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DEVELOPMENT OF THE DRY TAPE BATTERY CONCEPT
24 January to 30 April 1964

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ABSTRACT

Expanded magnesium, giving a current density of 1 amp/in.² at a polarization of 0.2 volt, has been tentatively selected as the best anode for combined tape construction. Anode development was concentrated on the use of magnesium or aluminum foil, pressed powder, and sprayed metal forms. Although aluminum has a higher theoretical energy density than magnesium, the latter was chosen because of its higher potential and greater ease of starting. Considerable hydrogen evolution from the reaction of magnesium with electrolyte necessitated the selection of open structures, e.g., expanded metal, for gas removal.

The preferred method for electrolyte supply is a continuous feed of macrocapsules. Encapsulations of water in thin films of FEP Teflon[®], Aclar[®], or aluminum-Mylar[®] laminate are being tested. Initial payloads of greater than 80% have been obtained, and a 60% payload after three years appears to be possible. Theoretical electrochemical requirements for electrolyte are far less than the amount required for the complete wetting necessary for efficient discharge, and methods of maintaining a local excess of electrolyte at the discharge area are being investigated.

The organic oxidizer, 2,4,6-trichloro-triazine-trione, has been tentatively selected as the cathode active material for the complete tape system because of its high discharge rate. Efficient, high-rate discharge of meta-dinitrobenzene has not been achieved.

Several lightweight, low-voltage motors have been tested for running the dry tape mechanism by parasitic power. These motors provide 30 oz-in. of torque and consume 150 to 200 milliwatts at 11 to 15% efficiency. Parasitic operation, with the drive motor consuming about 10% of the output power, (15% motor efficiency) was achieved by combining three silver peroxide tapes, connected in series, with a motor and a variable speed transmission. A major improvement is possible if a more efficient motor can be obtained. *Conf*

Author

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I. INTRODUCTION

This work is a continuation of work performed under Contract NAS 3-2777. During that program the feasibility of the Dry Tape Concept was demonstrated using a divalent silver oxide-coated, porous polypropylene tape that was drawn between two current collectors. One of these current collectors consisted of a zinc block that also served as the anode. The other was a silver plate that contacted the silver oxide coating. Electrolyte was supplied by a second tape prewetted with electrolyte and stored separately ("dual tape" system). The system was activated by bringing the two tapes together just prior to the current collectors, the divalent silver oxide-coated tape being wet by the electrolyte tape.

The tapes were driven by a spring-wound motor contained in a separate housing. Also within this housing was a metering and load section. Four such drive housings together with 20 tape decks were supplied to NASA for demonstration.

In continuous operation, silver peroxide utilizations of over 90% were obtained at current densities of 1 ampere per square inch.

While contract NAS 3-2777 was successful in all of its objectives, the major one of which was to prove the feasibility of the concept, the choice of the silver peroxide/zinc couple and the use of a spring-wound drive were conveniences. The latter provided a reliable method for driving the tapes but did not provide for parasitic operation. The former allowed us to compare our results with an established battery system.

The present program is aimed at developing the following:

1. Methods of efficiently utilizing high energy anodes and cathodes on tapes.
2. A method of incorporating a high energy couple into a single tape configuration.
3. Methods of electrolyte encapsulation and tape activation.
4. A weight-optimized tape conversion device capable of supplying its own power for unattended, stop-start operation.
5. Methods of supplying multiple cell voltages from the dry tape system.

The successful attainment of the above objectives will have two important advantages. First, very high energy density materials that normally must be used in reserve type cells where the entire system is activated at once will be usable in stop-start operation. By applying these couples to tape we will be able to activate the tape at

a rate dictated by the load demand. Second, for those high energy couples that are mass transport- or diffusion-limited in primary battery configurations, we will be able to operate continuously near the flash current discharge rate. This allows us to make a high energy, low rate system into a high energy, high rate system.

II. PHASE 1 - SINGLE COMPONENT CONFIGURATION DEVELOPMENT

A. ANODE DEVELOPMENT

1. Preparation

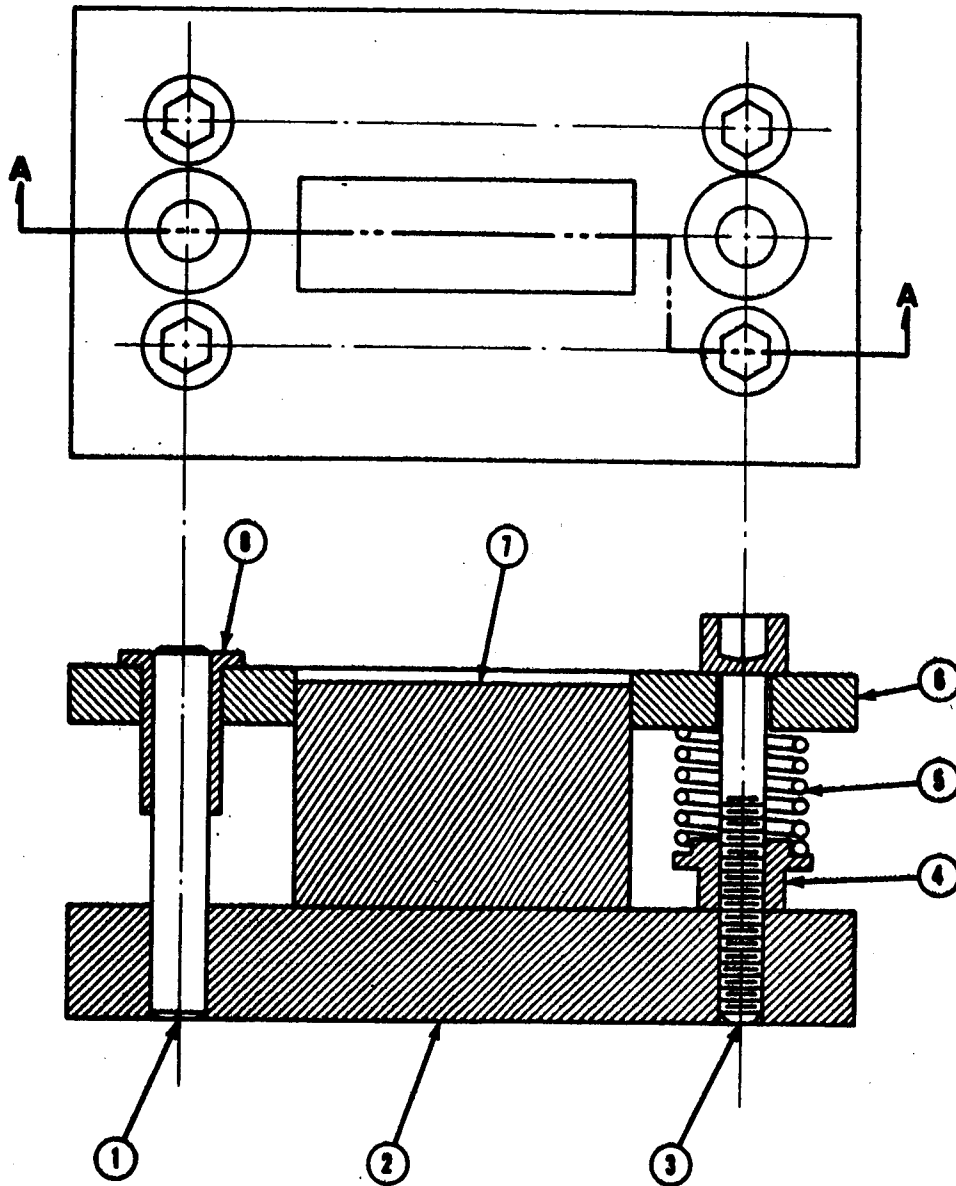
The objective of this portion of the program is the development of tape anodes using lithium, magnesium, or aluminum as the active element. Considering present technology levels, major emphasis is being placed on the latter two materials. These are attractive since they offer high energy densities. They have not been used extensively in conventional systems due to the complicating factors of anode corrosion and poor battery shelf life. However, the short period of time between activation, discharge, and removal of any section of a tape electrode minimizes these difficulties and should provide ample freedom to overcome the self-imposed design criteria of extremely high current density operation. Anode configuration and electrolyte suitability for Al and Mg have been studied in the present effort in this phase.

For a dry tape application, we have studied three anode forms: (1) a solid or foil type, (2) a porous powder composition, and (3) a flame-sprayed metal on a tape backing. In the samples tested, the foil was obtained commercially, the flame spraying was done by a local vendor, and the porous powder electrodes were manufactured using a die mold of the type shown in Figure 1. In the latter case, the composition powders were approximately 20 to 100 mesh in size and the final electrodes averaged 30% to 40% void volume. Dimensions of all test electrodes were either 1 in. x 1 in. or 1 in. x 3 in., the latter being the size of the die mold.

2. Testing

As the investigation progressed from the foils to the sprayed and pressed powder samples, the testing methods were varied among the three configurations shown schematically in Figure 2. Initially, the "open" cell was used to test the foil forms in over 20 electrolytes of various types and strengths. A sampling of the results is presented in Figure 3 where the linear relationship indicates that at the high current densities considered, IR solution losses are the predominant contributor to electrode polarization. Since the solution conductance must be considered if drains are to approach 1 amp/in.², the reference electrode placement intentionally includes a portion of the electrolyte IR (i.e., the use of carefully placed Luggin capillaries is considered unrealistic). The use of this method, however, demands reasonable control over the interelectrode distance "d" (approximating ultimate electrode spacing) as obtained in both the "sandwich" and "open sandwich" cells.

With the above electrolyte preference phases completed for both Mg and Al in foil form, testing progressed to the "sandwich" cell method for investigation of the non-rigid pressed powder and flame-sprayed samples of magnesium. All results on the three forms of Mg in sandwich testing were poor, as shown in Figure 4, and were analyzed as IR losses because of H₂ gas blockage discussed below. To permit evaluation of these higher area forms, the "open sandwich" method of testing was adopted.



SECTION AA

LEGEND

- | | |
|--------------|------------|
| 1. Guide Pin | 5. Spring |
| 2. Base | 6. Plate |
| 3. Bolt | 7. Die |
| 4. Locknut | 8. Bushing |

Figure 1 Die Mold for Porous Powder Electrode Manufacture

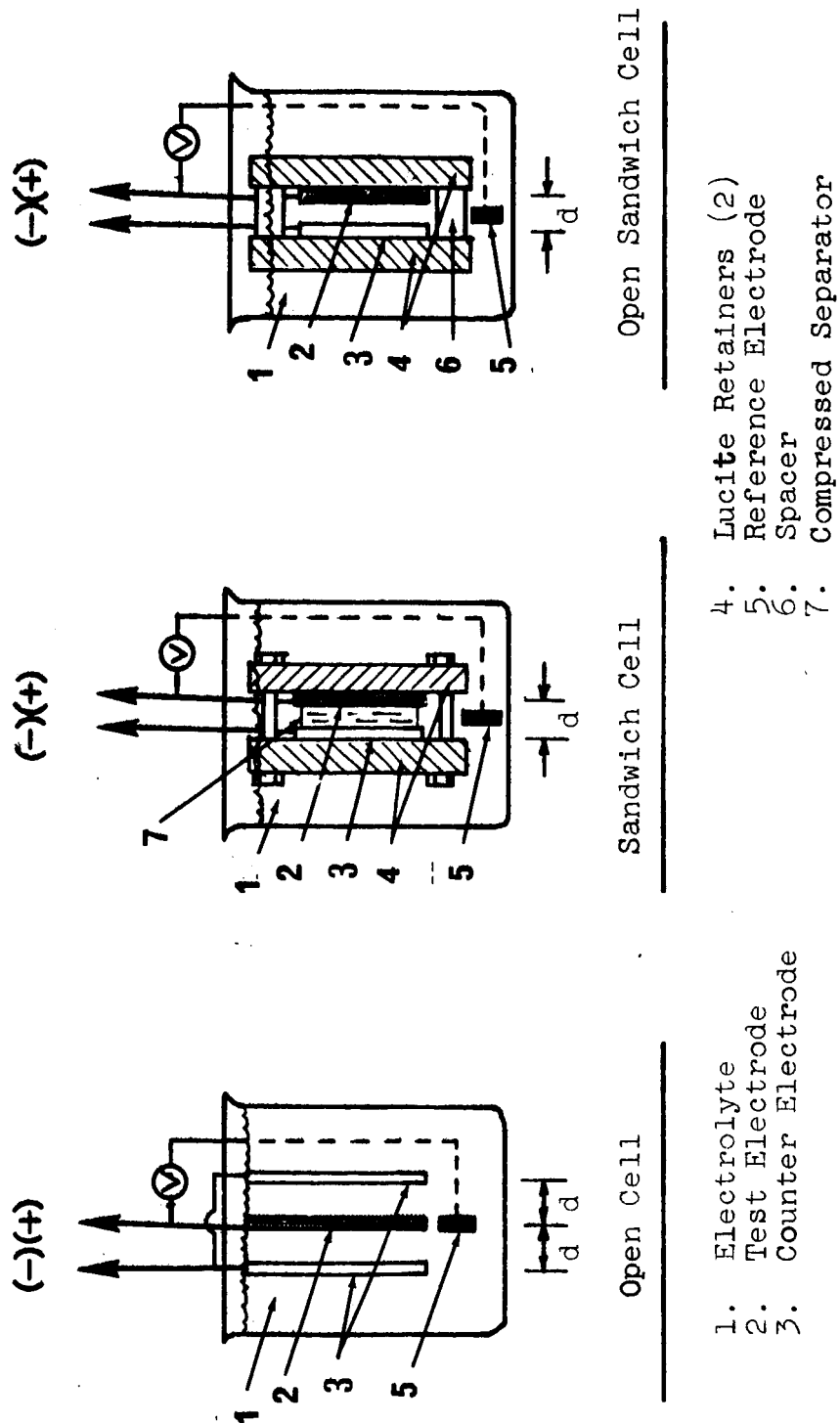


Figure 2. Schematic Representation of Test Methods

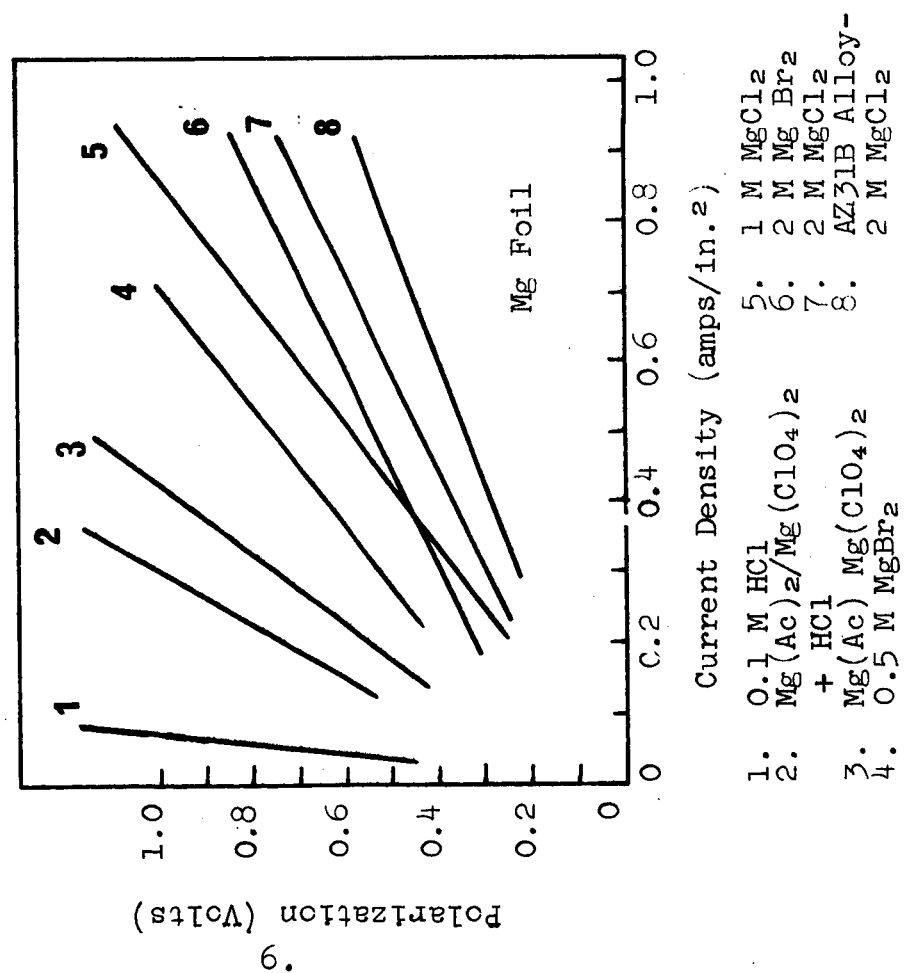
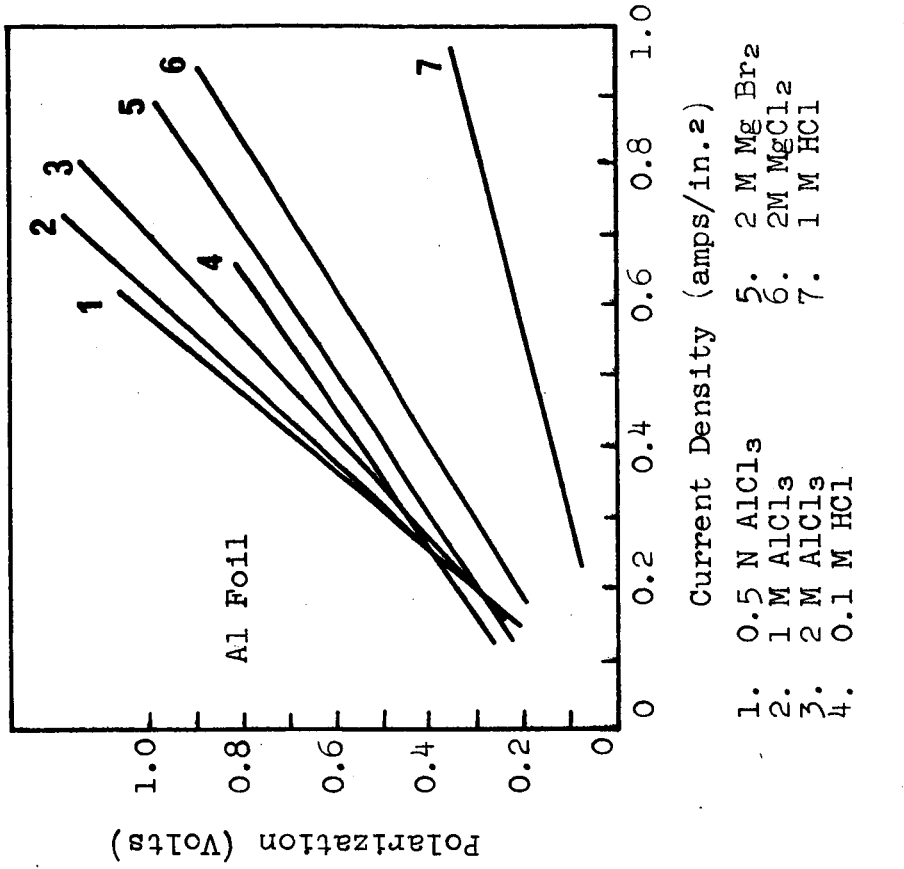
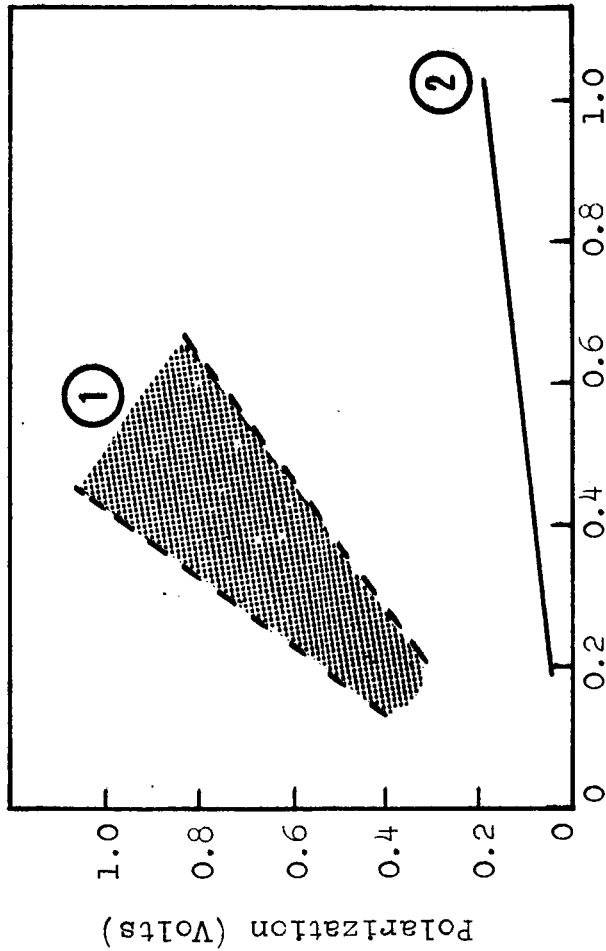


Figure 3. Open Cell Test Results: Mg and Al Foil



Current Density (amps/in.²)

1. Most Results for Foil, Powder, Flame Spraying
2. Expanded Magnesium in 2M MgCl₂

Figure 4. "Sandwich" Test Results: Magnesium as Foil, Powder, Flame Sprayed and Expanded Metal

Here, the spacing "d" is maintained along with an open structure, allowing escape of gas. Results of the pressed powder tests are shown in Figure 5. Little or no improvement for Mg is seen and only moderate benefit is shown for the Al samples. Although H₂ gas again played a minor role, the lack of extensive benefit from increased surface area was expected in systems where the discharged product was highly soluble in the electrolyte. Finally, for the sprayed samples of both metals, performance equivalent to the solid foil could not be obtained with any of the test methods. Gas evolution was once more a factor.

3. Gassing Difficulties

The above results become more reasonable in light of the following considerations. Both Al and Mg have protective oxide surface films that must be dissolved to permit discharge of the underlying metal. For high current operation, therefore, selection of the electrolyte involves the consideration of both conductivity and oxide film solubility. The very process of film dissolution, however, causes exposure of the reduced metal to the aqueous electrolyte and, since both Al and Mg will replace hydrogen, gassing results. Magnesium is more active in this respect and, accordingly, shows greater effects of the gassing condition. This is further complicated for magnesium because the hydrogen evolution increases as the anodic current increases, an unusual phenomenon known as a "negative difference effect".

In both the "open" and "open sandwich" testing methods discussed above, the H₂ gas escapes naturally, rising between the plates. However, in the "sandwich" cell, the gas is largely trapped in the tight package, creating prohibitively high electrolyte resistance and causing increased current density in the areas still accessible. Both of the latter factors would register as increased polarization. Similarly, each of the three types of electrodes studied is affected differently by the gas problem. The foils have a relatively uniform surface with relatively uniform gassing and moderately easy H₂ escape if space is provided. On the other hand, the porous powders possess increased surface area in an equivalent volume, which undoubtedly results in increased gassing. The pores quickly clog with hydrogen, which tends to nullify the higher area benefits. Finally, the sprayed metal is so intimately attached to the tape backing that gas evolved from the underside of each particle becomes trapped in the tape preventing any reasonably efficient discharge.

4. Material Selection

The great dependency of high current density electrode operation on solution conductance is indicated in the results of the above testing. Since the possibility of obtaining similar conductivities in nonaqueous solutions for room temperature operation is remote, the use of lithium as a high-rate anode is equally remote. Accordingly, no tests for lithium are planned in the near future although changes in design characteristics (lower current density operation, etc.) may rekindle interest at a later date.

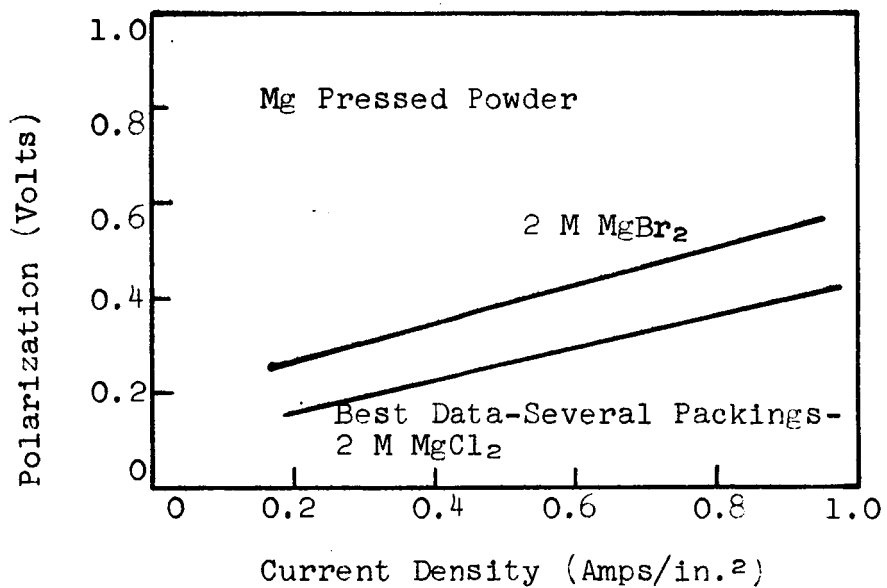
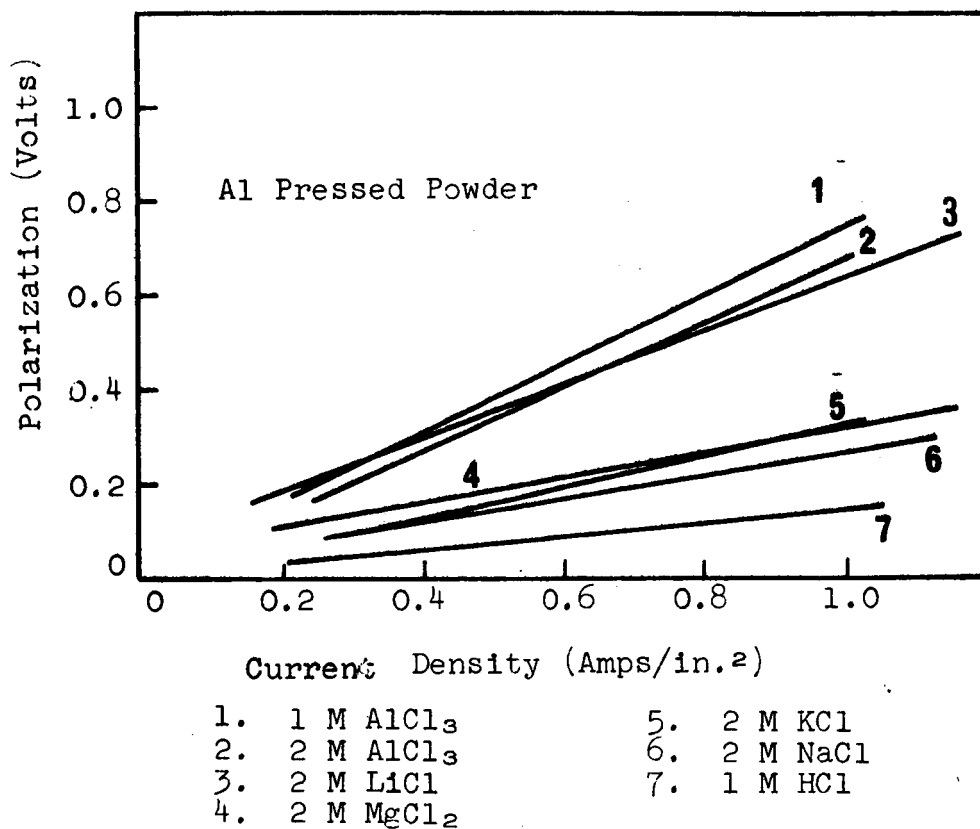


Figure 5. Open "Sandwich" Test Results:
Al and Mg Pressed Powders

A comparison of aluminum and magnesium in the results obtained to date involves several factors. Generally, the polarization suffered by Al at any given current density is less than that for Mg, although the difference is essentially nullified when expanded metal is used, as discussed later. Coulombic efficiencies, not yet verified, are expected to be comparable with a slight edge for aluminum. Also, aluminum apparently offers a greater choice of electrolytes and has a natural energy density advantage of 2.98 amp-hr/g to that of 2.20 amp-hr/g for magnesium. The overwhelming factor, however, is the electrochemical potential. Magnesium is approximately 0.8 volt more electronegative than aluminum (approx. -1.6v (SCE) to -0.8 v(SCE) open circuit). The net effect is illustrated in assumed full cells using meta-dinitrobenzene as cathode material; a magnesium cell would develop an operating potential of 0.9 v to 1.1 v against 0.2v to 0.4v for aluminum. The tremendous difference in power outputs is obvious, and, accordingly, magnesium has been temporarily selected as the anode material.

5. Design Considerations

Analysis of the testing to date has shown that elimination or rapid escape of H₂ gas is necessary to achieve maximum performance from magnesium. Proper design of the collector-anode combination should help overcome many of the difficulties. With this in mind, tests were successively made on perforated sheet, crudely woven strips, and expanded metal. Each possessed increasingly greater ability to vent H₂ gas and each gave progressively better results. The expanded magnesium performance in the "sandwich" cell, the most difficult test method from a gassing standpoint, is shown in Figure 4. Here it is seen that measured polarization at 1 amp/in.² was less than 0.2 volt.

Incorporation of the above improvements into a tape anode configuration is possible through several variations. The expanded metal itself could be used if it can be obtained in sufficiently thin base material (0.001 in.) to match expected loadings per square inch. A fine woven screen mesh seems likely to produce the desired results. The collector and anode can be combined in a magnesium block grooved and channeled to provide the necessary gas escape manifolds. The immediate future effort in this area will be the acquisition and testing of samples using these and other design possibilities.

B. ELECTROLYTE ENCAPSULATION

Various methods of electrolyte encapsulation have been considered for supplying electrolyte as needed for discharge of the tape battery in a storable form compatible with stop-start operation. In any method for continuous supply of electrolyte, whether in macrocapsules or microcapsules, the wall thickness of containing material must be minimized to achieve a high payload. The smaller the capsule size, the thinner the capsule wall must be to provide the same percentage payload and, consequently, the more impermeable the wall material must be. With as assumed requirement of a 60 wt-% minimum payload after three years storage, micro-size capsules are eliminated as a possibility with

the present state-of-the-art, at least for encapsulation of aqueous phases. In fact, it appears that microcapsules offer promise only if the anode material is at least partially used as an encapsulant. Thus, a much greater capsule wall thickness could be used without the additional weight penalty.

A giant macrocapsule can easily meet the above payload-storage requirements. For example, a 500 ml polyethylene bottle with a 40-mil wall will provide a 95%+ payload with a loss of only 1/4% per year. However, this means of electrolyte storage would require additional mechanisms to dispense electrolyte at the desired rate to the desired location. Aside from the additional complexity, there is a definite minimum operation time below which this method suffers a weight penalty compared to other macrocapsules or to microcapsules. Our previous analysis indicates that for one set of conditions this minimum operation time was about 100 hours. While this minimum would vary with the conditions, we feel a macroencapsulation of dimensions suitable for supply with or on tape offers the best approach.

1. Macrocapsule Design Considerations

An electrolyte feed rate of 0.2 gram per square inch of tape has been used as a basis in designing a macroencapsulation system. While this is considerably in excess of the theoretical requirements for a magnesium m-dinitrobenzene couple with a capacity of 1 amp-min per square inch of tape, some excess of electrolyte is required to wet the active components and separator. Various modifications of the encapsulation system can be made to supply a larger or smaller amount of electrolyte as dictated by the anode and cathode studies. A single tube of packets can be used to supply two tapes as shown in Figure 6 if a smaller quantity of electrolyte is sufficient. This arrangement offers the advantages that (1) the container material is not on the tape surface and will not interfere with discharge, and (2) a simple puncture of the capsule and passage through rollers should efficiently distribute electrolyte to the two tapes with little loss. If more electrolyte is required, a wider packet could be used. This would provide a greater payload at the expense of increasing the surface area-to-volume ratio of the packet. In all cases, it will be advantageous to provide some means of obtaining a local retention of electrolyte at the current collectors. A wringer action produced by pressure rolls following the current collectors might be used to continually feed back a portion of electrolyte.

2. Encapsulating Materials

Our preliminary calculations indicate that electrolyte weight will be a major portion of the total weight of a completed system. Therefore, it is necessary to obtain a high payload in supplying electrolyte. This dictates use of the thinnest, least dense container materials consistent with permeability requirements. For the configuration illustrated in Figure 6, initial payloads greater than 80 wt-% are obtainable with film thicknesses of 1 to 2 mils (depending on film density) as the calculations summarized in Table 1 show. Payloads

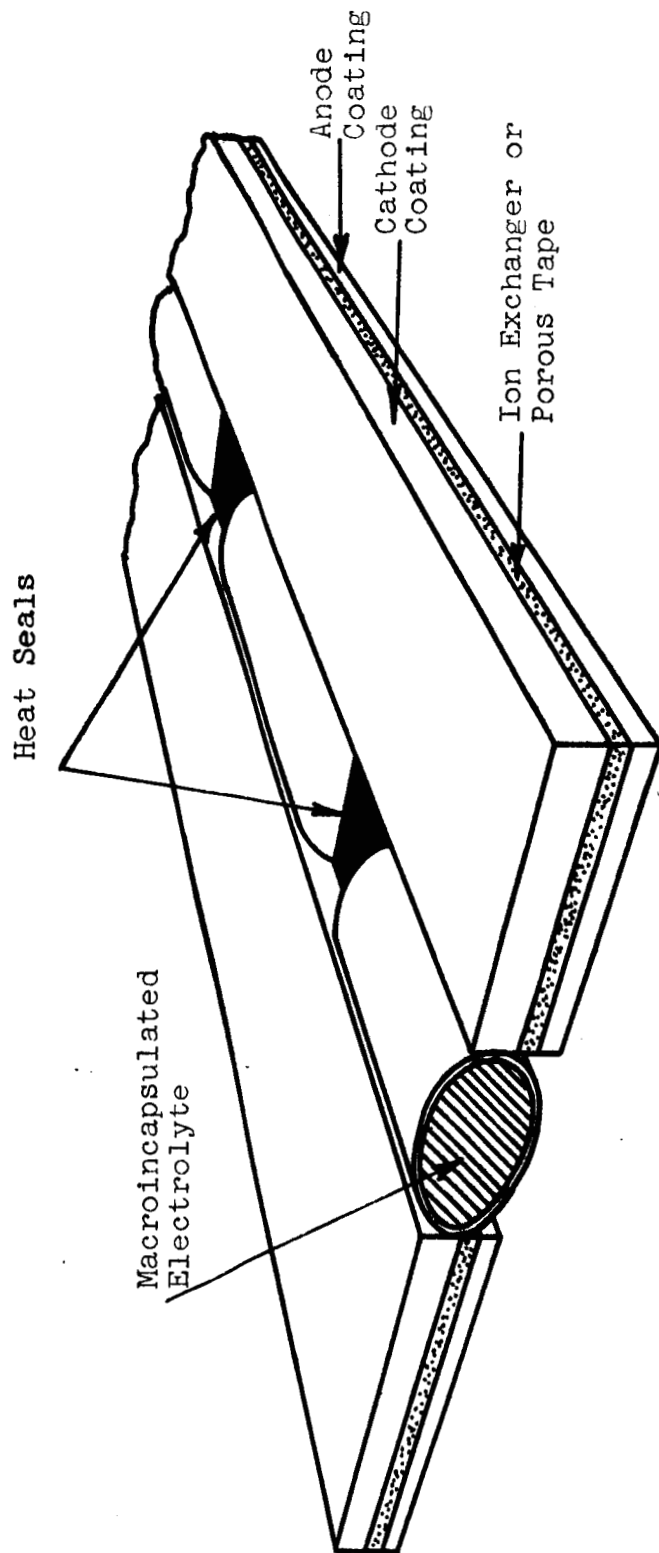


Figure 6. A Proposed Configuration for Tape-Electrolyte Incapsulation

Table 1

CALCULATED PAYLOAD AND SURFACE AREA
TO VOLUME RATIO FOR CAPSULES OF ELLIPTICAL CROSS SECTION*

Axis of Ellipse, mils		Internal Volume cc	Initial Payload wt-%	Surface Area per Unit Volume cm ⁻¹	Payload** 3 Years wt-%
Major	Minor				
300	10	0.20	82	40	60
150	10	0.10	80	31	65
150	20	0.15	83	28	68
65	65	0.20	90	13	80

* Capsule length - 1 in.; film density - 2.1 g/cc; film thickness - 1 mil; electrolyte density - 1 g/cc, includes allowance for heat seals

** Assuming 50% relative humidity difference at 25°C and film permeability of 0.002 g-mm/24 hr-sq m-cm Hg

greater than 60% are obtained after three years if the film permeability is of the order of 0.002 g-mm/24 hr-sq m-cm Hg.

From these considerations and the general characteristics desired, thermoplastic films are the choice for capsule material. Thermoplastics also offer the advantage of relatively simple capsule fabrication by conventional sealing methods, the seals generally being at least as impermeable as the film. Permeability and density data of the more impermeable thermoplastic materials available as thin films are summarized in Table 2. It is apparent that a film thickness greater than 2 mils is needed with most thermoplastics to obtain the low electrolyte loss level with aqueous electrolytes.

3. Capsule Fabrication

Of the numerous methods for sealing or joining thin thermoplastic films, thermal impulse and ultrasonic sealing have the widest applicability to the materials of interest in this work. A thermal impulse sealer, Sentinel Model 12-12AS, has been used to produce capsules of Aclar[®], Scotchpak[®] 25A20 (a Mylar[®]-aluminum laminate), etc., and polyethylene films with satisfactory results. The upper sealing head of this unit has been modified to produce a thinner seal with smaller clamping area.

4. Test Considerations and Methods

Finished capsules are being tested to determine the weight loss as a function of time in various environments. These environments are: (1) atmospheric pressure and zero relative humidity at 25°C, (2) same as (1) with reduced pressure and/or elevated temperatures, and (3) ambient conditions. Where capsule impermeability is such that weight loss cannot be detected in a reasonable period of time, elevated temperatures will be used to increase the loss rate to measurable levels. Various film samples will be separately examined for pinholes by spark discharge. Comparison of results on capsules tested at atmospheric and reduced pressure will indicate whether pinholes or imperfect seals are present, since the loss due to pinholes or leaks will depend on the total pressure drop across the capsule wall.

The diffusional losses will depend on the partial pressure difference of the diffusing component, which will remain essentially constant in these tests. Diffusional losses in films that exhibit very low solubility for the diffusing component should depend only on the partial pressure difference and not on the absolute values of the partial pressures. This means that the permeability should be essentially the same whether or not the film is in contact with a liquid or vapor and should be independent of the level of relative humidity difference.

Tests will also be made to determine composition of the electrolyte when solute-solvent systems are encapsulated. Deterioration of electrolytes due to transfer of gases into the capsule will also be investigated.

Table 2

WATER VAPOR TRANSMISSION AND DENSITY OF
SELECTED THERMOPLASTIC FILM MATERIALS

<u>Material</u>	<u>Permeability*</u>	<u>Specific Gravity</u>
FEP Teflon [®]	0.002	2.1
Aclar [®]	0.015***	2.1
Mylar-Aluminum Laminate**	0.02***	1.02
Polyethylene (h.d.)	0.03	0.95
Polypropylene	0.06	0.90
Saran [®]	0.10	1.2 - 1.7
Mylar [®]	0.2	1.4

* g-mm/24 hr-sq m-cm Hg (approximate values)

** 1 mil Mylar on each side of 1/2 mil Al foil

***100°F and 90% relative humidity

5. Test Results

Test data on capsules formed by thermal impulse sealing are summarized in Table 3 and Figure 7. While the 1-mil polyethylene capsule shows a large weight loss, the film density is low and, consequently, the payload is high. However, extrapolation of the data obtained indicates that after 100 days, the polyethylene capsule payload would be below that of the Al-Mylar capsule and below that of the Aclar film in 150 days. Use of a thicker polyethylene film would lower the initial payload but improve the slope of the payload versus time curve. Further tests and calculations are being carried out to determine the optimum density-permeability relationship for the capsule sizes desired. It should be noted that of the capsules tested, the Al-Mylar and the Aclar capsules are in the size range desired, while the polyethylene is probably considerably larger than will be required.

6. Future Work

In the next quarter, capsule tests will be extended to cover the conditions detailed in Section D with the suitable thermoplastics. These tests will also include encapsulations of a suitable electrolyte and composition analysis. Models are being constructed to test methods and efficiency of electrolyte release.

C. HIGH ENERGY CATHODE DEVELOPMENT

This section of the program was scheduled to begin at the end of the first quarter. Work will be primarily devoted to measuring the output of candidate cathode materials and to developing suitable cathode material-tape configurations.

1. Selection of High Energy Cathode Materials

The operating potentials and capacities of a number of promising cathode materials will be measured in tape configurations under both static and dynamic conditions. The most likely systems will be selected for further development.

The following compounds will be included:

<u>Cathode</u>	<u>Watt-hr/lb vs Mg at 1.4v</u>
o-Dinitrobenzene	567
Dinitrobenzoic acid	537
Trinitrobenzene	665
Picric acid	557
1-Carboxymethyl-1,3,5,5-tetranitropiperadine	715
3,6-Dinitrophthalic acid	497
2,4,6-Trichloro-triazine-trione	492
1,3,4,6-Tetrachloroglycoluril	519
Hexachloromelamine	677

Table 3

TEST DATA ON THERMAL-IMPULSE SEALED WATER MACROCAPSULES

Test Conditions: Ambient temperature (25°C), atm. pressure
40 to 50% relative humidity

Material	No.	Film Thickness mils	Film Weight g	Liquid Loading cc/in.	Surface Area/Unit Weight sq in./g	Initial Payload wt-%	Payload After Days	wt-%	Remarks
Al-Mylar 25A20	1	2.5	0.032	0.33	1.56	83.8	70	82.8	Single pack
Polyethylene	2	1	0.190	6.9	0.44	99.1	70	90.2	
Aclar	3	5	0.288	0.5	1.03	72.2	50	72.1	
Aclar	4	2	1.322	0.91	1.40	75.6	21	75.3	
FEP Teflon	5	2	0.419	0.088	5.7	43.3	-	-	Some air in capsules
Aclar	6	2	0.552	0.31	1.93	69.5	-	-	
KEL-F81 Tubing	7	3.5	0.335	0.17	6.5	78.2	11	78.0	Projected payload 3 years, 60 wt-%
Al-Mylar 25A20	8	2.5	0.223	0.21	4.8	81.9	-	-	

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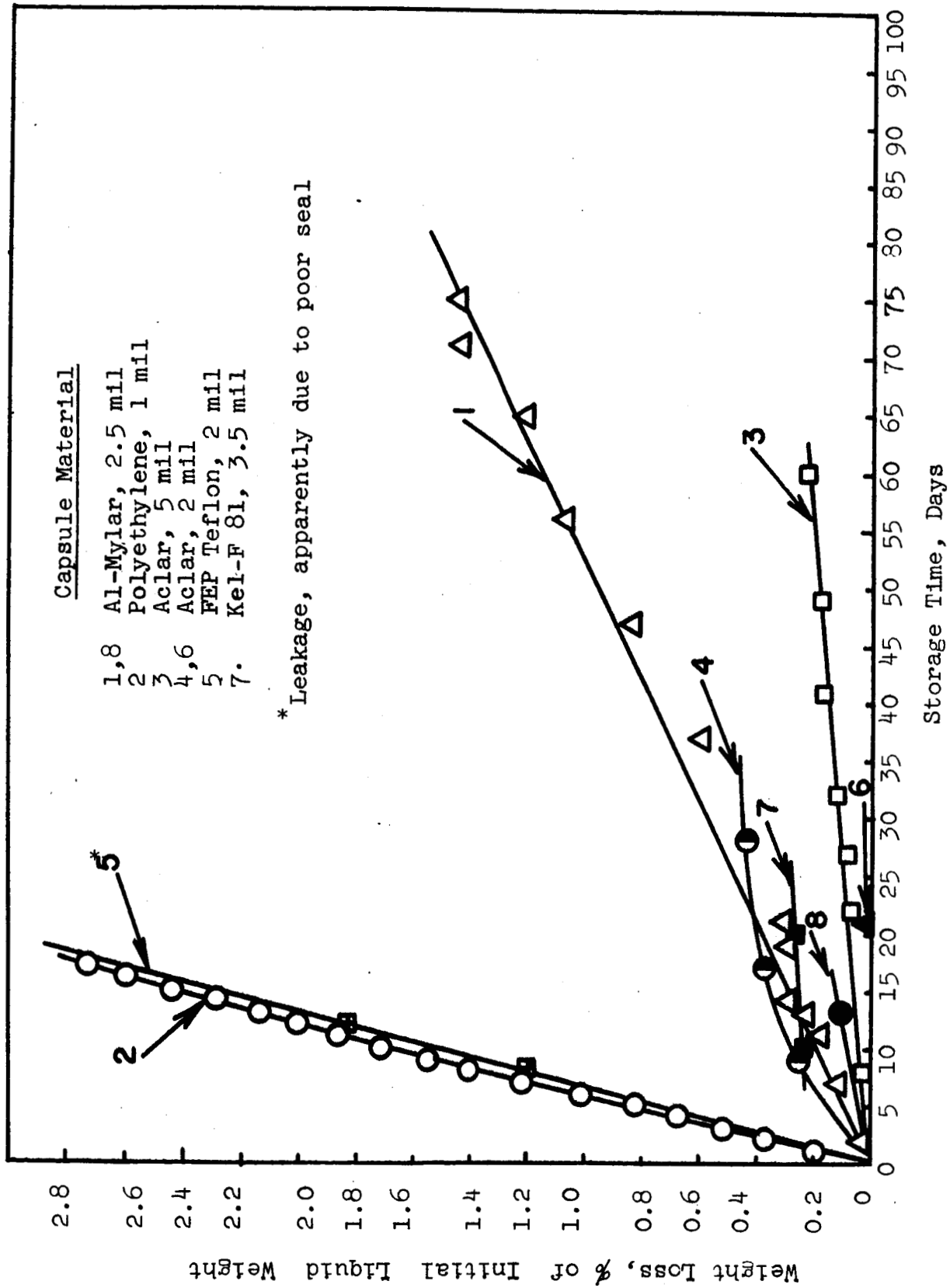


Figure 7. Weight loss of Incapsulated Water at Ambient Conditions (See Table 3)

In addition, further work to improve m-dinitrobenzene output will be continued.

2. Development of Practical Cathode-Tape Configurations

Methods for depositing cathode materials on tape will be investigated. Techniques under consideration include press molding, melt coating (when possible), solvent coating and slurry coating. The use of binders and water-soluble adhesives will be studied.

A dynamic tape tester is being developed to examine the effect of various dynamic mechanical parameters such as collector configuration, pressure and tape speed on the performance of new cathode-tape configurations.

III. PHASE 2 - DRY TAPE DESIGN

A. COMBINED CONFIGURATION AND TESTING

1. Introduction

The objective of this portion of the program is to combine the anode and cathode into a compatible configuration suitable for discharge in a tape system. Since this work will include variations in electrolyte, binder additives, and electrode design, as well as testing for outputs, stop-start capability, and storability, it is necessary that this phase be started as soon as possible. Development of the required electrodes, however, must await completion of several other phases that are being conducted concurrently. If a timely conclusion is to be reached, some assumptions must be made in this phase so that this combined testing phase can progress normally. Accordingly, the following electrodes are being prepared for use, to be replaced at a later date, if appropriate, by the results of the individual anode and cathode programs.

2. Anode

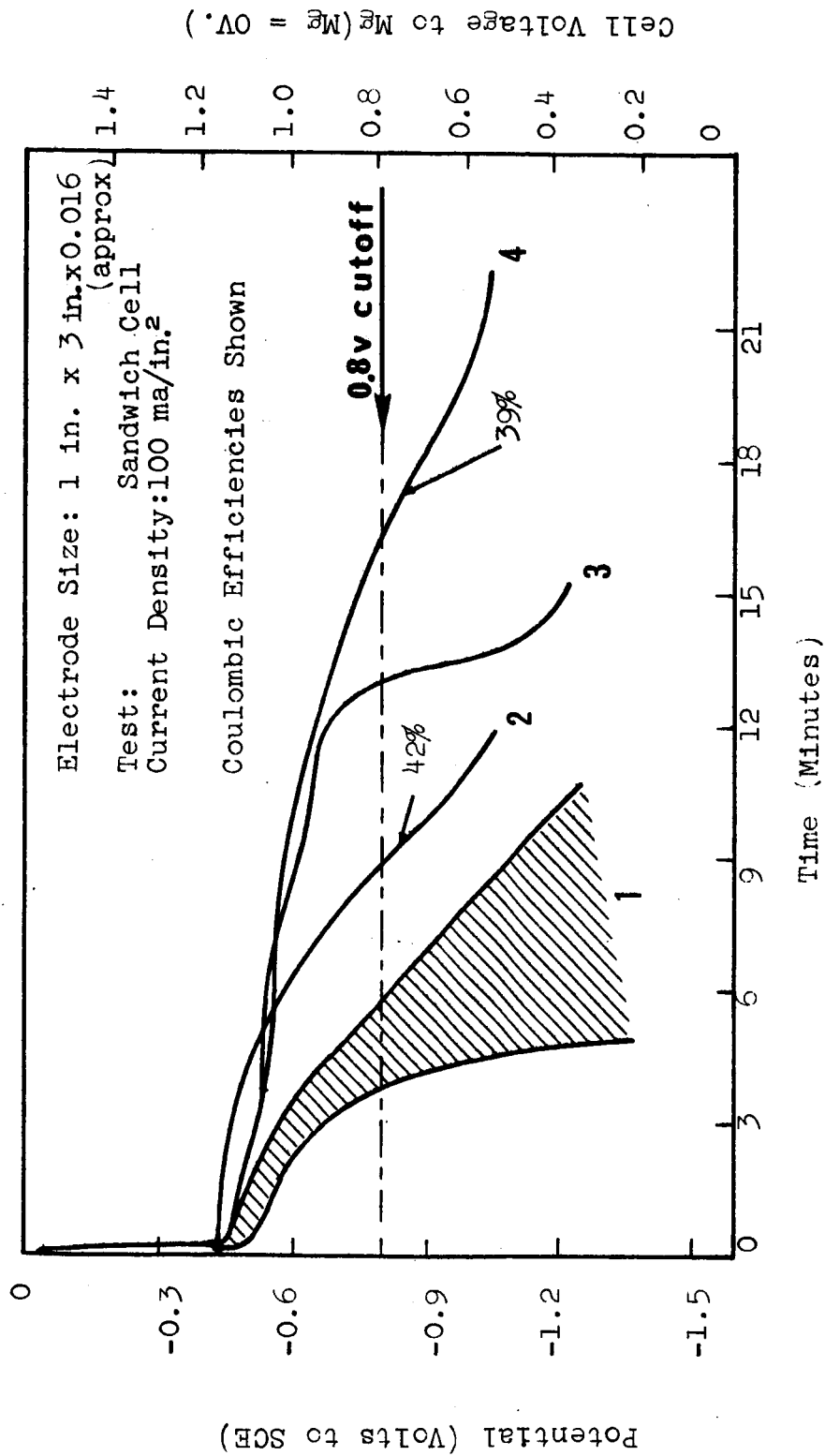
The results to date in the anode program (discussed elsewhere in this report) are being utilized for the combined testing. Sufficient expanded magnesium, although not of the desired base metal thickness, has been obtained to permit extensive use in this work. Combination anode-current collectors cut from magnesium block have been designed and manufactured for this phase; several gas manifold arrangements are included. All are awaiting minimum level performance certification of the cathode (discussed below) before joint testing can begin.

3. Cathode

Meta-dinitrobenzene (m-DNB) was selected as the cathode active material and pressed powder molding as the method of manufacture. All test samples are 1 in. x 3 in. and all discharges were run in the "sandwich" cell at 100 ma/in.² to establish a minimum performance level. Tests included the following variations:

- a. Conductor levels
- b. Conductor types (acetylene black vs graphite vs mixtures)
- c. Mixing methods
- d. Binder additives
- e. Molding pressure and void percentages
- f. Pore builders
- g. Electrolytes
- h. Vacuum impregnation of electrolytes

Dozens of tests encompassing the above factors were made; sample results are shown in Figure 8.



1. Many Test Results
2. Acetylene Black/m-DNB in 2 M MgCl₂
3. Acetylene Black/3 M Mg(ClO₄)₂/m-DNB in 2 M MgCl₂
4. Acetylene Black/m-DNB in 0.1 M HCl

Figure 8. Typical Discharge Curves for M-dinitrobenzene Cathodes

Acetylene black proved the most suitable conductor additive because of its incompressible nature, which resulted in an open pore electrode structure. Substitution of graphitic carbons resulted in much higher packing densities and poorer operation. At least 65%-70% voids were required to achieve reasonable efficiencies. The use of graphite with pore builders followed by solvent leaching did not provide results equivalent to those with acetylene black alone. Changing the mixing or blending methods had little effect. The best coulombic efficiency at 100 ma/in.² to a reasonable cutoff (-0.80 v(SCE)) was 42%: Acid electrolyte was preferred but equivalent performance could essentially be reached with MgCl₂. When acetylene black was used, adherence and flexibility were difficult to maintain.

From these results, it was decided that a thin, flexible, well adhered tape operating efficiently with m-DNB at high current densities would be difficult to obtain readily. Accordingly, optimization of m-DNB electrodes was left to the cathode development phase, and a new depolarizer was adopted for utilization in this joint configurational development.

Review of previous depolarizer work conducted in this laboratory resulted in the selection of 2,4,6-trichloro-triazine-trione acid as the cathode choice to replace m-DNB for this area of work. Although the theoretical energy density is less, operating voltage is much higher and the ability to support high current densities is better. Several tests of tape-style electrodes confirmed this and showed output per weight to exceed that of the m-DNB at the state-of-the-art where it was abandoned.

Tests to show the effects of conductor level, per cent voids, electrolyte types, etc., are being conducted to optimize this system to the point where it will permit the evaluations desired in this section. Sample results are shown in Figure 9.

B. TAPE MANUFACTURING METHODS

A general review of tape manufacturing methods and equipment will be carried out, aimed at developing the manufacturing techniques required for quantity production of coated tape. This work will involve the use of pilot equipment and controls to assess all of the manufacturing variables and will begin after selection of components proved out in the other phases of this work.

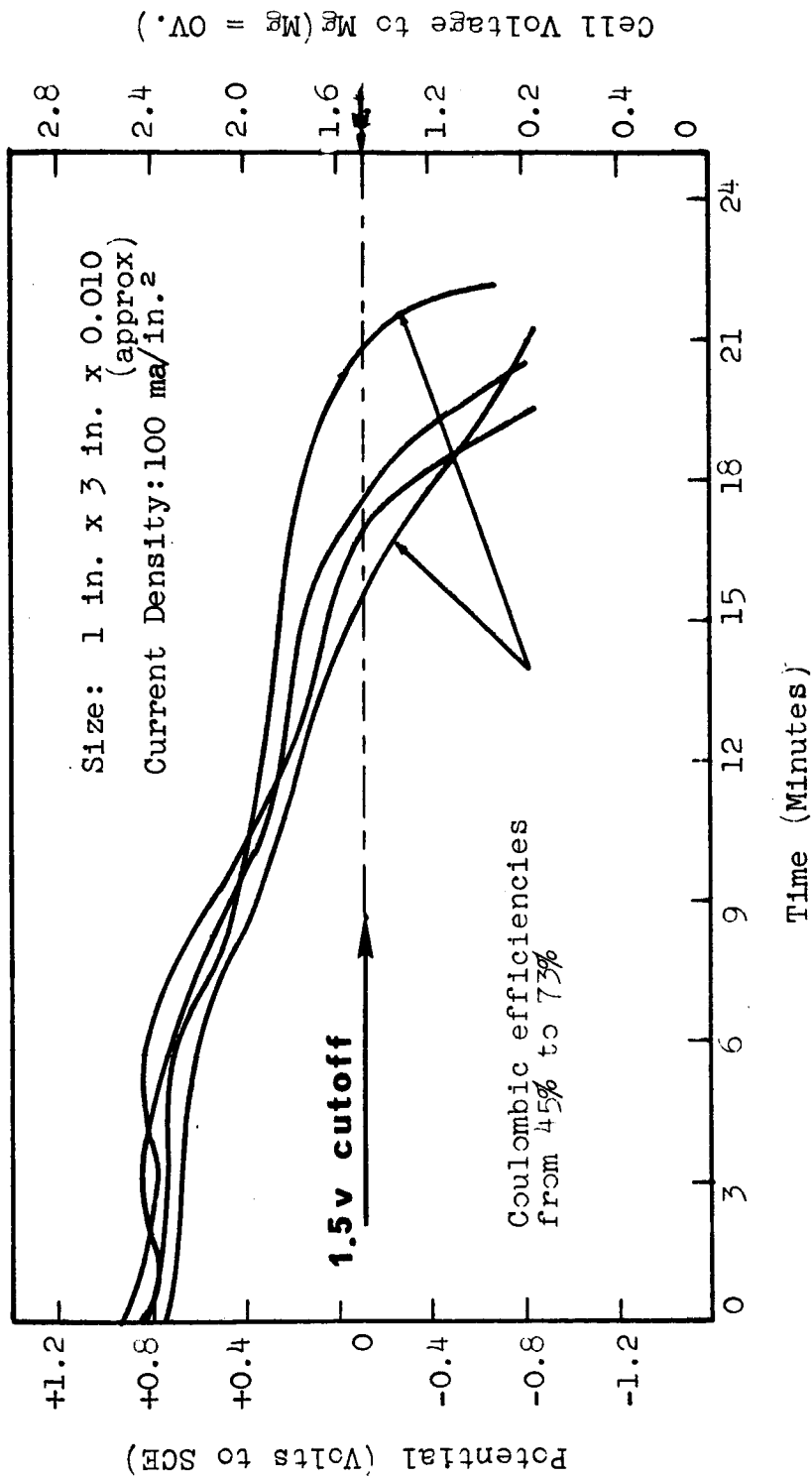


Figure 9. Typical Discharge Curves of 2, 4, 6-Trichloro-triazine-trione Cathode

IV. PHASE 3 - CONVERSION DEVICE DEVELOPMENT

A. DEVICE DEVELOPMENT

1. Objectives

The major objective of this phase is to demonstrate the feasibility of the Dry Tape battery producing high watt-hours per pound of weight.

To this end, the conversion device will be constructed having the following features:

- (a) The demonstration device will be built with enough tape to run 100 hours.
- (b) Three tape cells will be operated in series to demonstrate higher voltage capability.
- (c) The tape will be electrically driven by part of the electricity generated by the tape.
- (d) The device will demonstrate start-stop capability.
- (e) The drive mechanism will be capable of transporting the tape at various speeds up to one inch per minute maximum.

2. Tape Drive Analysis

In work toward obtaining maximum watt-hours per pound of weight and driving the tape at various speeds, various types of electric drives were studied. These included a permanent magnet dc gear motor with rheostat in the armature circuit; a shunt dc motor with rheostat in the field circuit; a constant-speed, permanent magnet dc gear motor with variable-speed transmission; and a stepping motor and electronic pulser with variable pulse provisions.

After evaluating various factors, the constant-speed, permanent magnet, dc gear motor with variable-speed transmission was selected. At the present time, this type of drive offers the following advantages:

- Operating voltage is minimal. Hence, the motor could operate with only two or three tape cells in series.
- Has a high output torque per milliwatt input and per pound of weight.
- Would not need any auxiliary devices such as a voltage booster or electronic pulser.
- State-of-the-art is very good with advances being made continually in reducing motor size and weight.

--Can be designed for automatic control of tape speed as power demand on the tape cells is varied, thus extending life of battery and maximizing utilization of battery capacity.

(a) Electric Motor

Many manufacturers were contacted to obtain information on small, efficient, lightweight permanent magnet motors. Since three tapes will be driven in series, the search centered on a 3 vdc motor capable of approximately 30 oz-in. of torque at a speed of 1 rpm. This search led to the purchase of the following five motors:

	<u>Cramer No. 1</u>	<u>Cramer No. 2</u>	<u>Escap No. 1</u>	<u>Escap No. 2</u>	<u>A. W. Haydon*</u>
Voltage, vdc	3	12	3	3	3
Output speed, rpm	1	1	3.0	15.0	2.0
Input, milliwatts	210	210	105	105	200
Output torque, oz-in.	30	30	7.0	1.4	15
Weight, oz	8 1/2	8 1/2	2	2	3 1/2

* on order

To date, both Cramer Motors and Escap No. 1 have been tested by applying known torque loadings, with a prony brake device (Figure 10), onto the motor shaft. The effects upon motor input current and speed were determined with the following results (Table 4):

Table 4

MOTOR CALIBRATION DATA

<u>Output Shaft Torque oz-in.</u>	<u>Voltage volts</u>	<u>Current Milliamperes</u>	<u>Speed rpm</u>
<u>CRAMER NO. 1</u>			
2	12	22.5	0.84
5	12	21.5	0.84
8	12	21.5	0.84
11	12	21.5	0.84
12	12	21.5	0.84
16	12	21.75	0.84
20	12	22.25	0.84
2	10	20.5	0.75
5	10	20.5	0.75
8	10	20.5	0.75
11	10	20.75	0.75
12	10	20.75	0.75
16	10	21	0.75
21	10	21.5	0.75

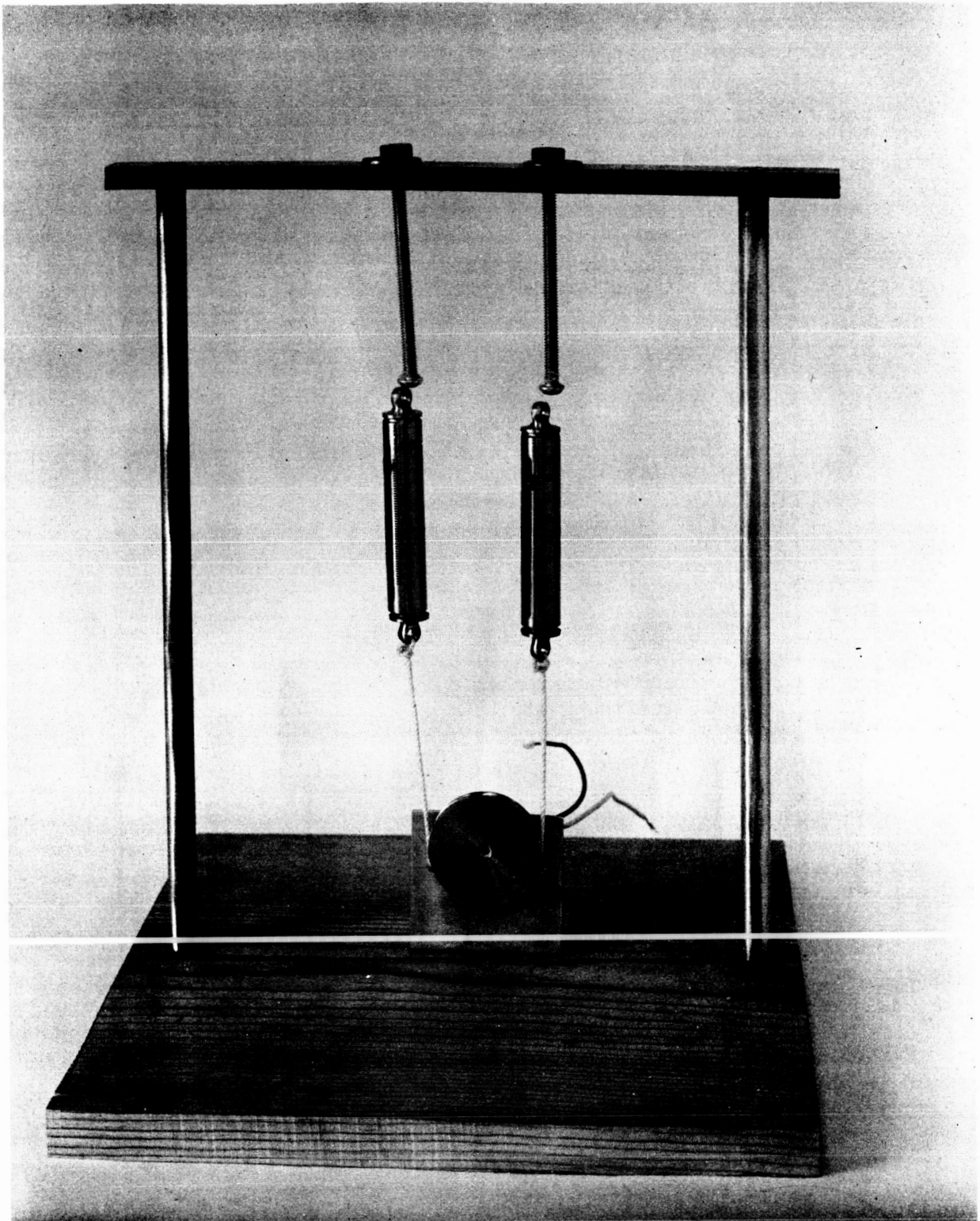


Figure 10. Prony Brake Device

Table 4 (continued)

MOTOR CALIBRATION DATA

<u>Output Shaft Torque oz-in.</u>	<u>Voltage volts</u>	<u>Current Milliamperes</u>	<u>Speed rpm</u>
2	8	19.5	0.68
5	8	19.5	0.68
8	8	19.5	0.68
11	8	19.5	0.68
12	8	19.75	0.68
16	8	19.75	0.68
2	6	18.75	0.43
5	6	18.75	0.43
8	6	18.75	0.43
12	6	19	0.43
16	6	19.2	0.43
16	4	18.75	0.25

CRAMER NO. 2

0	3	38	0.8
5	3	40	0.79
11	3	42	0.75
15	3	45	0.74
22	3	50	0.70

ESCAP NO. 1

0	3	13	15
3	3	45	12
4	3	50	11
5	3	54	10
6	3	59	9
7	3	74	7

The above data show that the motors tested use 150 to 200 milliwatts of power to provide about 30 ounce-inches of torque at 1 rpm. It should be noted that this input power is well under 10% of the expected output of three tapes in series. However, as 30 oz-in. at 1 rpm represents 22.2 milliwatts output, the 150 to 200 milliwatts input indicates a motor efficiency of only 11 to 15%. For this reason, the effort to find more efficient motors is continuing.

b. Variable Speed Transmission

As stated previously, the tentative decision was made to use a constant-speed motor and use a variable speed mechanical transmission device to vary tape speed. The types of variable speed transmission devices investigated thus far are shown schematically in Figures 11 and 12.

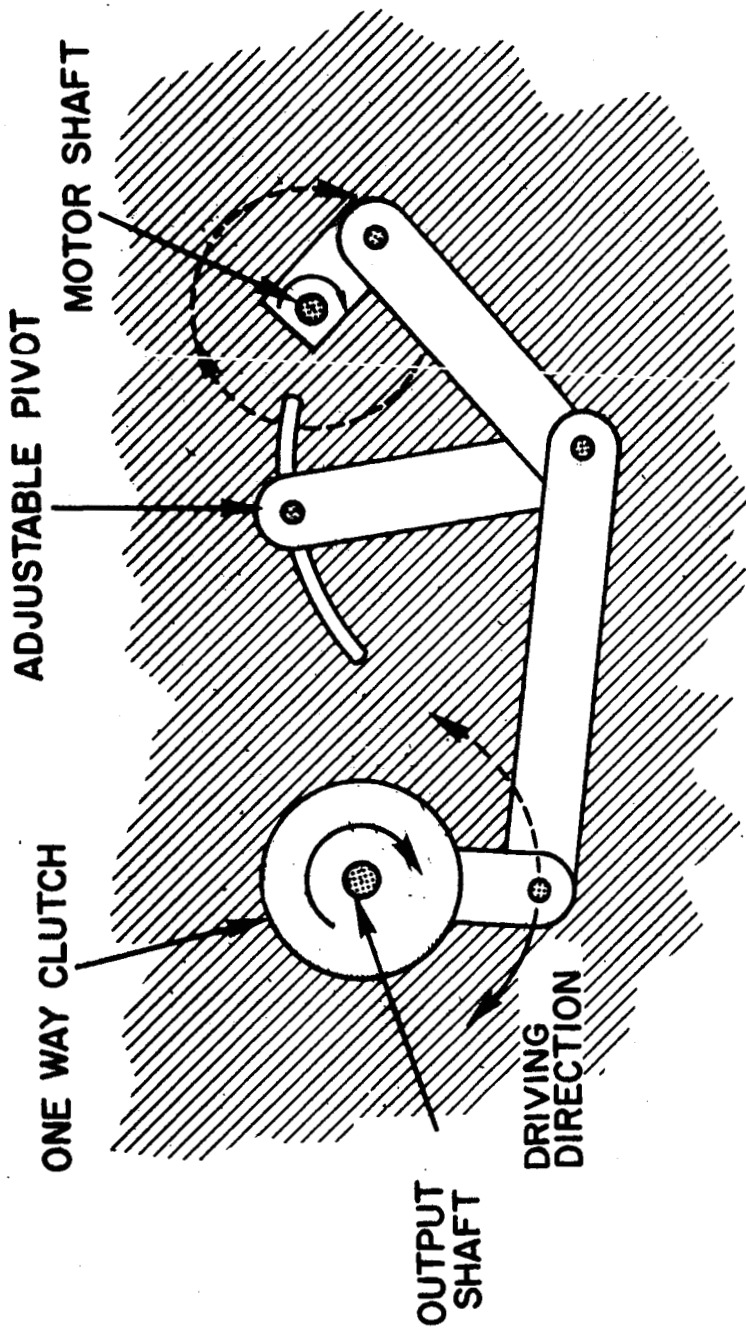


Figure 11. Oscillating Linkage Schematic

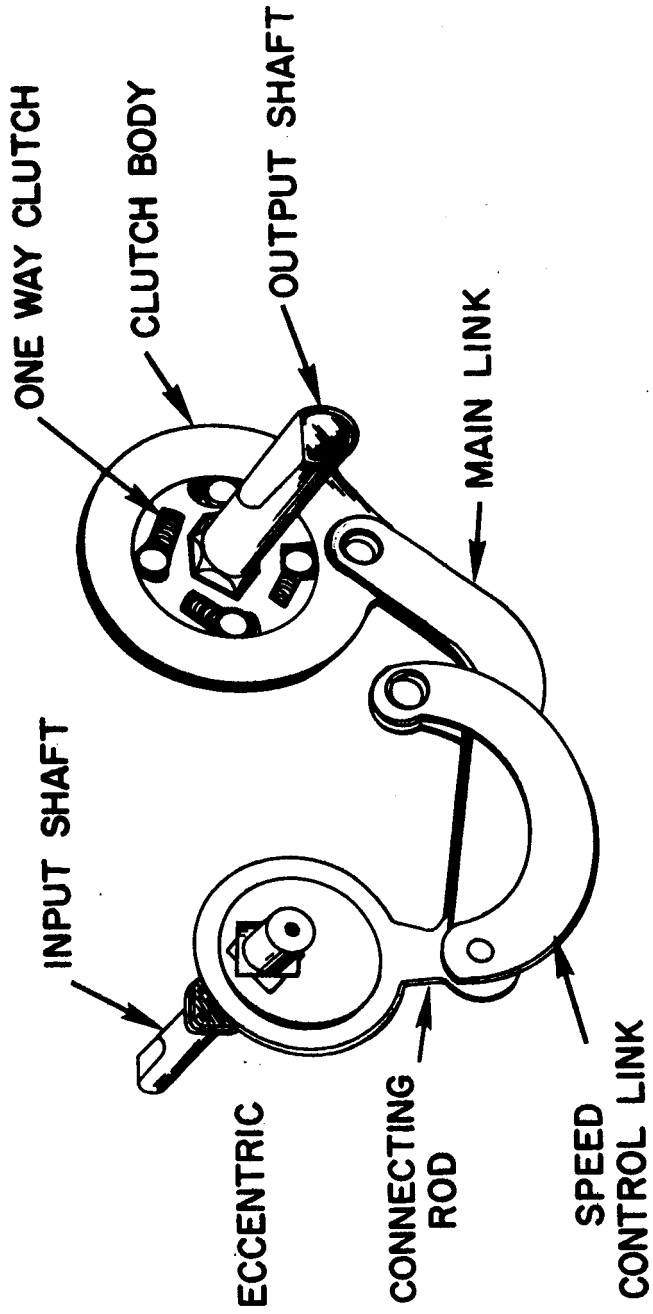


Figure 12. Zero-Max Drive

The linkage shown in Figure 11 is a four-bar linkage using a one-way clutch. Constant-speed rotation of the motor drive shaft will produce oscillating motion of the one-way clutch link. Thus, for each revolution of the motor shaft, the output shaft of the one-way clutch will turn part of a revolution. By varying the pivot point of the pivot link, the angle of rotation of the clutch output shaft can be increased or decreased to vary tape speed.

The arrangement shown in Figure 12 is similar but is based on the "Zero-Max; a Variable Speed Drive made by the Zero-Max Company of Minneapolis, Minn.

With the four-bar linkage mechanism, one drive has been constructed that uses a single one-way clutch, and one drive has been constructed that uses two one-way clutches. In the former case, there will be one drive shaft "impulse" per motor shaft revolution. In the latter, there will be two drive shaft impulses per motor shaft revolution. The latter has the advantage of a more continuous output shaft motion.

3. Current Collectors

Tests were conducted on a flat current collector and one with rollers to compare the forces required to pull tapes through.

Silver peroxide (Ag_2O_2)-coated tape was pulled through the current collector by being wound on a spool. This spool was driven by a variable speed motor through a calibrated torquemeter. The amount of torque required, hence the force, to pull the tape through the current collectors was measured with various amounts of normal force (tape squeeze) applied and with tape speed of 1 inch per minute.

a. Flat Current Collector

Figure 13 shows a schematic of the test set-up for the flat current collector. Figure 14 shows how much force is required to pull the tape through flat current collectors having a contact area one inch square. With dry tapes, the pull required was up to 5 ounces for 6.5 ounces of normal load. For the same normal load, a pull of 8 ounces was required when the tape was wetted with a 30% KOH solution. This increase in required pull from dry to wet is believed to be due to viscous drag of the wetted tape.

b. Roller Current Collectors

For testing roller current collectors, an assembly consisting of gold-plated brass rollers was used. The design was made so that various numbers of rollers up to 10, and rollers of various diameters, from $3/16$ in. diameter up to $7/16$ in. diameter, could be used. Figure 15 is a schematic of the roller current collector test set up.

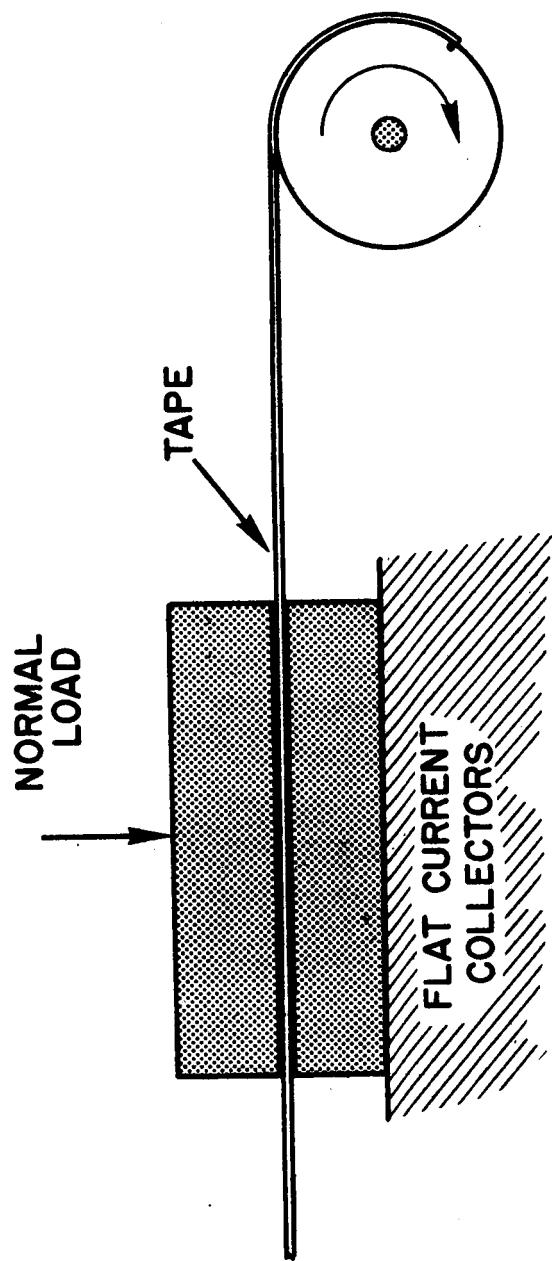


Figure 13. Flat Current Collector Schematic

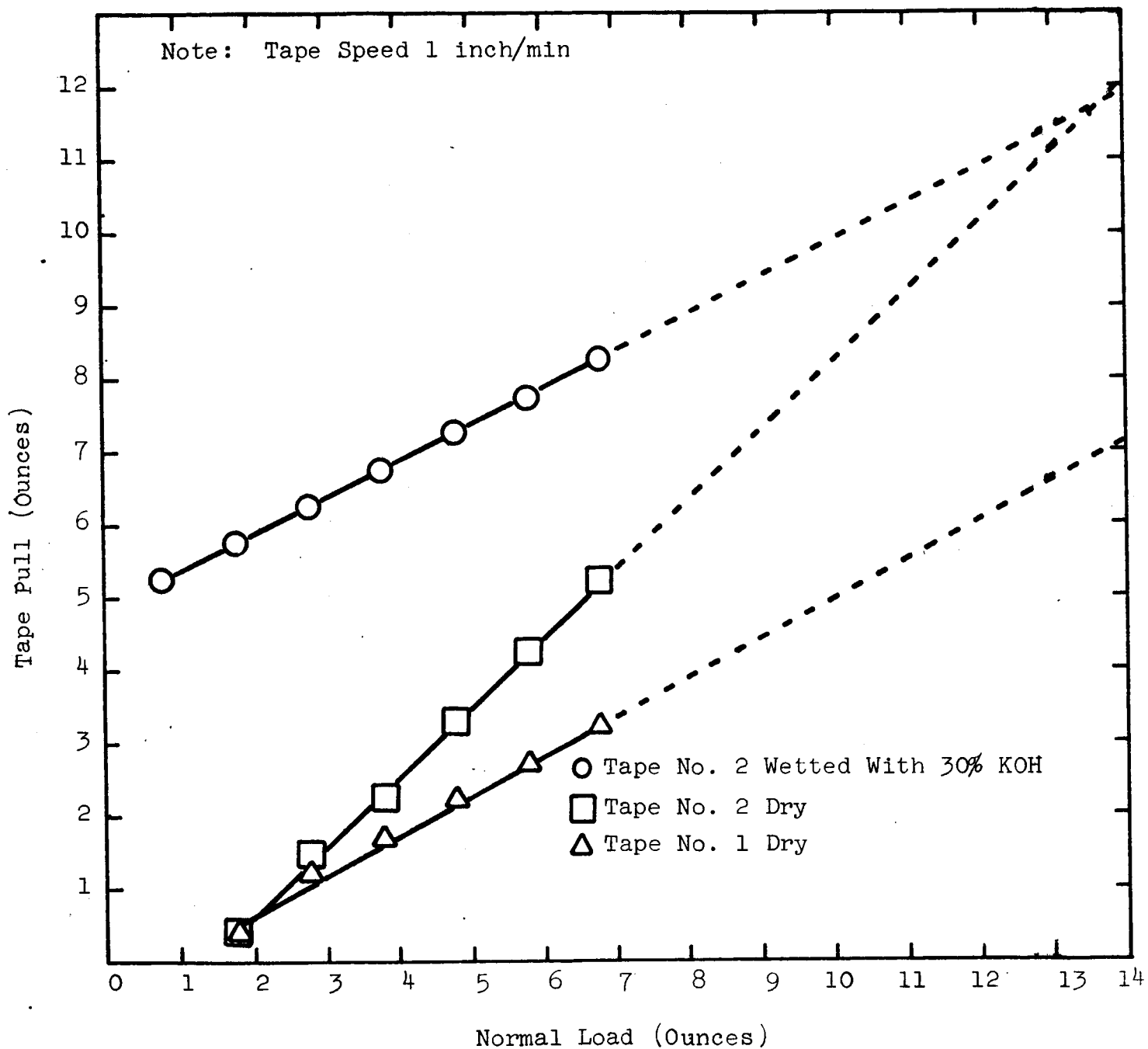


Figure 14. Tape Pull vs. Normal Load for Flat Current Collectors

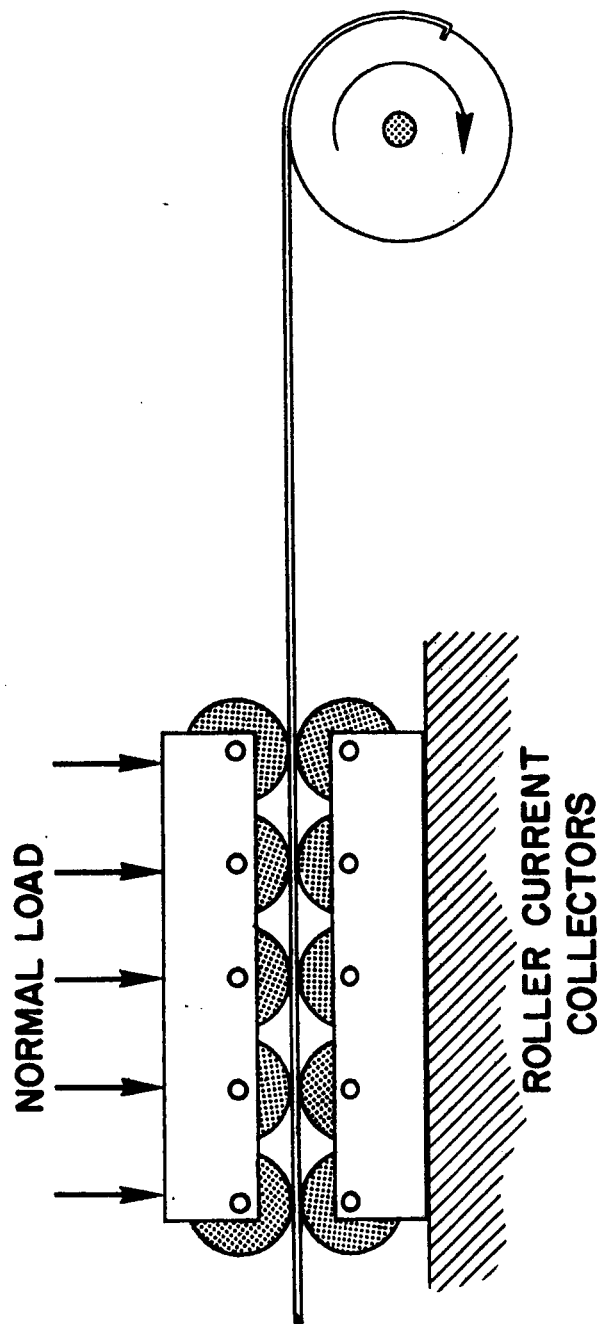


Figure 15. Roller Current Collector Schematic

Test results are shown in the three charts in Figure 16. With five sets of rollers (0.315 in. diameter upper, 0.440 in. diameter lower), the force required to pull the tape through is about four ounces with a normal load of 10 ounces. Roller diameter seems to have no effect on pull force and the number of rollers, five sets versus ten sets, seems to have no effect on pull force.

A comparison between the force required to pull dry tape through flat versus roller current collectors, then, shows the following:

- (1) At 6.5-ounce normal load, the tape pull is about 5 ounces for the flat collector versus only 2.5 ounces for the roller.
- (2) At 10-ounce normal load, the tape pull is about 8 ounces for the flat and 4 ounces for the roller.

In other words, the pull through rollers is about half the pull through flat current collectors for dry tape.

However, roller tests with wet Ag_2O_2 tape were not very successful. During these tests, current was drawn through the rollers using a zinc block as the anode and the upper rollers as the cathode current collector. When this electrical operation was attempted, the output became very erratic because of Ag_2O_2 material adhering to the rollers causing loss of contact. Even very high normal (squeeze) loadings up to 5 or 6 pounds were still not sufficient to overcome this loss of contact between the tape and the rollers because of adherence of the material. Consequently, testing with wet tapes with the rollers has been terminated until high energy tapes are available.

At this time, our conclusions concerning the rollers are:

- (1) The rollers reduce tape pull by approximately 50% compared with the flat current collectors (this neglects the fact that higher loadings may be required ultimately with the rollers to overcome the fouling problem.
- (b) The flat collectors require a tape pull of about 8 ounces. A reduction of this force by means of rollers is not expected to be significant when all factors, including fouling, are considered.
- (c) The roller collectors are considerably more complicated and involve more weight than the flat collectors.

On the basis of tests conducted so far, the design of the conversion device will proceed with flat current collectors. If tests with high energy tapes show that roller current collectors can be operated

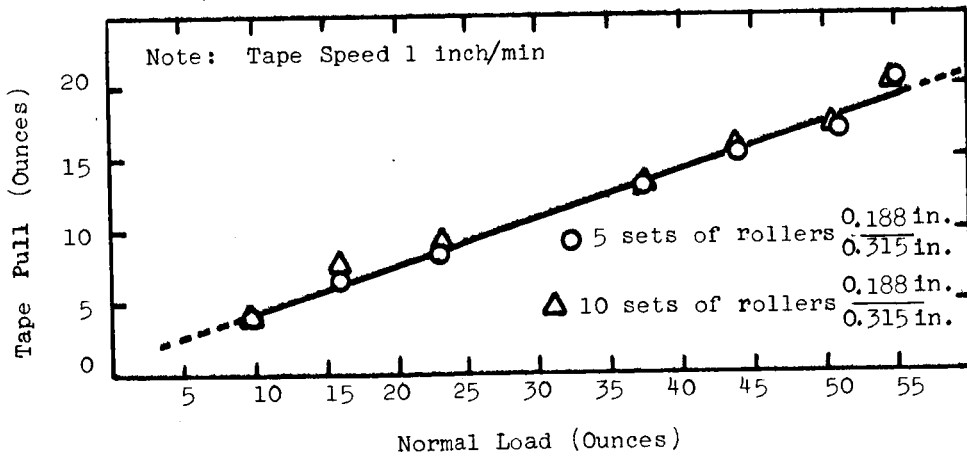
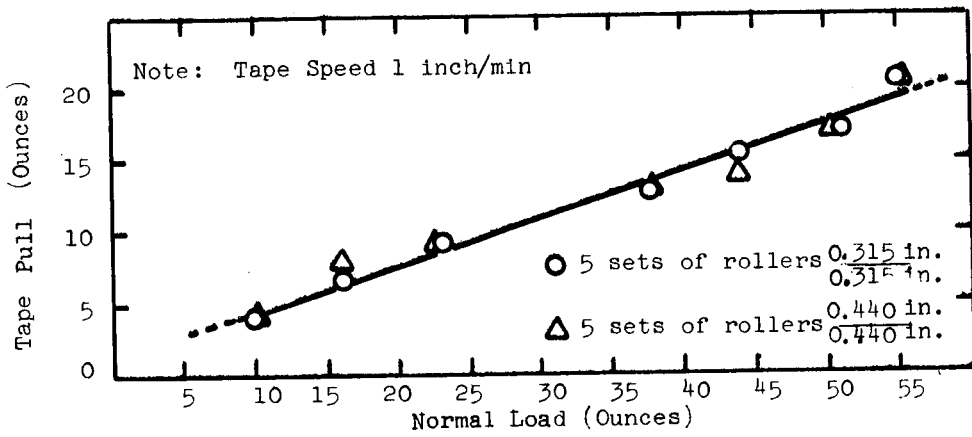
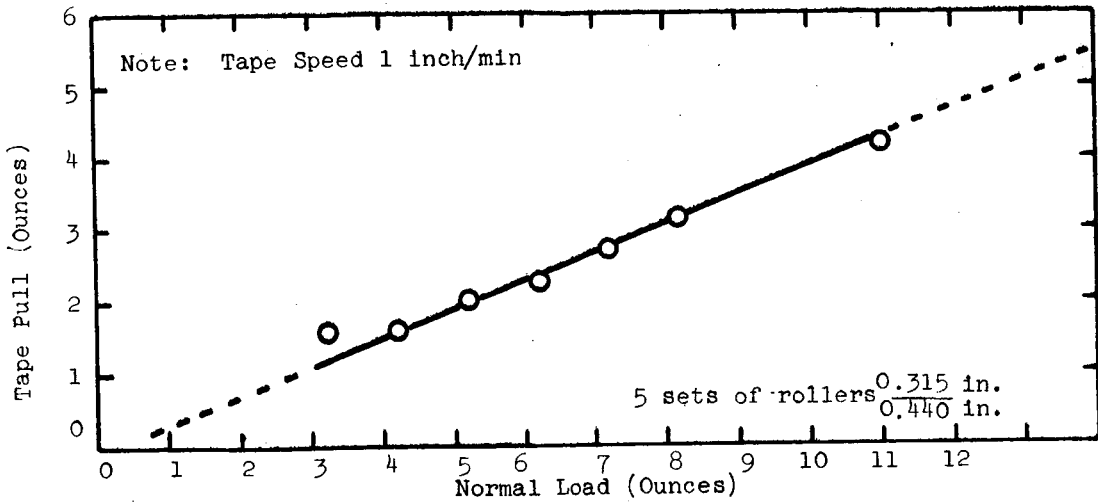


Figure 16. Tape Pull vs. Normal Load for Roller Current Collectors

satisfactorily, that is, without loss of efficiency due to adherence, the use of rollers will be re-evaluated in the light of weight and efficiency.

4. Triple Cell Breadboard Unit

Figures 17 and 18 are photographs of a triple tape breadboard device that has been built. As shown in these photographs, the motor-operated, double-clutch drive unit (Figure 19) turns a take-up spool, which pulls the tape through the current collectors.

a. Drive Operational Check

This test consisted of operation with three dry, dummy tapes. Tape speed and motor current were measured at minimum, intermediate, and maximum speed adjustment, and with 8.6 oz and 3.6 oz of weight on each current collector. The data taken are given in Table 5.

Table 5

EVALUATION OF TRIPLE-TAPE BREADBOARD
UNIT WITH DRY, DUMMY TAPE

<u>Speed Setting</u>	<u>Tape Speed in./min</u>	<u>Motor Voltage volts</u>	<u>Motor Current ma</u>	<u>Current Collector Weight oz</u>
Max.	1.05	2.7	41.5	8.6
Intermed.	0.52	2.7	39	8.6
Min.	0.28	2.7	39	8.6
Max.	1.1	2.7	39	3.8
Intermed.	-	-	-	-
Min.	0.25	2.7	38	3.8

These data indicate that:

- (1) the variable speed device has a speed range of 4 to 1
- (2) with unwetted tape, the current drain was the same for both values of normal force on the current collectors
- (3) the input power to the motor was 0.108 watts.

b. Single Tape Check

Before operating the unit with three active tapes, a single Ag_2O_2 tape test was conducted using a 35% KOH-wetted separator tape. Satisfactory operation was obtained.

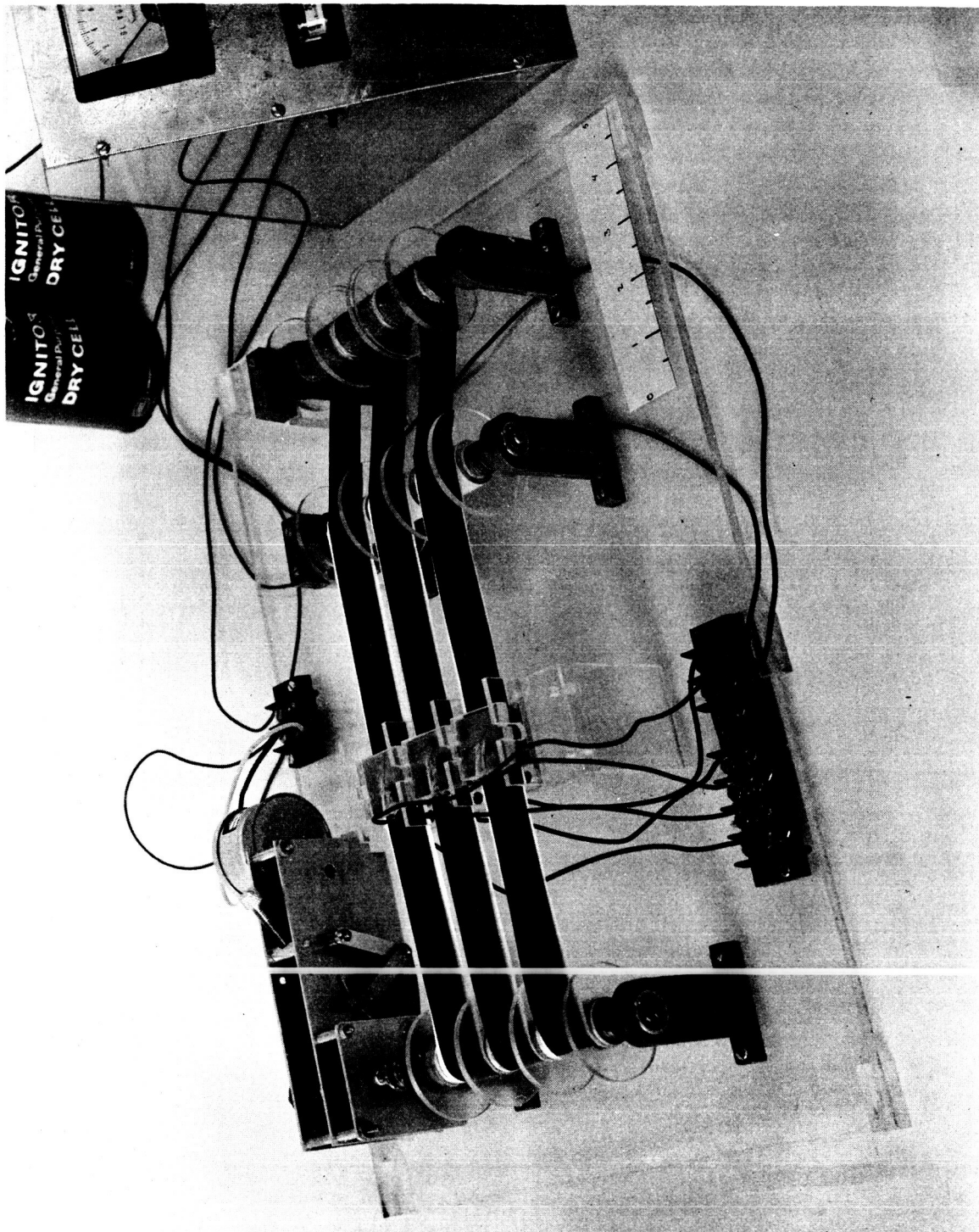


Figure 17. Triple Tape Breadboard Drive

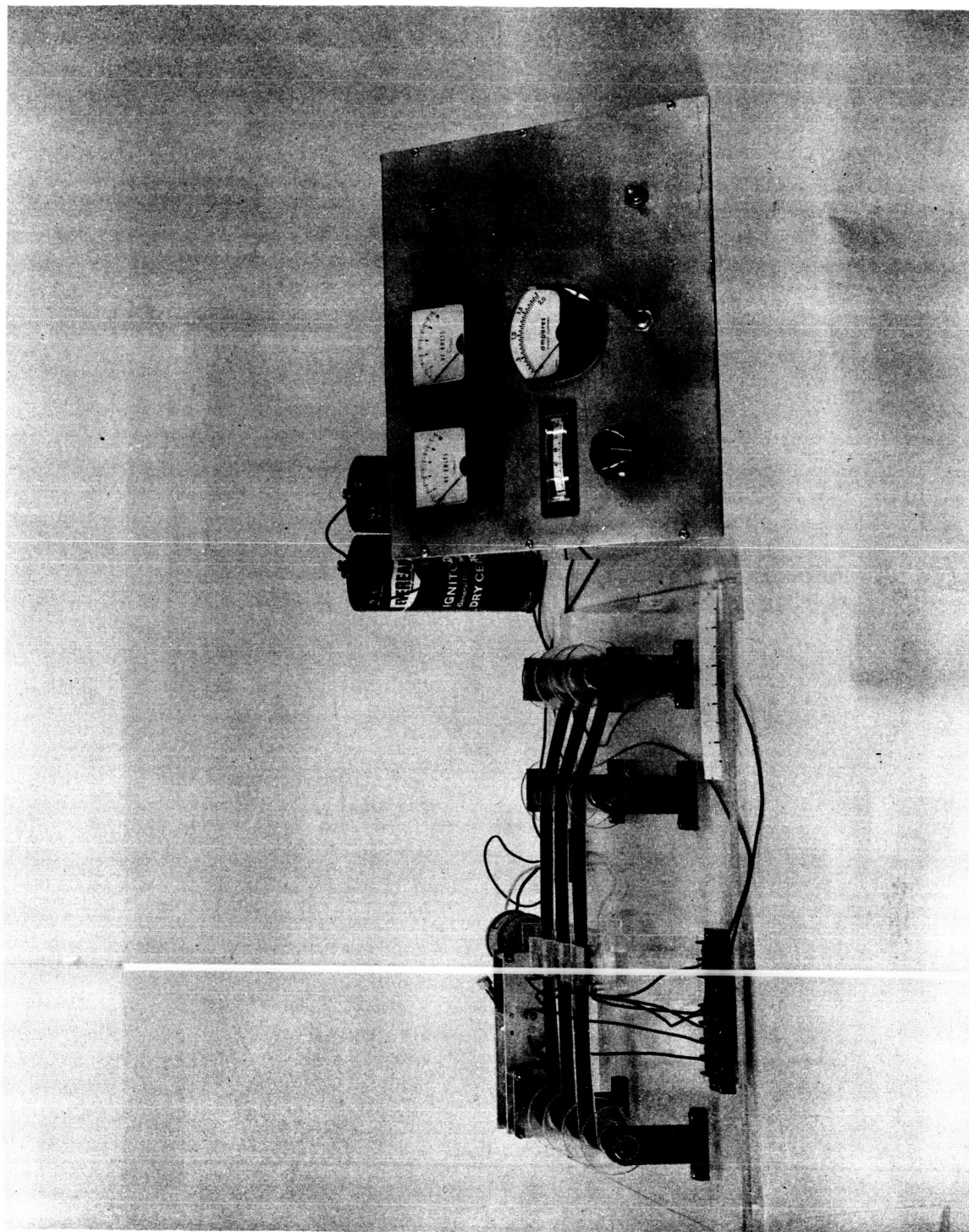


Figure 18. Triple Tape Breadboard Drive and Control

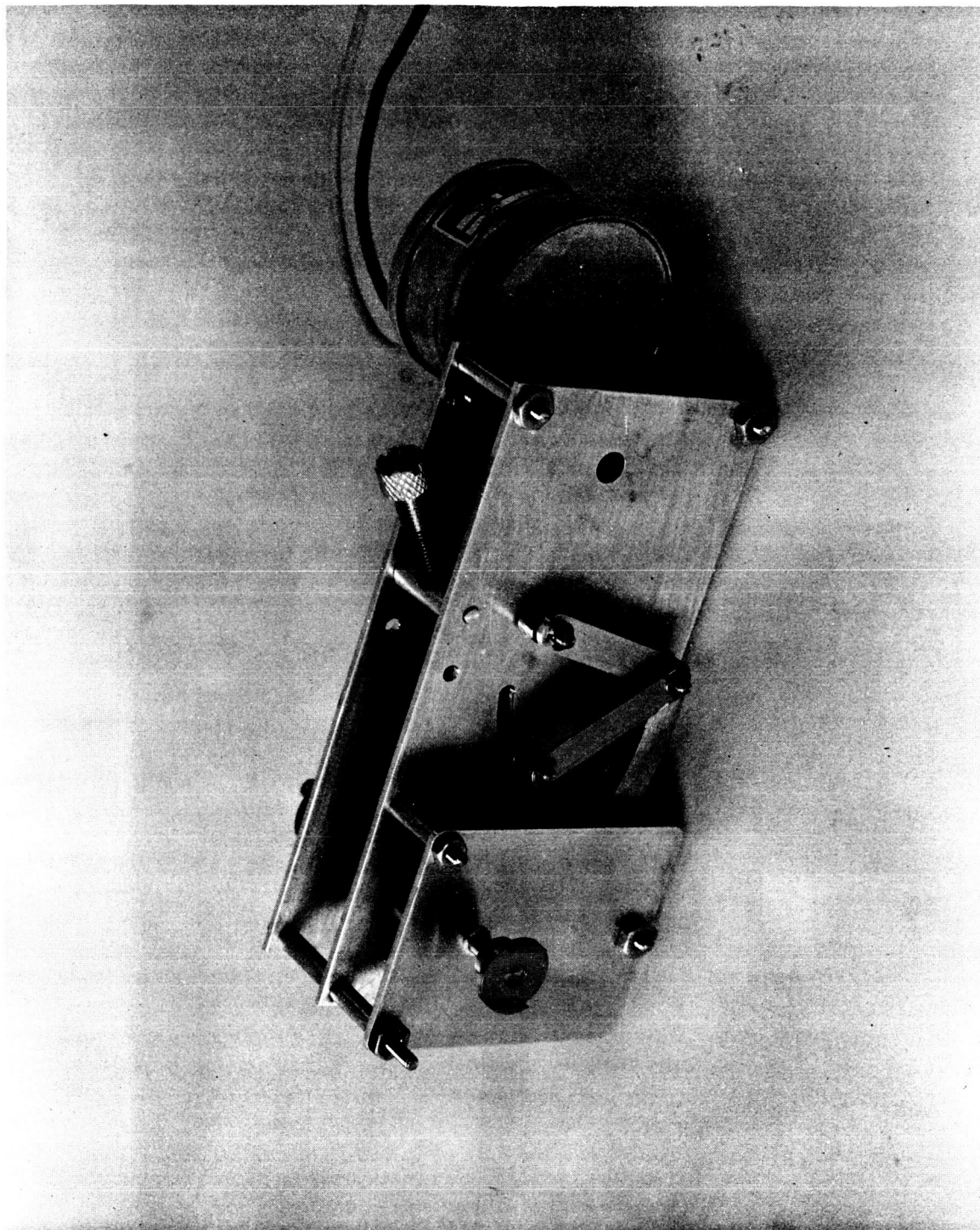


Figure 19. Adjustable Speed Drive Unit

c. Triple-Tape Operation

A test was conducted with three Ag_2O_2 tapes. Again, 35% KOH-wetted separator tapes were used. With the three tape cells connected in series, the results were as shown in Table 6.

Table 6

EVALUATION OF TRIPLE-TAPE UNIT WITH ACTIVATED TAPES

<u>Motor</u>			<u>Tape Load</u>		<u>Current Collector Weight, oz.</u>
<u>Speed</u>	<u>Volts</u>	<u>ma</u>	<u>Volts</u>	<u>Amps</u>	
Max	4	45	4.3	0	8.6
	3.7	40-55	4.1	0	8.6
Intermed.	2.8	37-45	3.0	0.35	8.6
	4.1	50	4.4	0	8.6
Min.	4.1	35-40	4.4	0	8.6
	3.0	35-40	3.3	3.3	8.6

These tests show that:

- (1) Parasitic operation was successfully achieved.
- (2) The voltage across the three tapes was 4.4 volts at "zero" load. Actually, although the load was zero, 40 to 50 milliamps were supplied to the motor, so the 4.4 volts is not really the open circuit voltage, which inadvertently was not recorded.
- (3) Towards the end of the tape run, the take-up spool failed. Because of inadequate construction, the take-up spool shaft began to slip and the tape was no longer being pulled through the current collectors. For this reason, the test was concluded until a better spool could be made.

5. Objectives for Tape Drive

- a. Investigate smaller motors developing approximately 10 oz-in. running torque instead of 30 oz-in.
- b. Design, build and test (2) "start-stop" devices
 - (1) Spring motor
 - (2) Primary or secondary battery start with appropriate circuitry.

- c. Investigate lightweight variable speed mechanisms
 - (1) As presently conceived but substituting materials of lower specific weight, etc.
 - (2) Use a rheostat in series with armature of a dc shunt motor for speed control.
- d. Investigate methods and devices for applying electrolyte to tape.
- e. Build a breadboard incorporating these more favorable results from the foregoing investigations.
- f. Start component life tests.

B. DEVICE OPTIMIZATION

Sufficient breadboard tests have been conducted with the first breadboard devices to give specific ideas for future optimization of the conversion device. Some of these are:

- Materials
- Material thicknesses
- Required motor output torque
- Desired motor efficiency
- Start-stop device - electrical
- Start-stop device - mechanical

The next breadboard device will be assembled incorporating these refinements. Further tests will be performed with the new breadboard, and concurrently, satellite life tests will be performed on components.

V. PHASE 4 - MULTIPLE CELL BATTERY

A breadboard multiple-tape device was operated to evaluate the electric motor and mechanical components of the conversion device and to determine the presence of new problems attendant with multi-tape operation. It did not represent the optimum design or method.

In the process of this testing, successful parasitic operation from three Ag_2O_2 tapes in electrical series was achieved.

COST DATA

<u>Personnel</u>	<u>Hours</u>
Byrne, J.	102
Gruber, B.	210
Gee, F.	6
Him, J.	16
Hurley, R.	549
Kafesjian, R.	513
Klunder, K.	498
Linxweiler, T.	10
Power, W.	8
Smith, J. O.	48
Sumrall, J.	56
Tomaski, J.	482
Wolanski, T.	157
Zirin, L.	<u>416</u>
Total	3071

Total Cost 1/24/64 - 4/30/64 -- \$46,659