FABRICATION AND DELIVERY OF NON-DESTRUCTIVE READ OUT MEMORY BUFFERS USING LAMINATED LAYER TECHNIQUE

SUMMARY TECHNICAL REPORT

Contract No. NAS8-11986

Prepared for:

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Huntsville, Alabama

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) 4.00

Microfiche (MF) .75

ff 653 July 65

June 1966
MRC No. 519

RESEARCH REPORT

MATERIALS RESEARCH CORPORATION
ORANGEBURG, NEW YORK

FABRICATION AND DELIVERY OF NON-DESTRUCTIVE READ OUT MEMORY BUFFERS USING LAMINATED LAYER TECHNIQUE

Summary Technical Report

Contract No. NAS8-11986

Prepared by:

Neal Kenny

Theodore P. Janus

Raymond J. Carpenter

MATERIALS RESEARCH CORPORATION

Orangeburg, New York

June 1966
MRC No. 549

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

SUMMARY

The purpose of this program was to determine if laminated foil techniques could be used to fabricate non-destructive read out memory buffers.

Our efforts were concentrated toward producing uniform characteristics in the storage elements by very carefully controlling the materials and processing procedures used in preparing the foils. Since the preparation of memories from foils does not entail disproportionation of the material into the individual atomic species, as it does when making thin films by vapor or electro deposition, we expected to be able to produce foil materials with very uniform composition, structure and performance.

We concluded from our investigation that, in fact, metallic foils could be produced with such uniformity and could be successfully used in electronic memories. When compared with thin film memories, the foils have the advantage of uniformity, but the thin films have the advantage of higher speed operation. The excellent uniformity of the foils suggests that they will have greater long time reliability than thin films; however, the experiments necessary to establish this fact have not yet been performed.

We also developed a new geometry for foil storage devices, assembled it, and successfully operated it.

We then designed, assembled, and delivered a card-programmable memory, the operation of which is based on the same foil devices. In the card-programmable memory, the foil devices are used to read, at high speed, the information stored on magnetic cards. By using a novel design principle, the foil devices are capable of reading the information from the cards at high speed without any relative motion between the foil devices and cards.

1.0 INTRODUCTION

The purpose of this program was to conduct the research necessary to fabricate a non-destructive read out memory buffer using laminated foil techniques.

In order to accomplish this objective, the program was divided into three phases. The first phase was a materials and processing study that had as its objective the production of metallic magnetic foil with exceptional uniformity of composition, structure and magnetic characteristics.

The second phase of the program was a device design study in which we examined and tested a number of different magnetic storage devices composed of magnetic foils.

Since in Phase I we were able to produce metallic foils of the required uniformity, and since in Phase II we were able to design a novel magnetic storage element, we proceeded to Phase III of the program, which had as its objective the design and assembly of a memory incorporating the foil storage device.

Because the characteristics of the foil storage device were applicable for use in card-programmable memories, and because an investigation revealed an increasing need for this type of memory, the memory that we developed was a magnetic card-programmable memory which incorporated the non-destructive read out feature that we desired. The memory itself is composed of three units: magnetic cards, an encoding unit, and a reading unit.

This report includes the results of the three phases of the investigation, a description of the card-programmable memory, and our conclusions and recommendations pertinent to the applications of foil technology in memory systems.

2.0 MATERIAL AND PROCESSING STUDIES

2.1 Introduction

The principal objective of this portion of the program was to study materials and processes which could be used to produce low cost magnetic storage devices with uniform characteristics.

As part of the materials study, we examined the B-H characteristics and switching speeds of five nickel-iron alloys and studied how these properties varied with impurity levels in the alloys. We further determined how these same magnetic properties were influenced by rolling procedures, heat treatments, magnetic annealing, laminating and welding. And finally, we related these materials and processing studies not only to the intrinsic magnetic behavior of discrete test samples, but also to the performance of an array of storage devices which were built into completed memory planes. The emphasis throughout all this work was to produce storage devices with uniform performance characteristics.

2.2 Preparation of Materials

2.2.1 Material Compositions

Three alloys were selected for initial investigation:

Alloy #1 - 81.5% Ni, 18.5% Fe,

Alloy #2 - 4% Mo, 79% Ni, 17% Fe,

Alloy #3 - 3% Co, 80% Ni, 17% Fe.

These alloys are commonly used in small signal magnetic applications and were selected to determine if more careful control of composition and fabrication procedures would result in magnetic properties that are significantly more uniform than the properties of commercially prepared material. This class of nickel-iron alloys are referred to as permalloys and are useful in buffer memories because they possess:

i) low magnetostriction;

ii) low crystallographic anisotropy energies (desirable for minimizing skew), yet are capable of having strong uniaxial anisotropies induced in them;

iii) high permeability and reasonably high saturation magnetization;

iv) high squareness ratio in easy direction;

v) low coercive force.

In Alloy #2, the molybdenum addition increases the electrical resistivity of the nickel-iron alloy and thereby reduces eddy current losses at high frequency. In Alloy #3, the cobalt addition increases the coercive force of the base alloy which is beneficial when the alloy is used in certain "keeper" applications. In addition to the above alloys, foils of pure iron and pure nickel were also prepared for comparison purposes.

Previous experience in preparing these types of alloys has shown that uniform magnetic properties can be produced only if the composition and structure are carefully controlled and are uniform throughout the material. For this reason, the material preparation facilities were under the control of the Project Director.

2.2.2 Melting Procedure

The permalloys were melted and homogenized by the same techniques that are used in the production of ultra-high purity alloys manufactured by Materials Research Corporation for sale to most of the major research laboratories in the country. The starting materials were high purity rods of nickel, iron, molybdenum and cobalt, which had been triple pass zone refined (electron beam). (See the attached Specification Sheets 1 and 2 for typical analyses of the nickel and iron used.) The starting materials were then arc melted in purified argon to form a rod of permalloy about 9 inches long and 3/8 inch diameter. In order to homogenize the rod and ensure uniform composition, the permalloy rod was then double pass zone leveled using electron beam zone refining techniques. The electron beam zone refiner which was used is shown in Figure 1.

A brief description is in order of the electron beam zone refining process which was used both to purify the elements which were used as the starting materials in the

Specification Sheet #1

MATERIALS RESEARCH CORPORATION

Orangeburg, New York 10962 • 914 ELmwood 9-4200

ADVANCED MATERIALS DIVISION

Material: Nickel

Preparation: 3 pass electron beam zone refined

Report: Typical Mass Spectrometer Analysis performed by Battelle Memorial Institute

Impurity	Content (ppm)	Impurity	Content (ppm)
Li	<0.02	Rh	<0.01
Be	<0.001	Pd	<0.03
B	0.005	Ag	<0.02
C	37.0	Cd	<0.08
N_2	3.0	In	<1.0
O_2	18.0	Sn	<4.0
H_2	0.2	Sb	<2.0
F	0.005	Te	<1.0
Na	<0.04	I	<0.008
Mg	0.02	Cs	<0.1
Al	0.3	Ba	<0.03
Si	0.2	La	<0.008
P	<15.0	Ce	<0.008
S	<0.12	Pr	<0.008
Cl	0.1	Nd	<0.03
K	0.2	Sm	<0.04
Ca	0.1	Eu	<0.02
Sc	<0.01	Gd	<0.04
Ti	0.15	Tb	<0.01
V	<0.01	Dy	<0.04
Cr	1.5	Ho	<0.01
Mn	0.03	Er	<0.03
Fe	12.0	Tm	<0.01
Co	<0.1	Yb	<0.05
Ni	---	Lu	<0.01
Cu	<0.04	Hf	<0.03
Zn	<0.4	Ta	<0.5
Ga	<0.4	W	1.5
Ge	<0.7	Re	<0.02
As	<0.04	Os	<0.03
Se	<0.03	Ir	<0.02
Br	<0.03	Pt	<0.03
Rb	<0.03	Au	<0.15
Sr	<0.3	Hg	<0.03
Y	<0.08	Tl	<0.02
Zr	<0.15	Pb	<0.02
Nb	<0.02	Bi	<0.01
Mo	0.5	Th	<0.012
Ru	<0.03	U	<0.012

MATERIALS RESEARCH CORPORATION
Orangeburg, New York 10962 • 914 ELmwood 9-4200

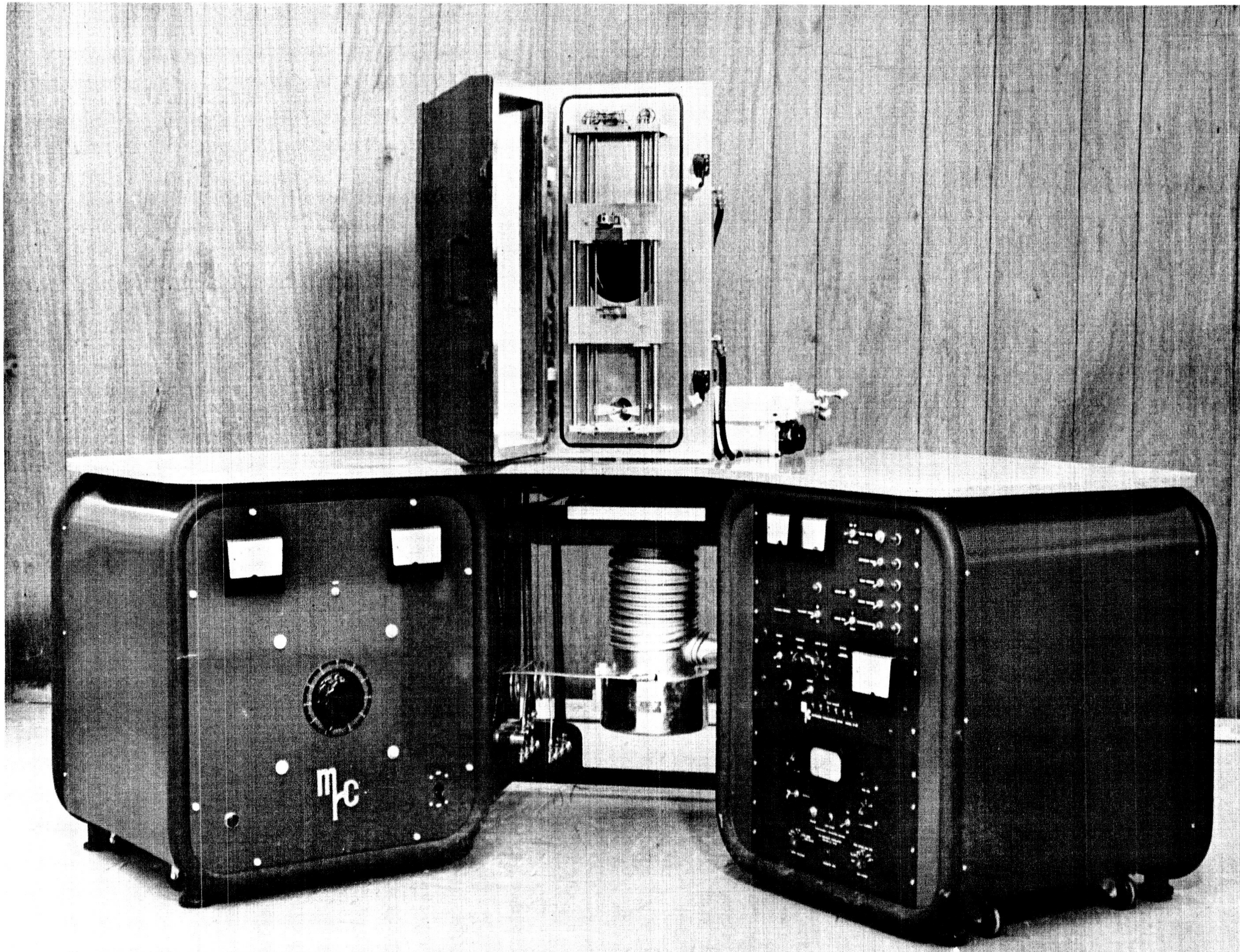
ADVANCED MATERIALS DIVISION

Material: Iron

Preparation: 3 pass electron beam zone refined

Report: Typical Mass Spectrometer Analysis performed by Battelle Memorial Institute

Impurity	Content (ppm)	Impurity	Content (ppm)
Li	0.004	Rh	<0.03
Be	0.005	Pd	<0.08
B	<0.0008	Ag	<0.04
C	8.0	Cd	<0.08
N_2	7.0	In	<0.06
O_2	7.2	Sn	<0.02
H_2	< .1	Sb	<0.02
F	Interference	Te	<0.07
Na	0.8	I	<0.007
Mg	8.0	Cs	<0.006
Al	Interference	Ba	0.04
Si	<0.5	La	<0.006
P	0.3	Ce	<0.006
S	1.2	Pr	<0.006
Cl	3.0	Nd	<0.02
K	0.2	Sm	<0.025
Ca	2.0	Eu	<0.012
Sc	<0.025	Gd	<0.025
Ti	0.5	Tb	<0.006
V	<0.1	Dy	<0.03
Cr	0.6	Ho	<0.01
Mn	<0.1	Er	<0.4
Fe	---	Tm	<0.3
Co	0.3	Yb	<0.02
Ni	1.2	Lu	<0.006
Cu	<0.2	Hf	<0.025
Zn	<0.8	Ta	<1.0
Ga	<0.5	Re	<0.012
Ge	<1.0	Os	<0.02
As	<0.1	Ir	<0.012
Se	<1.0	Pt	<0.025
Br	<0.15	Au	0.4
Rb	<0.08	Hg	<0.03
Sr	<0.08	Tl	<0.012
Y	<0.04	Pb	<0.015
Zr	<0.06	Bi	<0.008
Nb	0.03	Th	<0.008
Mo	0.2	U	<0.008
Ru	<0.1		



ELECTRON BEAM FLOATING ZONE REFINER
MRC MFG. CORP. MODEL EBZ-93

Figure 1

alloys, and to homogenize the alloys themselves. When the zone refining process is used to purify an element, it operates on the principle that impurities have a different degree of maximum solubility in the molten element than they do in the solid element. Consequently, if a narrow zone is melted in an element which is in the form of a rod, there will be either a concentration or depletion of impurities in the molten region. The zone is kept narrow so that the level of impurities can equilibrate in a short time. Now, if this molten zone is repeatedly moved in one direction along the length of the rod, the impurities will form a concentration gradient along the length of the rod. Fortunately, in the elements used in this investigation, the most troublesome impurities are all more soluble in the liquid than in the solid, and consequently all impurities follow the molten zone and are swept to the same end of the rod. This end of the rod is cut off and discarded; the other end of the rod has been purified since it has been depleted of impurities.

In this investigation, the elements which were purified in this manner were then mixed together in the proper proportions to give alloys of the desired composition, and then these mixtures were arc melted together to form the desired alloys. In order to ensure that the composition and structure were uniform along the length of each alloy rod, the rods were subsequently zone leveled in the same apparatus used for the zone refining process.

The two processes are quite similar in that a narrow molten zone is formed in the rods in both cases. However, in the zone leveling process, the molten zone is slowly moved in first one direction along the rod, then the other. The slow back and forth movement of the molten zone smooths out gradients in the alloy concentration along the rod and also produces a uniform strain-free structure.

In the present investigation, the zone refining and zone leveling operations are carried out in high vacuum and the molten zone is formed by electron beam bombardment of the rod. The molten zone is self-contained due to surface tension forces, thus avoiding contamination of the rod by a crucible. By performing these operations in high vacuum, future purification is produced by volatilization of many impurities from the elements at the zone refining and leveling temperature. A typical analysis of permalloy produced in this manner is given in Specification Sheet #3.

2.3 Processing Procedures

2.3.1 Rolling and Slitting Schedule

The zone leveled permalloy rods were cold rolled on a two-high Stanat rolling mill (see Figure 2) to tape 0.008 inch thick, slit to the desired width

ULTRA-HIGH PURITY PERMALLOY

FORMS AVAILABLE:

Alloys —

Alloys of specified compositions are prepared by arc melting electron beam float-zone refined iron and nickel into alloy rods.

Fabricated Forms —

Fabricated from electron beam refined materials. All fabrication processes conducted at room temperature to eliminate impurity pick-up. Available in cold worked or annealed condition.

Wire: 0.001″ minimum diameter.

Sheet: 0.002″ minimum thickness and 5″ maximum width.

Rod: ½″ maximum diameter.

Special Shapes —

Tensile specimens, creep specimens, prepared in single crystalline and polycrystalline form.

Thin ribbon foils to 0.0004″ thickness.

Single Crystals —

Grown by electron beam float-zone refining in a vacuum of 10^{-6} torr. Available in ⅛″, or ¼″ diameters in lengths to 12″, of random orientation.

Grades —

Grade I —Three pass electron beam float-zone refined.

Grade II—Single pass electron beam float-zone refined.

NOMINAL ANALYSIS:

	Grade I	Grade II
Interstitial Content (O_2, N_2, H_2, C)	30 ppm	50 ppm
Substitutional Content	20 ppm	100 ppm

PROPERTIES:

Crystal Structure	FCC
Etchant	HNO_3-H_2O, equal parts

ADVANCED MATERIALS DIVISION
MATERIALS RESEARCH CORPORATION
Orangeburg, New York 10962 • 914 ELmwood 9-4200

February 1965

MRC ADVANCED MATERIALS DIVISION

Figure 2

(1/4-1/2 in.) and re-rolled on a four-high Stanat mill to a thickness of 0.002 inch. The tape was taken to a Sendzimer mill and further rolled to 0.0005 in. thick. Samples of the tape were taken at various thicknesses for magnetic and metallurgical tests.

During the rolling sequence, the tape did not receive any intermediate stress relief anneal which might have caused contaminants to diffuse into the alloy. During rolling, the tape experienced a 99 percent reduction in area which is a relative measure of the deformation energy contained in the sample. The deformation energy in turn influences the annealing kinetics of the foil. Figure 3 is a photograph of foils of various thickness and width; the wide foil on the right is 0.0005 in. thick and 4 inches wide.

2.3.2 Annealing Apparatus

The reason for annealing the foil was to eliminate the strain energy of deformation, and thereby reduce the coercive force and increase the switching speed of the foil.

The furnace in which the annealing is performed is shown in Figure 4. It is capable of reaching 1200°C, although best results from annealing permalloy have so far been achieved by holding one hour at 1050°C. An Inconel retort is shown in the furnace in Figure 4, which permits anneals

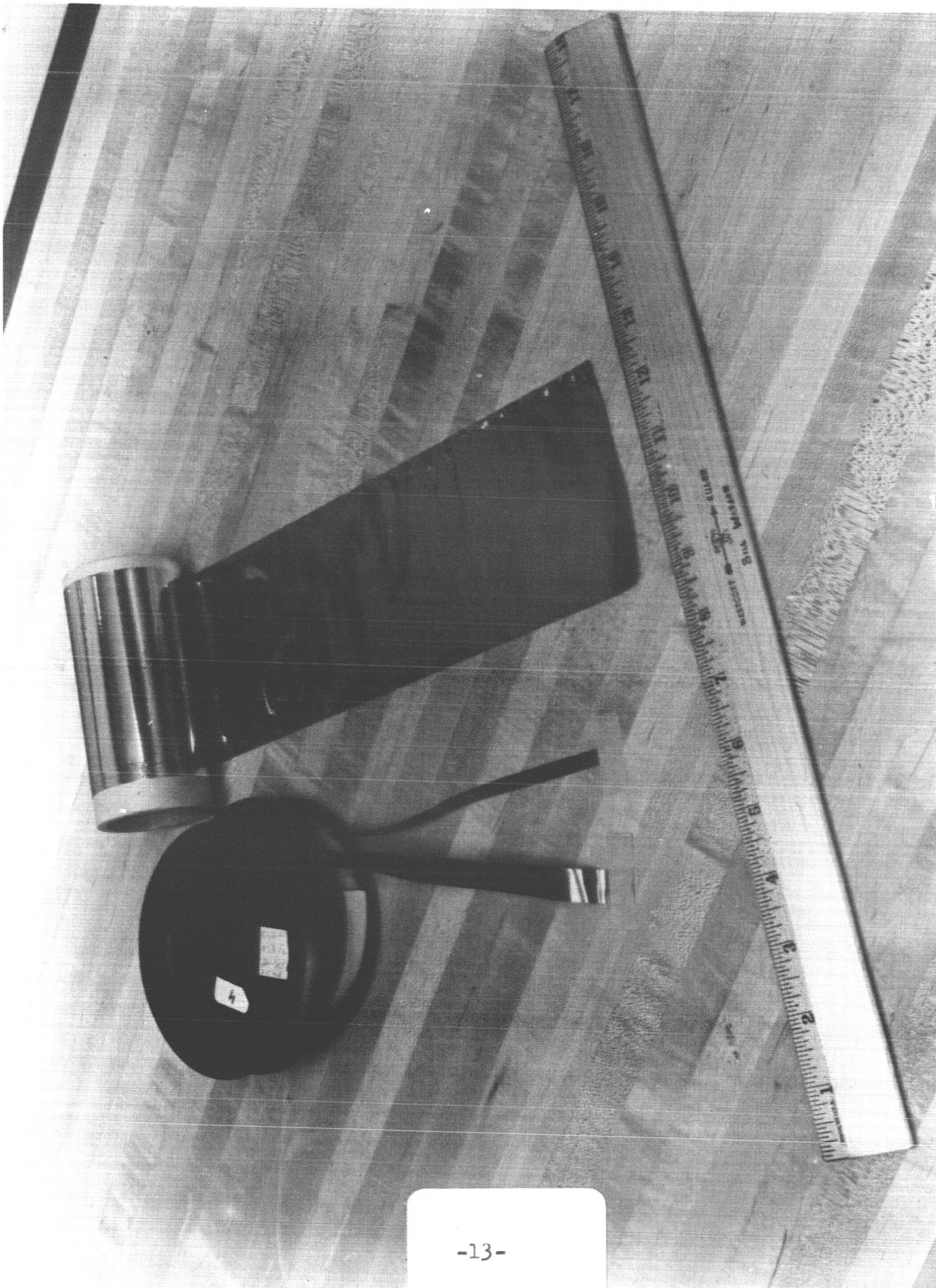


Figure 3 - Prepared Foils

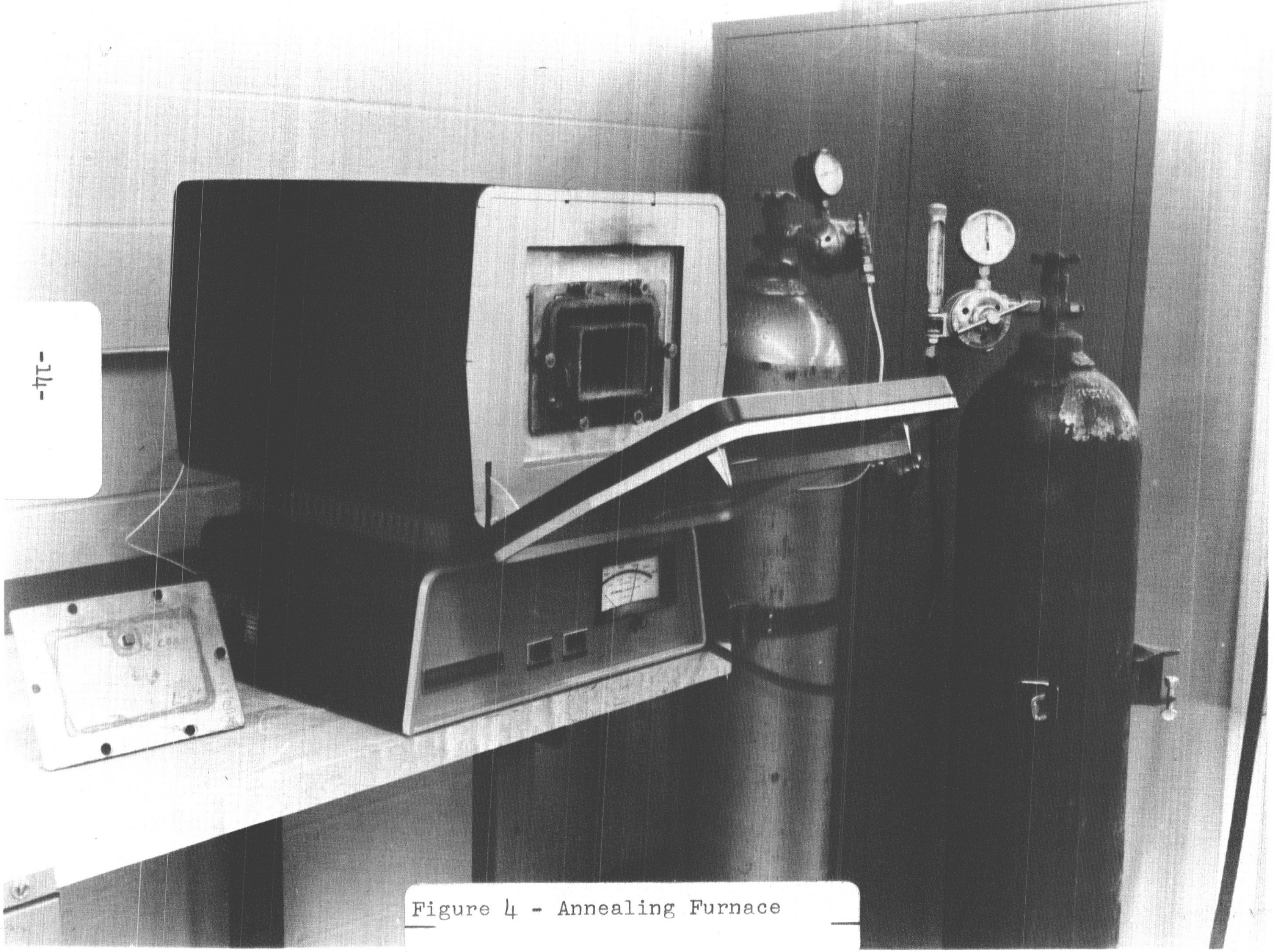


Figure 4 - Annealing Furnace

to be carried out in inert, oxidizing or reducing atmospheres.

In some applications, it is desirable to cool the foil from the annealing temperature through the Curie temperature, in the presence of an orienting magnetic field. The orienting magnetic field is supplied by an auxiliary winding wrapped on the rectangular muffle shown in the furnace. It is capable of producing a 50 oersted D.C. magnetic field within the furnace.

2.4 Effect of Materials and Processing Procedures on the Magnetic Properties of Foils

2.4.1 Effect of Alloy Composition

The purpose of this portion of the work was to determine which alloy had the most favorable and uniform magnetic characteristics when used in a completed array of magnetic storage devices.

The emphasis throughout this entire work was to produce uniform magnetic characteristics in a complete array of storage devices, not just in discrete test samples. Consequently, we were concerned not only with producing a magnetic foil with uniform composition and structure, but also in developing an assembly procedure that would maintain uniform performance of the storage devices when constructed into a complete memory plane. The manner in which we achieve uniform composition and structure in the material is discussed throughout this Section 2.4; the effect of the assembly procedure on uniformity of the memory plane is discussed in Section 4.0.

In addition to uniformity, the alloy that we wanted to use in the word-organized memory had to possess the following characteristics:

i) Low magnetostriction, to reduce strain sensitivity of the foil.

ii) A D.C. closed flux path, coercive force of less than 2 oersteds, to reduce the drive currents of the memory.

iii) A saturation flux density of at least 5 kilogauss, to provide a satisfactory output signal from the switching device.

iv) An easy direction of magnetization in the device to provide storage states, and a hard direction of magnetization (perpendicular to the storage directions) as the "read" state of the device when operated in the word-organized mode.

v) A square-loop B-H curve in the easy direction with a ratio of at least 0.90 between the remanent and saturation flux densities, in order to minimize shuttle noise and to maximize the desired output signal.

vi) No flux remanence in the hard direction, yet the occurrence of flux saturation in this direction for magnetic fields of less than 10 oe; the first condition prevents storage occurring in the read state, the second ensures that low read currents can swing all the stored flux and thereby maximize the output voltages.

vii) A switching speed of less than 0.5 microseconds.

The alloys which we chose to investigate were:

Alloy #1 - 81.5% Ni, 18.5% Fe

Alloy #2 - 4% Mo, 79% Ni, 17% Fe

Alloy #3 - 3% Co, 80% Ni, 17% Fe.

All the alloys were prepared from high purity materials by the zone refining and zone leveling techniques described in Section 2.2.2. All three alloys satisfied the seven requirements outlined above (except that Alloy #3 had a coercive force of 5 oe). All three alloys exhibited extremely uniform composition and structure produced by the zone refining and zone leveling processes. Since both Alloy #1 and Alloy #2 had excellent characteristics, they were both used in other phases of this development work and in the final memory plane.

Consequently, we conclude that it is possible, using zone refining and zone leveling techniques, to routinely prepare magnetic permalloy foils of exceptionally uniform composition, so uniform in fact that performance variations caused by compositional fluctuations have never been observed. This is a significant result because compositional fluctuations are a very serious problem in vacuum deposited and electro deposited thin films of permalloy.

The experimental measurements and techniques that we used to arrive at the above conclusions are the same as the techniques described in the following section in which the effects of rolling and annealing procedures on the structure and, hence, on the magnetic characteristics, of the foil are discussed.

2.4.2 Effect on Magnetic Properties of Structural Changes Caused by Rolling

Before discussing how rolling affects structure, a brief explanation is in order of what is meant by "structure of the alloy." We are all familiar with pictures of unit cells of pure metals in which the positions of atoms relative to one another are shown as black dots on the corners or faces of an imaginary cube or hexagon. In the case of pure nickel, the atom positions are on the corners of a cube, with additional nickel atoms at the mid-point of each cube face. Now, if another unit cell is placed next to the first so that the two cells have one common face (i.e. four corner-atoms and one face-atom are common to the two cells), and if this process is repeated in three dimensions until a much larger cube is built up, the atoms in this larger cube are in the same position relative to one another, as are the atoms in a single crystal of nickel. Note that the sequence of atoms in the original unit cell is the same as the sequence of atoms in the entire single crystal. Note, too, that the macroscopic form of the single crystal does not necessarily have to be the same as the form of the unit cell, which in this case is cubic. By adding more unit cells in the X and Y directions than in the Z direction, a single crystal can be built up which is a rectangular parallelepiped. The necessary and sufficient condition, therefore, that a crystal be single is that the sequence of atoms be the same throughout the crystal.

Now, if two single crystals are somehow joined together so that the sequence of atom positions changes at the interface of the crystals, then the crystals are said to form a bicrystal. Similarly, if many single crystals are joined together with a discontinuous sequence at each interface, this aggregate of single crystals is said to form a polycrystalline material. One can also think of this polycrystalline material in terms of an aggregate of unit cells which have varying spatial orientations with respect to one another. If all the unit cells could be made to assume identical orientations, the polycrystalline material would revert to a single crystal.

In a polycrystalline metal, it is common metallurgical practice to refer to the individual single crystals as grains, and to refer to the interface between crystals as a grain boundary. Figure 5 is a photograph taken through a microscope at 100x of the surface of a permalloy foil which was carefully polished and then etched in acid. (In the permalloy we are using, 20% of the nickel atoms have been replaced by iron atoms; however, the sequence of atoms remains the same as that for pure nickel.) The acid attacks the grain boundaries more rapidly than the grains themselves, thus delineating the grain boundaries in the picture. The orientation of each individual grain (single crystal) would have to be determined by the diffraction of a beam of x-rays from each individual grain.

Returning to the original definition, the term "structure of the alloy" refers in this case to the condition of the polycrystalline aggregate. For example, the foil shown in Figure 5 has an annealed structure in which the grains are strain-free and equiaxial. However, an x-ray investigation would show that the orientations of the individual grains are not completely random, rather there is a preferred orientation of the grains caused by the prior rolling and heat treatment. The structure therefore has a preferred orientation or texture.

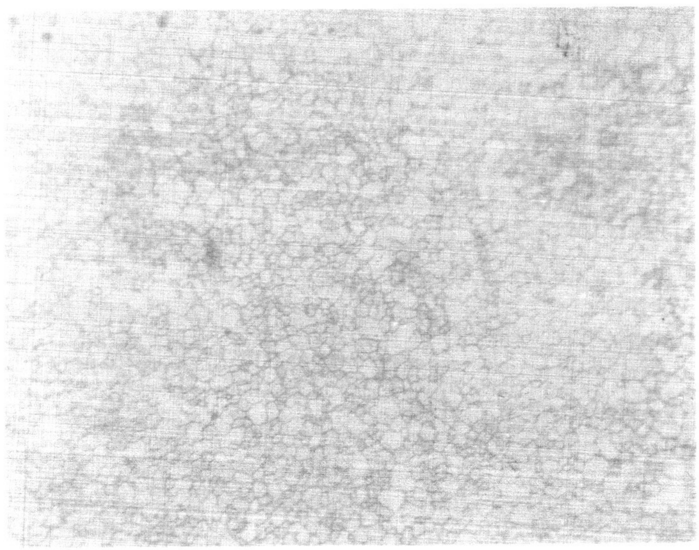


Figure 5

Grain Structure of Annealed

Permalloy Foil

(Magnification 100x)

Similarly, rolling this annealed foil causes equiaxed grains to plastically (irreversibly) elongate and causes some grains to rotate into preferred directions. Consequently, the structure in this case consists of elongated, highly strained grains which have a preferred orientation different from that of the annealed foil. A subsequent re-anneal of this rolled foil at a high temperature (but less than the melting point) supplies enough thermal energy to the strained grains to allow them to spontaneously re-orient themselves, thereby assuming a new grain shape which is free of strain. This process is called recrystallization and occurs entirely in the solid state. Note that although the shape and orientation of the individual grains are changed during recrystallization, the macroscopic shape of the sample is not changed.

As mentioned previously, the reason we are interested in the structure of the alloy is because it has a very great effect on the magnetic properties of material. If the structure is strained, or if there is a preferred orientation in the structure, the magnetic properties will be different than in a strain-free random polycrystal. For example, the energy needed to magnetically saturate an individual grain of the metal (crystalline anisotropy) will vary with different orientations of the grain with respect to the field. Likewise, the change in length of a grain which occurs when the grain is magnetized (magnetostriction) will be different in different directions within the grain. Now, if there is a preferred orientation of grains in the material, then the energy to saturate and the magnetostriction will not be the average bulk values, but rather will be a weighted average that favors the preferred orientation: the magnetic properties will be anisotropic.

It is also important to realize that the properties of polycrystalline structures cannot be anticipated by extrapolating the magnetic characteristics of single crystals. For example, permalloy single crystals of composition near 80 Ni-20 Fe have very little crystalline anisotropy (i.e. they can be magnetized with almost equal ease in each of the three principal crystal directions, [100], [111] and [110]); and they have low magnetostrictive coefficients. However, polycrystalline alloys of the same composition can be made highly anisotropic and can also be sensitive to strain.

2.4.3 Effect of Foil Processing Steps on Magnetic Properties of the Foil

2.4.3.1 Effect of Rolling - Rolling of the zone leveled rods of permalloy into the form of a tape causes grain elongation in the rolling direction. This grain elongation causes the initially spherical grains to become needle-like in shape (similar to the needle-like particles of iron oxide in magnetic tape), and these acicular grains of permalloy prefer, because of demagnetizing forces, to be magnetized only along their length. The result is a pronounced magnetic anisotropy in the foil, even in foils of 81.5% Ni-18.5% Fe, which in annealed single crystal form have low anisotropy energy and magnetostriction coefficients. B-H loops of as-rolled foils of 81.5% Ni-18.5% Fe are shown in Figures 6 and 7 in which the magnetic field is parallel to the rolling direction in the first picture and perpendicular to the rolling direction in the second. The samples are in the form of 1/4 inch diameter spots to avoid shape anisotropy. Figure 8 is a display of the voltage produced in a pickup coil by the switching sample as a function of a sinusoidal magnetic field applied in the rolling direction. The noise on the peak is Barkhausen noise caused by discontinuous domain wall movement; this noise is present in all as-rolled foils and is caused by internal strains. The preceding measurements were made on permalloy melted at MRC and rolled to final thickness without any intermediate annealing. The magnetic characteristics are therefore typical of the preferred orientation of the grains caused by rolling and the distortion (strain) of the grains.

Foil similar to the above was purchased as-rolled from a well-known manufacturer. However, this foil had quite

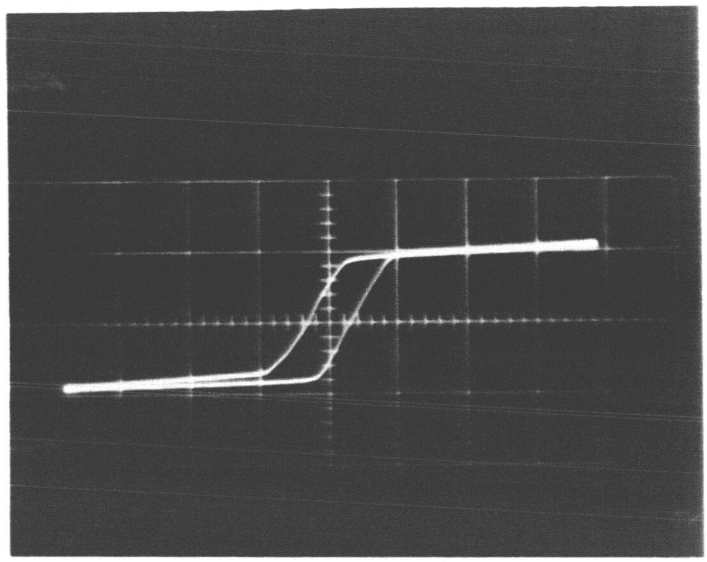


Figure 6

B-H Loop of As-Rolled 81.5% Ni-18.5% Fe Foil (MRC)
Magnetic Field Parallel to Rolling Direction
$H_c = 5.5$ oe

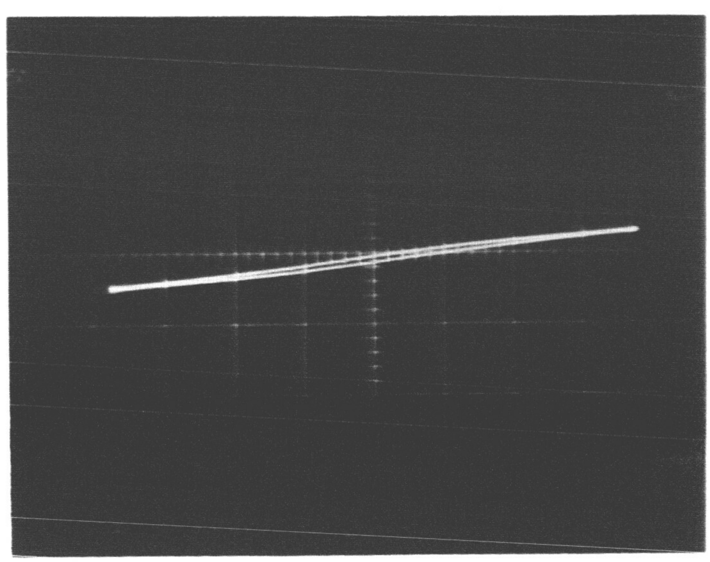


Figure 7

B-H Loop of Same Foil but Magnetic Field Perpendicular to Rolling Direction

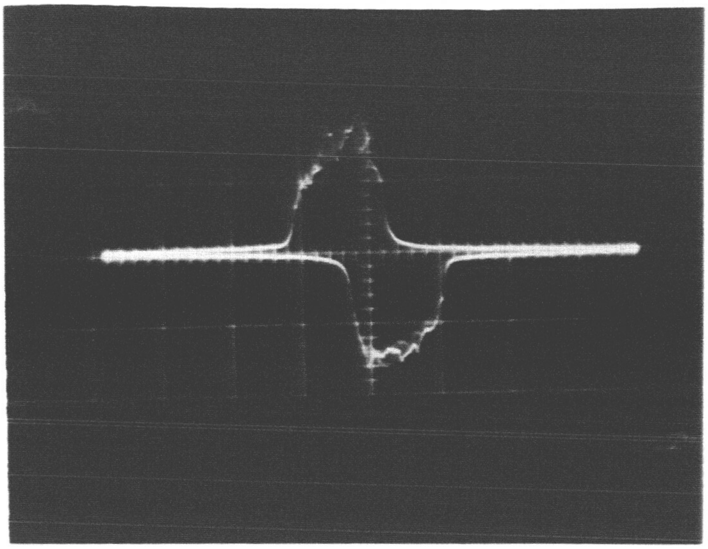


Figure 8

Time Rate of Change of Flux versus 60 cps Magnetic Field. MRC As-Rolled Foil Showing Barkhausen Noise which is completely removed by annealing.

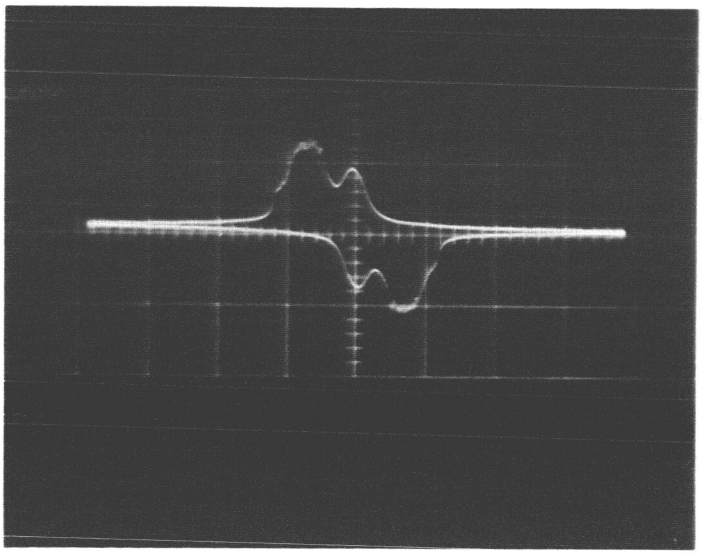


Figure 9

Commercially Available Foil Showing Double Signals Produced by Grains of Rolling Texture and Grains of Annealing Texture.

different characteristics as shown in Figure 9. The larger peak with Barkhausen noise is associated with the as-rolled texture (preferred orientation); the smaller, "clean" peak is associated with an annealed texture. This foil was rolled to a thick tape and apparently had to be stress-relief annealed to allow further reduction to thin tape. The anneal produced an annealing texture which in turn was not completely masked by the subsequently produced rolling texture. Unfortunately, the relative magnitude of the two peaks depends upon the amount of reduction the foil is given following the anneal, and it has been our experience that this is not held constant by the manufacturer, since different batches of "identical" foil supplied to us, although individually uniform, showed noticeable variation from batch to batch. In addition, the intermediate anneal reduces the anisotropy of the foil.

In summary, by cold rolling permalloy rods into foil, it is possible to produce a pronounced magnetic anisotropy even in low magnetostrictive alloys such as 81.5% Ni-18.5% Fe. The anisotropy is caused by the formation of needle-like grains during the rolling process that prefer to be magnetized only along their length. This anisotropy is, of course, very useful since it produces both easy and hard magnetization axes in the foil, which is necessary for magnetic storage of information in a word-organized mode.

2.4.3.2 Effect of Annealing - It is very important to realize that the actual heat treatment has very little direct effect on the magnetic properties of the material; however, the heat treatment has a very large effect on the structure of the alloy and, as explained in Section 2.4.2, it is this change in structure which is responsible for the change of magnetic characteristics of the alloy.

Magnetic alloys of composition 4% Mo - 79% Ni - 17% Fe, and 81.5% Ni - 18.5% Fe were annealed at temperatures between 800° and 1000°C in nitrogen and hydrogen atmospheres, with and without magnetic orienting fields. The amount of cold work prior to annealing was also a variable.

The results of the annealing can be summarized as follows:

1) Annealing the foil for 1 hour between 800° and 1000°C produces strain-free equiaxial grains which have a preferred orientation, but this preferred orientation does not result in a magnetic anisotropy of the foil.

2) Barkhausen noise, which results from discontinuous domain wall movements, is completely eliminated by annealing. The switching peak is therefore more uniform in shape and magnitude.

3) The anisotropy induced by cold rolling is completely removed.

4) The switching time of a given size sample is increased by annealing. This is not an intrinsic effect,

but rather is caused by the loss of cold-worked anisotropy. It has been our observation that any time an anisotropy is introduced into the foil, the switching time is decreased. At 60 cps there is almost a factor of two difference between switching time of the as-rolled and annealed material.

2.4.3.3 Effect of Magnetic Field During Annealing - Some experiments were performed to try to introduce a magnetic anisotropy in the material by applying a magnetic field to the foil during annealing. An anisotropy has been introduced by this method in some composition permalloys and is often successfully used for thin films.

For foils of composition 81.5% Ni-18.5% Fe, and 4% Mo-79% Ni-17% Fe, it was found that the presence of magnetic fields up to 100 oe had no effect on the foils. Neither the B-H loop characteristics, nor the switching speeds were altered. There was also no induced anisotropy. It appears that a magnetic field can induce an anisotropy only in permalloy foils which are strain sensitive, e.g. permalloys of compositions near 50% Ni-50% Fe.

The fact that anisotropies can be induced in thin films of 81.5% Ni-18.5% Fe compositions by the application of a magnetic field during either vapor deposition or electro deposition, is apparently caused by the fact that the atoms have considerable mobility during condensation on the substrate and can be more easily directed by the magnetic field to preferred sites. Furthermore, during vapor and electro deposition, the substrates are not heated above the Curie temperature.

In summary, we have found that magnetic annealing of foils of compositions near 81.5% Ni-18.5% Fe does not produce a magnetic anisotropy, but that a considerable anisotropy can be produced by cold working the foil and also by controlling the shape of the sample.

2.4.3.4 Effect of Grain Size - By controlling the annealing conditions, the average grain size of the foils could be changed throughout the range of 0.3 to 1.5 mils. However, this variation in grain size did not produce any variation in magnetic properties of the foils. Since grain boundaries are known to impede domain wall movements, one can conclude that the average domain size does not lie in the range 0.3 to 1.5 mils. If the domains and grains were approximately the same size, a five-fold variation in grain size would produce a large change in domain wall-grain boundary interactions, which would result in noticeable changes in magnetic properties (Barkhausen noise, switching speeds, etc.). One would expect therefore that the average domain size is less than 0.3 mil; this prediction could be verified with a Kerr magneto-optical apparatus.

2.5 Conclusions

It is possible to draw some very specific conclusions from our materials and processing studies.

1) Through the use of zone refining and zone leveling procedures, it is possible to produce extended lengths of magnetic foil, 6-8 microns thick, of exceptionally uniform composition. This is significant because compositional control is a serious difficulty with vacuum deposited and electro deposited thin films.

2) Through the operation of rolling permalloy rods into foil, it is possible to produce very pronounced magnetic anisotropies, even in low magnetostrictive alloys. The effect is produced by grain elongation, and the resultant anisotropy can be usefully employed in word-organized memory devices.

3) Through the operation of annealing the rolled foil, it is possible to reduce the cold worked anisotropy to any desired degree, or to completely eliminate it. If annealing is carried to completion, the elongated grains recrystallize in the solid state to form new, strain-free equiaxial grains.

4) It is not possible to induce a magnetic anisotropy in foils of 81.5% Ni-18.5% Fe, or 4% Mo-79% Ni-17% Fe alloys by annealing them in a magnetic field, although we recognize that this can be done in thin films of the same compositions.

5) In order to tailor the magnetic properties of the permalloy to fit the specific requirements of a type of magnetic storage device, one should change the properties by altering the structure of the permalloy by rolling and/or stress-relief annealing, and by controlling the geometry of the storage device.

3.0 DEVICE DESIGN STUDIES

3.1 Demagnetization Experiments

It was anticipated at the beginning of this program that the individual memory bits would be composed of two spots of magnetic alloy, one placed above the other, between which there was electrical isolation and magnetic coupling (Fig. 10). Consequently, in the study of the effect of material variables on magnetic properties, the samples which were used were in the form of spots; not double spots in which the magnetic coupling would complicate the interpretation of magnetic characteristics, but rather in the form of single spots.

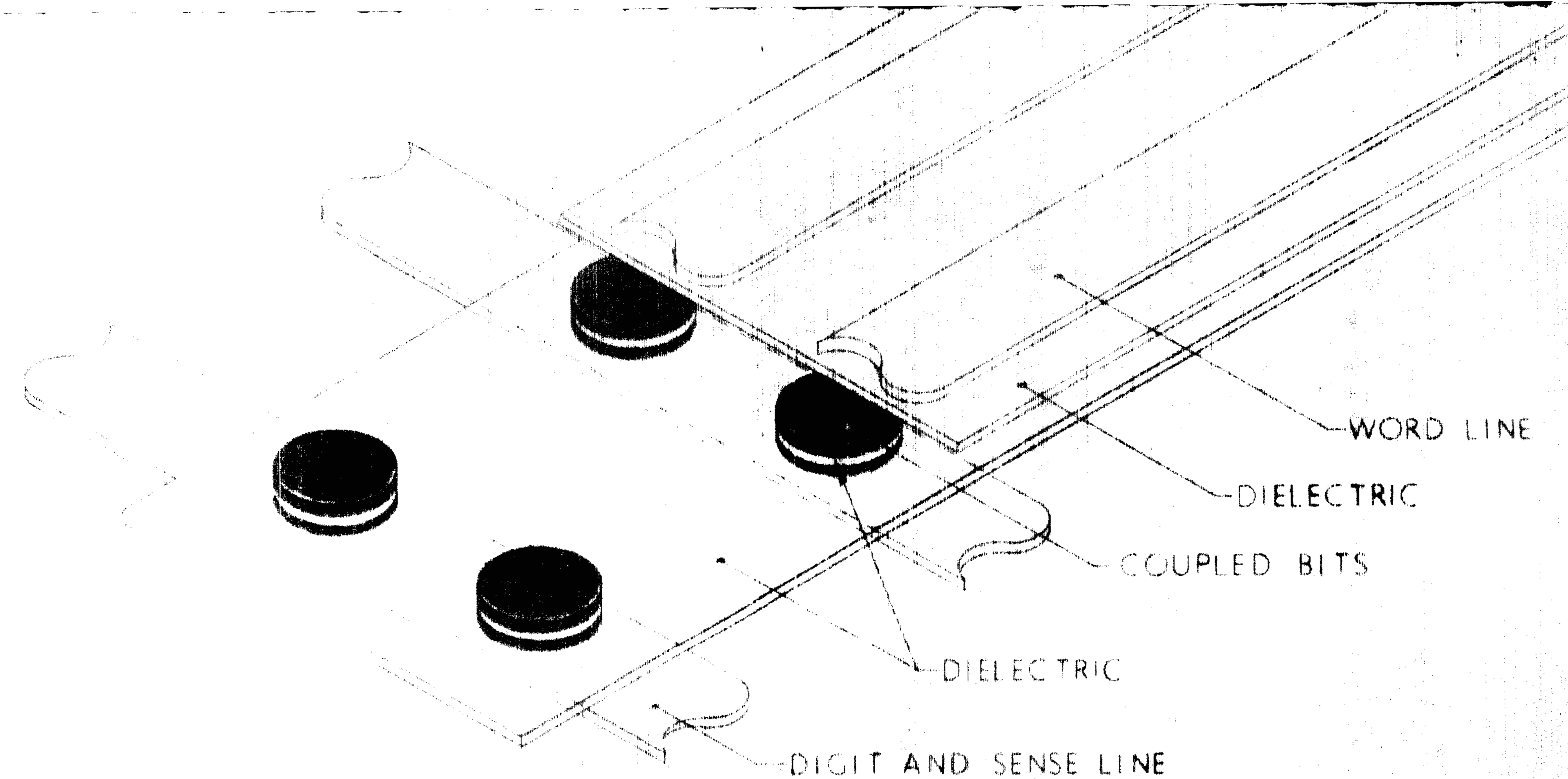
The B-H switching speed measurements which were made using these single spot samples can be summarized as follows:

i) The sample geometry, that is, the diameter to thickness ratio of the spot, had an extremely pronounced effect on the squareness of the B-H loop and upon the switching time. For example, a 1/2 inch diameter spot, 1/2 mil thick, has an as-rolled squareness ratio (Br/Bs) of 0.60, while a 1/4 inch diameter spot of the same thickness has a squareness ratio of only 0.31. The corresponding switching times for 180° rotation at 60cps simusoidal drive is 1.0 ms for the 1/2 inch diameter spot and 2.0 ms for the 1/4 inch diameter spot.

Both the poorer squareness ratio and the longer switching time of the 1/4 inch diameter spot can be directly attributed to demagnetization effects which are more pronounced in this sample with the less favorable diameter to thickness ratio.

The practical consequences of a poor squareness ratio for a bit in a linear select memory is that disturb degradation becomes very serious and output signals are also lowered; the practical consequence of a long switching time is, of course, reduced output signal and increased cycle time.

ii) The importance of the demagnetizing effects was confirmed in the following experiments made on a permalloy strip 1/8 inch wide, 12" long and 1/4 mil thick. The sample was magnetized in the direction of its length but only along a one-inch region in the middle of the strip. The high length to thickness ratio minimized demagnetizing effects in the saturated region. The squareness ratio and the switching time were monitored as small lengths were cut from the ends of the permalloy strip. When the initial 12-inch length had been reduced to 2 inches, the squareness ratio had been reduced by a factor of two and the switching time increased by a factor of three. The effect was again attributed to demagnetization changes within the sample.



Double Element Memory Cell
Figure 10

iii) Finally, two samples were etched from a strip of permalloy with a very pronounced rolling anisotropy: both samples were 1/2 inch long, 1/8 inch wide and 1/2 mil thick. However, one sample was etched so the easy axis lay parallel to the long direction; in the other, the easy axis lay parallel to the width. When both were switched (under identical conditions) along their easy axes, the sample with the easy axis parallel to the sample length (less demagnetization) switched 2.5 times faster than the other sample.

The three sets of experiments summarized above demonstrated very clearly to us how deleterious the effects of demagnetization can be. We conclude therefore that for single layer spots of foils 1/8-1/4 mil (6-8 microns) thick and 1-5 mm in diameter, the excellent magnetic characteristics of permalloy are compromised to such an extent by demagnetization that the single layer foil spots would not be useful in this program.

3.2 Magnetic Coupling of Foil Spots

We proceeded to investigate the extent to which demagnetization was reduced by magnetically coupling two spots. The method of coupling had, of course, to be consistent with our approach of batch fabrication of memories using non-vacuum techniques.

In order to maximize magnetic coupling, it is necessary to bring the two spots as close together as possible; yet in a coupled spot memory bit it is often desirable to have at least one drive line pass between the two spots. If this is done using non-vacuum techniques, the minimum spot separation that can be reliably achieved is 1-2 mils.

We tested the extent of magnetic coupling between such spots by comparing the B-H and switching characteristics of the coupled spots to the characteristics of the single spots previously described.

Unfortunately, there is not a significant enough reduction in either input drive levels or switching time for these coupled spots to claim that they offer a significant improvement over the single layer spots.

3.3 Closed-Flux Path Geometries

In the two-layer coupled spot geometry, it is the high reluctance air gaps which limit the flux in the magnetic circuit. It is the flux-limiting air gaps which require greater drive currents to saturate the magnetic spots, and which lower the squareness ratio and switching speed of the magnetic elements.

In order to optimize the performance of the coupled spot elements, it is necessary to achieve much better magnetic coupling between the spots. Reducing the separation of the spots (despite the fact that we are at the practical limits already) would help but would not be sufficient. The most efficient method is to replace the air gaps with ferromagnetic material which closes the flux path of the spots.

We have made closed flux path toroids from 1/4 mil permalloy foil and have achieved improved performance compared with the coupled spots in the following manner:

1) The squareness ratio increases from 0.31 to 0.60 for single layer spots up to 0.95 for the closed flux path geometry.

2) The coercive force for the closed flux path geometry is a factor of three lower than for single spots.

3) The closed flux path geometry switches 30 times faster.

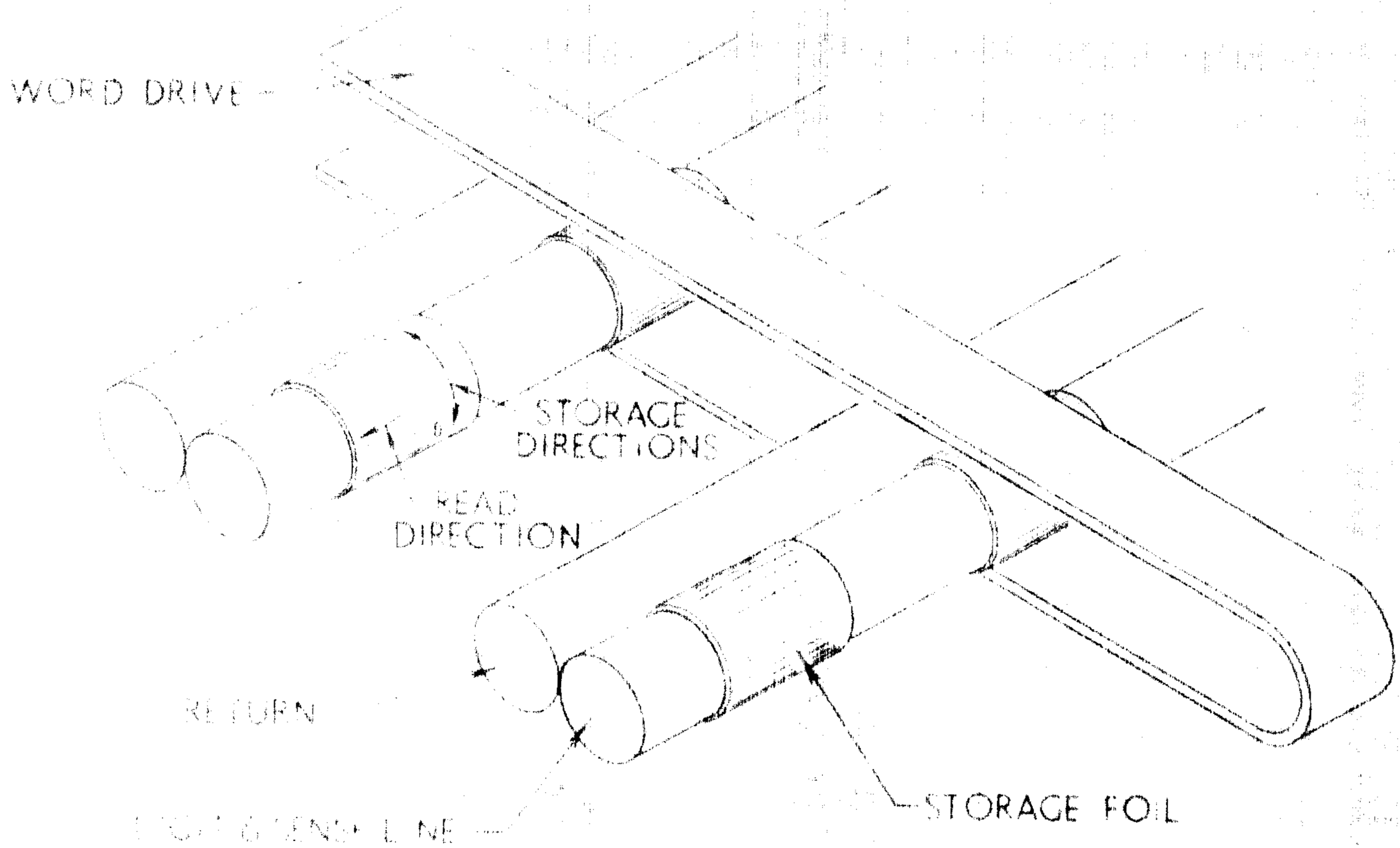
4) There is a pronounced anisotropy between the characteristic of the material when measured along the circumference (closed flux path) as opposed to a measurement along the length (open flux path). There is an easy axis around the circumference of the toroid (storage direction). This anisotropy is a consequence of the shape or geometry of the toroid, and is present even in toroids composed of isotropic foils.

In summary then, we consistently noted, no matter what the composition, purity, rolling or annealing schedule of the foil, that the magnetic properties of any particular foil were always improved by forming the foil into a geometry that permitted a closed magnetic flux path to be established. (Within the context of this program "improved" magnetic properties means an increased squareness ratio, reduced coercive force, and increased switching speed.)

Consequently, we have concentrated our efforts on developing storage elements composed of closed flux path foils, in particular permalloy foils welded onto copper drive lines.

3.4 Intended Operational Mode

The individual storage elements which we developed are composed of permalloy foil (1/4 or 1/2 mil thick) welded onto 10 mil copper alloy wire. (See Figure 11.) These elements, and the manner in which we assemble them are discussed in detail in Section 2, but by first discussing the intended operational mode of the element, one can better understand the reasons underlying certain processing procedures. The element is designed to be used in a memory operated in a word organized (linear select) mode. This mode of operation requires only a two-wire array in which the digit and sense pulses share a common wire. In our storage element, the common wire is the wire on which the foil is mounted; the second wire is orthogonal to the first and is in the form of a twisted one-turn strap.



WELDED FOIL MEMORY
FIGURE 11

In this operational mode, the information of the bit is stored in remanent flux directions around the circumference of the wire. In order to interrogate the bit, the remanent flux is switched parallel to the direction of the wire. In a similar manner, before writing information into the bit, the flux is first switched to the read direction (axial direction) and a digit pulse of the proper polarity is applied to direct the flux into the desired remanent state around the circumference of the wire.

If the axial direction can be made an unstable remanent flux direction, then the digit pulses used to direct the flux from the axial direction into the storage states can be relatively small; that is, relatively small compared with the digit pulses needed to cause 180° switching from one storage state to the other. The reason it is important to use low value digit pulses is that the digit pulses must pass through storage bits in more than one storage word. If the pulses are low enough, they will not disturb the information stored in the bits and yet will write information into all bits which have been "set" into the unstable axial direction.

3.5 Required Magnetic Characteristics of Welded Foil

In order to operate the storage elements in the manner described in the previous section, it is necessary that the welded foil have the magnetic characteristics detailed in Section 2.4.1 and summarized below:

i) The wire ideally must have no remanent flux in the axial direction when the word field is zero, and yet it must saturate in this axial direction for word currents of less than one ampere. The saturation field (H_k) should be less than 10 oersteds.

ii) The wire must store easily in the circumferential direction, and the magnitude of the remanent flux should approach the magnitude of the saturation flux ($Br/Bs = .90$). The coercive force (approximate 180° switching threshold) at the operational frequencies should be about 3-5 oersteds.

There are, of course, other required characteristics such as low magnetostriction and high remanent flux density, but these are a function of the material composition. The two characteristics mentioned above, which will be referred to as B-H characteristics, can be influenced to a certain extent by the fabrication and geometry of the storage element foil.

In summary, a controlled anisotropy must be introduced into the foil; the manner in which this is accomplished is described below.

3.6 Introduction of Anisotropy

3.6.1 Intrinsic Anisotropy

The intrinsic anisotropy is induced by cold rolling the permalloy from rod form into tape. As previously explained, the severe distortion inherent in the rolling operation causes the spherical grains to be elongated in the rolling direction. The result is that the needle-like grains prefer to be magnetized only along their length, producing a direction of easy magnetization along the length of the tape, and directions of hard magnetization along the width and thickness of the tape. The induced anisotropy can be quite pronounced as can be seen in Figures 6 and 7. It should be mentioned that annealing the foil will cause the elongated grains to break up into a number of smaller equiaxial grains, thus eliminating the anisotropy.

The advantage of utilizing this intrinsic anisotropy in a magnetic device is that it is a very intense effect and yet very easy to produce. However, although it is possible to reduce the remanent flux ratio (Br/Bs) in the hard direction to a negligibly small amount, it is difficult to do this and yet have saturation occur in the hard direction for fields of less than 10 oersteds, since the two effects vary inversely.

3.6.2 Shape Anisotropy

If a magnetic material is completely isotropic, it can still exhibit appreciable anisotropic magnetic properties by being formed into a sample with at least one size dimension different from the others by a factor of ten. The cause of this "shape" anisotropy is the presence of virtual demagnetizing fields which are present at the surfaces of all magnetic material. These surface demagnetizing effects can influence the internal flux density of the sample to a greater degree along the short dimensions of the sample.

Another way to envision the effects of shape anisotropy is to picture a magnetic material in the form of a cube. When saturation occurs in any direction in the cube, there must be an external flux closure path through the surrounding air. Since the reluctance of the air path is so much greater than the reluctance of the magnetic material, it is the reluctance of the air path that limits the flux of the magnetic circuit composed of the magnetic cube and air.

Now, if one dimension of the cube is appreciably decreased with respect to the other cube dimensions, the air path of the external flux associated with this short dimension has increased, and hence, so has the total reluctance of the air path. This increased reluctance will further limit the flux density which can be established along the short dimension; consequently, this direction will become a "hard" magnetization direction. Note that this argument is valid only if there is external flux closure.

When the foil is welded into a toroid around a wire, there is a closed flux path within the material in the circumferential direction, and hence no demagnetizing effects in this direction. However, when the flux is switched into a direction parallel with the toroid axis, there must be external flux closure. Consequently, this direction is a hard direction of magnetization. The result is that the toroid, which is made from isotropic material, has anisotropic properties and can be used as a memory element in the manner which has been described in section 3.4.

It is important to realize that the axial direction can be made a "harder" direction by reducing the length of the toroid. For example, a toroid 50 mil in diameter and 1/2 inch long has a saturation field in the hard direction of 13 oersteds and a value for Br/Bs of 0.50. If the toroid length is reduced to 1/8", the values become 20 oersteds for saturation and 0.20 for Br/Bs. Similarly, for a 1/16" length, the saturation and remanent ratios are 50 oersteds and 0.08 respectively. It is therefore very easy to choose a toroid length with the proper balance between the saturation field and remanent ratio in the hard direction. It should also be mentioned that, in the circumferential direction (easy direction), the value of Br/Bs is 0.98 and the coercive force is 2.5 oersteds.

In summary, we find it more convenient to establish the desired anisotropy in the memory cell by controlling the size and shape of the element rather than by introducing the anisotropy solely by cold working the foil.

3.7 Welded Foil Geometry

As a result of our design studies, we concluded that optimum performance from a magnetic foil used as a magnetic storage element would be achieved if the foil had a closed flux path geometry in the storage direction, and if the desired anisotropy was introduced in the hard direction by controlling the shape of the element, e.g. controlling the ratios of length, diameter and thickness of a toroid.

Using the element's dimensions to adjust the anisotropy was found to be operationally easier than using the structural anisotropy of the foil which is introduced to the desired degree by rolling and annealing.

We had previously concluded from our materials and processing studies, that it was meaningful to use metallic foils to produce magnetic storage elements of uniform performance.

The storage element which resulted from these considerations was a foil of permalloy (81.5% Ni-18.5% Fe) that was welded onto a copper alloy wire so that the foil formed a toroid 125 mils long, 10 mils diameter, with 1/4 mil wall thickness. (See Figure 11.)

The circumferential directions of the toroid are directions of easy magnetization and can be used as information storage states; the axial direction of the toroid has been made a hard direction by utilizing shape anisotropy, and it is this axial direction into which the flux of element is swung during the read cycle.

Binary information is written into the storage element by passing either a positive or negative pulse along the copper alloy support wire. The resultant magnetic field sets the element into the desired circumferential storage direction. The stored information can be read or extracted from the element by passing a positive pulse along the word strap shown in Figure 11. The magnetic field caused by this pulse swings the stored flux parallel to the axis of the toroid, thereby creating a voltage pulse in the copper alloy support wire. The polarity of this voltage pulse is determined by the storage direction from which the stored flux emerged and, hence, is related to the information stored in the bit.

3.7.1 Magnetic Characteristics of Discrete Storage Elements

The magnetic characteristics of individual welded foil storage elements are as follows:

Alloy: 81.5% Ni-18.5% Fe, or 4% Mo-79% Ni-17% Fe.

Squareness Ratio (Br/Bs): .98

D.C. Coercive Force (H_c): 2.5 oersteds

Hard Direction Saturation Magnetomotive Force (H_k): 20 oersteds

3.7.2 Operational Characteristics of Discrete Storage Elements

The operational characteristics of the storage elements are more significantly described for an array of elements plus associated electronics, i.e. for the complete memory system. Such a system description is given in Section 4.5; however, some typical ranges of operational conditions for individual storage elements are given below.

Read Cycle:

Read Current I_W	0.8-1.0 amps.
Pulse Risetimes	50-100 nanosec.
Pulse Widths	0.5-1.0 microsec.

Flux Switching Time (from storage state to read state) under above conditions: 200-500 nanosec.

Output Voltage	$\pm$ 1 mv.

Write Cycle:

Write operations must be preceded by a read operation in order to set the flux into the metastable axial direction. This is a consequence of the word-organized mode of intended operation.

Write Currents I_d	$\pm$ 250-400 milliamps.
Pulse Risetimes	50-100 nanosec.
Pulse Widths	0.5-1.0 microsec.

3.8 Welding Procedure

All welding is presently being done by manually positioning the foil between miniature electrodes of a spot welder. The process can be automated by using commercial seam welders, but the volume of welding we are presently doing does not justify the more elaborate apparatus.

The first step in the operation is to tack-weld the edge of the foil to the core wire. This core wire, which is used as the digit and sense line of the memory, is usually made of 10 mil diameter phosphor-bronze alloy for ease of welding. After tack-welding the edge of the wire to the core, the foil is wrapped in a single turn around the wire until it overlaps the first edge, and then the overlap seam is spot-welded along its length. The welded spots are themselves overlapped so as to produce a seam weld. The final storage element is thus a toroid made from a foil 1/4 to 1/2 mil thick, and 1/16 to 1/8 inch long, welded to a copper alloy wire. The final memory will have as many toroids on a single wire as there are words in a plane.

It is important to note that the welded seam does not produce a discontinuity in the magnetic flux path of the toroid. This was confirmed in a number of experiments, and is consistent with the fact that the as-welded metallurgical structure is similar to the as-annealed structure of the rest of the foil.

3.9 Advantages and Disadvantages of This Storage Element Design

The advantages of welding the foil to the wire are as follows:

1) The element has a closed flux path geometry in the storage direction with the attendant improvement in performance characteristics.

2) There is excellent coupling between the bit and the digit and sense line.

3) The material need not be disproportionated in order to put it in the wire as is the case when the permalloy is either electroplated or vapor-deposited on a substrate. This is extremely important from a quality control point of view.

4) The fabricating procedure is a continuous, rather than batch, process which allows a higher yield to be realized. In a continuous process each bit can be tested before final assembly and defected ones rejected; in a batch process the acceptance of the entire batch-fabricated plane depends upon the acceptance of each and every bit within the plane since the bits cannot be altered.

5) It is very easy, using this process, to change the composition or the thickness of the magnetic material. It is, of course, possible with this technique to use multi-component alloys as the storage material. One, therefore, can take advantage of an extensive range of material characteristics that are not available from the electroplated or vapor-deposited technique.

The disadvantages of this technique are:

1) The foil switches by domain wall movement rather than by the coherent rotation mechanism of thin films. As a result, the foil will not switch much faster than 200 nanoseconds.

2) The drive currents are somewhat higher for the foils compared with thin films. However, since thin films cannot be driven by integrated circuits either, the difference in drive currents may not be significant.

In summary, the foil technology is clearly superior to thin film technology in producing magnetic materials of uniform composition, structure and performance. However, in high speed or exceptionally low drive current applications, the thin metallic films are more appropriate.

4.0 CARD PROGRAMMABLE MEMORY SYSTEM

4.1 Introduction

The welded foil element that we developed is capable of being operated in a conventional read/write memory using a linear select organization. When the element is used in such a memory, its purpose, of course, is to store information.

However, the welded foil element can be used in another type of memory in which the element is used as a magnetic field detector. In this type of memory, information is stored on magnetic cards and the welded foil elements are used to detect the information on the cards. The result is a card programmable memory system in which a vast amount of data can be compactly stored on magnetic cards.

A plane of these foil elements is very well suited to reading information from magnetic cards. The plane itself is of favorable geometry for interfacing with magnetic cards: the planes have the required sensitivity and they are also rugged enough to be used in contact with cards that are repeatedly inserted and removed.

An investigation revealed to us that there is very little developmental work in progress on card programmable memories, and yet there is a rapidly increasing need for these memories in industry, defense and space. These applications are detailed in Section 5.0, but they include the areas of security, inventory control, identification friend or foe (IFF) systems, BORAM systems, read-only memories, and generation of digital pulse trains.

Since the need for card programmable memories is fast outstripping the development work on these memories, and since our welded foil elements could make a meaningful contribution in this area, we decided to concentrate our efforts on developing an improved card programmable memory.

The result of this development work was the card programmable memory system shown in Figure 12. The system consists of magnetic cards for information storage, an encoding unit for entering the information on the card, and a reader unit for rapidly extracting the information from the card. Complete descriptions of the magnetic cards, the encoding unit, and the reader unit are given in Section 4.2 through 4.5.

4.2 The Magnetic Storage Card

4.2.1 Physical Characteristics

The present storage card is 2 1/4 inches wide by 3 3/4 inches long by 0.050 inch thick, and is composed of magnetic bits laminated between two sheets of vinyl. The card is humidity resistant, can be placed in boiling water without softening, is rigid and abrasive resistant, and cannot be folded, spindled or easily mutilated. Although the card can be destroyed by fire, it cannot be ignited, and is physically very durable. It would be very difficult to alter the stored information.

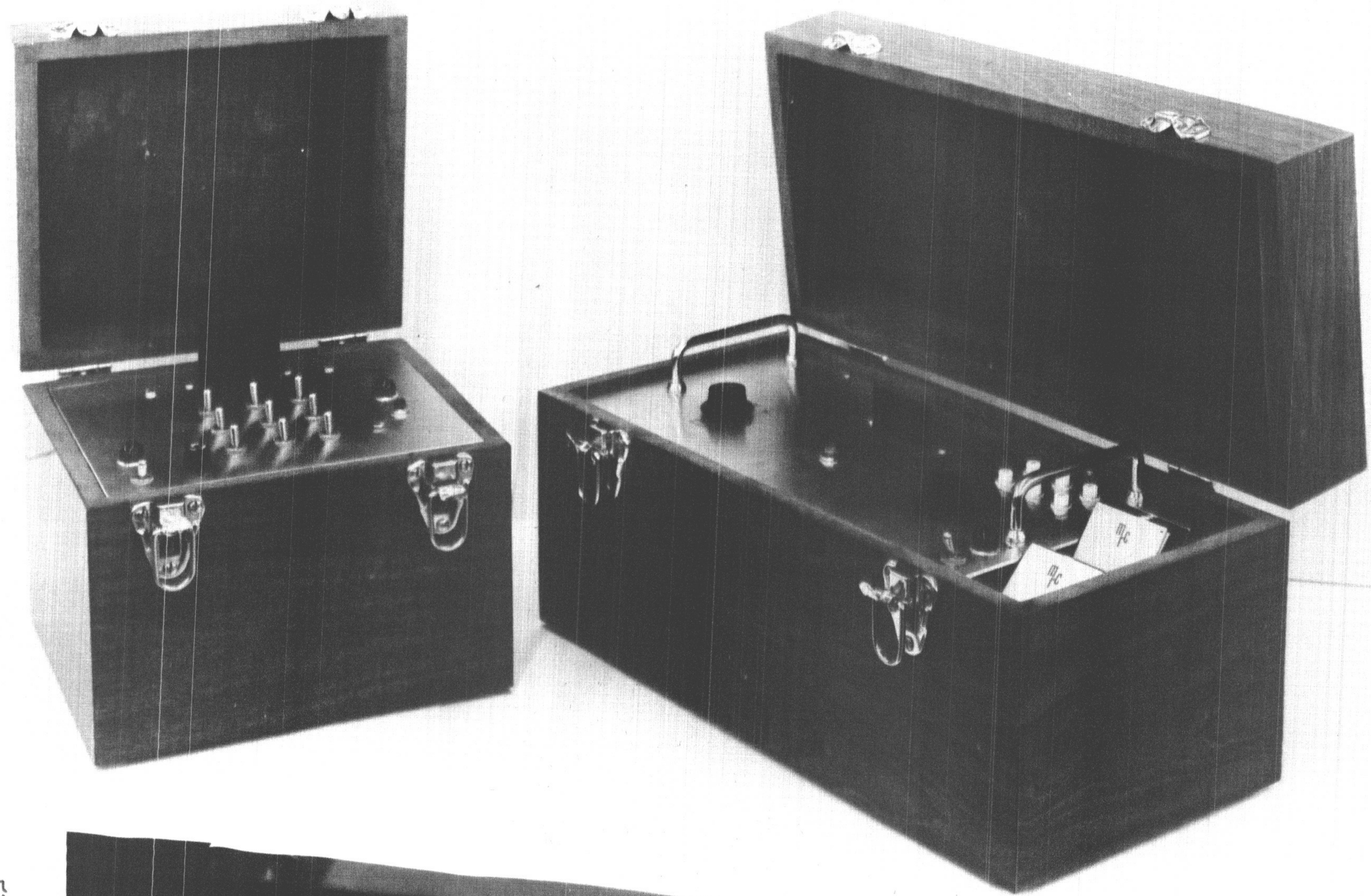


Figure 12 - The Card Encoder and Card Reader

4.2.2 Magnetic Characteristics

The storage medium is a one-mil foil of a cobalt-iron-vanadium (52-38-10) alloy that has a preferred anisotropy induced by rolling; that is, the foil prefers to be magnetized along the rolling direction.

The D.C. coercive force of the material is about 300 oe for a closed flux path geometry, and the remanent flux density is about 8800 gauss. It is the high value of the coercive force that makes it difficult to accidentally alter the information on the card by placing it near electronic equipment. (Note: The coercive force of permalloy, a nickel-iron alloy, is only 0.05 oe, and this alloy can be disturbed by the earth's field.) It is worth mentioning that a #12 copper wire carrying a 20 ampere current produces a magnetic field of only 4 oe. The information contained on the cards has proven to be very durably stored. The fact that the information is stored in binary, rather than analog form, would help to prevent degradation even if the card were somehow exposed to an intense field (>200 oe).

The magnetic alloy inside the card is not a continuous foil but rather has been etched into discrete bits. At present, the prototype cards have bits in the form of squares 1/8 inch by 1/8 inch on 3/8 inch centers in the X direction, and 1/4 inch centers in the Y direction. At this packing density, each 2 1/4 inch by 3 3/4 inch card can contain 90 bits, and a single column card-magazine one foot long can at present contain 2.3×10^4 bits. We anticipate a significant increase in the storage capacity of the card, since we have not begun to approach the interaction distance of the bits. Based on our preliminary work, we expect to easily produce a packing density of 50 bits/sq. in. which is equivalent to 4×10^6 bits/cu. ft.

4.3 The Encoding Unit

The magnetic bits prefer to be magnetized in only two directions: either parallel or anti-parallel to the rolling direction of the foil. When the bits are exposed to a magnetic field that is large enough to magnetically saturate them in either of these directions, it is the nature of the bits to remain almost completely saturated in the magnetization direction, even when the magnetic field is removed. Consequently, these two saturation states or directions can be used to store binary information.

Information can be written on the cards by placing each bit across the poles of an electromagnet; the polarity of the magnet current determines whether the bit is magnetized parallel or anti-parallel to the rolling direction.

In practice, the storage card is inserted in an Encoder and is automatically positioned in front of an array of electromagnets which simultaneously write information into all the bits. The Encoder is shown in Figure 12. A block diagram of the encoder is shown in Figure 13, and a schematic circuit diagram of the unit appears in Engineering Drawing #001 at the end of this report. The toggle switches on the top panel are used to determine the sense of the currents in the individual electromagnets, and hence the information stored in each bit. For laboratory operation, the switch array (binary input) is convenient, but for a field unit the switch array would be replaced by binary coded decimal (BCD) encoding dials.

When information is wirtten on the card, the operator usually demands a verification display of the information. Since a permanent display and record of the information is desirable, we plan to use a binary printer in conjunction with the Encoder.

4.4 The Magnetic Card Reader

4.4.1 The Detector Plane

The welded foil elements were assembled into an engineering model of a typical detector plane. The first planes contained nine detectors (3 words x 3 bits) and were assembled using the same materials and techniques that would be used in a larger array.

The detectors are mounted on a rectangular glass epoxy board in which there is a rectangular window. The outer dimensions of the board are 3 3/8 in. by 2 1/2 in. by 1/16 in.; the dimensions of the window are 1 1/4 in. by 1 1/8 in.

BLOCK DIAGRAM OF CARD ENCODER

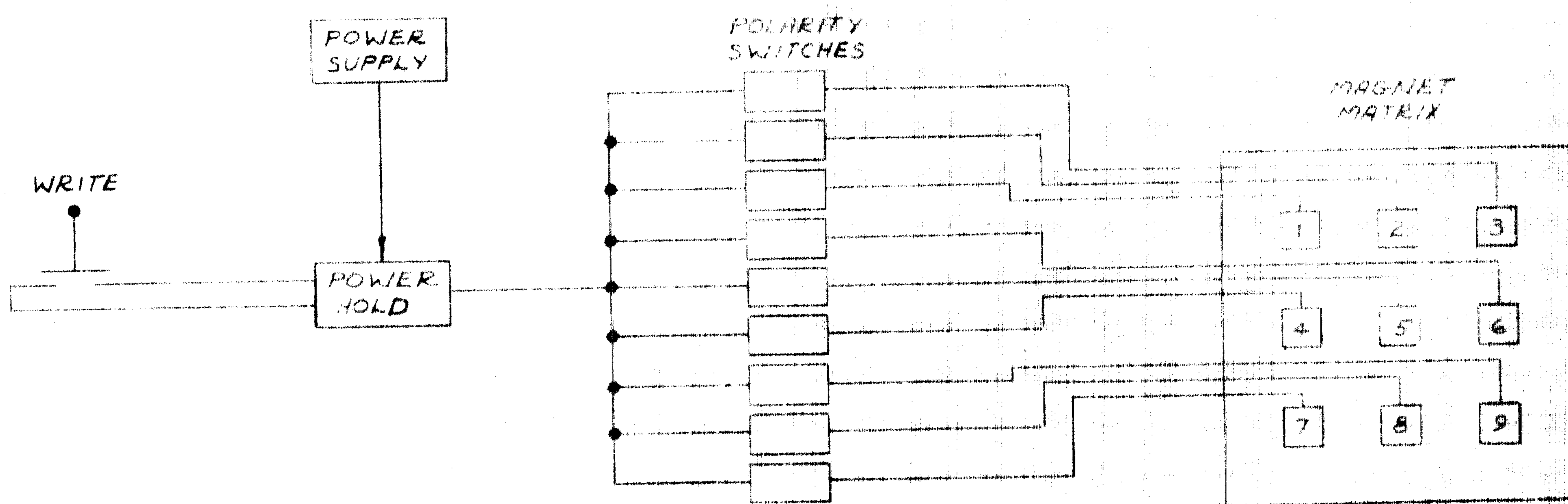


Figure 13

CONTRACT #NAS 11986

There are three parallel lines of detectors strung across the window in the board. On each detector line there are three welded foil elements, which as previously described, are 1/8 in. long toroids mounted on 3/8 in. centers. There are also three word lines that run in a direction perpendicular to the detector lines, and pass over the detector lines at the location of the toroids. These word lines are two twisted pairs of 7 mil copper wires that are wired so that they form a virtual two-turn solenoid around each toroid. It is these word lines that carry the read current which is used to set the flux of the toroid into the axial direction.

In the original design the word lines were straps that made a single pass around the toroids. However, by using twisted pair word lines, there is improved magnetic coupling to the bit and, just as important, there is an attendant reduction in spurious coupling between the word and sense lines. The combined result is a significant improvement in the signal-to-noise ratio of the switching device.

There is one other set of lines on the planes. These are three 10 mil copper wires that are run parallel to each detector line, and are electrically connected to one end of each of the detector lines. These return lines cause more effective pickup of the flux changes that occur during the read operation.

4.4.2 The Interaction of Card and Plane

As previously mentioned, information is stored in the card bits by saturing them in a direction either parallel or anti-parallel to the rolling direction of the foil. The same amount of flux is stored in both saturation directions, the difference in state is one of polarity. Consequently, the mechanism of reading must be capable of distinguishing polarities of magnetization rather than flux levels.

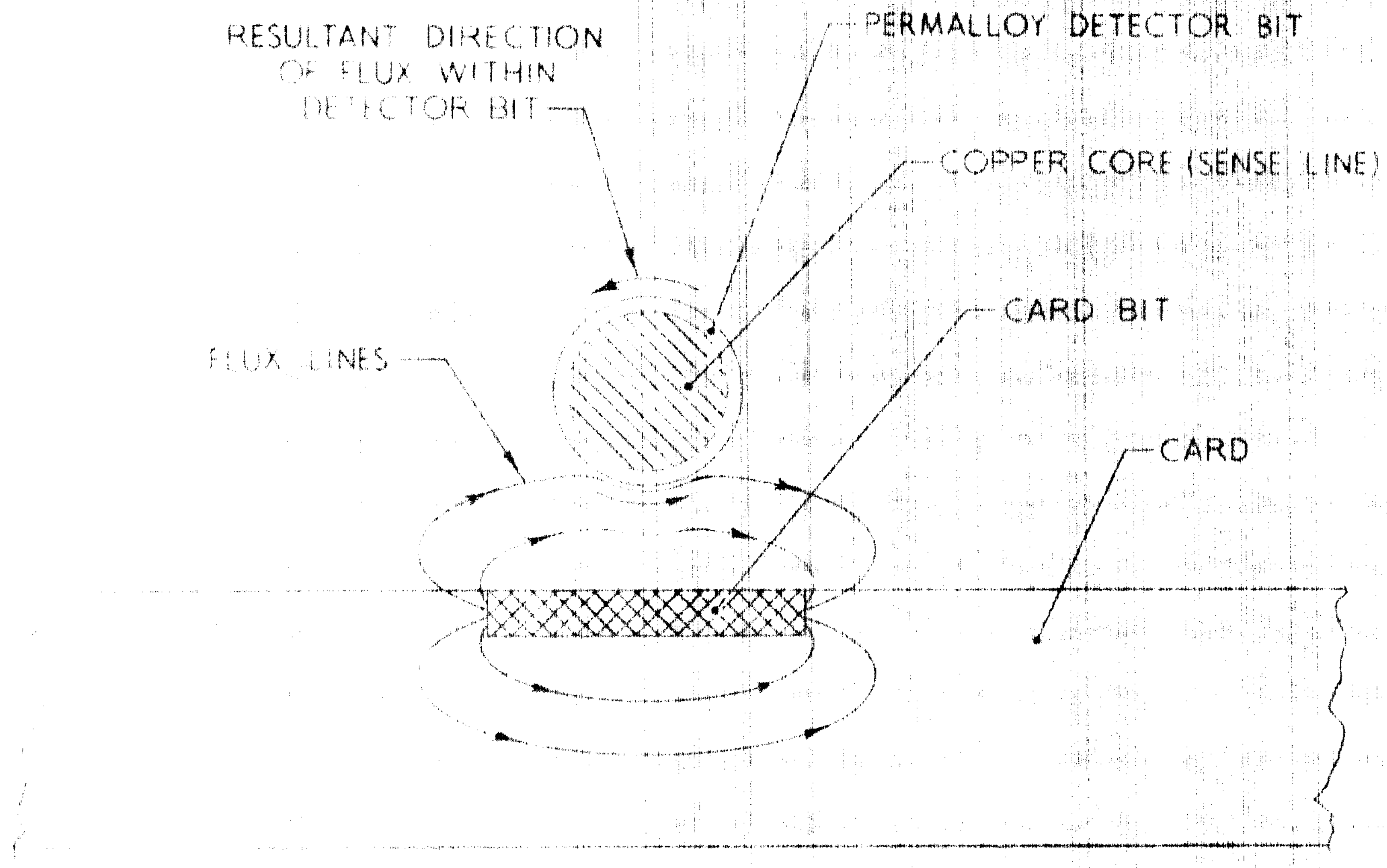
The polarity of magnetization is determined by sampling the external closure flux surrounding each bit. Since each card bit has a planar geometry and is in a state of saturation, it is necessary that flux closure occurs externally. The polarity of this closure flux is, of course, determined by the polarity of the flux within the bit. Each detector within the card reader intercepts only a small portion of the flux external to each bit; the intercepted field levels are about 20 oersteds per bit.

The detectors within the card reader which sense the polarity of magnetization are the welded foil elements. As explained in Section 3.7, the flux within the welded foil prefers to remain in a state of saturation directed around the circumference of the tube. The flux can reside in either sense around the circumference.

Now the reason this element can sense the polarity of the bits on the magnetic card is that the polarity of the external field of each bit is capable of controlling the circumferential direction in which the flux of the detector tube will reside. Therefore, when the detector tube flux is swung along the tube length to produce a voltage, the polarity of this voltage pulse will reflect the polarity of the bit on the magnetic card. The relationship between the card bit and the detector element is illustrated in Figure 14.

The magnetic field required to switch the flux of the detector from one circumferential direction to the other is only about 0.5 oe, and as mentioned previously, the detector intercepts a field of about 20 oe from each bit. Now, because of the soft magnetic nature (low coercive force) of the permalloy detector, it requires a relatively low field and hence low power, to swing the circumferential flux into an axial direction and thus produce a voltage. Furthermore, the high remanent flux density of permalloy (6000 gauss) produces a high voltage when switched. It is important to note that the low field level (about 10-20 oe) which causes the flux in the detector to swing into an axial direction, has no effect on the flux stored in the magnetic card bits since this material has a coercive force of about 300 oe.

In practice, the circumferential flux of the detector is swung into an axial position by placing the detector element inside a virtual two-turn solenoid through which can be passed one ampere pulses.



RELATIONSHIP OF DETECTOR BIT TO CARD BIT

Figure 14

In summary then, the polarity of the external flux of each magnetic card bit controls the storage direction of the detector element. When the flux of the detector element is swung into an axial direction, the polarity of the resultant voltage reflects the polarity, and hence the information, of the magnetic card bits. The advantage of this method is that the information contained on the magnetic card is in no way disturbed by the interrogation, and furthermore, the power required for interrogation is considerably reduced.

There is a detector element in the Reader box for every bit contained on the magnetic card. The detectors are electronically operated in a word organized mode, that is, the information is addressed in blocks (words) and the outputs of each bit within a word are simultaneously sensed. It would be possible, of course, to have only one set of detector elements in the Reader, and to mechanically move each word underneath the detectors. The system, however, is considerably more simple, faster and reliable by eliminating the mechanical movements.

4.5 The Card Reader Electronics

The electronics associated with the card reader must perform two operations: first, it must drive the circumferential flux of the detector into an axial direction, and second, it must be capable of sensing and amplifying the resultant voltage. The circuits which perform these operations are described below. It is worth noting the simplicity of these circuits, since it is this simplicity which produces the high reliability of the system.

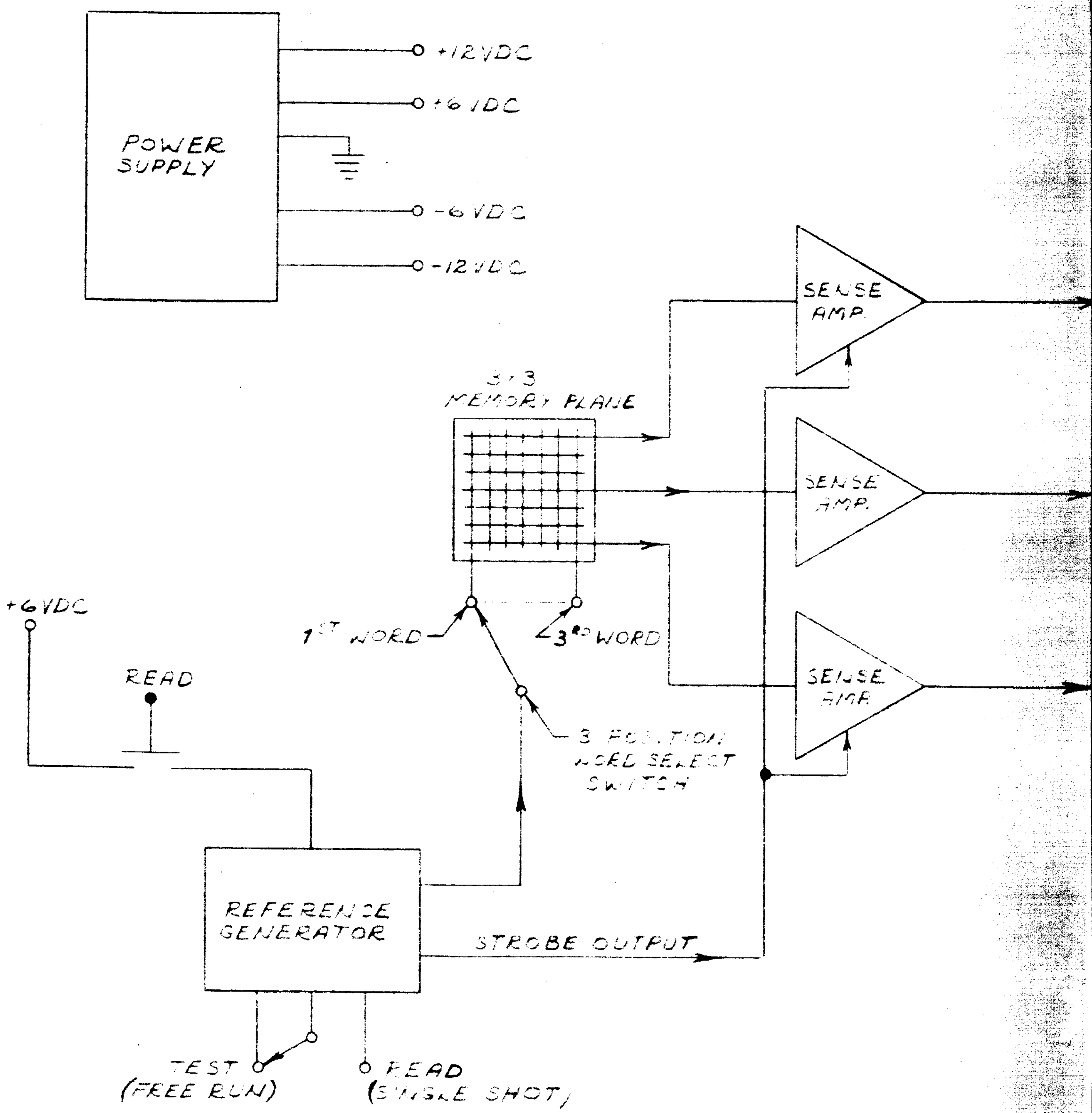
Due to the word organized mode of operation, there is one word drive circuit which is sequentially switched from word to word. However, there is one amplifier circuit for each bit in any word, and this results in a faster, simultaneous read-out of the information on the card. A block diagram of the card reader is shown in Figure 15.

4.5.1 Drive Circuits

The drive circuit supplies a "read" pulse to the two-turn solenoid that causes the circumferential flux of the detector to swing into the axial direction. In the present system, the drive circuit supplies to the word solenoid a one-ampere pulse, 500 nanoseconds wide, with a 50 nanosecond risetime. The drive circuit is a reference generator which is composed of an oscillator (0.2-1.0 mc), a single-shot multivibrator, a high speed power switch, and a network to compensate for word line inductance. One end of the word solenoid is held at +12 volts, the other end is grounded through the power switch. (See Engineering Drawings #002 and #003 at the end of this report.)

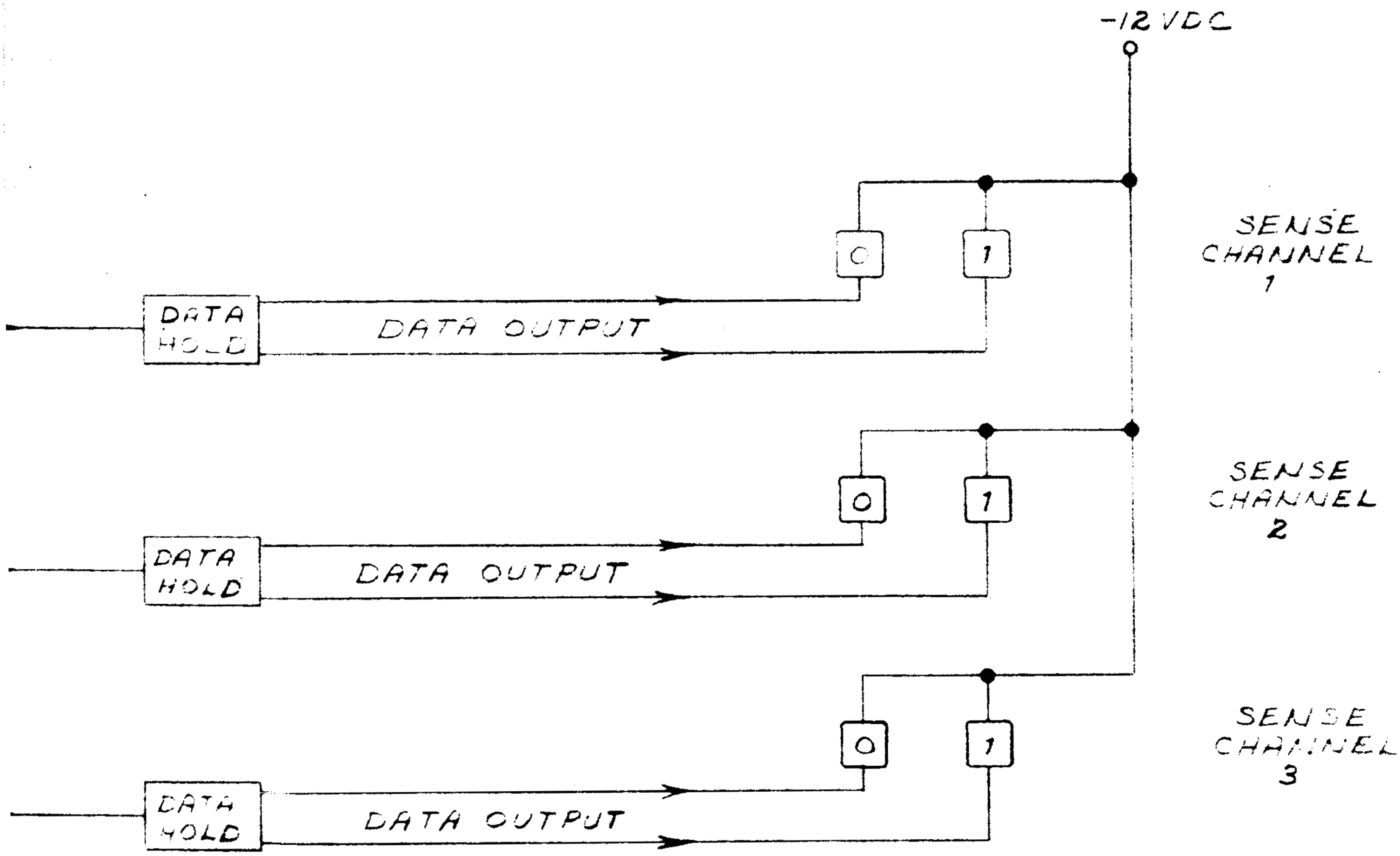
4.5.2 Amplifying Circuits

The output signal produced by the detector element is fed into a pulse transformer with an insertion gain of 6:1.


POWER SUPPLY
+12VDC
+6VDC
-6VDC
-12VDC
SENSE AMP.
SENSE AMP.
SENSE AMP.
3×3 MEMORY PLANE
+6VDC
1ST WORD
3RD WORD
READ
3 POSITION WORD SELECT SWITCH
REFERENCE GENERATOR
STROBE OUTPUT
TEST (FREE RUN)
READ (SINGLE SHOT)

FIGU

...M OF CARD READER

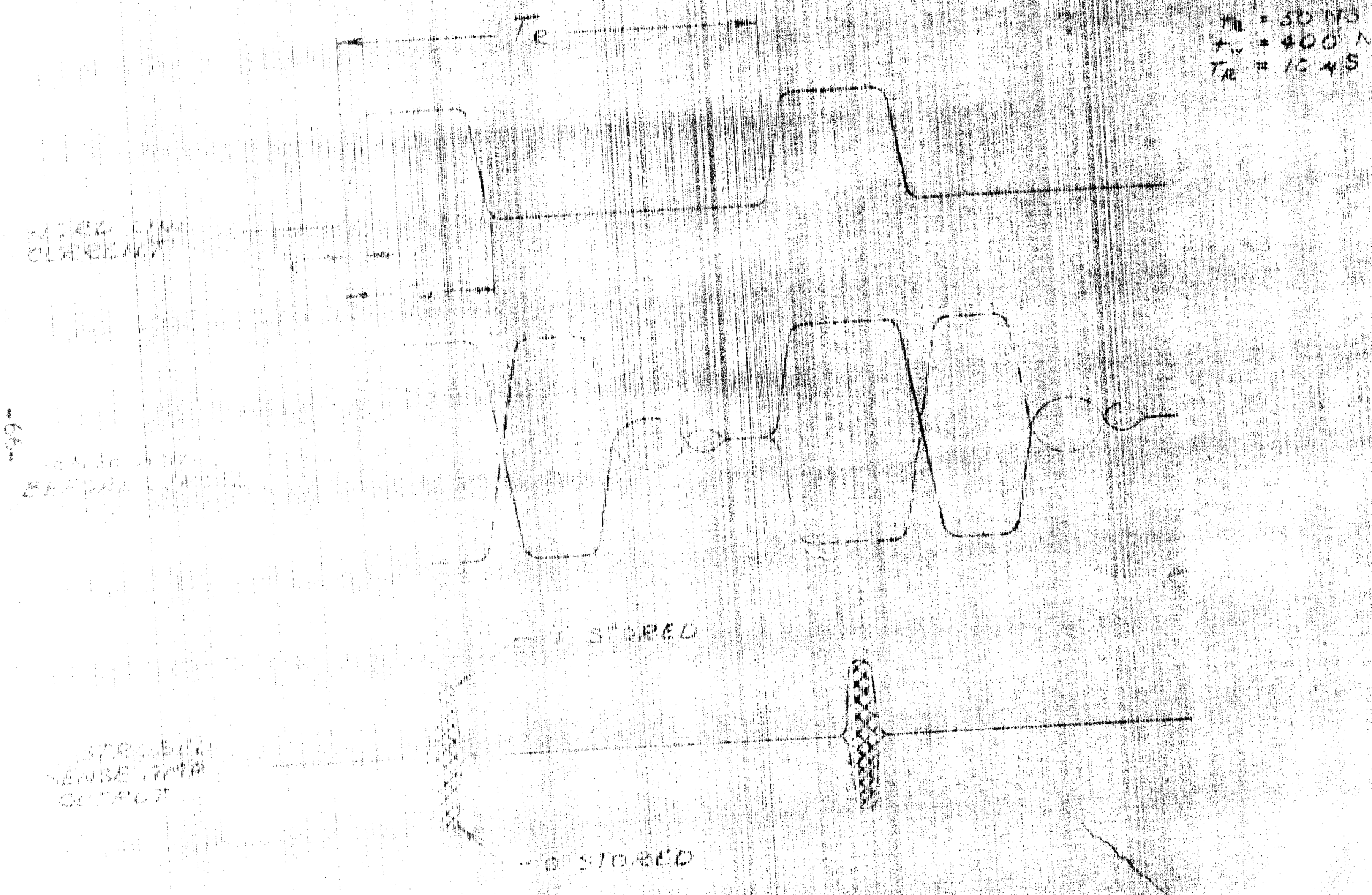


This transformer precedes the first two differential stages of the sense amplifier, which has a high common mode rejection (>80 db) at these operational frequencies. At this point, the signal is strobed by a gate which is activated by a single-shot multivibrator in the reference generator. (See timing diagram in Figure 16.) The strobed output signal is further amplified by a complementary stage and stored in a bistable multivibrator. The three amplifier stages have a gain greater than 4000. At present, the multivibrator is connected to a semiconductor switch which is capable of switching 24 volts at current levels above 100 ma; however, this capacity can be easily increased.

It is at this point that the buffer stages could be added to interface the card reader with other display, computational or control systems.

The sense and hold circuits are shown in Engineering Drawing #004.

TIMING DIAGRAM OF CARD READER



CONTRACT # NAS 11986

FIGURE 16

5.0 APPLICATIONS OF CARD PROGRAMMABLE MEMORIES

There is a rapidly increasing need for card programmable memories in industry, defense and space.

In industry, the areas of application are in control and security. In the area of control, the memory system can be used in inventory control, plant maintenance control, shipping and receiving records, invoicing, and production job-costing. In each case the magnetic cards are used as unit records that are associated with a particular item or job. The rugged nature of the cards makes them particularly well-suited for these field applications. In the area of security, the cards are used for personnel identification and as pass-cards to provide access to secured areas.

In defense, the areas of applications are again control and security. But now the area of control includes, not only the applications as discussed above, but also control of operations. For example, the card programmable memories are useful for block-oriented random-access memories (BORAM), and are used by the Army for storing field data, such as firing tables, codes-of-the-day, etc. In the area of security, the cards are particularly well-suited for battleground identification friend-or-foe (IFF) systems.

In space, the card programmable memory is useful for storing contingency programs on board manned flight vehicles for deep space missions. Before a mission begins, it is possible to predict the difficulties that would be produced if a component were to fail in flight. As a result, a contingency program can be stored on magnetic cards that would adjust other on-board systems to compensate for the component failure. On deep space probes, these programs would have to be carried on board rather than held at a terrestial base, due to the communication time lags on these missions. It is very efficient to store these programs on cards because a large number of programs can be compactly stored in the flight vehicle. These cards remain completely independent of the central processing computer unless needed; consequently, the computer need not be burdened with a large mass of data which it is unlikely to use.

6.0 CONCLUSIONS

The conclusions that result from this work can be summarized as follows:

PHASE I - MATERIALS AND PROCESSING

1. Through the use of zone refining and zone leveling procedures, it is possible to produce extended lengths of magnetic foil 6-8 microns thick, of exceptionally uniform composition. This is significant because compositional control is a serious difficulty with vacuum deposited and electro deposited thin films.

2. Through the operation of rolling permalloy rods into foil, it is possible to produce very pronounced magnetic anisotropies, even in low magnetostrictive alloys. The effect is produced by grain elongation, and the resultant anisotropy can be usefully employed in word organized memory devices.

3. Through the operation of annealing the rolled foil, it is possible to reduce the cold worked anisotropy to any desired degree, or to completely eliminate it. If annealing is carried to completion, the elongated grains recrystallize in the solid state to form new, strain-free equiaxial grains.

4. It is not possible to induce a magnetic anisotropy in foils of 81.5% Ni-18.5% Fe, or 4% Mo-79% Ni-17% Fe alloys by annealing them in a magnetic field, although we recognize that this can be done in thin films of the same compositions.

5. It is possible to tailor the magnetic characteristics of alloys of both 81.5% Ni-18.5% Fe, and 4% Mo-79% Ni-17% Fe for use in word organized memories.

PHASE II - DEVICE DESIGN

1. The element has a closed flux path geometry in the storage direction with the attendant improvement in performance characteristics.

2. There is excellent coupling between the bit and the digit and sense line.

3. The material need not be disproportionated in order to put it in the wire as is the case where the permalloy is either electroplated or vapor deposited on a substrate. This is extremely important from a quality control point of view.

4. The fabricating procedure is a continuous, rather than batch, process which allows a higher yield to be realized. In a continuous process each bit can be tested before final assembly and defective ones rejected; in a batch process the acceptance of the entire batch-fabricated plane depends upon the acceptance of each and every bit within the plane since the bits cannot be altered.

5. It is very easy, using this process, to change the composition or the thickness of the magnetic material. It is, of course, possible with this technique to use multi-component alloys as the storage material. One, therefore, can take advantage of an extensive range of material

characteristics that are not available from the electroplated or vapor deposited technique.

6. The foil switches by domain wall movement rather than by the coherent rotation mechanism of thin films. As a result, the foil will not switch much faster than 200 nanoseconds.

7. The drive currents are somewhat higher for the foils compared with thin films. However, since thin films cannot be driven by integrated circuits either, the difference in drive currents may not be significant.

8. The foil technology is clearly superior to thin film technology in producing magnetic materials of uniform composition, structure and performance. However, in high speed or exceptionally low drive current applications, the thin metallic films are more appropriate.

PHASE III - DEVELOPMENT OF A CARD PROGRAMMABLE MEMORY

1. The foil storage elements operate very well as magnetic field detectors and can be used as detectors for reading information from magnetic cards.

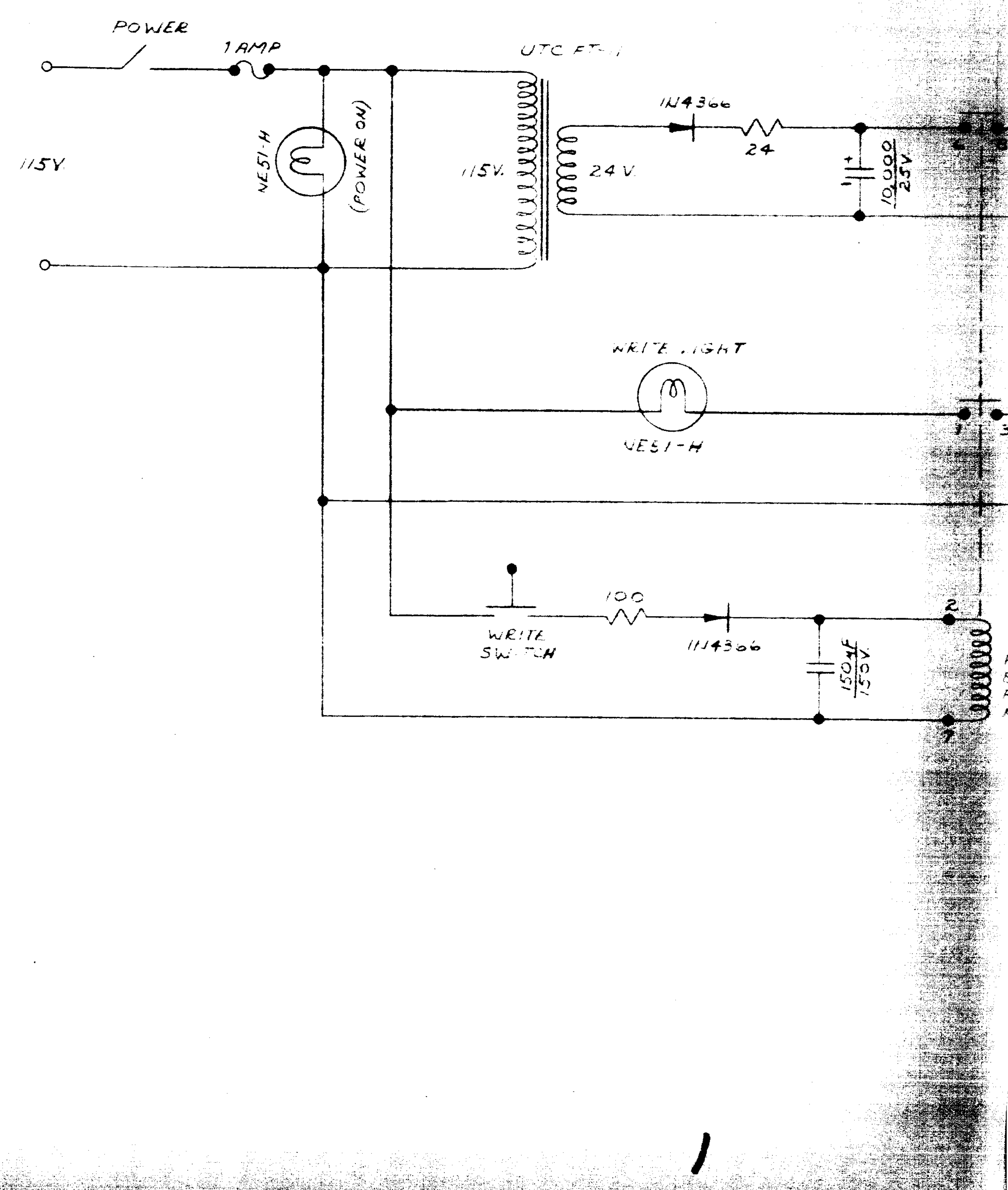
2. The detectors operate without relative motion between themselves and the magnetic cards, and are capable of reading the information in a non-destructive manner at clock rates up to two megacycles.

3. The information stored on the cards can be electronically altered and yet the information so stored is very durable and resists accidental degradation.

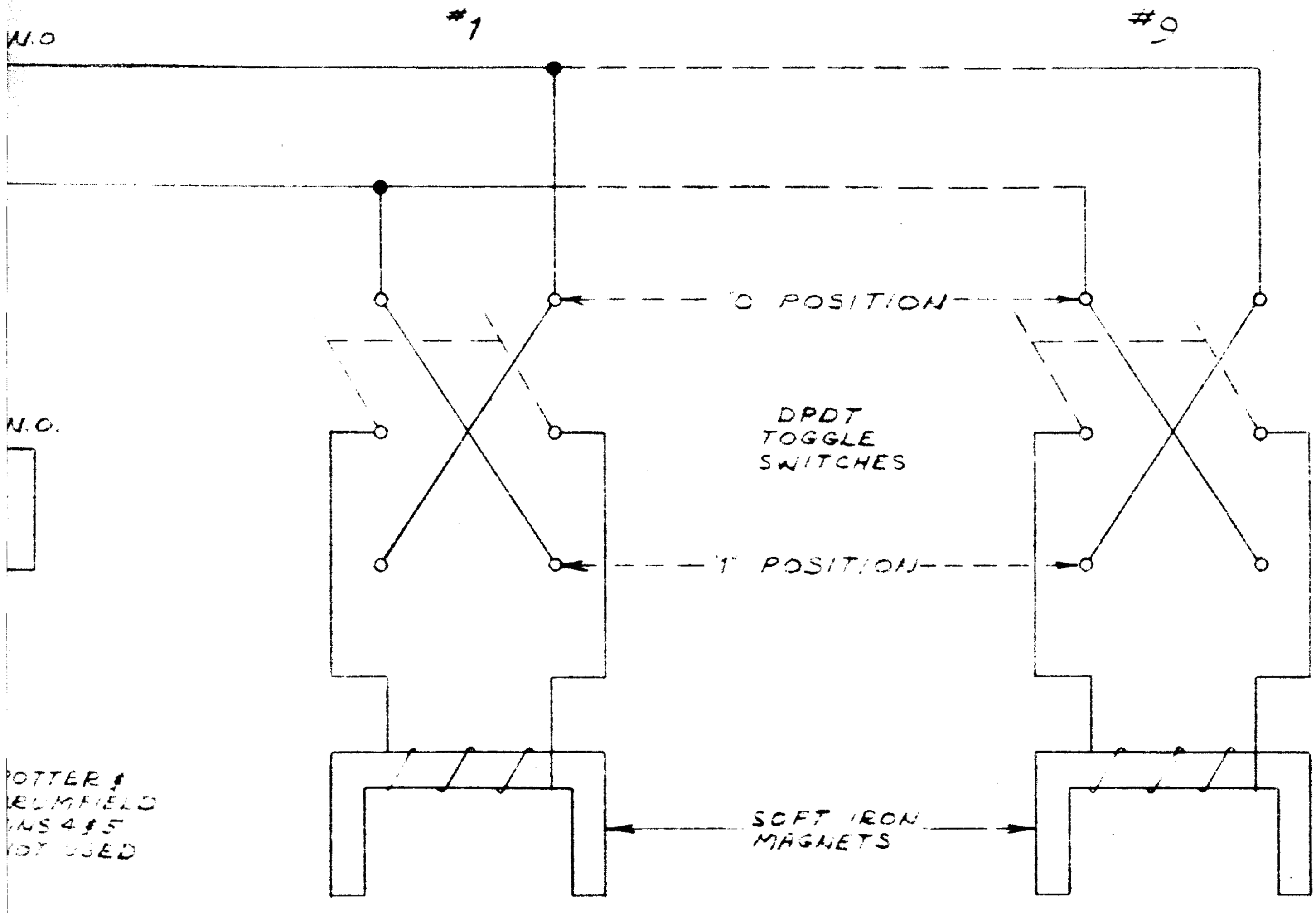
7.0 ACKNOWLEDGMENTS

Many men contributed to this project and the authors would like to publicly acknowledge the very capable assistance provided by Larry Skala, William Watson, John Schiavo and Robert Moyer.

SCHEMATIC DIAGRAM



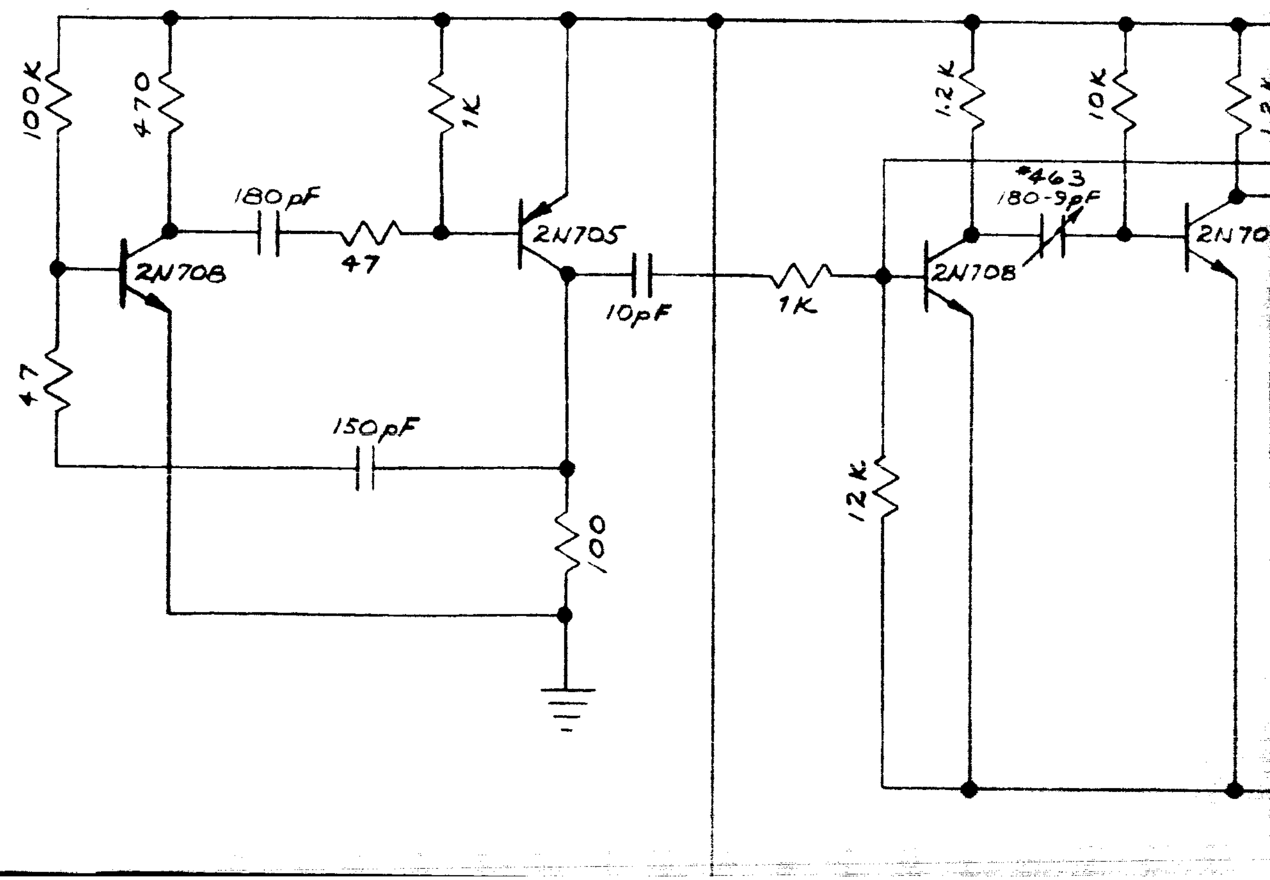
OF CARD ENCODER



2

CONTRACT # NAS 11986

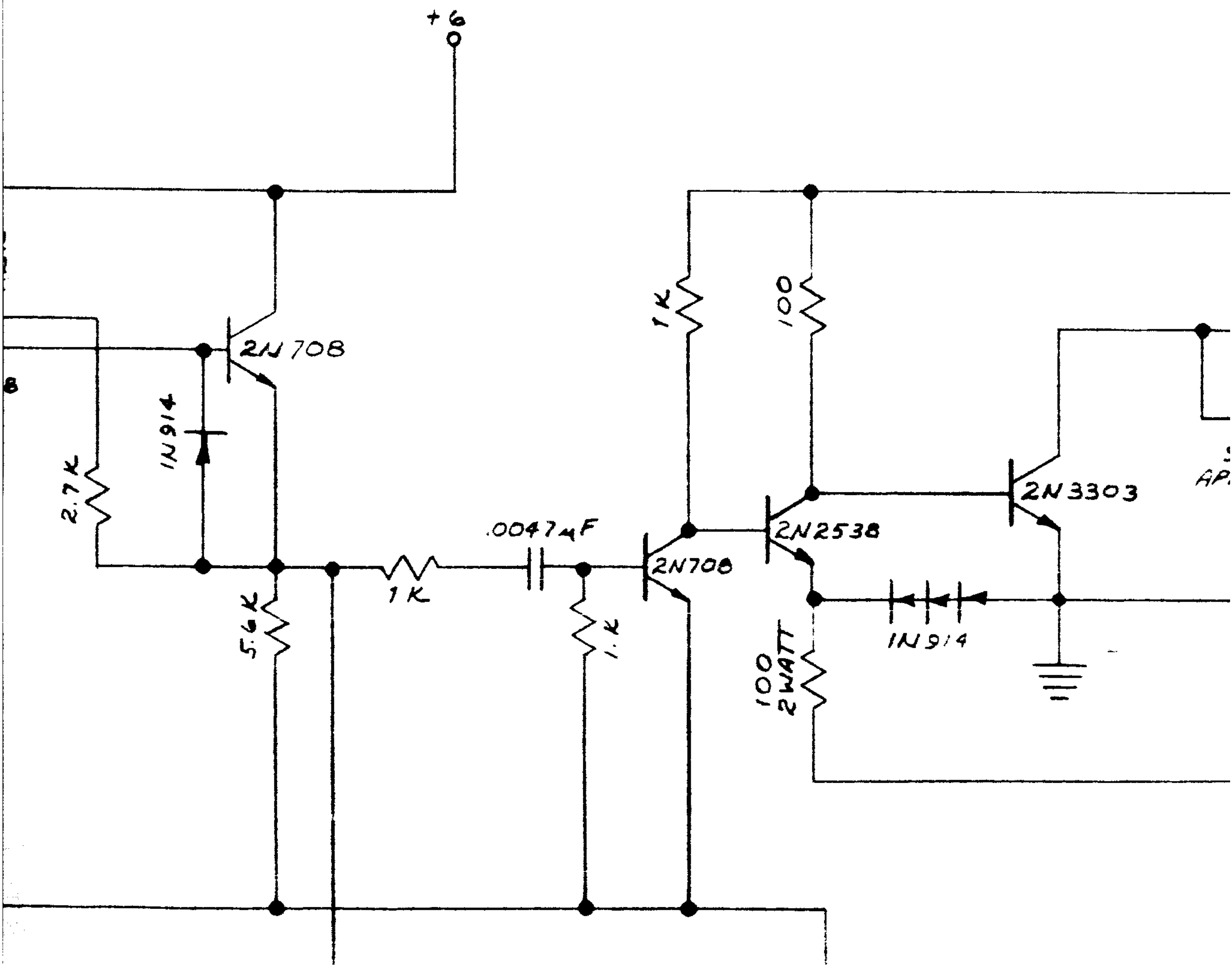
E.D
#001

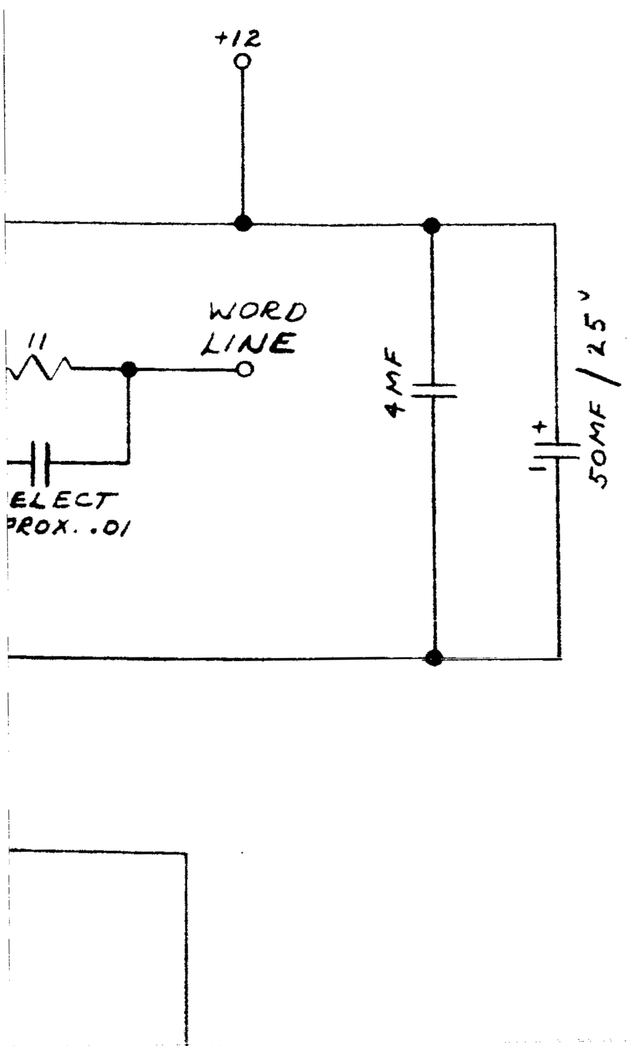


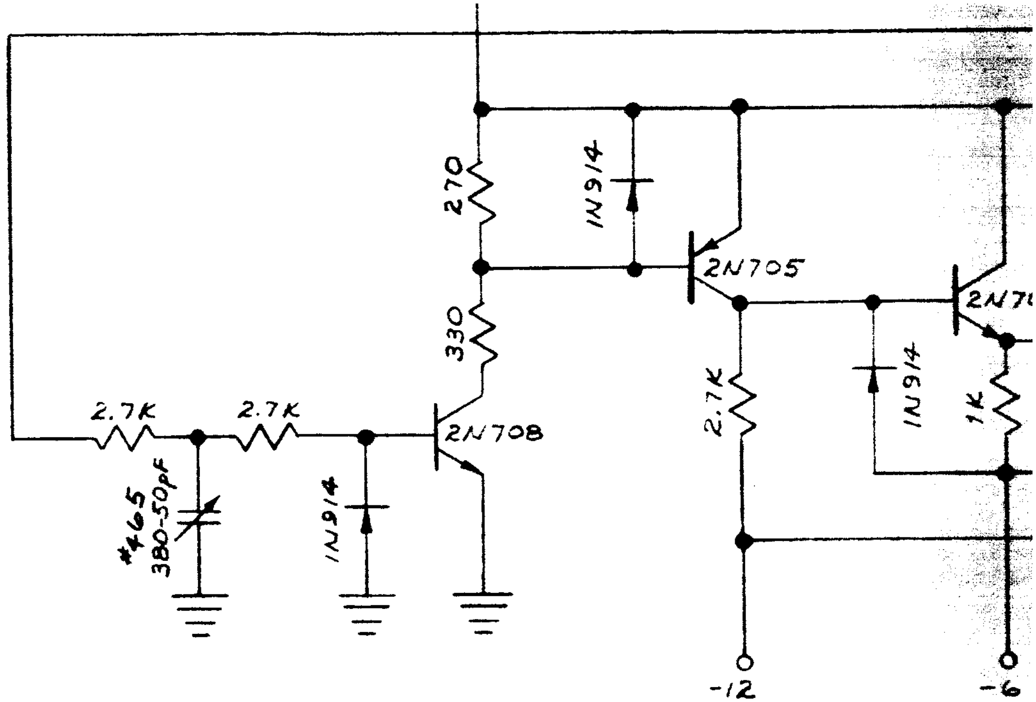
100K
470
1K
180pF
47
2N708
2N705
10pF
1K
47
150pF
100
1.2K
10K
#463
180-9pF
2N708
12K

REFERENCE GENERATOR

2

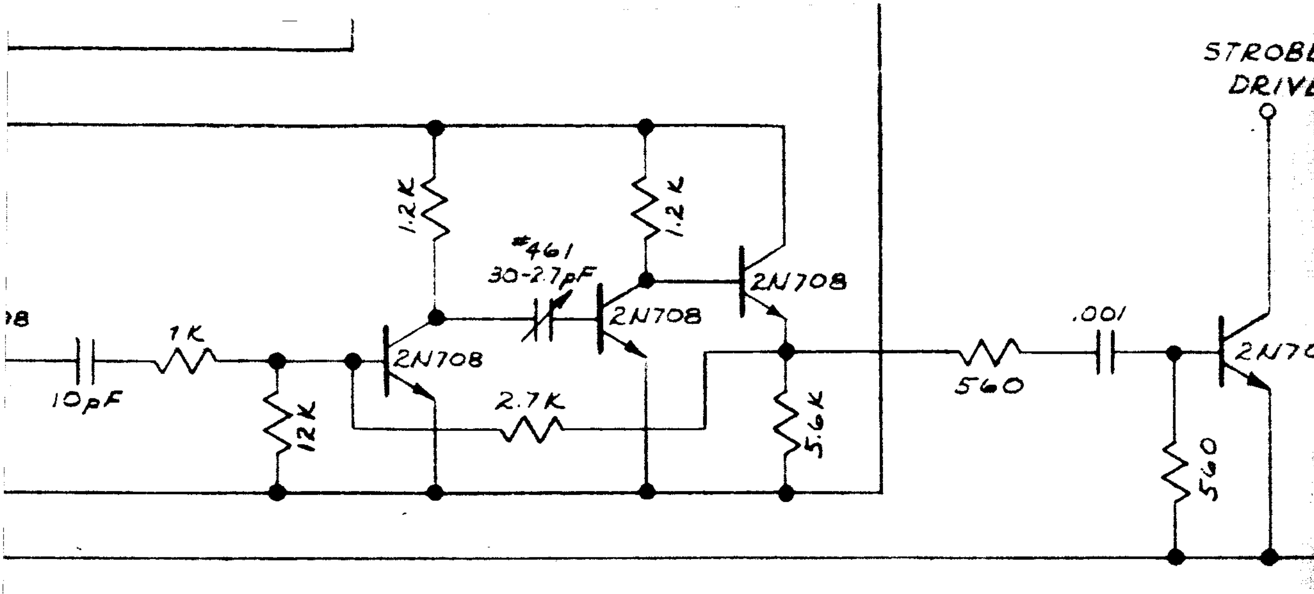



+12
WORD
LINE
11
ELECT
PROX. .01
4MF
+
50MF / 25V

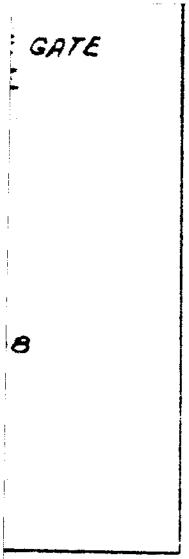


270
1N914
2N705
330
2.7K
2.7K
2N708
#465
380-50pF
1N914
2.7K
1N914
1K
-12
-6

4


STROBE
DRIVE
98
10pF
1K
12K
2N708
1.2K
#461
30-2.7pF
2N708
1.2K
2N708
2.7K
5.6K
560
.001
560
2N70

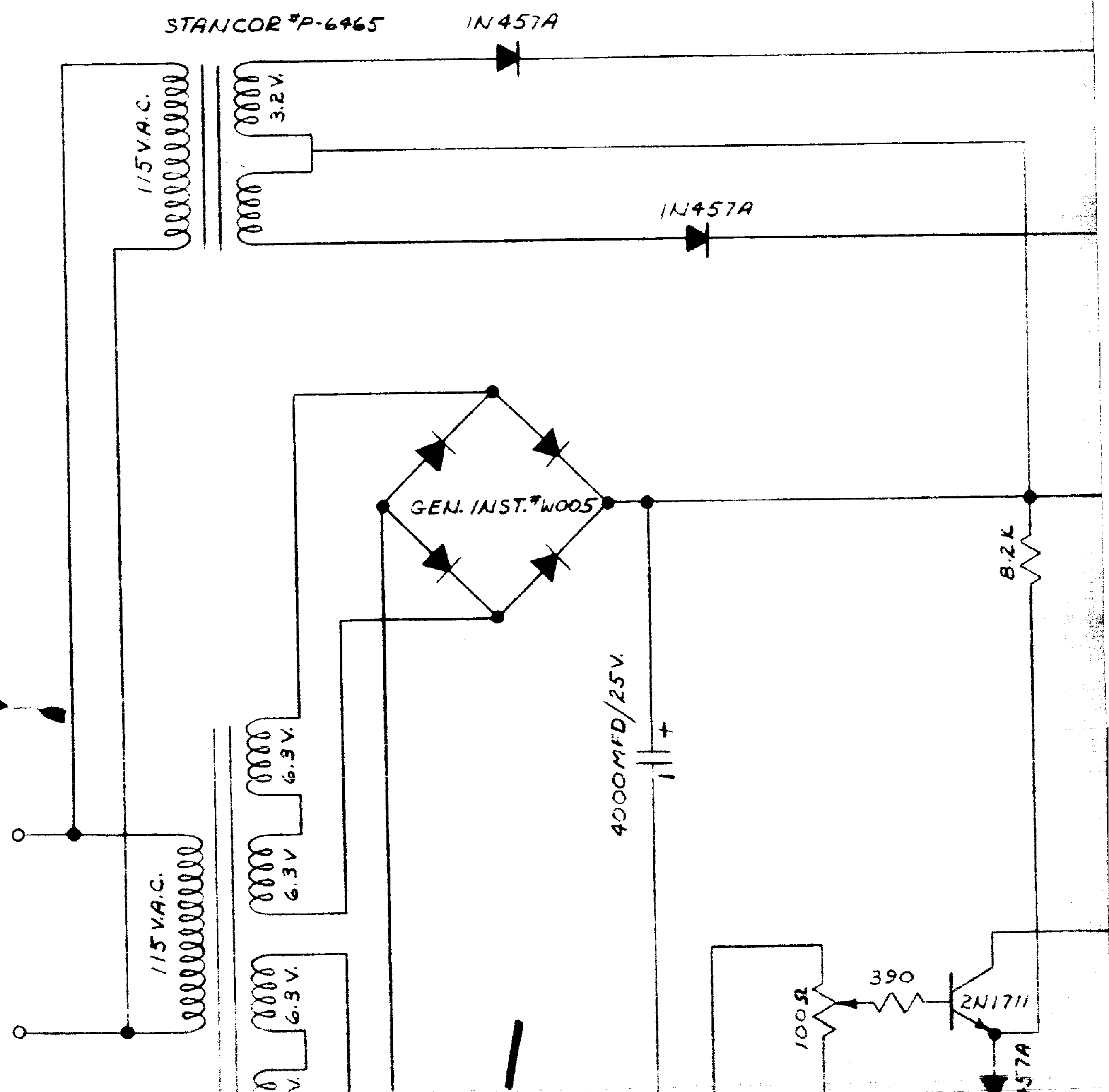
5



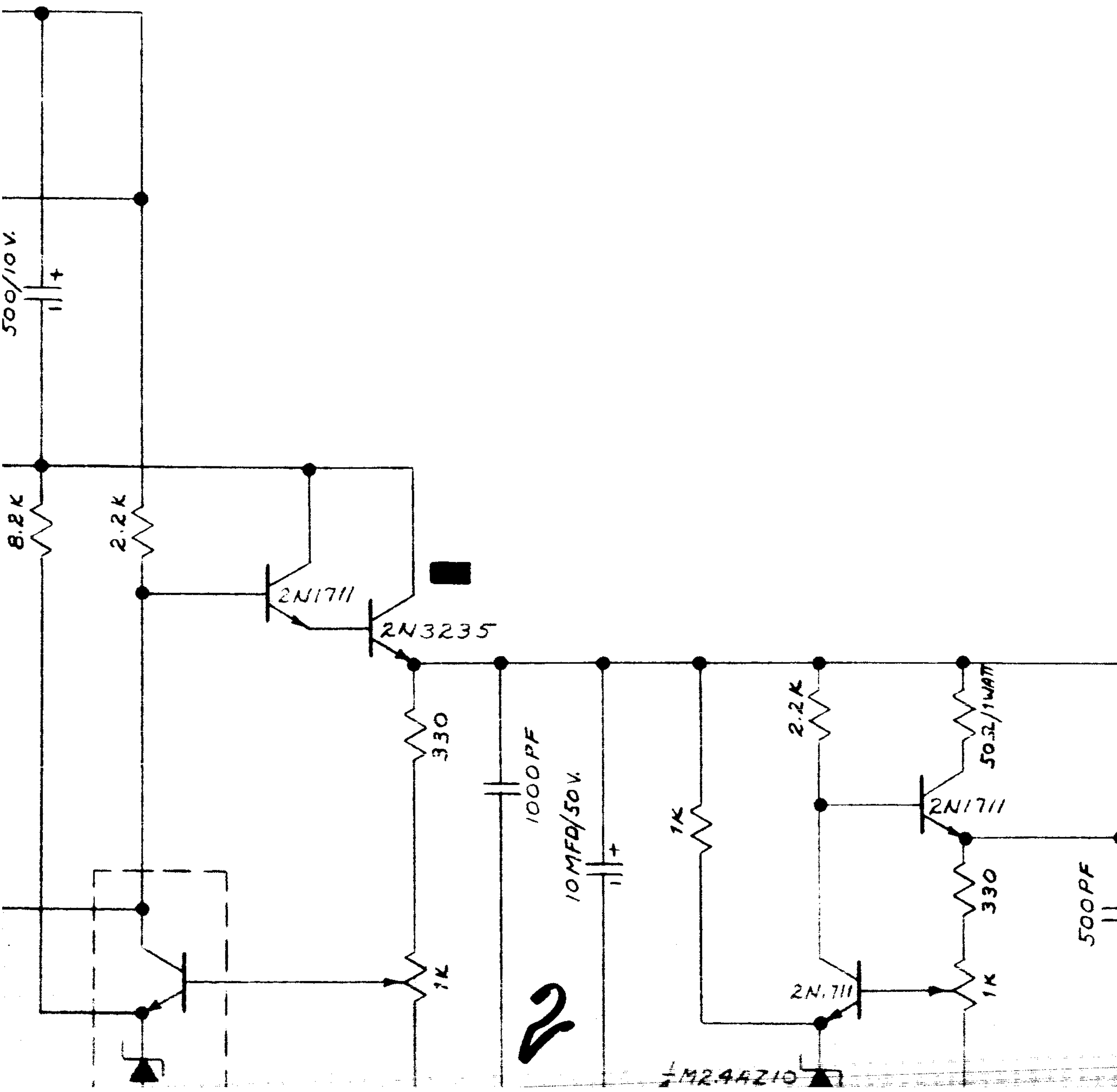
6

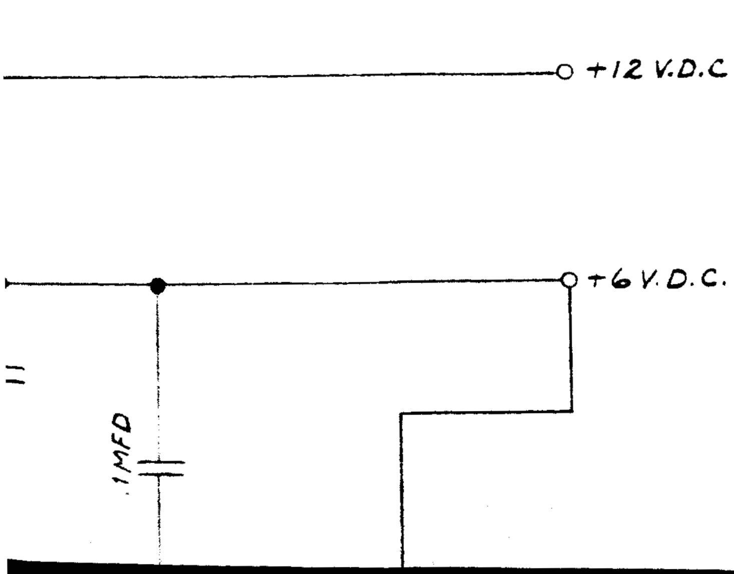
CONTRACT # NAS 11986

E.D.
#002

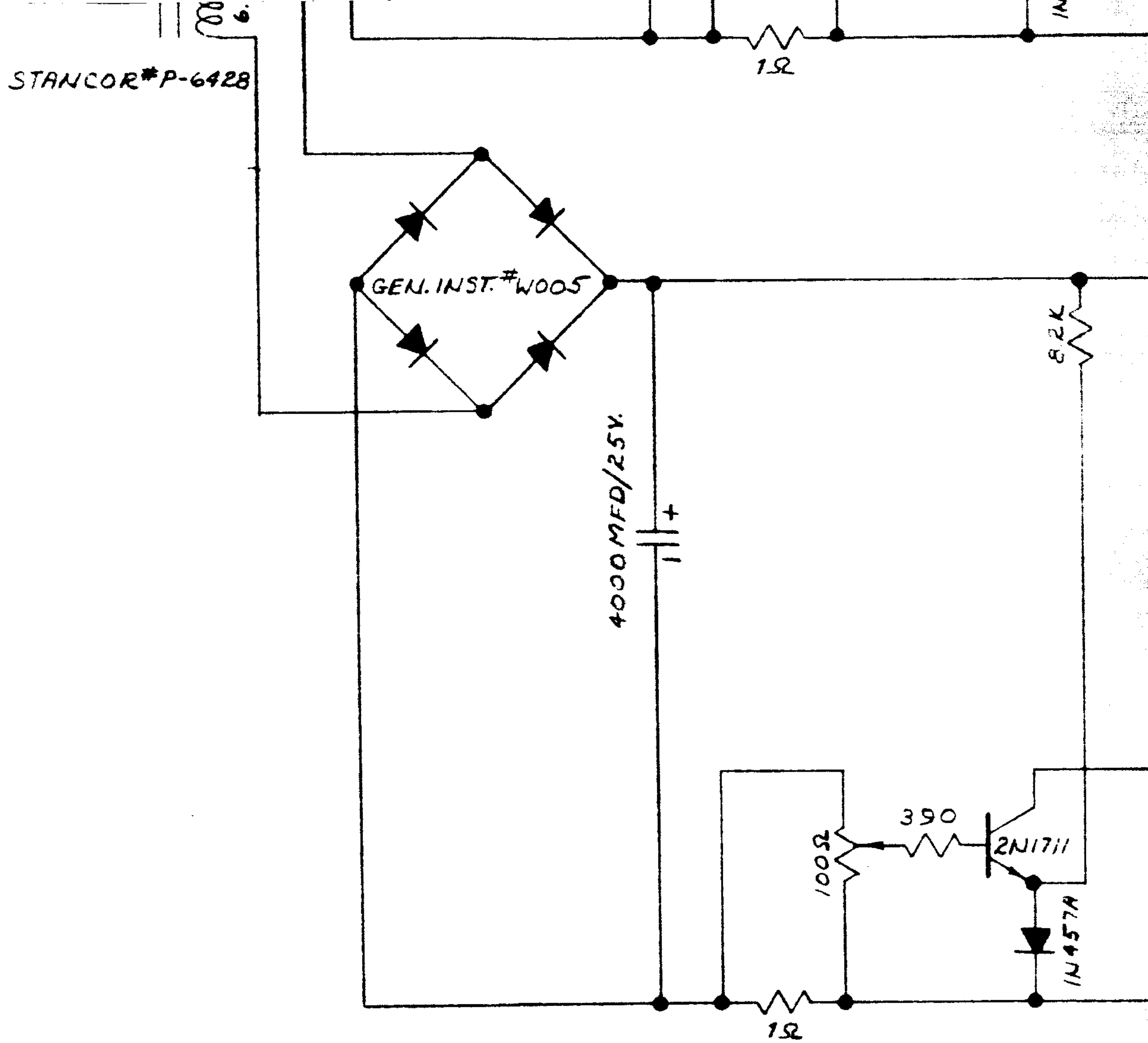

STANCOR #P-6465
1N457A
115 V.A.C.
3.2 V.
1N457A
GEN. INST. #W005
8.2 K
4000 MFD/25 V.
6.3 V.
6.3 V.
115 V.A.C.
6.3 V.
390
100Ω
2N1711

D.C. POWER SUPPLY

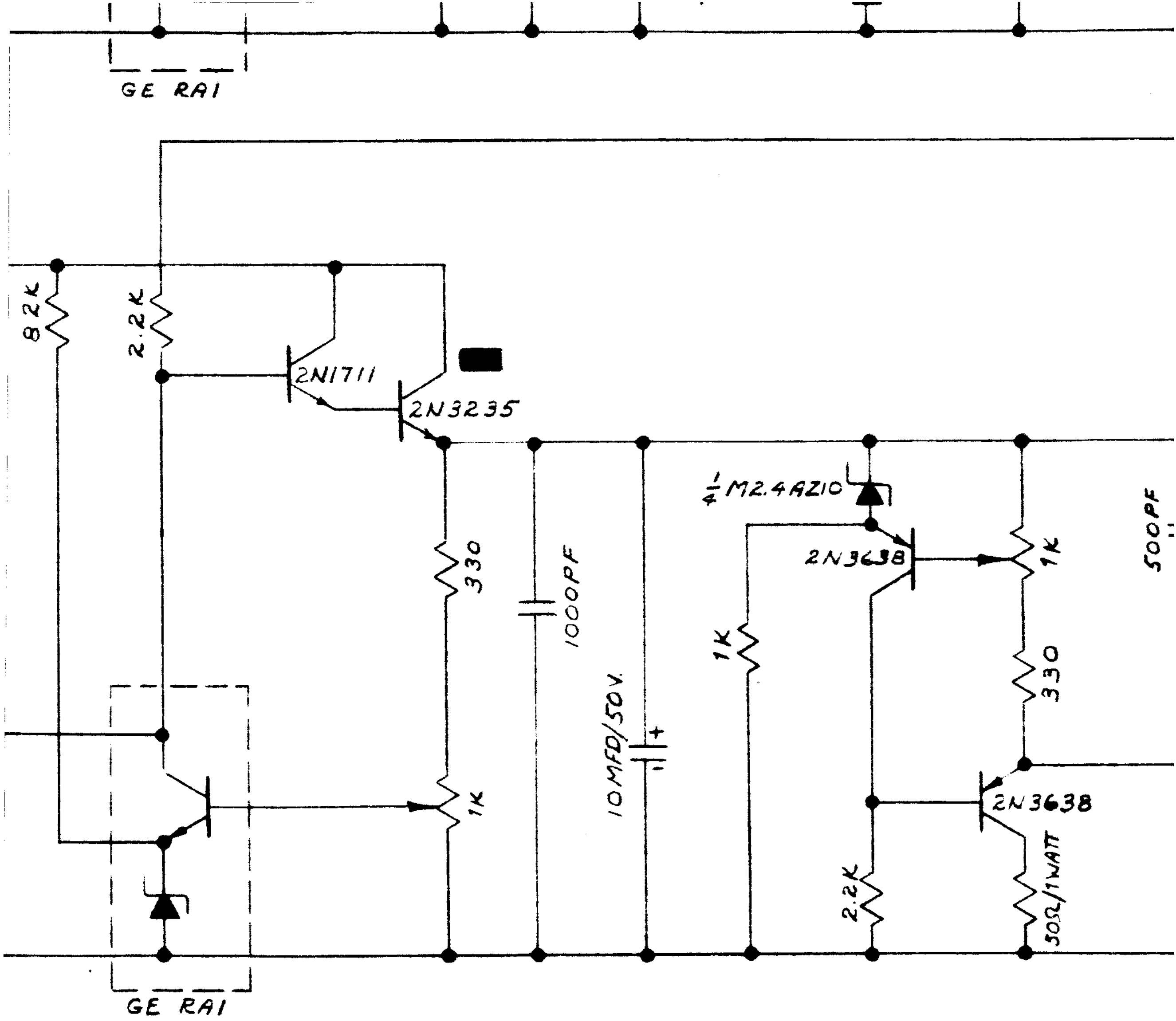


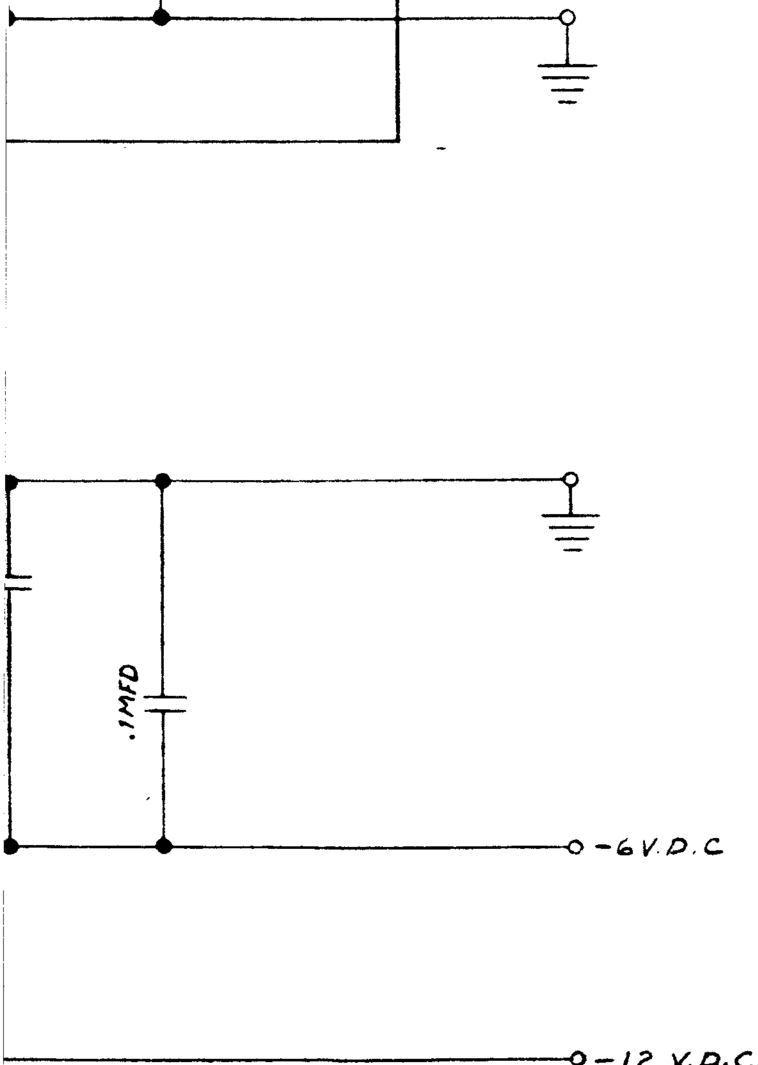


3


STANCOR#P-6428
1Ω
GEN. INST. #W005
8.2K
4000 MFD/25V.
+
390
100Ω
2N1711
1N457A
1Ω

4

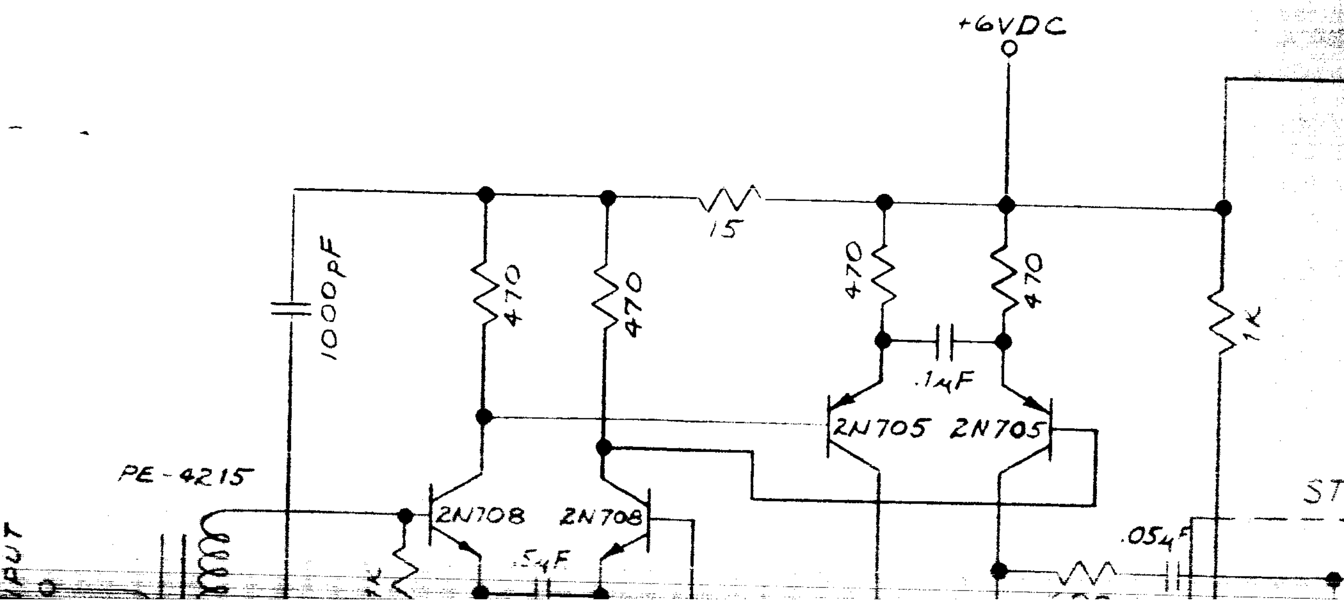

GE RA1
82K
2.2K
2N1711
2N3235
330
1000PF
10MFD/50V.
1K
1/4 M2.4AZ10
2N3638
1K
330
500PF
2N3638
2.2K
50Ω/1WATT
1K
GE RA1



6

CONTRACT # NAS 11986

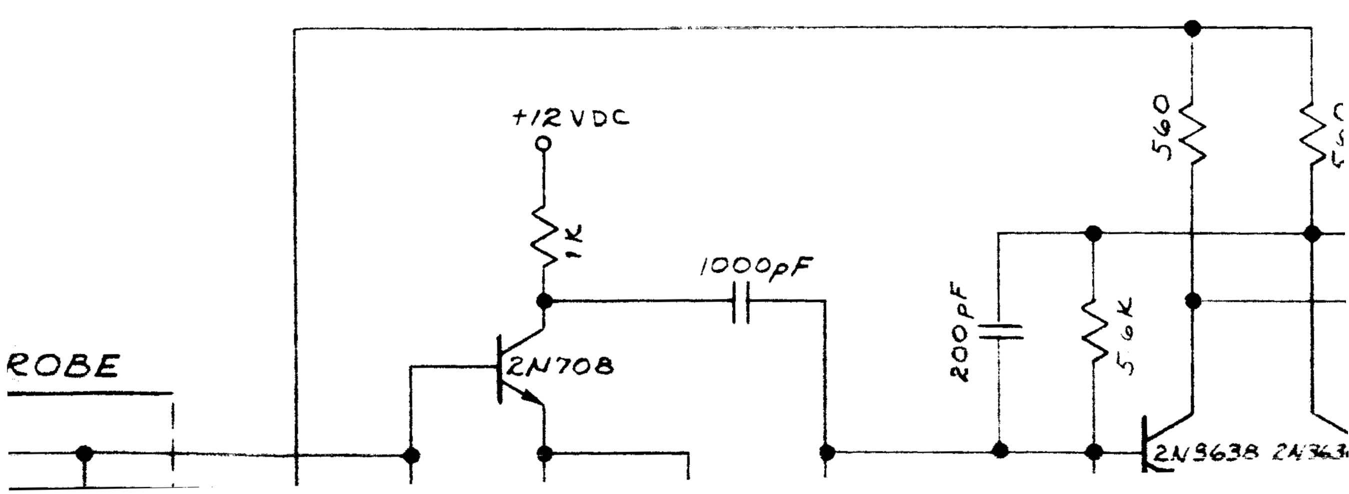
E.D.
#003



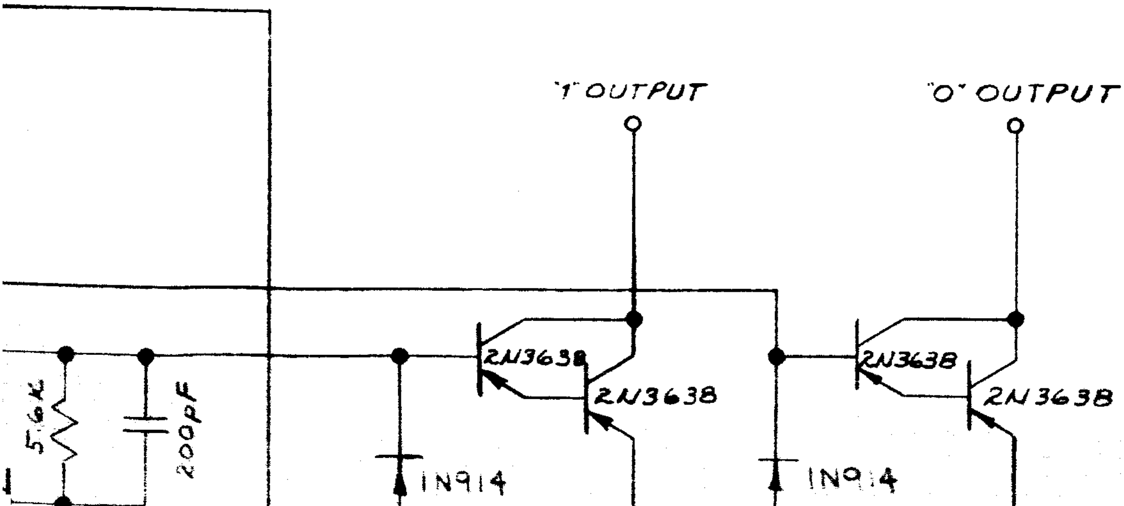
+6VDC
15
470
470
470
470
1000pF
.1µF
2N705
2N705
PE-4215
2N708
2N708
1K
.05µF
.5µF

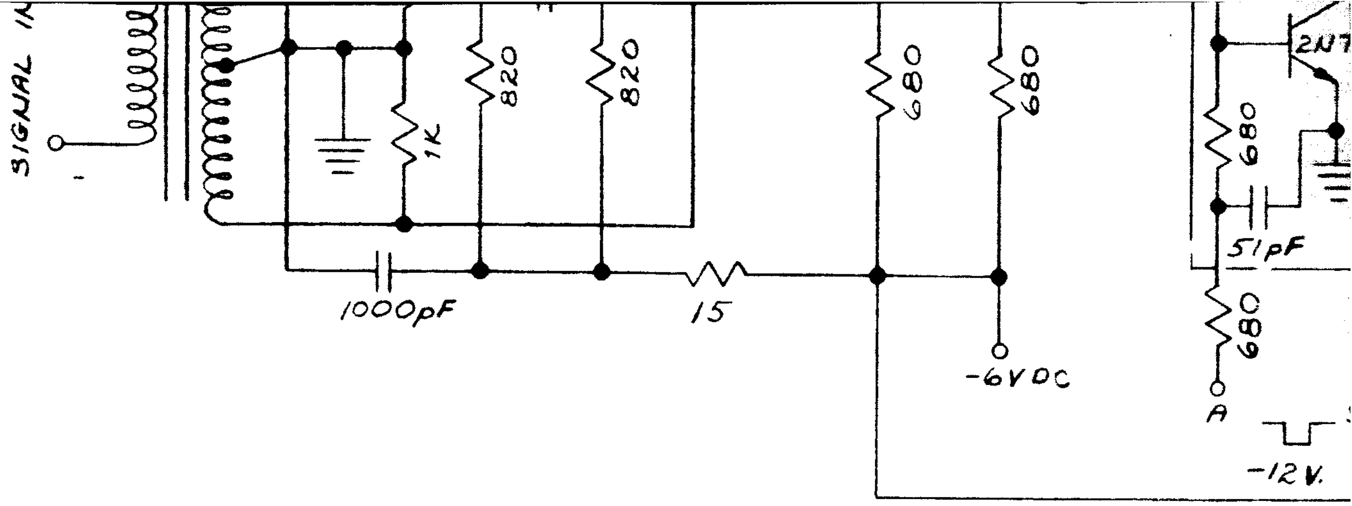
SENSE & HOLD CIRCUITS

2

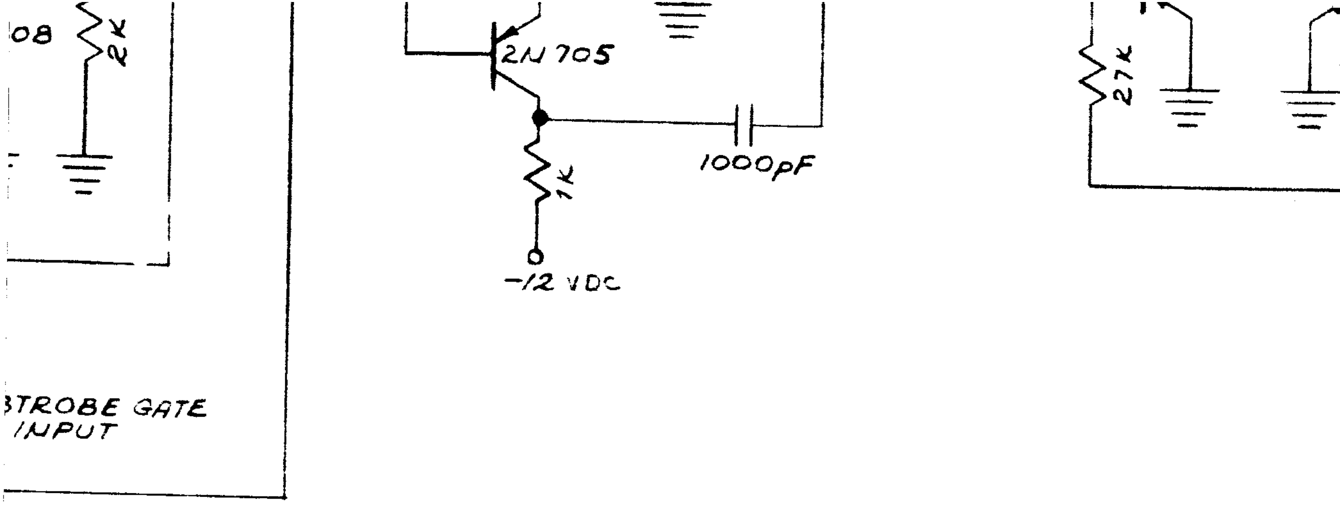


3


"1" OUTPUT
"0" OUTPUT
2N3638
2N3638
2N3638
2N3638
5.6K
200pF
1N914
1N914



4



5

6

CONTRACT #NAS 11986 E.D. #004