DEVELOPMENT OF A
TIME EVENT MARKER FOR A
MINIATURIZED RECORDING SYSTEM

April 15, 1958

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1.0 INTRODUCTION

This report covers the status of work on Project No. 74A to April 15, 1958.

1.1 Ninety percent of the applied effort has been directed to Project No. 74A, TEM, with Project No. 74B, SAD,, receiving secondary consideration.

2.0 DIFFICULTIES ENCOUNTERED WITH THE ORIGINAL MODEL

This model, completed at the time of submission of the February 15th report, was inadequate as follows: Operating voltage for the unit was nine volts, due to factors outlined in Paragraph 4.5 of the February 15th report. Also, failure of the calendar and sweep to operate reliably at low temperatures (-30 degrees F) was observed after submission of the last report.

2.1 Conclusion

To reduce operating voltage, new solenoids were required. To improve low temperature performance, the use of jeweled ratchet shaft bearings and lubrication with [redacted] oil was specified. STAT

2.2 Course of Action

The installation of new solenoids entailed making a new center plate, since these solenoids are longer than those on the original unit, (See Paragraph 4.5.3 of the last report), and as a consequence, extended over the edge of the old center plate. In view of the major changes required, it was decided (with prior verbal approval from the Technical Monitor) to fabricate a revised model including the changes above as well as several additional refinements.

3.0 PARAMETER CHANGES IN REVISED MODEL

3.1 Solenoids

The new solenoids were built and installed on the new center plate. The solenoid overhang was corrected by extending the new plate width .025 inches, and by moving the solenoid .040 inches closer to the ratchet wheel. This latter was accomplished by shortening the solenoid drive spring by .040 inches. The drive spring thickness was also increased 25%, giving an overall stiffness increase of 300%. It is felt that this will yield more positive and uniform drive action over a wider range of supply voltage, there being more impact energy consumed in the drive spring without undue flexure. The solenoids themselves incorporate these changes: (a) material changed from 4750 steel to relay steel #5, giving higher saturation flux density; (b) thickness of housing doubled at top, to decrease top gap reluctance; (c) coils wound with #41 AWG HS1 wire (instead of #42) to reduce the ampere turns per volt requirements and thus permit six volts operation of the unit.

3.2 Capacitors

The new solenoids have lower inductance since there are fewer turns. Whereas the #42 wire gave inductances of 750 mh average, the #41 wire yields inductances which are less by the ratio of turns, or 680 mh average. The critical capacitance required is $\frac{4L}{R^2}$, which previously was 70 mf. A value of 120 mf was used (See Paragraph 4.3, last report). For the new solenoids, $C_{critical} = 106$ mf, ($R = 160\ \Omega$). Since at -30 degrees F, coil resistance is 25% lower than at room temperature, C_c increases by 60% at -30 degrees F. So $106 + .6\,(106) = 170$ mf, the value of capacitance required to maintain operation at or above critical at all operating temperatures. As a result, the value of capacitance used was raised to 180 mf for 2CR and 3CR.* The value used with 1CR was unaltered, however, because this solenoid, having a lighter contact

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*See electro-mechanical schematic, enclosure D and wiring diagram, enclosure E.

finger load, operates satisfactorily at -30 degrees F (although oscillation in the current pulse is evident), and any increase in the value of capacitance here would increase the chance of double operation of 1CR around a sweep operation at the higher operating temperatures.

3.3 Bearings and Lubricants

Jeweled bearings were installed at the lower ratchet wheel pivots and all bearing surfaces (including watch bearings) were lubricated with [redacted] oil, in an attempt to improve low temperature operation. STAT This oil has relatively low viscosity at low temperature.

3.4 Difficulties Encountered in Fabrication

The new solenoids were copper and nickel-flashed all over, then the plunger working face was plated with 1 mil of copper to prevent the plunger from sticking closed due to residual pull. Finally, nickel flash was applied to the working face. The plating, however, began peeling, and considerable investigation was necessary before a correct procedure was obtained, namely, thorough pickling of the #5 relay steel was required before plating. The parts were then re-plated satisfactorily.

3.5 Summary of Performance, revised model

a. The engineering model delivered to the monitor on Friday, April 4, 1958 satisfactorily demonstrates the feasibility of this system. There are areas of doubtful reliability, mainly at low temperatures, due to increased mechanical loading on the solenoids. This problem was not wholly eliminated by the change outlined in Paragraph 3.3 of this report, but the cause of the difficulty (relative expansion between plunger and closely fitted sleeve with resultant binding) has been determined and corrective action (to increase the sleeve and plunger fit tolerance) will be taken.

b. Interpretation of Solenoid Current Pulse

Enclosure (A) shows photo-oscillograms of the input current to 1CR alone, to 1CR and 2CR, and finally to 1CR, 2CR, and 3CR. Each pulse has two dips during the first 15 milliseconds of conduction, points marked a and b. Point a represents plunger slowdown at incipient disc motion; point b represents plunger air gap closure. Solenoids 2CR and 3CR start to pass current (point c) before the energizing solenoid (1CR and 2CR, respectively) completes its stroke. This is because the control circuit disc contacts move onto the make position and then continue to move until centered on this position at plunger closure. The "steps" in the pulses beyond 60 milliseconds represent the plunger dropout points (point d). (It should be noted that both the time and current scales for 1CR pulse alone are magnified.)

3.5.1 The basic current pulse (the pulse unmodified by points a, b, c, and d discussed above) shown in enclosure A, is closely represented by the equation $i = \frac{E}{L} t \epsilon^{-at}$ when critically damped, i.e., when $C = \frac{4L}{R^2}$. Here "E" equals applied voltage, "L" is the solenoid inductance in henries, "t" the time in seconds from switch closure (t=o), "ϵ" the base of napierian logarithms, and "a" is $\frac{R}{2L}$ (where "R" is the solenoid resistance in ohms).

The total energy input to one pulse, then, equals

$$\int_0^\infty E i\,dt = E\int_0^\infty \frac{E}{L} t \epsilon^{-at}\,dt$$

$$C = \frac{4L}{R^2} \qquad = \frac{E^2}{L}\int_0^\infty t\epsilon^{-at}\,dt = \frac{E^2}{L}\left[\frac{\Gamma(2)}{a^2}\right]$$

$$a = \frac{R}{2L} \qquad = \frac{E^2}{L}\frac{1!}{\left(\frac{R}{2L}\right)^2} = \boxed{2\left(\frac{2L}{R}\right)\left(\frac{E^2}{R}\right) \equiv E^2 C_c}$$

3.5.2 When the circuit is overdamped (above critical), the current equation becomes

$$i = \frac{E}{2Lb}\left[\epsilon^{(-a+b)t} - \epsilon^{(-a-b)t}\right]$$

$$C > \frac{4L}{R^2} \qquad a = \frac{R}{2L} \qquad b = \sqrt{a^2 - \frac{1}{LC}}$$

3.5.3 When the circuit is underdamped (below critical, or oscillatory), the current equation becomes

$$i = \frac{E}{L\beta}\epsilon^{-at}\sin\beta t$$

$$C < \frac{4L}{R^2} \qquad a = \frac{R}{2L} \qquad \beta = \sqrt{\frac{1}{LC} - a^2}$$

Energy relations have not, as of the time of writing this report, been calculated for the latter two cases, thus the assumptions appearing in Paragraph 4.1 and discussed in Paragraph 4.2 below.

4.0 POWER AND ENERGY CONSUMPTION, REVISED MODEL

A study to determine power and energy requirements of the unit has been completed. Although peak instantaneous power is not of prime importance, peak instantaneous current is. This peak current (70 ma) occurs when 1CR, 2CR, and 3CR operate simultaneously (i.e., when all three discs index), and is nearly equaled by the current drain when

TEM sweep is operated (60 ma), although in the latter case the current drain is present for 1.2 seconds total duration, while in the former, the peak drain occurs for only several milliseconds. At any rate, the voltage source should be able to handle 70 ma continuous drain with no more than 5% fall off in terminal voltage.

4.1 Method of Calculation of Energy Consumed

Solenoids 1CR, 2CR, and 3CR consume energy (during each pulse operation) which is given by the equation ENERGY $= \left(\frac{2L}{R}\right)\cdot\left(\frac{E^2}{R}\right)$ where the energy appears in coil heating, magnetization of the iron, and mechanical work; capacitors C_1, C_2 and C_3 store an equal amount of energy during each pulse (which is later dissipated in the shunt resistors R_1, R_2 and R_3), so the total energy input during each pulse is $2\cdot\left(\frac{2L}{R}\right)\cdot\left(\frac{E^2}{R}\right)$ watt seconds. This is the transient energy. Following the pulse, each solenoid circuit remains closed for a certain length of time, depending on the solenoid in question. During this latter period, energy is consumed by the shunt resistor R_1, R_2 and R_3 in parallel with the internal capacitor shunt resistance, R_s, and is the "steady state" energy. The sum of transient energy and steady state energy gives the total energy consumed for a solenoid per operation. If this is multiplied by the known number of operations per sixty days, the total energy input is obtained. This energy, divided by the applied voltage E, yields the 60 day ampere-hour requirements for the solenoid.

For the sweep, the energy required by relay ST_2 per sweep operation is $\frac{E^2}{R}$ times the duration of the sweep (2.4 seconds). This times an assumed 1440 sweep operations per 60 days gives total energy to ST_2, which when divided by E, gives total ampere-hour requirements for ST_2. Similarly, the 10/sec. multivibrator requirement per sweep operation = $\frac{E^2}{R_{scr}}$ multiplied by the time of operation, plus I_1 E multiplied by the "rest" time, where the first term represents energy taken by the sweep during the "working" half cycle times the number of these cycles, so time of operation equals 1.2 seconds, or half the sweep duration. The last term represents energy taken by the multivibrator during the "rest" half cycle, multiplied by the number of these cycles, so "rest" time equals 1.2 seconds also, since the MV "on" and "off" times are equal. Now I_1 represents the current drawn by the MV during "rest" time, and equals 2 milliamps. This energy multiplied by 1440, gives total energy input to the 10/sec. MV and to SCR during a 60 day period, which when divided by E (applied voltage) gives ampere-hour requirement for the sweep.

4.2 Total Milli-ampere-Hour Requirements, revised model

Using the method outlined in Paragraph 4.1 above, the following calculations and values are obtained (see enclosure B). It should be pointed out that the values of transient energy for 2CR and 3CR are on the low side, since these solenoids (having more series capacitance) are operating above critical, and therefore, the equation $2 \cdot \left(\frac{2L}{R}\right) \cdot \left(\frac{E^2}{R}\right)$ for energy is low. This is at least partially compensated, however, by the fact that the steady state energy is large, being summed over the entire control circuit closure cycle. The large ampere-hour requirement of ST_2 can be reduced by the addition of an RC circuit to reduce hold-in current.

In conclusion, the values given in enclosure B are approximate in view of the foregoing in addition to possible parameter variations in the actual installation. A value of 160 MA-Hr. as a total possible maximum figure should be adopted.

5.0 AREAS REQUIRING FURTHER INVESTIGATION

The following improvements are being considered to (1) increase reliability in present model over a wide temperature range, (2) decrease the difficulty of assembly and adjustment of the unit, while increasing the precision of adjustment.

5.1 10/sec. Multivibrator

This packaged unit, at present, has no provision for adjustment of frequency. Furthermore, frequency varies 3% over the applied voltage range 5.5V to 6.5V and 3% over the temperature range 70 degrees F to -30 degrees F. Since this variation is inverse with both temperature and voltage, this effect is intensified by the fact that in general, battery voltage itself falls off with low temperature. As a result, a MV having more refined characteristics is desired, particularly in regard to provision for vernier frequency adjustment. Such a unit is on order for TEM.

5.2 Solenoid Design and Calendar Ratchet Design

Several refinements are in the offing here. A solenoid reversal, where the return spring drives the load, is being considered, because (a) less kinetic energy is delivered to the disc and ratchet assembly during drive, and (b) the ratchet and disc is always locked by the action of the ratchet wheel and stop pin against the drive spring. Thus, when not indexing, the disc cannot be moved in either direction.

Recent work indicates the solenoid itself may deliver more energy per watt-second input if one or two changes are made in the coil and plunger configuration. In this regard, more clearance between plunger and sleeve is also desired, to improve low temperature performance. (See Paragraph 3.5 a.)

5.3 Printed Circuit Plate

This plate gave considerable installation difficulty, as outlined in Paragraph 5.3 and 5.3.1 of the February 15th report. At this time, a new printed circuit plate has been received which "sandwiches" the printed circuitry (found on the bottom side of the old plate) between the top printed circuit plate and a flat plastic bottom plate. This new plate should be more readily mounted, as a result. Complete tests, however, are not available as yet.

5.4 Sweep Drive Design

The overtravel and eccentricity associated with the gearing system presently in use, may be eliminated by (a) driving the bridge directly with a long-stroke solenoid, (b) incorporating a positive detent into the bridge drive wheel to prevent overtravel. This problem is under investigation. A solenoid reversal, as outlined in Paragraph 5.2 above, may also be beneficial here.

5.5 Method of Winding Time Base

A solenoid powered winding mechanism has been considered to replace the negator mainspring. This system would require less space physically, but, of course, increases MA-HR battery requirements somewhat. One development considered uses a standard watch movement wound by a short stroke solenoid operating a ratchet on the center wheel, pulsed through contacts similar to the once/min. contacts of TEM time base.

5.6 Once/min. Watch Contacts

Use of the watch outlined in 5.5 wound by a short stroke solenoid, would allow replacement of both the TEM once/min. contact and the watch wind contact by a commutator-type contact ring, against which fingers ride in a manner similar to TEM Sweep. These fingers are attached to a shaft of the watch, which makes one revolution per minute. Thus, a bridge attached to this shaft and carrying contact fingers, can perform several switching operations analagous to those performed by the calendar printed circuit discs. This system, then, would eliminate the present contacts and replace them with moving fingers upon a divided stationary disc, yielding, in general, more reliable operation and more uniform make and break characteristics. Some work has been done along this line.

5.7 Method of Supplying Current Pulse to Solenoids

Also under consideration is the use of a circuit modification to preclude the relatively large instantaneous battery drains outlined in Paragraph 4.0 of this report. This amounts to an electrical "reversal," wherein instead of supplying heavy peak drains over a short period of time, the battery would supply light drains over long periods of time to charge the capacitor. When the control circuit closes, the charged capacitor would rapidly pour its charge into the solenoids, following which the small capacitor charging current would again build up capacitor charge through the battery. Work is being done to determine the relative value of this method compared to that presently in use, when small electromotive cells are employed as the source voltage. It is with small cells (incapable of handling large instantaneous currents) that this circuit would show possible superiority. (See Enclosure C for circuitry comparison)

5.7.1 This proposed circuit has the inherent disadvantage that R_1, being in series with the capacitor shunt resistance R_s, and comparable in value, acts as a voltage divider so that C_1 will not charge to the full value of E (according to the ratio $\frac{R_s}{R_1 + R_s}$). If R_1 is thus limited in value, however, the leakage current, after C_1 is essentially fully charged, cannot be reduced to negligible value, thus a "standby" energy term appears. If R_1 is increased in value to reduce this "standby" energy, a higher value of E is needed to supply like amounts of charge to C_1.

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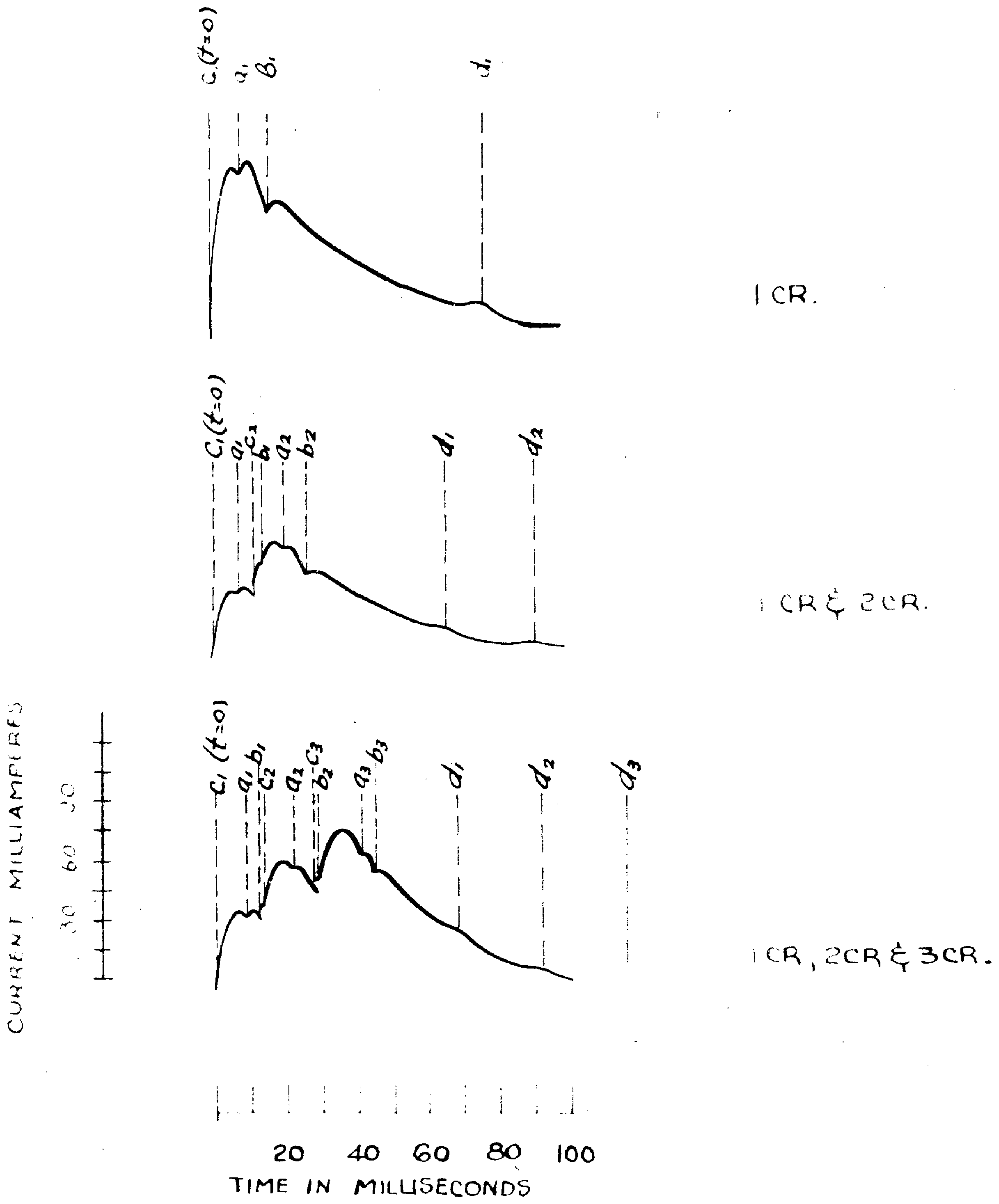
STAT

ENCLOSURE A


c₁(t=0)
a₁
b₁
d₁
1 CR.
c₁(t=0)
a₁
c₂
b₁
a₂
b₂
d₁
d₂
1 CR & 2CR.
c₁(t=0)
a₁ b₁
c₂
a₂
c₃
b₂
a₃ b₃
d₁
d₂
d₃
1CR, 2CR & 3CR.
CURRENT MILLIAMPERES
30
60
90
20
40
60
80
100
TIME IN MILLISECONDS

CALCULATION OF TOTAL AMPERE HOUR REQUIREMENTS OF TEM, PROJECT 74A,

OVER A SIXTY DAY OPERATING PERIOD

1CR: Transient Energy (per operation) $= \left(\frac{2L}{R}\right)\left(\frac{E^2}{R}\right) \times 2$

where $E = 6V$ $R = 160\ \Omega$

$L = .680h$ $= \underline{3.82\ MWS}$

Steady State energy (per operation) $= \dfrac{E^2 t_1}{\dfrac{R_1 R_s}{R_1 + R_s}}$

where $R_1 = 10^5\ \Omega$ $t_1 = 3$ sec

$R_s = 2\ M\ \Omega$

$= \underline{1.14\ MWS}$

Total Energy Consumed, 60 day period $= 4.96 \times 86.4 \times 10^3$

$= 4.28 \times 10^5$ MWS

Ampere Hours required $= \dfrac{4.28 \times 10^5}{6 \times 3.6 \times 10^3} = \boxed{19.8\ MA\text{-}HR}$

2CR: Transient Energy (per operation) $= \underline{3.82\ MWS}$

Steady State energy (per operation) $= \dfrac{E^2 t_2}{\dfrac{R_2 R_s}{R_2 + R_s}} = 6.24$ MWS

$R_2 = 1.5\ M\ \Omega$ $t_2 = 120$ sec

$R_s = 1.33\ M\ \Omega$

Total Energy consumed, 60 days $= 10.06 \times 8.64 \times 10^3$

$= \underline{.866 \times 10^5\ MWS}$

Ampere Hours Required $= \dfrac{.866 \times 10^5}{6 \times 3.6 \times 10^3} = \boxed{4.01\ MA\text{-}HR}$

Similarly, 3CR: Transient Energy = 3.82 MWS

S. S. Energy $= \dfrac{E^2 t_3}{\dfrac{R_3 R_s}{R_3 + R_s}}$

$t_3 = 1200$ sec.

$R_3 = 22\ M\ \Omega$

$R_s = 1.33\ M\ \Omega$

So S. S. Energy = 34.4 MWS

Total Energy, 60 days, $= 38.2 \times 86 = 3.29 \times 10^3$ MWS

Ampere Hours required $= \dfrac{3.29 \times 10^3}{6 \times 3.6 \times 10^3} = \boxed{.152\ MA\text{-}HR}$

TOTAL CALENDAR AMPERE HOUR REQ. = $\boxed{24.0 \text{ MA-HR}}$

SCR: Energy per Operation $= t_1 \left[\frac{E^2}{R} + I_1 \; E \right]$

$E = 6V$
$R = 160\ \Omega$
$t = 1.2$ sec
$I_1 = 2$ MA

$= \underline{284 \text{ MWS}}$

Energy per 1440 operations $= 1440 \times 284$

$= \underline{408 \times 10^3}$ MWS

Ampere Hour requirement $= \frac{408 \times 10^3}{6 \times 3.6 \times 10^3} = \boxed{18.9 \text{ MA-HR}}$

ST$_2$: Energy per Operations $= t \; \frac{E^2}{R}$

$t = 2.4$ sec
$E = 6V$
$R = 200\ \Omega$

$= \underline{431 \text{ MWS}}$

Energy per 1440 Operations $= 431 \times 1440$

$= \underline{620 \times 10^3 \text{ MWS}}$

Ampere Hours Required $= \frac{620 \times 10^3}{6 \times 3.6 \times 10^3} = \boxed{37.3 \text{ MA-HR}}$

TOTAL SWEEP AMPERE HOUR REQ. = $\boxed{56.2 \text{ MA-HR}}$

TOTAL TEM (74A) AMPERE HOUR REQ. = $\boxed{80.2 \text{ MA-HR}}$

[redacted]

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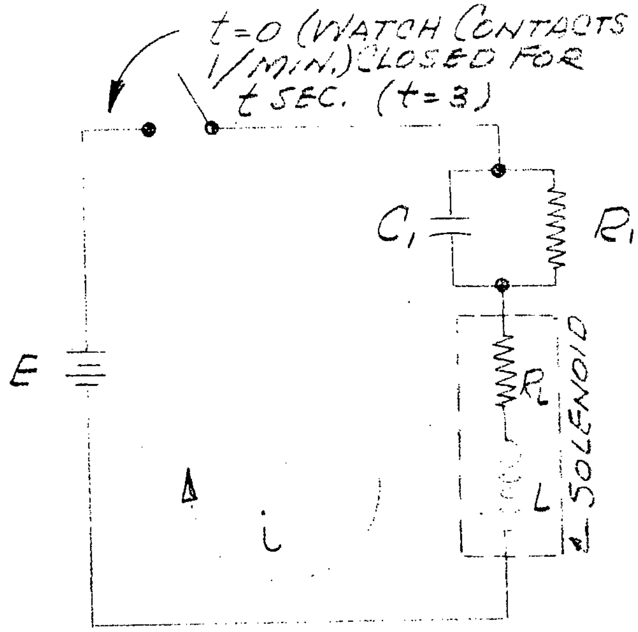
STAT

PRESENT



$E = 6V.$
$R_1 = 10^5 \Omega$
$C_1 = 120 \mu f.$
$L = 680 mh.$
$R_S = 160 \Omega.$

PEAK BATTERY CURRENT $= .73 \frac{E}{R_L}$

$= \boxed{27.4 MA.}$

TRANSIENT ENERGY $= \left(\frac{2L}{R_L}\right)\left(\frac{E^2}{R_L}\right)$

$= 3.82 MWS$

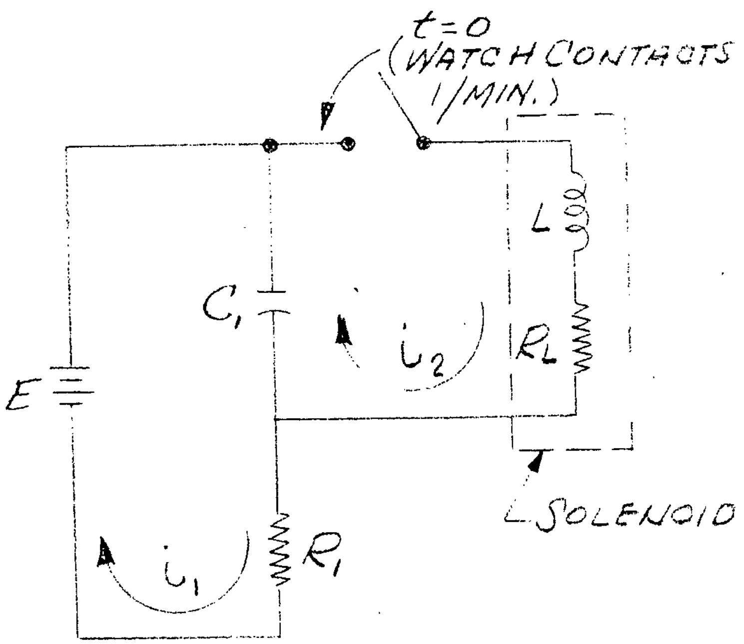
STEADY STATE ENERGY $= \frac{E^2(t)}{(R_1 + R_L)}$
$t = 3$ SEC.

$= 1.14 MWS.$

STAND BY ENERGY $= 0$

TOTAL ENERGY /MIN. $= \boxed{4.96 MWS.}$

CONSIDERED



PEAK BATTERY CURRENT $= i = \frac{E}{R}$

$= \boxed{60 \mu A}$

TRANSIENT ENERGY $\approx \left(\frac{2L}{R_L}\left(\frac{E^2}{R_2}\right)\right)$

$\approx 3.82 MW$

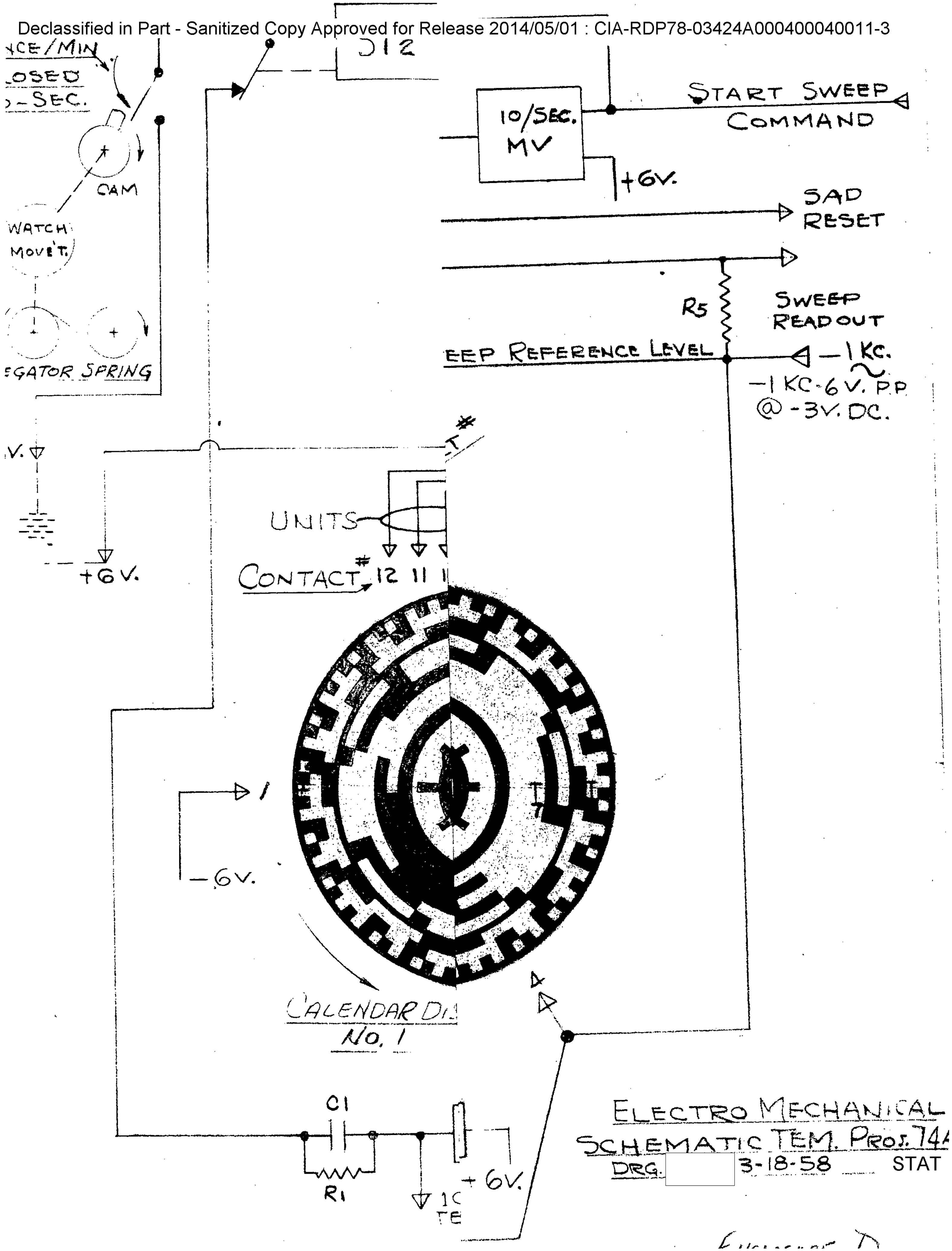
STEADY STATE ENERGY $= \frac{E^2(t)}{R_1 + R_2}$
$t = 3$ SEC.

$= 1.14 MWS.$

STAND BY ENERGY $\approx \frac{E^2 t_1}{R_1 + R_L}$
$t_1 = 5$ SEC.

$\approx .0855 MWS$

TOTAL ENERGY/MIN. $\approx \boxed{5.01 MWS}$



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