MEMORANDUM NO. M-70

SERVOMECHANISMS LABORATORY
Massachusetts Institute of Technology
Cambridge, Massachusetts

TO: 6345 Staff Members

FROM: Jay W. Forrester

SUBJECT: Data Storage in Three Dimensions

DATE: April 29, 1947

6345

Illustrations:

A-30363 A-30491
A-30488 A-30492
A-30489 A-30493
A-30490

The storage of operating instructions and numerical data is perhaps the most important and difficult operation in large scale digital computers. Large scale computers have in the past been made impractical by lack of satisfactory data storage means. Electrostatic storage tubes show satisfactory promise of operating as storage devices for the Whirlwind series of computers. It is, however, clear that storage tubes do not represent the ultimate in data storage devices. If other promising storage methods can be discovered they will be studied for evaluation. The storage method outlined below shows some promise and will be investigated to determine its possibilities. Glow discharges which might permit 3-dimensional storage arrays as outlined below are now being investigated as a thesis subject by Mr. Markel. The outcome of his work should indicate the lines for future study if additional work is shown to be desirable.

The concept of digital storage has passed from that of a vacuum tube, namely, the storing of a piece of information in a flip-flop circuit to surface storage where a single circuit controls many points of information on an area. This method of storing on an area as used in our electrostatic tube and the RCA Selectron still falls far short of effective use of the volume occupied by the storage equipment. Efficient storage will be possible only if points can be closely spaced in a 3-dimensional volume. Storage in a volume can be readily imagined if a suitable form of non-linear impedance having a double valued current-voltage characteristic is available. Such an impedance might support two different values of conduction current at a given operating voltage.

Examples of such an impedance characteristic are provided by the ordinary gas discharge tube and also by the germanium crystal rectifier in the reverse current direction. The gas discharge requires a voltage to initiate conduction which is higher than that required to maintain current flow. The reverse current characteristic of the germanium crystal rectifier is shown in drawing No. A-30363. Operation of a storage system using a double valued impedance is most simply explained for 2-dimensional storage before proceeding to the 3-dimensional system.

Consider drawing No. A-30488. Illustrated are two sets of conductors crossing one another. Imagine a double valued impedance element tied between each crossover point of the two sets of conductors. Let the impedance characteristics of each of these elements be as shown in A-30363. As typical operating voltages for the impedance, assume that V_m is the breakdown voltage between the first and second stable operating points, identified on the drawing as currents I_1 and I_2. Identify the transition voltage from the second to the first operating states as the extinction voltage V_e. The normal operating voltage V_0 is capable of sustaining either current I_1 or I_2.

Suppose that the storage junction at the point 43' is to be placed in conducting condition I_2. All lines 1 to 6 are normally at 0 volts and all lines 1' through 6' are normally at V_0 volts. The voltage on 3' is raised and the voltage of line 4 is lowered by an equal amount until their difference exceeds voltage V_m. This is above the breakdown voltage and conduction will be in the region "C". Voltages at 4 and 3' can then be returned to normal with assurance that the impedance between line 4 and 3' is in the second conducting state. In the above operation, all other impedance elements either continued to operate at voltage V_0 or if connected to either line 4 or line 3' were raised half way between voltage V_0 and V_m. Either way, the unselected impedance elements would have remained in their respective operating regions adjacent to current I_1 or current I_2.

Current conduction in the region I_1 is established by a similar process wherein the voltage 3' is lowered and the voltage on line 4 raised by an equal amount until their difference is less than the voltage V_e.

The information stored at the non-linear impedance point can be read by noting the current change at line 4 caused by a voltage pulse at line 3'. An impedance in state I_1 will conduct only a small change in current in response to a voltage pulse compared to the change in current which will be conducted by an impedance in state I_2.

Three-Dimensional Glow Discharge Storage

It should be possible to develop a useful double valued impedance storage cell as a low pressure gas glow discharge. In drawing No. A-30489 is shown a typical static current versus voltage relationship for a gas discharge from 0 current into the region of arc conduction. Current is plotted on a logarithmic scale. It will be noted, as in drawing A-30363, that two stable operating currents can exist, one prior to breakdown of the glow discharge which represents an extremely small current with little current change as voltage changes and one in the abnormal discharge region where current is relatively high and where current change is great with a change in voltage. The normal discharge region is one of essentially constant voltage with varying current. In this region the cathode area is not entirely covered by the glow discharge. After the cathode is entirely covered by the glow discharge conduction exhibits the characteristics of the abnormal discharge region where a positive resistance characteristic predominates. For a glow discharge storage cell, the normal discharge region should be shortened as much as possible through the use of small cathode areas. Such a static discharge curve might exhibit the characteristics of drawing No. A-30490. Operation at current I_1 and I_2 and at voltages between V_e and V_m would be as described earlier. It would be necessary to design the glow discharge electrodes in such a manner that the positive resistance characteristic in the region of I_2 would stabilize current glow without a series resistor.

Consider now a possible physical arrangement of glow discharge gaps and a selecting system for switching to the proper storage cell. If a glow discharge is used for storage then a gas breakdown system might well be used to switch the incoming lines, for writing, and for reading. Suitable switching must be incorporated inside the tube to reduce the number of external lines and the number of vacuum seals. Consider a switching system and 3-dimensional storage matrix as shown in drawing No. A-30491. The matrix consists of a 2-dimensional array of parallel wires extending through perforated plates. In addition to passing through the storage plates the 2-dimensional array of wires also passes through clearance gaps in the horizontal and vertical selecting bars and in the collector plate. Glow discharges may be established at each of these intersections between storage wires and the plates and bars.

The schematic diagram in drawing No. A-30492 shows the arrangement of gas discharge gaps involved in a single selection and operating process. Gap A exists between a vertical selection bar and the storage wire. Gap B is between a horizontal selecting bar and the storage wire. Gap C lies between the collector plate and the storage wire, while Gap D is between the storage wire and the storage plate. Gap E is between the storage plate and the outgoing lead to this plate while Gap F is between the storage plate and the common control wire to all storage plates. The following table shows a compatible set of gap characteristics.

Table

Gap	Ignite Voltage	Operate Voltage	Extinquish Voltage
A	V_e	V_e	V_e
B	V_e	V_e	V_e
C	$2V_e$	V_e	V_e
D	$3V_e$	$2V_e$	V_e
E	V_e	V_e	V_e
F	$2V_e$	V_e	V_e

Gaps A, B, and E show voltage regulator characteristics with constant voltage drop over a wide current range. Gaps C and F show a relatively high breakdown voltage but with a large cathode area which does not reach the abnormal glow region in operation. Gap D is the storage gap previously described which exhibits a high breakdown voltage and an operating point in the abnormal glow region. All gaps operating in the normal region are stabilized by current limitation at the abnormal glow gap D. Drawing No. A-30493 shows the three shapes of glow discharge characteristics at the six gaps.

Drawing No. A-30492 shows normal holding voltages at the various electrodes with arrows showing electron flow paths during standby conditions. A potential difference of $2V_e$ exists across gap D which may be in either the conducting or non-conducting state. Consider the following sequences of switching and controlling operation.

1. Selection

Selection of a storage gap is done in such a manner that the controlled voltage V_4 on the collector plate and voltage V_7 on the common wire can be used for establishing either the conducting or non-conducting state at the gap or to read the state of the gap. The following steps are required:

a. Reduce V_6 to voltage $2V_e$ and raise V_7 to $3.5V$.

Result: Gap E extinguishes. Voltage V_5 drops. Gap F fires when V_5 equals $1.5V_e$. Voltage across D has dropped to $1.5V_e$ but does not alter its on or off condition. After breakdown of gap F, V_5 rises to $2.5V_e$ bringing drop across all gaps D in this plate to $2.5V_e$.

b. Reduce V_7 from $3.5V_e$ to $3.0V_e$.

Result: V_5 returns to $2.0V_e$.

c. Raise V_1 and V_2 from $-V_e$ to 0. Reduce V_4 from $-0.5V_e$ to $-1.5V_e$.

Result: Gap A and B extinguish (probably only one was originally on). V_3 rises to $0.5V_e$. Gap C breaks down and is the only conducting gap in the collector plate. This operation disconnects the storage wire from gaps A and B and connects it to the collector plate through gap C.

d. Raise V_4 to $-V_e$.

Result: V_3 is now at 0 volts under the control of V_4 and V_7. Only the gap C for the particular storage wire under consideration and the gap F for the particular storage plate under consideration are fired. No other C or F type gaps are conducting. All other storage wires and storage plates are controlled by their respective V_1, V_2, and V_6 voltages.

2. Gap Control

Switching is now complete and the sequence can be followed to write 0, write 1, or read at the gap selected. By a corresponding process to steps a through d the line V_4 and V_7 could have been connected to any other storage gap. Voltages at operating points are now as follows:

$$V_4 = -V_e, \quad V_3 = 0, \quad V_5 = 2V_e, \quad V_7 = 3V_e$$

a. Assume the digit 1 is to be written corresponding to conduction at gap D. Reduce V_4 to less than $-1.5V_e$. Raise V_7 to more than $3.5V_e$.

Result: Voltage across gap B is above $3.0V_e$ and breakdown will occur. The maximum voltage across any other gap D is $2.5V_e$ and other gaps will not be ignited.

b. Assume that the digit 0 is to be written corresponding to no conduction at gap D. Raise V_4 above $-0.5V_e$. Reduce V_7 below $2.5V_e$.

Result: Voltage across D is below V_e and the gap will be extinguished. The minimum voltage on any other storage gap will be $1.5V_e$ so that other conducting states will not be affected.

c. Assume as the third possibility that the condition of gap D is to be read. Hold V_4 at $-V_e$. Raise V_7 from $3V_e$ to $3.5V_e$.

Result: If D is conducting there will be a large current increase through gap D which can be observed as an increase of current to the collector plate. If gap D is not conducting little current increase will occur at the collector plate.

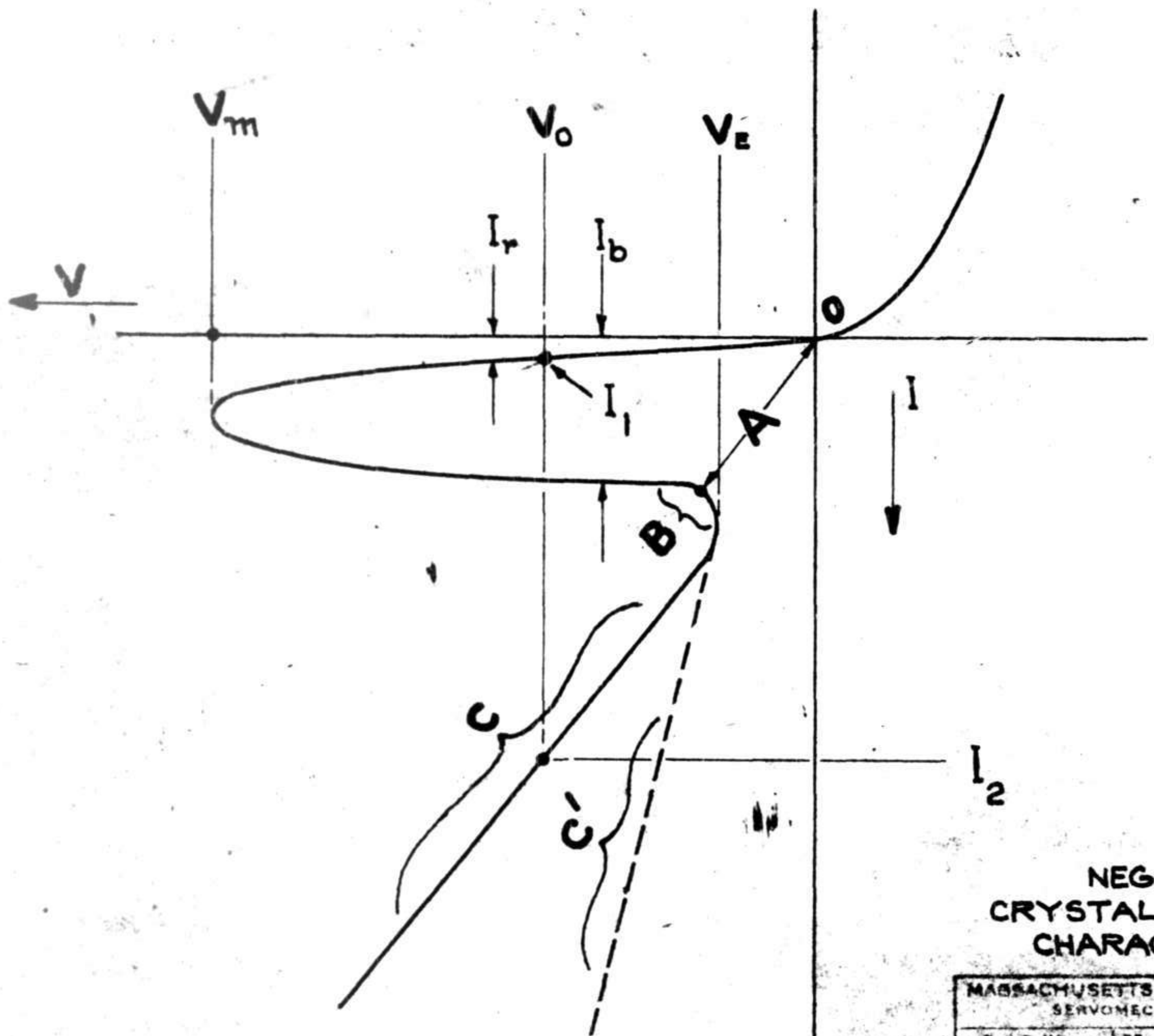
The storage and switching system described above requires discharged gaps which can be constructed to meet specified breakdown and extinction voltages and which exhibit extreme stability in these voltage characteristics.

Firing and deionizing time must be short and the pulse impedance of a gap must be low. The above discussions have been carried out in terms of the static glow discharge characteristic. This static characteristic is known not to hold under pulse conditions but it is anticipated that similar curves, differing in numerical values, will prevail.

Until additional information is collected and until tests with especially designed gaps have been completed, it will be impossible to evaluate the promise shown by the system outlined above. The major problems seem to be the short operating times required and the problem of obtaining uniformity in gaseous discharge performance.

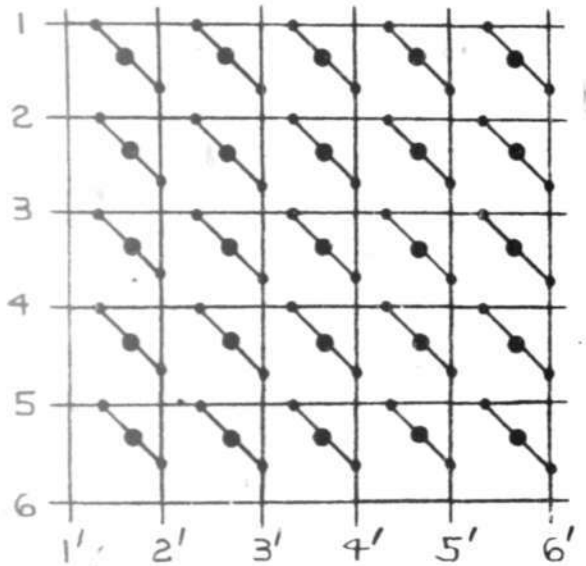
Advantages of the system are rather obvious. Storage sensity will be high since storage is in a volume rather than in individual circuits or on a surface. Mechanical assembly will be relatively easy except for the problems involved in obtaining accurate gap tolerances and performance. The system inherently includes most of the switching as well as the storage function. The number of seals necessary to be brought through the glass are practical and amount to the cube root of the number of storage gaps plus the two control wires. In construction the storage volume might take the form of parallel metal plates perforated for passage of the storage wires with these plates interleeved by ceramic barriers to confine the glow discharge to the individual gap structure. Work on this storage method will be assigned low priority until it reaches the stage where evaluation is possible.

JWF:vh



NEGATIVE
CRYSTAL RECTIFIER
CHARACTERISTICS

MASSACHUSETTS INSTITUTE OF TECHNOLOGY SERVOMECHANISMS LABORATORY		
D. I. C. NO. 6345	DR	CK
ENG. JWF 3/11/47	APP.	A-30363



VOLTAGES FOR OPERATION

OPERATION	VOLTAGE ON ONE OF LINES 1 THRU 6	VOLTAGE ON ONE OF LINES 1' THRU 6'
SUSTAIN	0	V_0
ESTABLISH CONDUCTION (CURRENT STATE I_2)	$< -\frac{V_0 - V_m}{2}$	$> V_0 + \frac{V_m - V_0}{2}$
EXTINGUISH (CURRENT STATE I_1)	$> \frac{V_0 - V_e}{2}$	$< V_0 - \frac{V_0 - V_e}{2}$
READ	0	$> V_0$

SEE A-30363 FOR SYMBOLS

= DOUBLE VALUED IMPEDANCE

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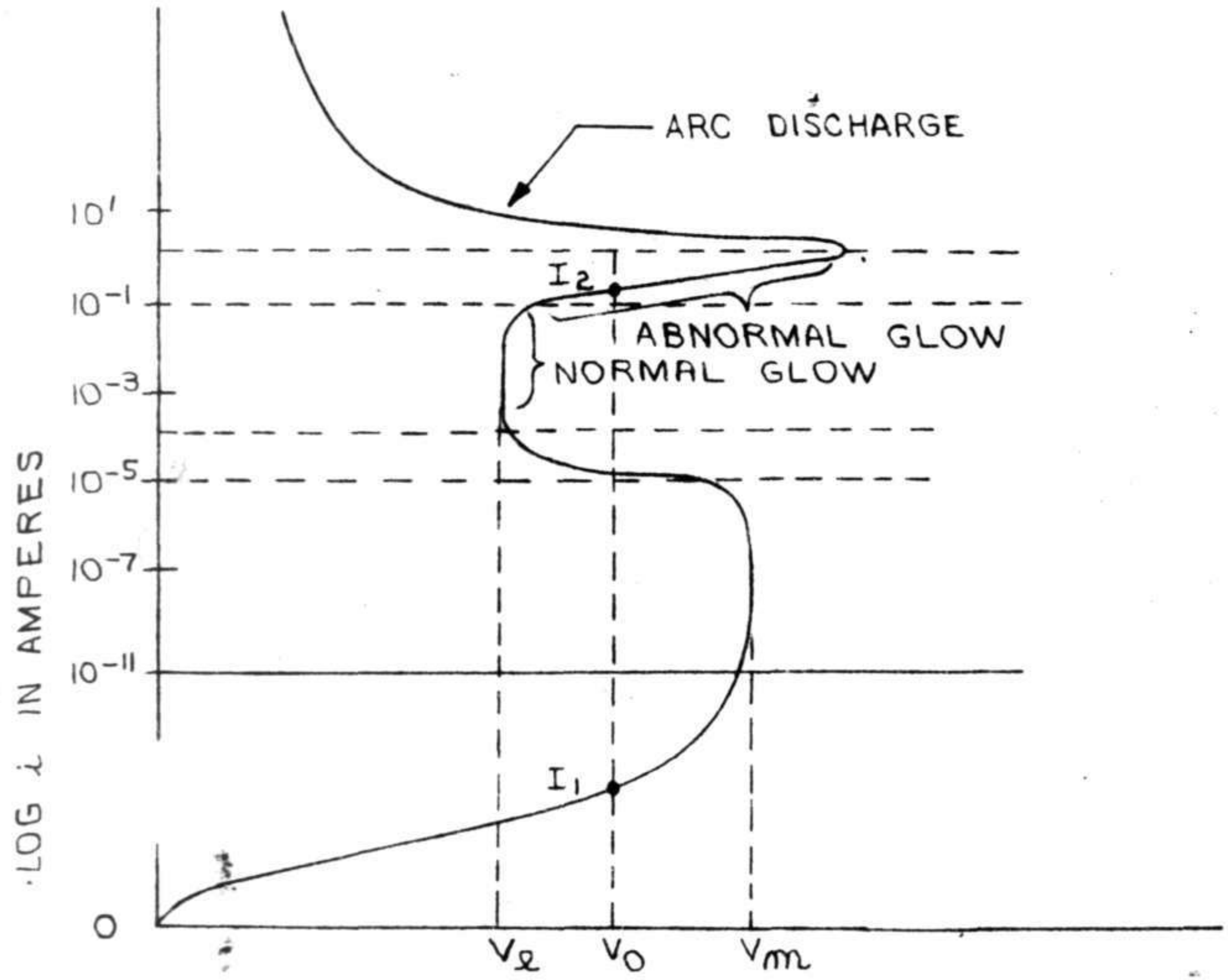
TWO-DIMENSIONAL STORAGE ARRAY USING DOUBLE-VALUED IMPEDANCE ELEMENTS

SCALE:	DR. D.L.O. 5-6-47		A-30488
ENG. JF 5/9/47	CK. MG 5-7-47	APP.	



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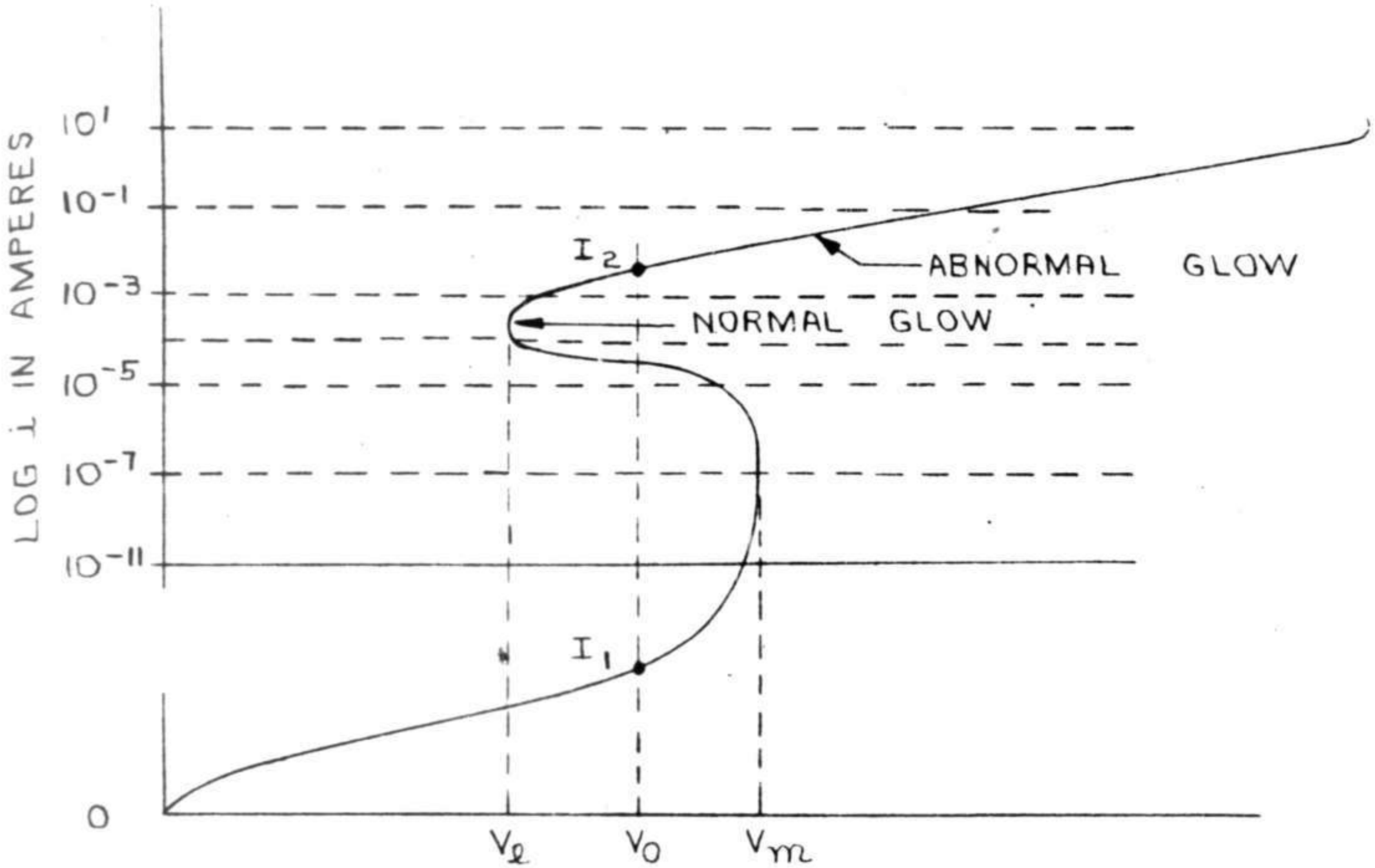
GLOW CHARACTERISTICS FROM TEXT WITH ADDITIONS

SCALE:	DR. D.L.O. 5-6-47	A-30489
ENG. JF 5/7/47	CK. [illegible] 5-7-47	APP



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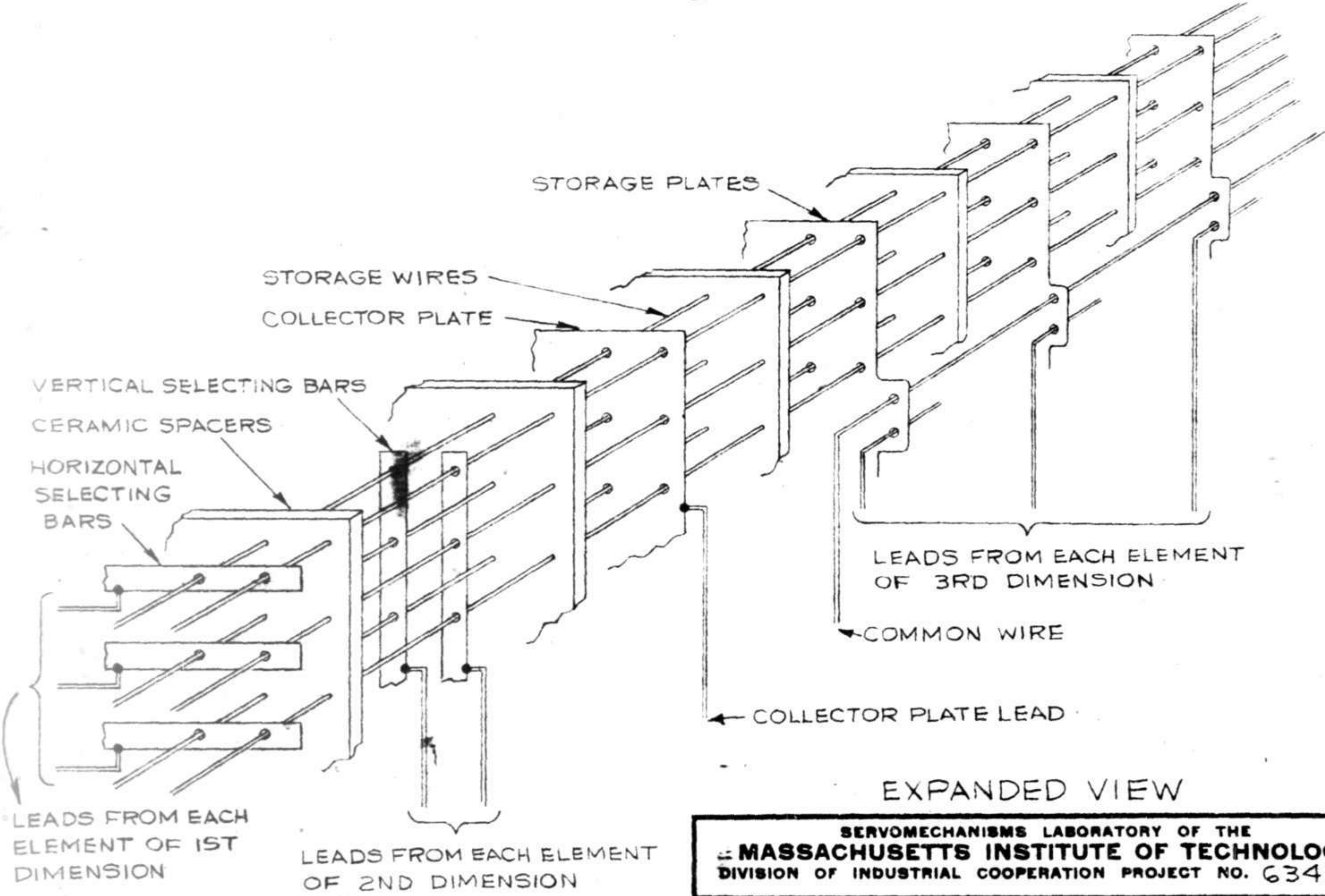
IDEAL STORAGE - CELL CHARACTERISTICS

SCALE:	DR. D.L.O. 5-6-47	A-30490
ENG. 5/9/47	CK. 5-7-47	AP.



EXPANDED VIEW

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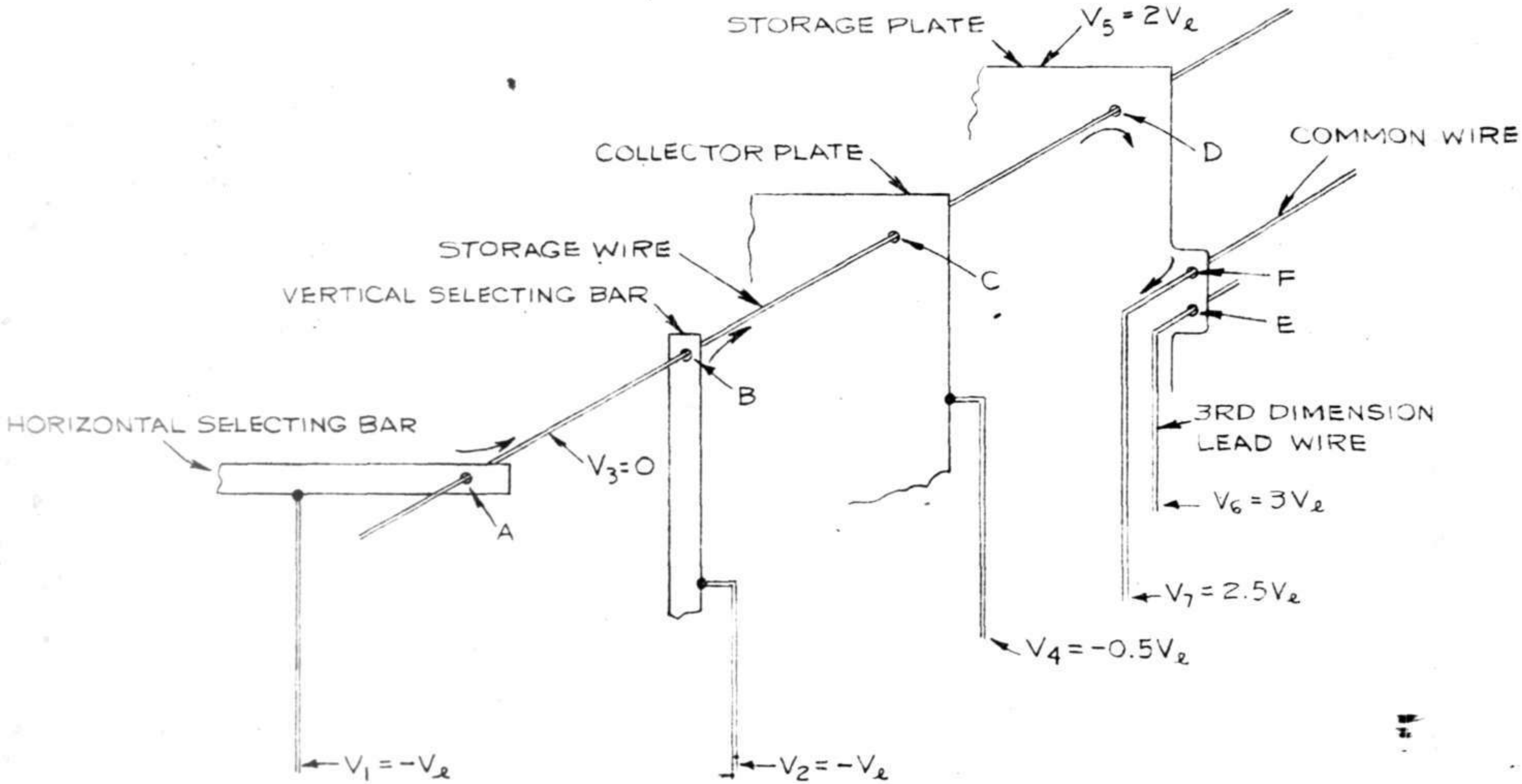
3-DIMENSIONAL STORAGE

SCALE: NONE	DR. F. Brunswick 5-6-47	A-30491
ENG. 5/9/47	CK. 5-7-47	



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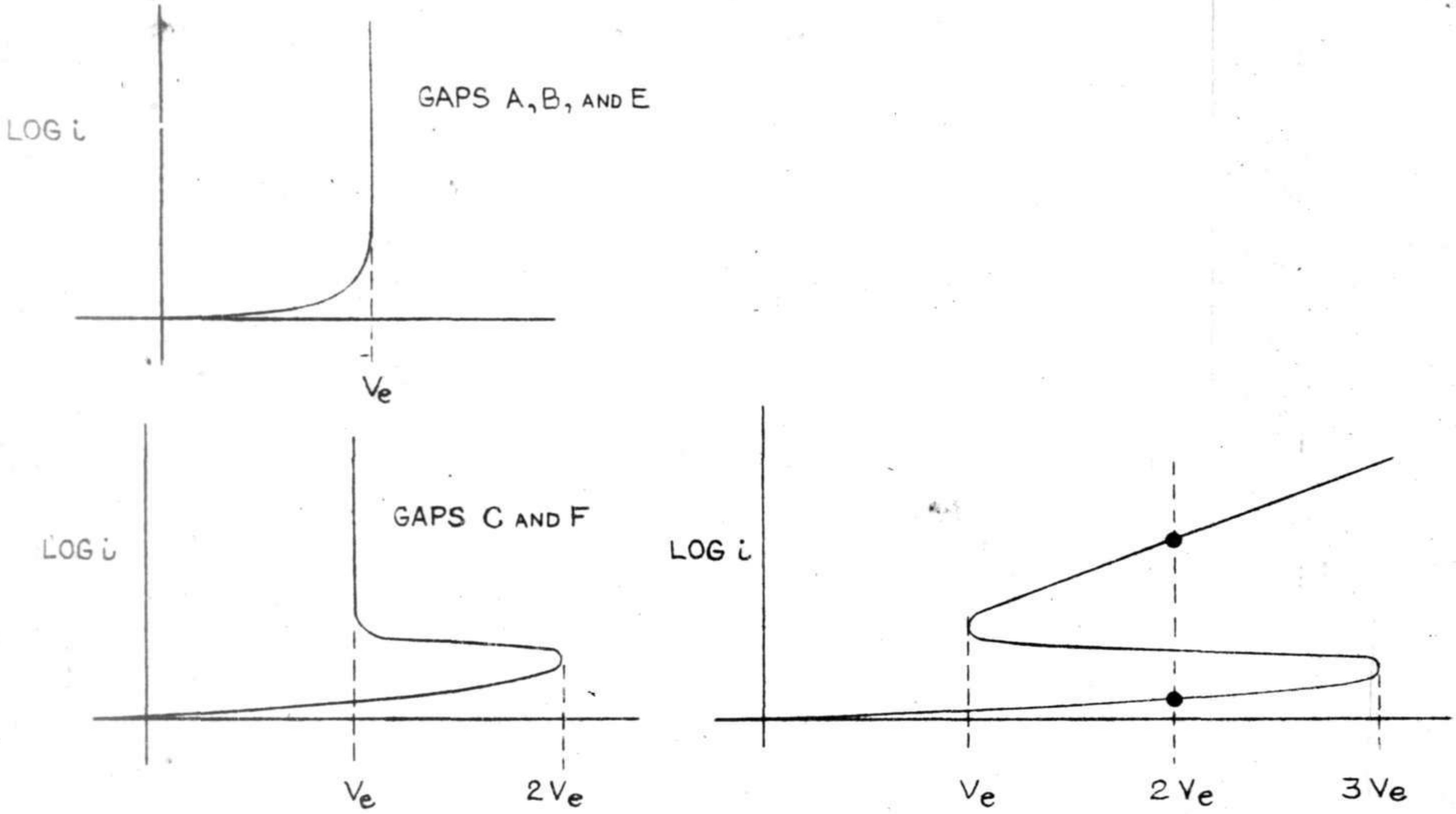
SCHEMATIC OF STORAGE GAPS

SCALE: NONE	DR. F Brunswick 5-6-47	A-30492
ENG. 5/7/47	CK. 5-7-47	APP

A-30493



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COMPOSITE OF GAP CHARACTERISTICS

SCALE:	DR. F. WOLSKY 5-6-47	A-30493
ENG. 5/9/47	CK. 5-7-47	APP.