ + 13.38 (0.7762)(0.8588) \\ = 13.29 + 8.92 = 22.21 \text{ volts}$$

Correcting for the diode voltage drop:

$$E_{o3} \Big]_m = 22.21 - 0.7 = 21.51 \text{ volts}$$

$E_{o3} \Big]_m$ occurs 1.17 msec beyond completion of the generated voltage pulse.

APPENDIX B

ARTILLERY SHELL SETBACK VELOCITY PROFILE

I. Calculation of Projectile Acceleration

Time for breakaway of the core from its housing depends on the acceleration characteristics for the projectile and the g level defined by the safing device, and is part of the determination of the total time required to charge the capacitor bank. Another portion is the transit time, or the time to complete relative motion between the core and the housing. A third is the settling time, which is a characteristic of the charging circuit alone. The sum of these three is the rise time, which is required to be less than 5 milliseconds over a range of setback forces from 3,000 g's to 30,000 g's. Because breakaway time and transit time are highly dependent on the acceleration profile for the projectile, it was necessary to obtain such information for projectiles representative of the acceleration extremes. Information on projectile kinetics was furnished for 105-mm (high acceleration) and 106-mm (low acceleration) projectiles, and is included as Figures B-1 and B-2. The acceleration profile for these projectiles (within the time range of interest) was obtained by fitting the velocity curves with a quadratic function of time using the velocity data at 1 msec and 3 msec.

A. 105-mm Projectile:

$$\text{Let } v = C_1 t + C_2 t^2 \text{ ft/sec.}$$

Where t is in msec

From the curve:

$$v = 150 \text{ ft/sec at } t = 1 \text{ msec}$$

$$v = 1050 \text{ ft/sec at } t = 3 \text{ msec}$$

$$150 = C_1 + C_2$$

$$1050 = 3C_1 + 9C_2$$

$$450 = 3C_1 + 3C_2$$

$$600 = 6C_2$$

$$C_2 = 100$$

$$150 = C_1 + 100$$

$$C_1 = 50$$

$$v = 50t + 100t^2 \text{ ft/sec}$$

$$a = \frac{dv}{dt} = 50 + 200t \text{ ft/sec/msec}$$

B. 106-mm Projectile:

$$v = C_1t + C_2t^2$$

From the curve:

$$v = 65 \text{ ft/sec at } t = 1 \text{ msec}$$

$$v = 330 \text{ ft/sec at } t = 3 \text{ msec}$$

$$65 = C_1 + C_2$$

$$330 = 3C_1 + 9C_2$$

$$195 = 3C_1 + 3C_2$$

$$135 = 6C_2$$

$$C_2 = 22.5$$

$$65 = C_1 + 22.5$$

$$C_1 = 42.5$$

$$v = 42.5t + 22.5t^2 \text{ ft/sec}$$

$$a = \frac{dv}{dt} = 42.5 + 45t \text{ ft/sec/msec}$$

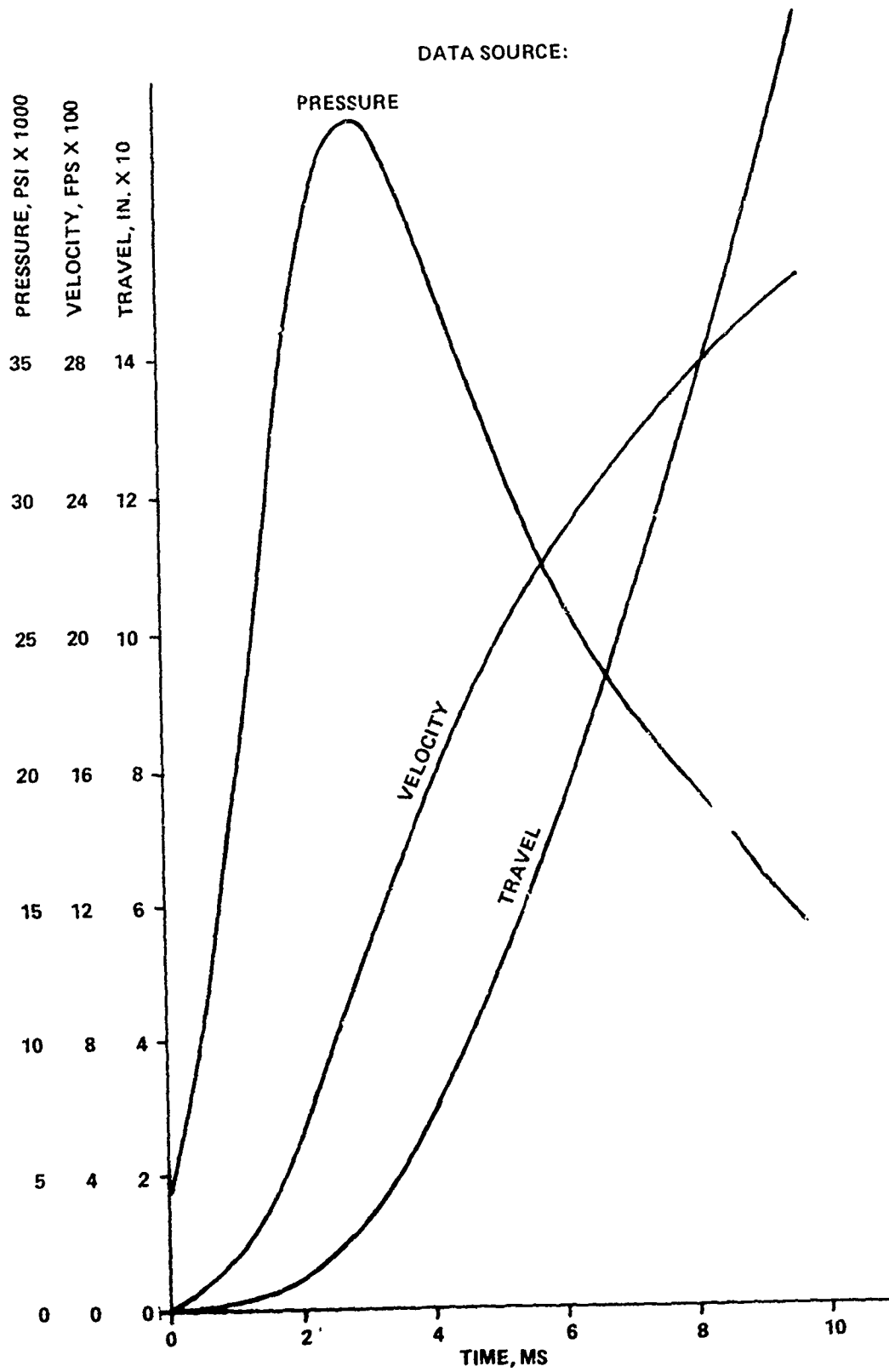


Figure B-1. Cannon: 105-MM, M68 Projectile: XM603

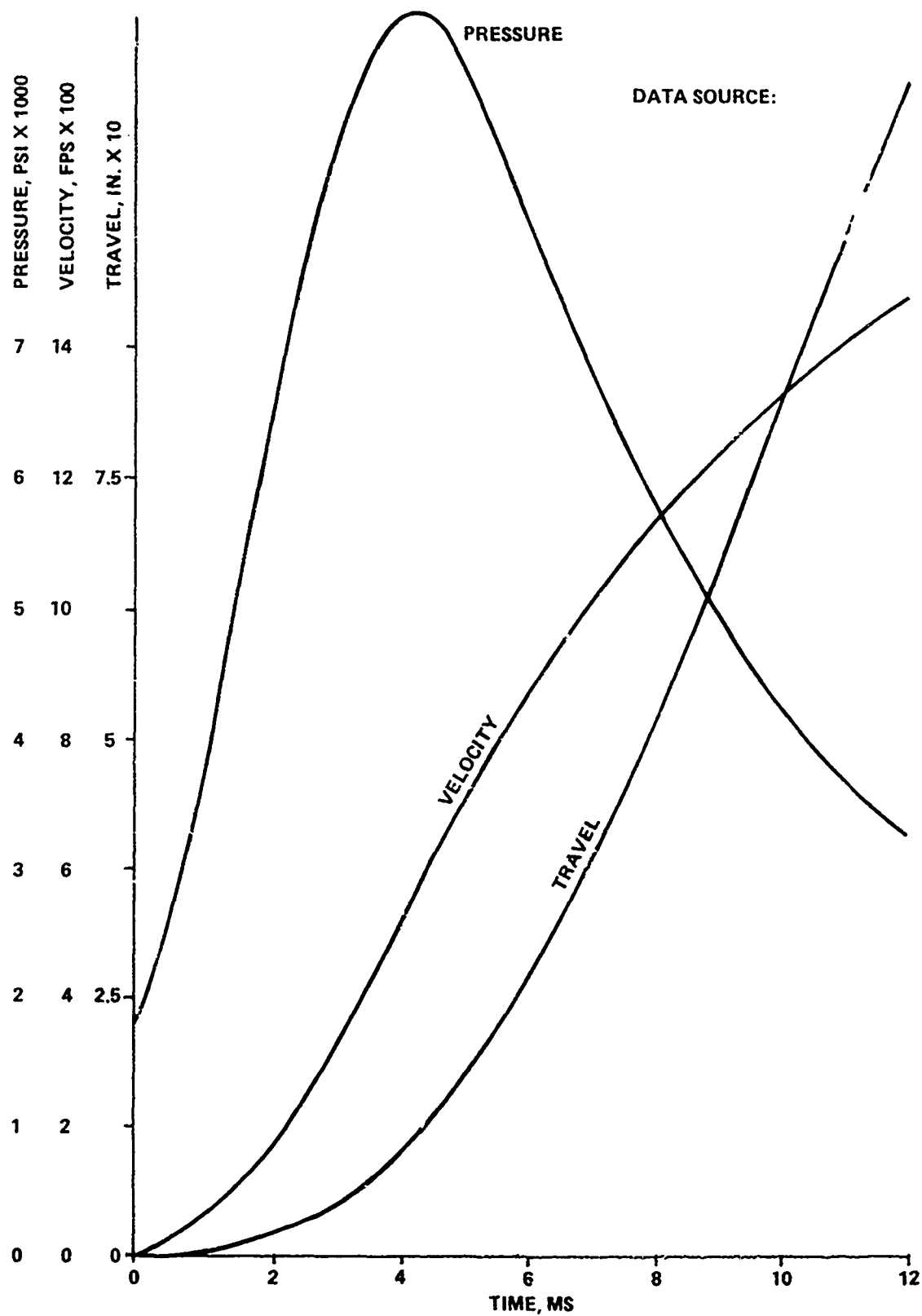


Figure B-2. Cannon: 106-MM, M40A1 Projectile: XM595

II. Calculation of Breakaway Time

To illustrate the influence of the safing device threshold, times will be determined for both 1000 g and 3000 g settings.

A. 105-mm Projectile:

Let t_{b1} = breakaway time at 1000 g's

and t_{b3} = breakaway time at 3000 g's

Where t_b is in msec

$$1000 \text{ g's} = 1000 (32.17)(10^{-3})$$

$$= 32.17 \text{ ft/sec/msec}$$

$$3000 \text{ g's} = 3 (32.17) = 96.51 \text{ ft/sec/msec}$$

$$32.17 = 50 + 200 t_{b1}$$

t_{b1} is negative, indicating instant breakaway ($t_{b1} = 0$)

$$96.51 = 50 + 200 t_{b3}$$

$$t_{b3} = \frac{46.51}{200} = \underline{0.233 \text{ msec}}$$

B. 106-mm Projectile:

$$32.17 = 42.5 + 45 t_{b1}$$

t_{b1} is again negative, indicating instant breakaway ($t_{b1} = 0$)

$$96.51 = 42.5 + 45 t_{b3}$$

$$t_{b3} = \frac{54.01}{45} = \underline{1.200 \text{ msec}}$$

III. Calculation of Transit Time

As with breakaway time, transit time will be calculated for both 1000 g and 3000 g safing device thresholds.

A. 105-mm Projectile:

Let t_{t1} = transit time, 1000 g breakaway

and t_{t3} = transit time, 3000 g breakaway

where t_t is in msec

$t = t_b + t_t$, t_b is a constant

$a = 50 + 200 (t_b + t_t)$ ft/sec/msec

$$= (50 + 200 t_b) + 200 t_t$$

$$v = (50 + 200 t_b) t_t + 100 t_t^2$$

$$S = (25 + 100 t_b) t_t^2 + \frac{100}{3} t_t^3, \text{ where units are (ft/sec)(msec),}$$

or millifeet

$$S_t = \text{transit distance} = 0.2 \text{ in.}$$

$$S_t = \frac{0.2}{12} = \frac{50}{3} \times 10^{-3} \text{ ft} = \frac{50}{3} \text{ millifeet}$$

$$\frac{50}{3} = (25 + 100 t_b) t_t^2 + \frac{100}{3} t_t^3$$

$$50 = (75 + 300 t_b) t_t^2 + 100 t_t^3$$

$$2t_t^3 + (1.5 + 6t_b) t_t^2 = 1$$

$$2t_{t1}^3 + 1.5 t_{t1}^2 = 1$$

$$t_{t1} = \underline{0.607 \text{ msec}}$$

$$2t_{t3}^3 + [1.5 + 6(0.233)] t_{t3}^2 = 1$$

$$2t_{t3}^3 + 2.398 t_{t3}^2 = 1$$

$$t_{t3} = \underline{0.506 \text{ msec}}$$

B. 106-mm Projectile.

$$a = 42.5 + 45 (t_b + t_t) \text{ ft/sec/msec}$$

$$= (42.5 + 45 t_b) + 45 t_t$$

$$v = (42.5 + 45 t_b) t_t + 22.5 t_t^2$$

$$S = (21.25 + 22.5 t_b) t_t^2 + 7.5 t_t^3 \text{ millifeet}$$

$$S_t = \frac{50}{3} \text{ millifeet}$$

$$\frac{50}{3} = (21.25 + 22.5 t_b) t_t^2 + 7.5 t_t^3$$

$$50 = (63.75 + 67.5 t_b) t_t^2 + 22.5 t_t^3$$

$$0.45 t_t^3 + (1.275 + 1.35 t_b) t_t^2 = 1$$

$$0.45 t_{t1}^3 + 1.275 t_{t1}^2 = 1$$

$$t_{t1} = \underline{0.784 \text{ msec}}$$

$$0.45 t_{t3}^3 + [1.275 + 1.35 (1.200)] t_{t3}^2 = 1$$

$$0.45 t_{t3}^3 + 2.895 t_{t3}^2 + 1$$

$$t_{t3} = \underline{0.564 \text{ msec}}$$

IV. Calculation of Rise Time

Rise time will be calculated using a settling time of 1.174 msec, corresponding to the calculated settling time for a 217 turn unit when charging a 600 mfd capacitor. Units having fewer turns are faster in response and therefore have a shorter settling time.

A. 105-mm Projectile:

Let t_{r1} = rise time, 1000 g breakaway

and t_{r3} = rise time, 3000 g breakaway

Let t_s = settling time

$$t_r = t_b + t_t + t_s$$

$$t_{r1} = 0 + 0.607 + 1.174 = \underline{1.781 \text{ msec}}$$

$$t_{r3} = 0.233 + 0.506 + 1.174 = \underline{1.913 \text{ msec}}$$

B. 106-mm Projectile:

$$t_{r1} = 0 + 0.784 + 1.174 = \underline{1.958 \text{ msec}}$$

$$t_{r3} = 1.200 + 0.564 + 1.174 = \underline{2.938 \text{ msec}}$$

All of the above values are within the 5 msec rise time allowed. Because of the 1000 g shear pins used for the delivered units, rise times are predicted to be 2 msec or less.

V. Setback Velocity Profile

The transit time equations may be used for determining setback velocity as a function of time. With 1000 g safing, breakaway time is zero, resulting in an identity between the transit time equations and the equations for projectile motion.

Because of the very short duration of transit, the effect of curvature of the velocity profile becomes insignificant. Therefore, a constant acceleration may be used in order to simplify the velocity expression, and thereby simplify the expression for generated voltage. This amounts to approximating the applicable portion of the velocity curve by a linear segment. The velocity change during setback, assuming 1000 g breakaway, will be:

A. 105-mm Projectile:

$$\begin{aligned} v &= 50 t_{t1} + 100 t_{t1}^2 \\ &= 50 (0.607) + 100 (0.607)^2 \\ &= 30.35 + 36.84 = \underline{67.19 \text{ ft/sec}} \end{aligned}$$

B. 106-mm Projectile:

$$\begin{aligned} v &= 42.5 t_{t1} + 22.5 t_{t1}^2 \\ &= 42.5 (0.784) + 22.5 (0.784)^2 \\ &= 33.32 + 13.83 = \underline{47.15 \text{ ft/sec}} \end{aligned}$$

APPENDIX C

ENGINEERING DRAWINGS

GENERAL ELECTRIC

TITLE		.DEPT		CODE IDENT NO		LOCATION		
Setback Generator, Assy.				PL				
DRAWING CODES		FOR GE USE ONLY		UNIT OF MEASURE CODES		REVISION CODES		
1. VENDOR ITEM - SPEC CONT DWG		4. SHORT FORM DWG		0. GRAMS 5. SETS		1. ITEM ADDED 4. IDENT NO. CHGD 6. EDIT CORRECTION		
2. VENDOR ITEM - SOURCE CONT DWG		5. INSEP ASSY		1. PIECES 6. OUNCES		2. ITEM DELETED 5. IDENT NO. AND		
3. ALTERED OR SELECTED PT		6. MCHD PT		2. FEET 7. INCHES		3. QTY CHGD QTY CHGD		
		7. CUST PURN PT		3. POUNDS 8. PINTS				
				4. GALLONS 9. OTHER				
ITEM NO.	ZONE	DWG CODE	IDENTIFICATION NO.	DESCRIPTION/ NOMENCLATURE	CODE IDENT NO	QTY	U / M	REV CODE
1			3920W12G700	Setback Generator		1		
2			2890W15G700	Cup Assy.		1		
3			2874W17P1	Support Cup		1		
4			2433W16G700	Coil Assy		1		
5			3705W17	Coil Form		1		
6			6285W64	Ring		1		
7			4594W33P1	Insulator		2		
8			2735W14G700	Core Assy.		1		
9			2734W15P1	Core		1		
10			5145W19P1	Disk Magnet		2		
11			8898W13P1	End Washer		1		
12			8898W13P2	End Washer		1		
13			5637W17P1	Pin		2		
SYM		REVISIONS						
MADE BY		APPROVALS		CONTRACT NO.		PARTS LIST FOR		
ISSUED						CONT ON SHEET SH NO		

REV		3920W12		2		3		4		5	
REVISIONS		DATE		APPROVED		ZONE		LTR			
DESCRIPTION											

G700

NOTE:
 1. CEMENT PIN P3 IN PLACE WITH
 LOCTITE 307.
 2. STRIP AND SOLDER TIN LEAD ENDS

FOR G.E. USE ONLY		SEE SEPARATE PARTS LIST (FOR ASSEMBLY DWGS ONLY)		ADDITIONAL CONTRACT NOS	
ABER GEN		SIGNATURES	DATE	GENERAL ELECTRIC	
F.N.F.		DESIGNED	10/9/73	AEROSPACE INSTS AND CONTROLS SYSTEMS DEPT WILMINGTON MA	
MATL CODE		CHECKED		TITLE	
MATERIAL		ISSUED		GENERATOR, SET BACK	
CON		ENGRG		CONTRACT NO	
GE		MFG		SIZE	
				CODE IDENT NO	
				B	
				DWG NO	
				97424	
				3920W12	
				SCALE	
				WT	
				SHEET	
				1	

REV		B		2890W15	
ZONE		LIT		REVISIONS	
DATE		DATE		APPROVED	
DESCRIPTION		DATE		APPROVED	

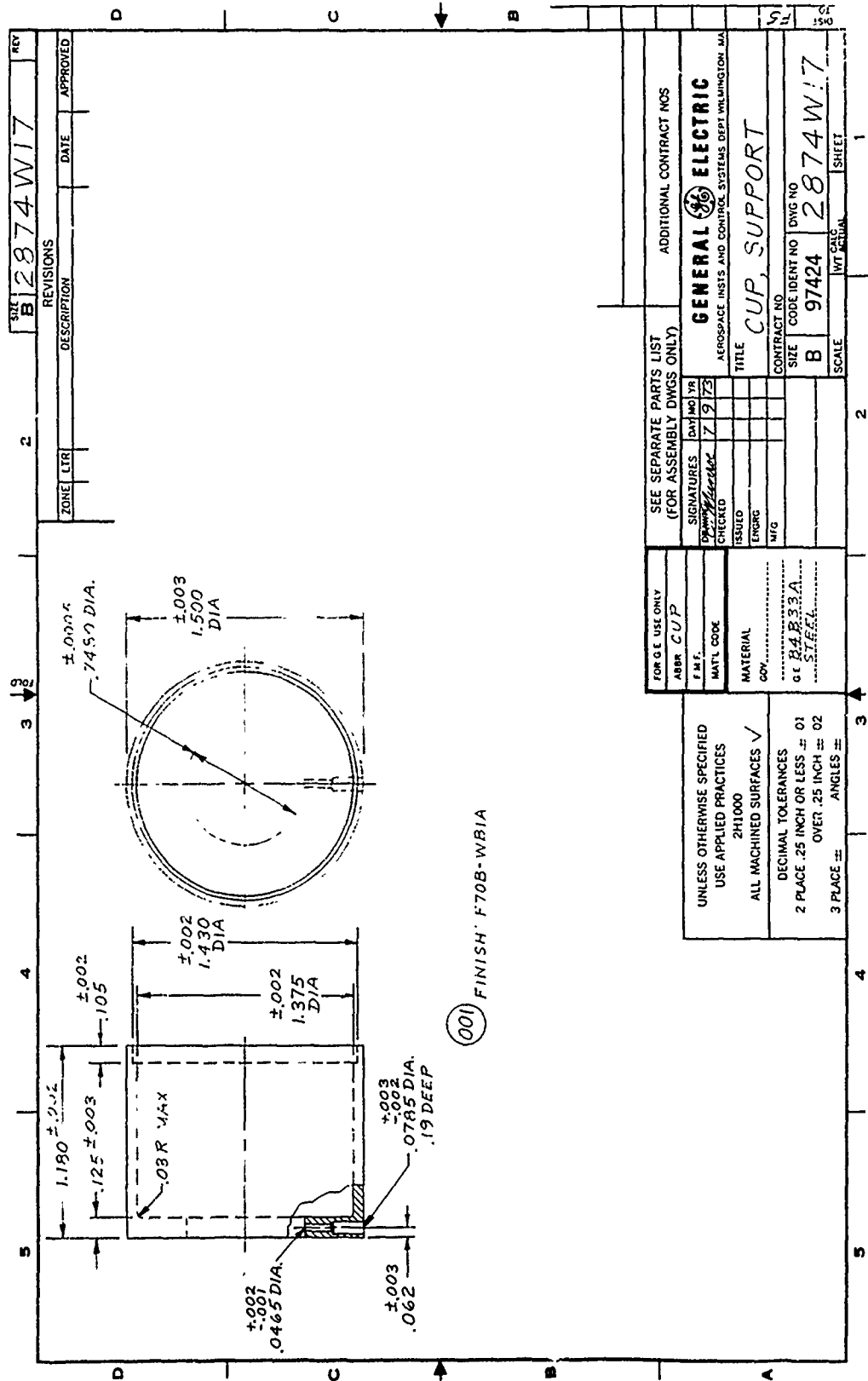
1. MOLD COIL IN PLACE WITH ARMSTRONG A12.
COIL FORM I.D. TO BE CONCENTRIC WITH
CENTER HOLE WITHIN .008 T.I.R.

2. ROLL END OVER TO SECURE P3.

3. FILL VOID BETWEEN LEAD AND HOLE
WITH ARMSTRONG A12

6700

FOR G.E. USE ONLY		SEE SEPARATE PARTS LIST (FOR ASSEMBLY DWGS ONLY)		ADDITIONAL CONTRACT NOS	
ABBR	CUP	SIGNATURES	DATE	MO	YR
F.N.F.			7/3	9	73
MAT'L CODE		CHECKED			
MATERIAL		ISSUED			
QTY		ENG'G			
		MFG			
UNLESS OTHERWISE SPECIFIED USE APPLIED PRACTICES		GENERAL ELECTRIC AEROSPACE INSTRUMENTS AND CONTROL SYSTEMS DEPT WILMINGTON, MA			
ALL MACHINED SURFACES ✓ 2H1000		TITLE CUP ASSY.			
DECIMAL TOLERANCES		CONTRACT NO.			
2 PLACE .25 INCH OR LESS ± .01		SIZE			
3 PLACE ± ANGLES ±		CODE IDENT NO.			
		B 97424			
		DWG NO.			
		2890W15			
		SCALE			
		SHEET			
		1			



REV		2874W17	
REVISIONS		DATE	
ZONE	LTR	DESCRIPTION	APPROVED
2			

SEE SEPARATE PARTS LIST (FOR ASSEMBLY DWGS ONLY)		ADDITIONAL CONTRACT NOS	
SIGNATURES	DAY MO YR	GENERAL ELECTRIC	
CHECKED	7 9 73	AEROSPACE INSTR. AND CONTROL SYSTEMS DEPT WILMINGTON, MA	
ISSUED		TITLE	
ENG'G		CUP, SUPPORT	
MFG		CONTRACT NO	
		B 97424	
		DWG NO	
		2874W17	
		SCALE	
		1	
		SHEET	
		1	

SIZE B		2433W16		REV.	
ZONE		LTR		REVISIONS	
DESCRIPTION		DATE		APPROVED	

5		4		3		2	
---	--	---	--	---	--	---	--

VIEW SHOWING DIRECTION OF WINDING

G NO.	WIRE SIZE	NO. OF TURNS
700	.0285	210
701	.0571	54

G700,701

NOTE:
1. FINISHED COIL MUST NOT OVERLAP
COIL FORM OR EXCEED .680 RADIUS.

FOR G E USE ONLY		SEE SEPARATE PARTS LIST (FOR ASSEMBLY DWGS ONLY)		ADDITIONAL CONTRACT NO.	
ADDR	COIL	SIGNATURES	DATE	NO. OF	DATE
F.M.F.		CHECKED	1/3/73	19	73
MAT'L CODE		ISSUED			
MATERIAL		T.O.R.G.			
GOV.		MFG			
G.E.		CONTRACT NO.			
UNLESS OTHERWISE SPECIFIED USE APPLIED PRACTICES		AEROSPACE INSTS. AND CONTROL SYSTEMS DEPT WILMINGTON, MA		TITLE	
ALL MACHINED SURFACES ✓		GENERAL ELECTRIC		COIL ASSY.	
DECIMAL TOLERANCES		CONTRACT NO.		CONTRACT NO.	
2 PLACE .25 INCH OR LESS ± .01		SIZE		CODE IDENT NO.	
3 PLACE .25 INCH ± .02		B		97424	
ANGLES ±		SCALE		DWG NO	
		1		2433W16	
		SHEET		1	

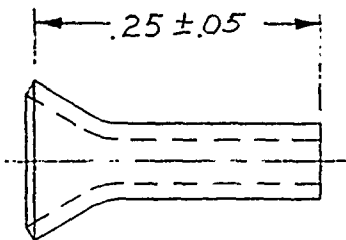
REV		3705W17		2		3		4		5	
ZONE		LTR		DATE		APPROVED		DESCRIPTION		REVISIONS	
D		C		B		A		D		C	

001 MATERIAL EPOXY FIBERGLASS

FOR GE USE ONLY		SEE SEPARATE PARTS LIST (FOR ASSEMBLY DWGS ONLY)		ADDITIONAL CONTRACT NOS	
ADDR FM, COIL	SIGNATURES	DAY	MO	YR	GENERAL ELECTRIC AEROSPACE ELCT. CO., 217 WILMINGTON, MASS. U.S.A.
7 MT	CHECKED	10	9	73	
MAT'L CODE	ISSUED				
MATERIAL	ENG'G				TITLE
CON	MTG				FORM, COIL
UNLESS OTHERWISE SPECIFIED USE APPLIED PRACTICES		CONTRACT NO		SIZE	
ALL MACHINED SURFACES ✓		B		97424	
DECIMAL TOLERANCES		CODE IDENT NO		DWG NO	
2 PLACE 25 INCH OR LESS ± .01		B		3705W17	
3 PLACE ± .005 ANGLES °		SCALE		SHEET	
		1		2	

SIZE **A** 4594W33 REV

REVISIONS			
LTR	DESCRIPTION	DATE	APPROVED



(001) MATERIAL: A16B45C, 1/16 HEAT SHRINKABLE INSULATED TUBING

NOTE:
HEAT SHRINK TUBING TO APPROXIMATE
SHAPE SHOWN

UNLESS OTHERWISE SPECIFIED USE APPLIED PRACTICES 2H1G00 ALL MACHINED SURFACES ✓		DECIMAL TOLERANCES 2 PLACE .25 INCH OR LESS $\pm .01$ OVER .25 INCH $\pm .02$ 3 PLACE $\pm$ ANGLES $\pm$		ADDITIONAL CONTRACT NOS	
SEE SEPARATE PARTS LIST (FOR ASSEMBLY DWGS ONLY)					
FOR G.E. USE ONLY	SIGNATURES	DAY	MO	YR	GENERAL ELECTRIC AEROSPACE ELECT EQUIP DEPT-WILMINGTON, MASS., U.S.A. INSULATOR CONTRACT NO. SCALE WT CALC ACTUAL SHEET
ABBR INSUL	DRAWN <i>C. Monroe</i>	13	12	73	
F.M.F.	CHECKED				
MAT'L CODE	ISSUED				
MATERIAL	ENGRG				
GOV	MFG				
G.E. SEE PART					

5		4		3		2		1	
D		C		B		A			

G700

NOTE:

- ASSEMBLE P.2 TO P.1 AND P.3 & 4 TO P.2 USING LOCTITE 307. ORIENT P.2 SO THAT NORTH SEEKING POLES ARE AS SHOWN.
- Grind core OD to dimension shown after assembly of magnets to pole pieces.

UNLESS OTHERWISE SPECIFIED USE APPLIED PRACTICES		FOR G.E. USE ONLY		SLE SEPARATE PARTS LIST (FOR ASSEMBLY DWGS ONLY)		ADDITIONAL CONTRACT NOS	
2H1000		CORE		SIGNATURES		DATE	
ALL MACHINED SURFACES ✓		MATERIAL		CHECKED		DATE	
DECIMAL TOLERANCES		GOV.		ISSUED		TITLE	
2 PLACE .25 INCH OR LESS ± .01		OF		ENGRG		CONTRACT NO	
3 PLACE .25 INCH ± .02		MFG		WFG		SIZE	
ANGLES ±						CODE IDENT NO	
						R 97424	
						DWG NO.	
						2735W14	
						SCALE	
						1:1	
						SHEET	
						1	

GENERAL ELECTRIC

AEROSPACE INSTRUMENTS AND CONTROL SYSTEMS DEPT WILMINGTON, DE

CORE ASSY

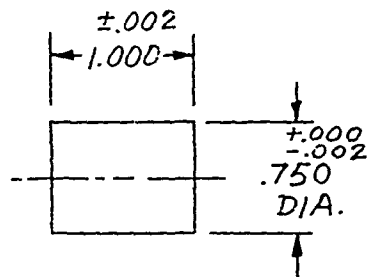
SIZE
A

2734W15

REV

REVISIONS

LTR	DESCRIPTION	DATE	APPROVED



001

UNLESS OTHERWISE SPECIFIED
USE APPLIED PRACTICES
2H1000
ALL MACHINED SURFACES ✓

DECIMAL TOLERANCES
2 PLACE .25 INCH OR LESS $\pm .01$
OVER .25 INCH $\pm .02$
3 PLACE $\pm$ ANGLES $\pm$

SEE SEPARATE PARTS LIST (FOR ASSEMBLY DWGS ONLY)

ADDITIONAL CONTRACT NOS

FOR G.E. USE ONLY	SIGNATURES	DAY	MO	YR	GENERAL ELECTRIC AEROSPACE ELECT EQUIP DEPT-WILMINGTON, MASS., U.S.A. TITLE CORE
ABBR <i>CORE</i>	<i>E. H. Hume</i>	7	9	73	
F.M.F.	CHECKED				
MAT'L CODE	ISSUED				
MATERIAL	ENGRG				
GOV	MFG				CONTRACT NO.
G.E. <i>B4B33A</i>					SIZE
<i>STEEL</i>					A
					CODE IDENT NO.
					97424
					DWG NO.
					2734W15
					SCALE
					WT CALC ACTUAL
					SHEET

DIST TO F-5

REV		B		5145W19	
ZONE		LTR		2	
DESCRIPTION		DATE		APPROVED	
D		C		B	

±.010
.734 DIA.
±.002
DIRECTION OF MAGNETIZATION
(001)

NOTES:
1. CHIPS NOT EXCEEDING .40 ACCEPTABLE.

FOR G E USE ONLY		SEE SEPARATE PART'S LIST (FOR ASSEMBLY DWGS ONLY)		ADDITIONAL CONTRACT NOS	
ABBR MAGNET		SIGNATURES		DATE	
F M F		CHECKED		7/19/79	
MATERIAL		ISSUED		ENGRG	
2H1000		MFG		CONTRACT NO	
ALL MACHINED SURFACES ✓		DECIMAL TOLERANCES		SIZE	
2 PLACE 25 INCH OR LESS ± .01		3 PLACE ± ANGLES ±		CODE IDENT NO	
UNLESS OTHERWISE SPECIFIED USE APPLIED PRACTICES		MAGNET, DISK		B	
2H1000		GENERAL ELECTRIC		97424	
2 PLACE 25 INCH OR LESS ± .01		AEROSPACE INSTS AND TOOL ROOM SYSTEMS DEPT WILMINGTON, MA		5145W19	
3 PLACE ± ANGLES ±		TITLE		SCALE	
DECIMAL TOLERANCES		CONTRACT NO		WT	
2 PLACE 25 INCH OR LESS ± .01		B		ACTUAL	
3 PLACE ± ANGLES ±		SHEET		1	

	SIZE A	8898W13	REV	
REVISIONS				
LTR	DESCRIPTION	DATE	APPROVED	

(001)

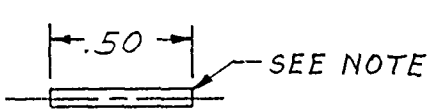
(002)

OTHERWISE AS P.001

UNLESS OTHERWISE SPECIFIED USE APPLIED PRACTICES 2H1000 ALL MACHINED SURFACES ✓	DECIMAL TOLERANCES 2 PLACE .25 INCH OR LESS ± .01 OVER .25 INCH ± .02 3 PLACE ± ANGLES ±
SEE SEPARATE PARTS LIST (FOR ASSEMBLY DWGS ONLY)	

FOR G.E. USE ONLY	SIGNATURES	DAY	MO	YR	GENERAL ELECTRIC AEROSPACE ELECT EQUIP DEPT - WILMINGTON, MASS., U.S.A. TITLE WASHER, END CONTRACT NO. SIZE A CODE IDENT NO. 97424 DWG NO. 8898W13 SCALE WT CALC ACTUAL SHEET
ABBR WSHR	<i>[Signature]</i>	10	9	73	
F.M.F.	CHECKED				
MAT'L CODE	ISSUED				
	ENGRG				
MATERIAL	MFG				
GOV					
G.E. B4B33A					
STEEL					

SIZE A		5637W18		REV
REVISIONS				
LTR	DESCRIPTION	DATE	APPROVED	



SEE NOTE 1

001

NOTE:
1. BREAK CORNERS
BOTH ENDS.

UNLESS OTHERWISE SPECIFIED USE APPLIED PRACTICES 2H1000 ALL MACHINED SURFACES ✓	DECIMAL TOLERANCES 2 PLACE .25 INCH OR LESS ± .01 OVER .25 INCH ± .02 3 PLACE ± ANGLES ±	
SEE SEPARATE PARTS LIST (FOR ASSEMBLY DWGS ONLY)		ADDITIONAL CONTRACT NOS

FOR G.E. USE ONLY	SIGNATURES	DAY	MO	YR	GENERAL ELECTRIC AEROSPACE ELECT EQUIP DEPT - WILMINGTON, MASS., U.S.A. TITLE PIN, STRAIGHT CONTRACT NO.
ABBR PIN, STR	<i>E. Munroe</i>	14	9	73	
F.M.F.	CHECKED				
MAT'L CODE	ISSUED				
MATERIAL STEEL	ENGRG				
GOV. _____	MFG				SCALE WT CALC ACTUAL SHEET
G.E. B4E11B3					
.045 DIA.					

SIZE A	CODE IDENT NO. 97424	DWG NO. 5637W18	DIST TO F5
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DOCUMENT CONTROL DATA - R&D

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d.			
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13. ABSTRACT This technical report summarizes the design, development and test of a setback generator and its associated energy storage module. The generator, measuring 1.5 inches in diameter and 1.2 inches in height, has produced over one million ergs of energy in laboratory tests. This energy is stored on a capacitor bank (energy storage module) to serve as a power source for an artillery fuze. The contract specifies a minimum energy requirement of 675,000 ergs. The setback generator developed on this program provides a unique feature in that it extracts energy from a magnetic field through a reverse saturation cycle. An important result of this feature is that the low magnetic forces between the core and its housing allowed the core assembly to release at very low acceleration input levels. This makes a generator of this design particularly attractive for use in rocket and mortar fuze applications. Laboratory and field tests have demonstrated that the generator of this general design can produce nearly 400,000 ergs in a 30g setback environment. Test units which were fabricated were evaluated under both laboratory and gun launch environments. The results of these tests confirmed the output predicted from analytical studies to be consistent with those results demonstrated in the laboratory, but greater than those demonstrated in ballistic firings. The inconsistency is expected to be resolved following ballistic tests on the 20 deliverable units under this contract.			

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Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Magnetics						
Induction Generator						
Magnetic Pulse Generator						
Impulse Generator						

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