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EVALUATION OF RECORDING TECHNIQUES

June 1, 1955

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Physics Department

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Prepared by

[redacted] STAT

Chairman, Physics Department

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EVALUATION OF RECORDING TECHNIQUES

I. Introduction: The original statement of the task on which this work has been based called for examination of the general possibilities of some ten recording techniques, primarily selected by examination of the Patent Office files. Evaluation of resolution, dimensions and weight, availability, life, operational practicality, ruggedness, power requirements, stability, and basic limitations were desired.

Early in the work, it became evident that at least 100,000 different, realizable recording systems could be synthesized by combinations of known principles and by addition of new ideas. In view of this, it was essential to develop bases for comparison of different systems, based on definitions of terms and a system block diagram valid for the great majority of examples. This has been done, within budget limitations.

Since recording of information is a fundamental and continuing problem, this type of analytical effort is believed to be needed for comparison of possible approaches to hardware development.

II. Definitions of Terms: Recording is essentially a communication process wherein a message from a defined message source is received by the recording apparatus or recorder concerned, and is normally operated on in some manner to derive a form of signal to be recorded. In this process, some noise is unavoidably introduced. The signal plus noise are then applied to some kind of recording medium or record as forms of energy inputs which cause a change in state of the record, (and again in this process, noise may be introduced) so that the record medium may finally be said to have stored or recorded the signal (or the information represented by the signal).

At a later time, reading or reproducing apparatus can operate on the record to recreate the signal with introduction of more noise, and the signal may actuate a device which finally reproduces the message at the destination of the particular sequence.

The entire process is shown in Fig. 1 in simplified block diagram form. Nomenclature for the block labels has been carefully chosen; however the diagram can be made more general by inclusion of feedback, and perhaps by showing separate encoders for recording and scanning, as has been shown in Fig. 2. Definitions of terms are given where necessary for this study as follows. Terms not defined are encountered in recording literature, and should be defined (along with many others) in a more comprehensive analysis.

Access Time: Longest time required to cause a specified element of a record to be reproduced as a signal. Specification of a time usually implies scanning of the record in some manner. Statistical definitions (e.g. mean access time)

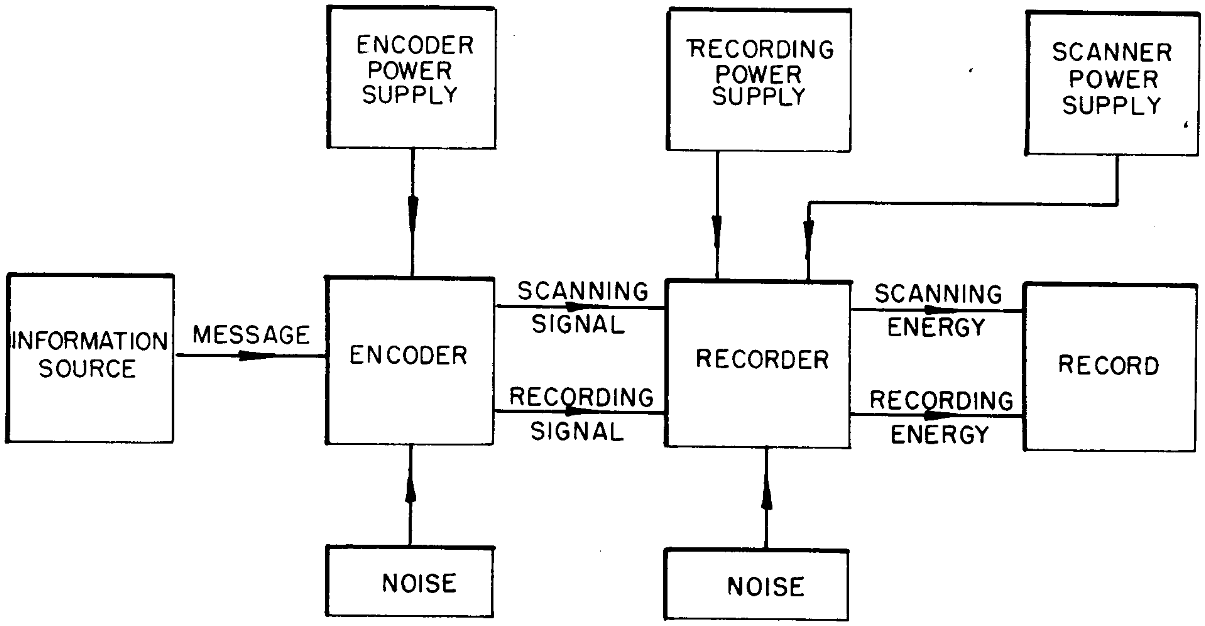

Figure 1A - RECORDING SYSTEM BLOCK DIAGRAM (SIMPLIFIED)

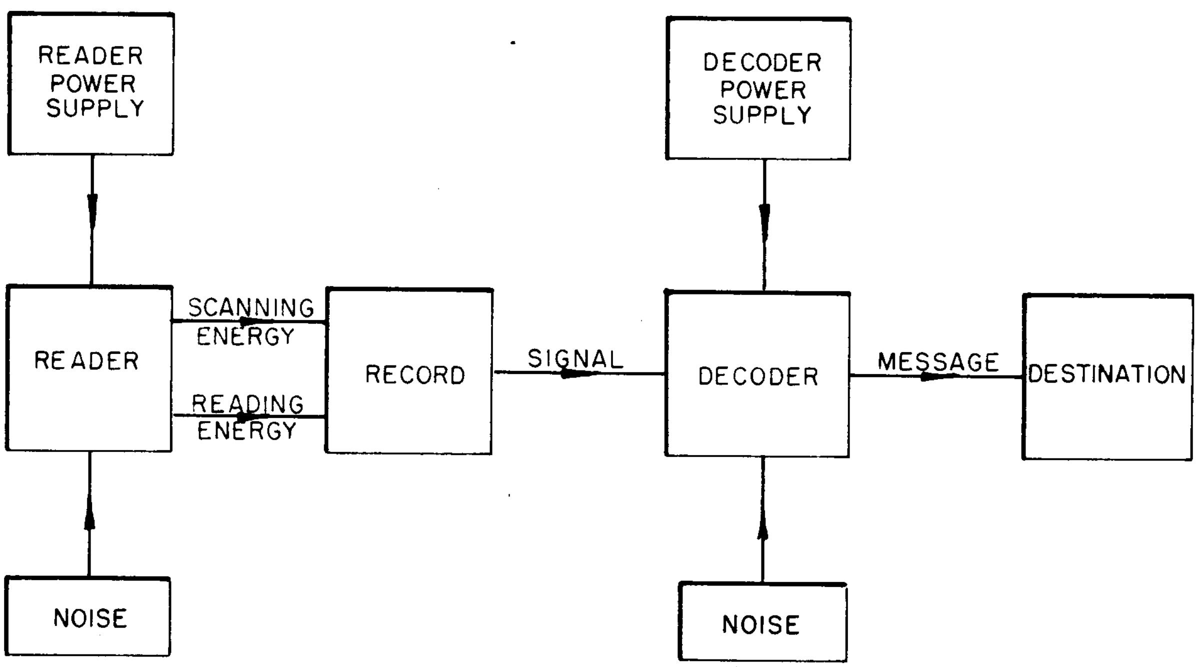

Figure 1B - READING SYSTEM BLOCK DIAGRAM (SIMPLIFIED)

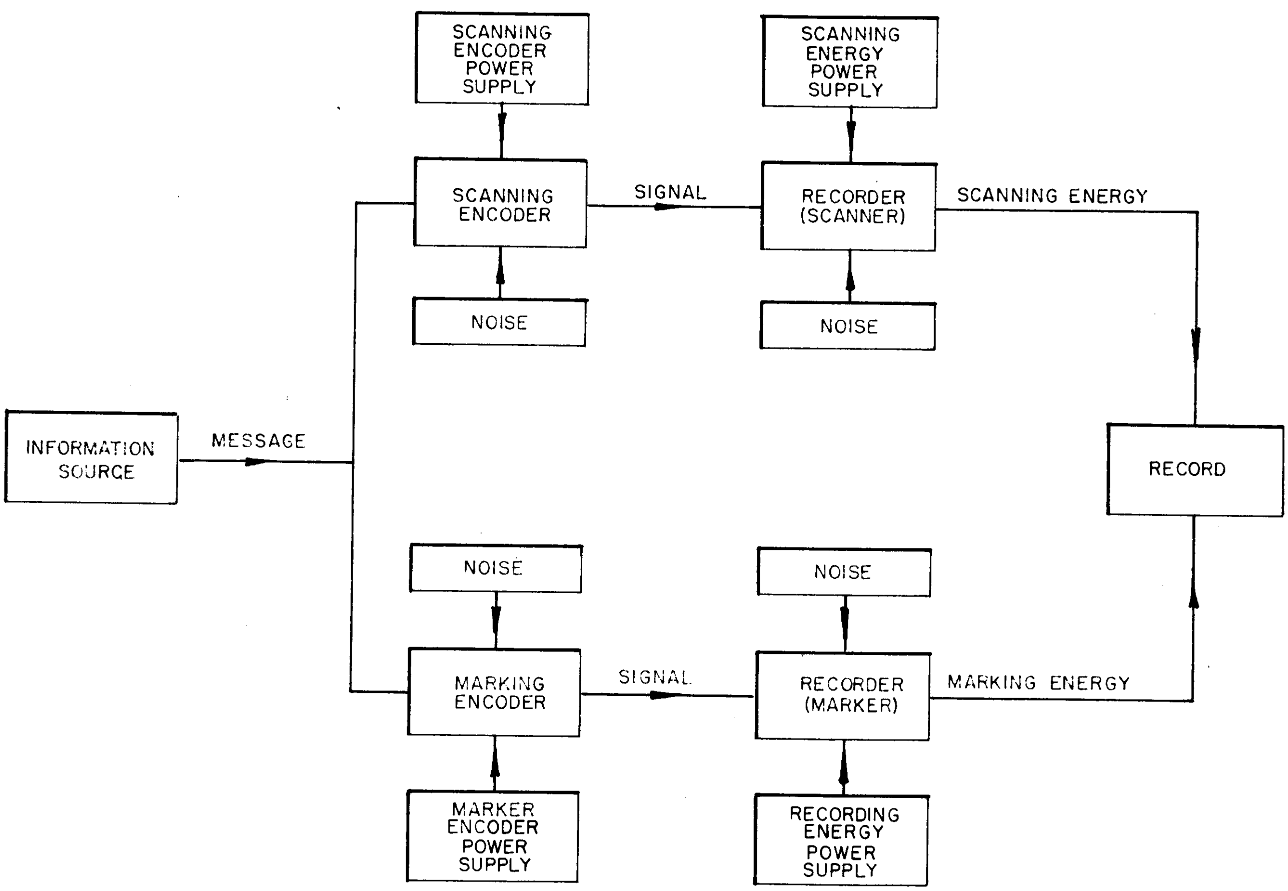

Figure 2 - RECORDER BLOCK DIAGRAM (FEEDBACK ELEMENTS NOT SHOWN).

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can be established, their nature depending on whether elements of information are stored in an order representative of their frequency of use, or in other orders.

Analog Data: Information expressed by specifying the amplitude of a signal for each instant of time during the duration of a message.

Binary System:

Bit: A basic unit of measure of information. One bit represents the information which can be stored by a device with two stable states.

Chart: A form of record.

Code: A code is a system for operating on a message (or a signal) in such a way as to produce signals suitable for recording by a particular process.

Coder: (See Encoder).

Coding: (See Encoding).

Coding System: (See Encoder or Code)

Data: (See Information).

Data Presentation: The process of making a message available to its destination in suitable form.

Data Reduction: The process of operating on stored information to increase its usefulness for a particular purpose.

Data Representation:

Decoder: A device which operates on a coded signal in a predetermined manner so as to produce a message corresponding to the signal.

Decoding: The process of operating on a coded signal in such a manner as to produce a message suitable for use by the destination of the message.

Decoding System: (See Decoder).

Destination: A device or system capable of receiving a message.

Digital Data:

Encoder: A device which operates on a message in such a manner as to suit the information contained in the message to transmission as a signal, i.e., a device which operates on a message and produces a signal.

Encoding: The process of operating on a message to produce a signal representing the message.

Energy Dimensions:

Head: (See Stylus).

Information: Knowledge describing the present or past operation of one or more physical systems.

Information Capacity: (See Information Storage Capacity).

Information Gain: Reduction in uncertainty or ignorance due to reception of information.

Information Source: A device or system which produces or generates a message conveying information.

Information Storage: A process whereby the knowledge of events may be perpetuated.

Information Storage Capacity: The property of a record measured by the number of stable states which can be distinguished in the record by the proper reading devices.

Information Storage Density:

Information Theory: Theory which establishes measures of information storage capacity, information content of messages, and related parameters. The theory also relates the rate at which information can be operated on by a system to bandwidth, power, accuracy, coding, etc.

Logging: (See Recording).

Mark: An element of a recording, not necessarily visible. This may be taken as the physical evidence that recording energy has been applied to the record medium at a specified point.

Memory: (See Record).

Memory Device: (See Record).

Memory Transfer Function:

Message: The output of an information source, usually one or more time functions representing information.

Modulation:

Noise: Energy introduced into the recording or reading process which causes the message reaching the destination to contain undesired differences from the original message fed into the system.

Noise Figure:

Pickup: (See Stylus).

Playback:

Quantization:

Radix:

Reader: A device which operates on a record and produces a signal corresponding to the recorded information. This is usually done by directing scanning energy and reading energy to the record or recording medium.

Reading Accuracy:

Reading Aperture:

Reading Energy: Energy applied to the record medium to convert the change of state corresponding to a mark into a signal element. The mark may, or may not, be altered by the reading energy.

Reading Precision:

Reading Resolution:

Reading Speed:

Record: A physical system which can undergo a relatively permanent change in state when operated on by (energy from) a recorder.

Record Capacity:

Recorder: A device which accepts a signal and operates on a recording medium in a manner so as to change the physical state of the medium to represent the signal, such that when the recording medium is subsequently explored by a reader the signal can be recreated. Usually the recorder serves to modulate streams of energy directed toward the recording medium, including scanning energy and recording energy.

Recording: Perpetuation of knowledge by transforming a recording medium so that when operated on by a reader or reproducer the medium will perform the act of reproducing that knowledge.

Recording Accuracy:

Recording Aperture:

Recording Energy: Energy which causes a change in state of an element of a record medium when applied to that element. The energy is controllable by the signal to be recorded in some manner.

Recording Medium: (See Record).

Recording Precision:

Recording Resolution: A measure of the smallest element of area (or volume) of the record which can store one or more bits of information. May be specified in bits per square inch, bits per cubic inch, or some other form such as lines per inch, etc.

Recording Speed:

Recording Stylus: (See Stylus).

Recording System: A system which performs the act of recording. The term often implies inclusion of a reading or reproducing system.

Reproducer: (See Reader).

Reproducing Stylus:

Sampling:

Scanning: A process by which a record is explored in a predetermined manner. Positioning of the record may be involved.

Scanning Aperture:

Scanning Energy: Energy employed to cause a recording medium to be systematically scanned or explored by a stream of energy in order to record or reproduce signal elements.

Self-Checking Code:

Signal: A stream of time-varying energy representing information encoded in some manner.

Signal/Noise Ratio:

Space Dimensions:

Space Domain Systems:

Stable State: A condition of an element of a record which can be distinguished from other states by the reader.

Stable State Levels:

Storage Density: (See Information Storage Density).

Store: (See Record).

Stylus: A device by which recording or reading energy is applied to (or withdrawn from) a record. Although this term is normally applied only to mechanical systems, it will be preferred to other terms such as "Head" for simplicity.

A[1] pickup needle or holder furnished with a jewel or other abrasive-resistant tip. A stylus may or may not be arranged for convenient replacement.

Time Dimension:

Time Domain Systems:

Transfer Function:

Weighing:

Writing: (See Recording).

III. Criteria for Evaluation of Recording Systems: The reason for comparative evaluation of recording systems is usually a specific operating need which must be filled as well and as quickly as possible. On the other hand, existing production equipment may fall so far short of meeting performance demands that the question in some cases becomes one of choosing a fundamental principle judged most suitable for development toward the ultimate goal.

In the first case, specifications may be kept quite simple. In the latter instance, a great deal more must be known about systems. Thus, it seems appropriate to establish a few simple recording system requirements, and then to examine the most general comparison criteria possible.

Elementary Criteria: There are a few factors which must be specified for any recording system. In a rough order of operating importance for the typical "practical" case, these are given in Table I for the most popular type of current system - magnetic tape - based on manufacturers' literature. Similar factors may be compiled for other systems, and generalized to form a basis for comparison. The first ten factors seem to be of greatest interest.

These practical factors can be analyzed in many ways, although the ambiguity of terms commonly used in manufacturers' literature makes the process difficult. Some "recording systems" or recorders include playback or reading facilities. Others do not. If the factors of Table I are separated into classes, one might use the data sheet of Fig. 3. Due to the limited scope of the present study, an even simpler data sheet was actually used.

Basic Criteria: In the line of basic criteria, it is of interest to note that Gerhard Hollander[2] selected the factors of resolution; minimum practical spot area; maximum practical density (bits per cubic inch); operating speed for recording and reading; cost per bit; and number of physical states possible

[1]IRE Standards on Electroacoustics: Definitions of Terms, 1951.
[2]Gerhard Hollander, "Digital Data Recorder. An Investigation of Dense Storage of Information" M.I.T. Servo Lab Tech. Memo. No. 6897-TM-12, October, 1953 (ASTIA AD No. 21487).

	Specification	Dimensions
1.	Recording Time	(Hours)
2.	Frequency Response	(Range in Cycles/Second)
3.	Size	(Dimensions - Inches)
4.	Weight	(Pounds)
5.	Power Consumption	(Watts)
6.	Type of Power Supply	(Voltage and Frequency)
7.	Signal/Noise Ratio	(Decibels)
8.	Number of Input Channels	(Number)
9.	Input Channel Impedance(s)	(Ohms)
10.	Input Voltage Levels	(VU)
11.	Drive Motor Flutter	(Per cent)
12.	Record Speed(s)	(Inches/Second)
13.	Input Equalization Characteristic	(Description)
14.	Record Size Capacity	(Reel Diameter - Inches)
15.	Type of Drive Motor(s)	(Description)
16.	Type of Rewind Motor	(Description)
17.	Starting Time - Record	(Seconds to Full Speed)
18.	Stopping Distance - Record	(Distance Record Moves - Inches)
19.	Provision for Monitoring	(Description)
20.	Output Impedance(s)	(Ohms)
21.	Output Power	(Watts)
22.	Output Voltage(s)	(Volts)
23.	Type of Recording Head	(Description)
24.	Provision for Controls	(Type and Number)
25.	Playback Time Accuracy	(Seconds/Minute of Recording)
26.	Record Loading Features	(Description)
27.	Rewind Time	(Seconds)

Table I

Practical System Specifications - Magnetic Tape Recorders
(Magnecord Models M30 and M80. Ampex Models 350 and 600)

Recording and Reading System Data Sheet   Type of Process ________

Description of System: ________________________

Availability: ________________________

Recording System

Frequency Response Range (Cycles/Second) ________

Power Consumption (Watts) ________ Type Power Supply ________

Signal/Noise Ratio ________ Input Impedance (Ohms) ________

Input Voltage Range (Volts) ________ No. Channels ________

Record Drive Noise ________ Type Drive ________

Input Equalization ________

Record Size Capacity ________ Record Starting Time (Seconds) ________

Record Stopping Distance or Time ________

Provision for Monitoring ________ Type Recording Head ________

Controls ________

Record

Recording Time (Seconds) ________ Signal/Noise Ratio ________

No. of Channels ________ Scanning Speed ________

Record Storage Capacity (Bits) ________

Scanning Geometry ________

Reading System

Frequency Response Range (Cycles/Second) ________

Power Consumption (Watts) ________ Type Power Supply ________

Signal/Noise Ratio ________ Type Drive ________

Reading Drive Noise ________ Output Power (Watts) ________

Output Impedance (Ohms) ________

General

Weight (Lbs.) ________ Dimensions (Inches) ________

____

____

____

Fig. 3 - Proposed Data Sheet

for one element of area. His problem apparently did not require power or energy considerations, but usually energy, accuracy, space, and rate of storage considerations can be "bartered" - one for the other - in a manner similar to power, bandwidth, reliability, and rate of data transmission in a communications system. Therefore energy must be taken into account. Indeed as this study has proceeded it has become increasingly evident that the supply, handling, and storage of energy are the main avenues along which further effort must be directed. (See Appendix A.)

To establish the more detailed considerations useful for prediction of ultimate capabilities of systems, it is useful to use the diagram of Fig. 1 as a basis, since choice of a system may finally depend on factors such as adaptability to coding, noise figure, ruggedness, or the like. Evidently, if one can specify the performance of each system element independently, it might be possible to synthesize an optimum recorder from operating requirements. Because of interactions among elements, the problem is not this simple. The "optimum" coder may be unsuited for use with the "optimum" scanning system, etc. However the building block approach is the most systematic, and so is followed here.

Detailed specifications must be worked out for each block in the diagram of Fig. 1. The blocks should be chosen so that they are as independent as possible, so that the most combinations of any group of blocks can be made.

Encoder Evaluation: The function of the encoder must not be minimized in importance. It receives a message of input information from outside the recording system (consisting of the output of a radio receiver, the voltage from an electrical transducer, or the like) and operates on this information to produce a signal suitable for recording.

Sometimes the encoder may only serve to make the recording process more efficient, such as by sampling the input information at intervals. At other times, the recording process cannot function without encoding. For example, the Ampex Model 700 recorder must modulate a carrier with low frequency geophysical data which cannot be recorded directly on magnetic tape.

Sampling is an extremely valuable function, since it can remove a burden of useless data from the recorder elements. In most recording, far more information is placed on the record than ever can or need be evaluated on playback. An example of useful coding is the actuation of the record drive only when a predetermined change takes place in the quantity being recorded.

Encoders can involve analog to digital data translation or conversion, generation of timing or marking signals, conversion of DC power to AC for synchronous motor drive, modulation, and many other processes. In the block diagram of Fig. 1, a single box is shown with both scanning and recording signal outputs to the recorder element. It is necessary to show both outputs because the two signals are often related in some manner.

There is justification for showing separate boxes for scanning and recording encoders as in Fig. 2. Consider a disc recorder which does not space grooves arbitrarily, but which (at a low frequency) positions the stylus for one groove by moving it as close as possible to the previous groove. This is a scanning coding operation, dependent primarily on the amplitude of previous signals (and the corresponding width of the lateral cut).

Information needed on encoders for evaluation includes the following:

1. Forms of Messages Accepted
   a. Input Voltage Range (Dynamic Range)
   b. Input Impedance
   c. No. of Input Channels
   d. Input Frequency Range
   e. Input Modulation (AM, FM, or PM)
   f. Coding of Input Signals
   g. Type of Energy Input

2. Forms of Outputs to Recorder
   a. Types of Coding Applied to Message
   b. No. of Output Channels
   c. Output Powers
   d. Output Impedances

NOTE: This assumes electrical messages. Others should be added for mechanical and other messages.

3. Overall Coder Performance
   a. Frequency Response
   b. Noise Figure
   c. Amplitude and Phase Distortion
   d. Coder Power Efficiency (Watts/Bit)
   e. Stability

4. Physical Characteristics
   a. Dimensions
   b. Weight
   c. Ambient Temperature Range
   d. Ambient Humidity Range
   e. Ruggedness
   f. Power Supply Requirements

Recorder Evaluation: This element is defined as the part of the system which actually operates on the record to produce changes in state. For example, a disc recording system would place in this category only the drive motor, turntable, and the magnetic or other cutting head. The lead screw mechanism could be considered as part of the drive motor since its guidance of the cutting head is unrelated to the signal or its coding. Scanning energy output would consist of the energy moving the cutting head in its spiral track along the disc, while recording energy would be that actuating the cutter. This distinction is not simple or obvious, since the pressure of the cutting head against the record forces the drive motor to supply part of the cutting energy.

Information required for evaluation of recorder elements includes:

1. Forms of Signals Accepted
    a. No. of Input Channels
    b. Input Impedance
    c. Input Power Range
    d. Input Frequency Range
    e. Forms of Input Coding
    f. Types of Energy Input

2. Forms of Recording Energy Outputs to Record
    a. No. of Output Channels
    b. Form of Recording Energy
    c. Output Power Range
    d. Output Impedances
    e. Recording Energy Frequency Range

3. Forms of Scanning Energy Outputs to Record
    a. No. of Output Channels
    b. Form of Scanning Energy
    c. Output Powers
    d. Output Impedances
    e. Scanning Energy Frequency Range

4. Overall Recorder Performance
    a. Total Running Time
    b. Record Starting Time (or Distance)
    c. Record Stopping Time (or Distance)
    d. Scanner Noise Figure
    e. Recorder Noise Figure
    f. Type of Operation Performed on Record
    g. Power Efficiency

5. Physical Characteristics
    a. Power Supply Requirements
    b. Dimensions
    c. Weight
    d. Ambient Temperature Range
    e. Ambient Humidity Range
    f. Ruggedness

Record (Recording Medium) Evaluation: Since the effort of the entire writing system is to change the state of elements of the record, properties of these components are essential to evaluation. Information required includes:

1. Type of Change in State
    a. Mechanism of Energy Storage
    b. Energy Conversion Processes Involved
    c. Energy Units of Change of State Measurement
    d. Density of Stored Energy

2. Energy Requirements - Recording
   a. Forms of Energy Accepted
   b. Range of Energy Input Rate
   c. Stored Energy per Bit of Stored Information

3. Energy Requirements - Scanning
   a. Forms of Energy Accepted
   b. Range of Scanning Energy Input Rate
   c. Energy Required per Unit of Scanning
   d. Possible Types of Scanning Geometry

4. Record Performance
   a. Time Stability
   b. Human Convenience of Record Data Presentation
   c. Access Requirements
   d. Processing Requirements
   e. Noise Figure
   f. Harmonic Distortion
   g. Record Frequency Response

5. Physical Characteristics
   a. Color(s)
   b. Dimensions
   c. Weight
   d. Ruggedness
   e. Temperature Coefficient of Stability
   f. Humidity Coefficient of Stability
   g. Power Supply Requirements

Reading System Evaluation: Similar criteria can be set up for each element of a reading system. Since a reading system which can get the most out of a record is almost a part of the recording system, this should be done. Reading systems were not considered specifically in definition of the original tasks on this project.

Overall System Evaluation: Since all records are intended to be subjected to later reading, complete recording - reading systems must be analyzed. There are a number of unique factors such as the ratio of complexity of the reader to that of the recorder which must be developed.

IV. Basic Types of Recording Systems: With some criteria established for evaluating (if not for measuring) recording system performance, it is possible to consider the number of possible systems which can be compared.

Commercially available systems unfortunately offer a very poor index of basic system promise. A system based on physical principles which are fundamentally inferior may reach a high state of engineering development (and consequently lower cost and wide acceptance) due to the energy and persistence of its proponents. Magnetic tape recording - evidently a promising principle - was only developed through a random process requiring many years. If the overall problem is systematically to apply effort to the areas which are the most promising from a scientific standpoint, all physically realizable systems should be listed, and elimination of all but a few should be made in an organized manner.

Since recording is broadly defined as the application of energy to a material in such a way as to produce a reasonably permanent change in state, energy is a primary consideration. Appendix A indicates useful work which can be done in treating recording and reading as energy conversion processes.

Study of the many possible methods of organizing the classification of all possible recording systems has suggested the following categories, which are presented in outline form because each can be applied separately to a system.

Possible Types of Recording Systems

I. Recording System Function: All recording systems must function as parts of playback systems (where the record marking is not necessarily visible, but playback is the main function), as graphic systems (where the primary function is to provide a visible record), or as combination systems (where both playback and visibility requirements are fulfilled). Examples of these systems in order are magnetic wire, ordinary recording pen on chart, and boundary displacement systems. (3)

A. Types of Energy Input: Recording systems of any of the above types may accept information inputs of different energy forms. The input energy form is commonly an electrical voltage or a mechanical displacement, or can be converted to one of these by suitable transducers not considered normally as a part of the recorder. An example of an electrical voltage input is the output of a photomultiplier tube, while a recording accelerometer with a pen scratching smoked glass, actuated by the displacement of a mass against a spring system is an example of a mechanical displacement input. (2)

1. Form of Energy Input: Any of the above systems may receive energy in analog or digital form, or conceivably a combination of both, since a chain of code - modulated pulses could be amplitude - modulated by a separate source of information. The number of separate channels which can be handled, and the input bandwidth, are affected by this category. (3)

a. Form of Recorder Coding: Any of the 3 x 2 x 3 systems outlined above may require further coding by the recorder to achieve optimum results for a given system. For these purposes coding is defined broadly to include such operations as modulating a carrier with the incoming signal, as is necessary to record very low frequency analog data on magnetic tape. Although many types of coding can be conceived, six would seem to suffice for most purposes, including coding either related or independent of the manner in which the record is scanned, and in each of these categories, the alternatives of an amplitude, frequency, or pulse modulated output. (6)

(1) Type of Applied Recording Energy: Systems of the above types may actually apply at least 10 different types of energy to an element

of area of a record. Although obviously a matter of definition, these have been chosen after review of the collected list of subject headings in Physics Abstracts as:

A.	Mechanical	F.	Magnetic
B.	Acoustic	G.	Electronic
C.	Optical	H.	Electromagnetic
D.	Thermal	I.	Nuclear
E.	Electrical	J.	Chemical

These are used as the principal basis for classifying all possible systems because additional categories will need to be added only if new forms of energy are discovered or adopted in general usage. (10)

(a) Change of State Produced in Record: Obviously, the same type of recording energy applied to different materials can cause different types of effects on the record, depending on the nature of the latter. For example, the application of heat to records could be made to result in color changes, deformation of the record material, changes in degree of magnetization, etc. Considering changes of the same nature (e.g. color changes) but in different materials (e.g. paper, metal foil, wax, or plastics) as separate types, it is estimated that a single type of applied recording energy can cause at least 12 different types of changes of state, on the average. (12)

((1)) Form of Scanner Coding: Scanning can be coded in a manner completely independent of all of the previous variables. In fact, a recorder with digital chart drive (from an escapement mechanism) and analog stylus drive (using a conventional D'Arsonval pen movement) can be easily visualized. This would seem to allow multiplication of the number of possible systems by at least the factor of 3, for the three common types of modulation. (3)

((a)) Type of Applied Scanning Energy: If this energy is considered as furnishing "chart" drive, there are ten possible forms of energy, as in (1) above. Actually, this term can broadly be interpreted to include the specification of both stylus and chart drive, so that many more combinations seem realistic. (10)

Even on this basis, which can probably be expanded by further study, the number of separately identifiable recording systems might be as high as 3 x 2 x 3 x 6 x 10 x 12 x 3 x 10, or 388,000. To show that each separate specification is necessary, the hypothetical example of a package shock recorder used:

I. Recording System Function: Should be combination system, with record visible for easy monitoring, but capable of automatic statistical analysis of a large number of records.

A. Type of Energy Input: Will be mechanical displacement, since the data to be recorded measures the shocks experienced by a package of material in transit over a period of weeks or months.

1. Form of Energy Input: Will be analog, since it is desired to know the amplitude of each shock as a function of its duration.

a. Form of Recorder Coding: Will be amplitude modulation of a mechanical signal, since an accelerated mass will drive a recording stylus perpendicular to the direction of chart travel. Acceleration is converted to displacement by a spring-loaded mass.

(1) Type of Applied Recording Energy: Will be mechanical - motion of spring-loaded stylus across record material.

(a) Change of State Produced in Record: Material removal - scratching of stylus across smoked glass plate.

((1)) Form of Scanner Coding: Since chart must be moved at one constant speed while no shocks are being experienced and at another (faster) constant speed during shocks, pulse modulation of the independent (scanning) variable is required. Geometry is linear x-y system since stylus moves in straight line.

((a)) Type of Scanning Energy: Clockwork motor will be used, with two speeds selectable by a sensitive threshold accelerometer independent of that used for stylus motion. Thus scanning energy is mechanical.

V. Data Sheets for Recording Systems: On the basis of the actual forms of energy applied to change the state of an element of record area (or volume), there are ten possible categories. Sample rough data sheets for recorders in some of these categories are shown to the limited extent possible in this brief study. The design of the data sheet is subject to improvement by further work on Chapter III of this report. It is believed that at least 1000 data sheets could be included in a reasonably thorough coverage of systems worth evaluation on separate bases. At the beginning of each section is a tabulation of the various principal types of subclasses conceived for each system to date.

Combination Systems: Some systems combine one or more forms of recording energy, for example, when a blast of heated gas is directed at a record. Such systems should be classified under both energy headings when the change in state of the record results partially from each type of energy.

Conclusions: It is not possible to compute such important factors as record storage capacity or storage density from the typical manufacturers information. Noise figures are seldom given, nor are power supply requirements of the recording process itself isolated.

A. Mechanical Recording Energy Systems: In these systems mechanical energy is applied to the recording material, and actually causes the change in state of the record material. (The strict definition of the term, "change in state," must be liberalized to include mechanical transfer of materials such as ink to the recording medium.) Principal types of these systems are:

1. Material Removed From Record
   a. Punched Holes or Voids (Punch)
   b. Notched Edges (Punch)
   c. Scratched Grooves (Stylus)
   d. Cut Grooves (Stylus)
   e. Absorption of Gas or Liquid from Record

2. Material Added to Record
   a. Ink (Pen)
      (1) Magnetic Ink
      (2) Dye - Containing Ink
      (3) Radioactive Ink
   b. Pencil
      (1) Graphite Pencil
      (2) Fluid Graphite Pencil
      (3) Radioactive Pencil
      (4) Magnetic Particle Pencil
   c. Liquid Spray
      (1) Magnetic Liquid
      (2) Dye-Bearing Liquid
      (3) Radioactive Liquid
   d. Gas Spray
   e. Sputtered Wax
   f. Spray of Solid Particles (Aerosols)

3. Record Material Displaced
   a. Embossing Stylus
   b. Gas Jet Stream
   c. Abrasive Particle Stream

4. Record Material Changed in Physical State
   a. Contact Stylus - Pressure Sensitive Record

General Criteria - Mechanical Systems
   a. Ungrooved or Pregrooved Blanks
   b. Stylus Motion - Vertical or Lateral
   c. Stylus Drive
      (1) Electromagnetic
      (2) Electrostatic
      (3) Piezoelectric
      (4) Hydraulic
      (5) Mechanical
   d. Records Processed or Unprocessed after Recording
   e. Record Materials - Rheology
   f. Gas or Liquid Propulsion Means
      (1) By Pump
         (a) Form of Actuating Energy

(2) By Capillary Action
(3) By Gas Pressure
(4) By Gravity

g. Number of Possible States of Record Element of Area

Type **Mechanical**

Recording Process

Description of Process: Ink-Paper (Brush Penmotor)

Geometry: Paper Chart Pen Length 3 in.; 40 mm peak to peak pen swing up to 70 CPS

Time Duration Range: ---

Frequency Response: 0.2 to 100 CPS (With amplifier) for 80% of maximum
0 to 30 CPS (No amplifier) for 100% of maximum

Total Record Storage Capacity:

Dimensions of Recorder: 5' x 4" x 1-5/8" Pen Overhang 1-3/8"

Input: 1500 ohms

Weight: 4 lbs.

Power Supply: ---

Reproducer: ---

Driving Impedance for Optimum Damping: 250 ohms

Sensitivity: 1.1 mm/volt or 1.6 mm/ma at pen point

Anti-Freeze Ink: Purple, suitable to -20° F.

Pen Friction: Signals giving less than 2 mm deflection may be affected.

Storage Density: Not known, since width of pen trace not specified

Type **Mechanical**

Recording Process

Description of Process Embossing - Film

(Miles Reproducer Co. "Walkie Recordall")

Geometry Belt - 150 hours can be filed in container 1" x 3" x 6"

Time Duration Range 90 minutes to 8 hours (4 hours per side)

Frequency Response Not specified - probably to 2500 cycles

Total Record Storage Capacity

Dimensions of Recorder 4" x 9" x 15"

Input

Weight 11.5 lbs. for model CC4B

Power Supply Flashlight cells plus "B" Battery

Reproducer

Storage Density Insufficient data given

Reference: Miles Reproducer Company, Inc., 812 Broadway, New York 3, New York

Type **Mechanical**

Recording Process

Description of Process ___ Ink Pen - Paper

(Texas Instruments - Dual Recording Milliammeter Model A)

Geometry ___ Rolled Chart 100' long, 6" wide

Time Duration Range ___

Frequency Response ___ 0 to 6 cps

Total Record Storage Capacity ___

Dimensions of Recorder ___ 8" x 9" x 11"

Input ___ 1 ma full scale at 15,500 ohms

Weight ___ 15-1/2 lbs.

Power Supply ___ 50 watts for heater power

Reproducer ___

Chart Speeds ___ 12" per minute to 12" per hour

Chart Speed Accuracy ___ ± 2%

Chart Drive ___ 28 volts dc or 115 volts ac motor

Operating Temperature Range ___ - 20° to + 55° C.

Pointer Accuracy ___ ± 5%

Storage Density ___

Reference:

Type **Mechanical**

Recording Process

Description of Process: Embossing - Plastic Disc (Sound Scriber Executive Recorder)

Geometry: Disc Diameter 6" maximum

Time Duration Range: 8 minutes to 30 minutes for 33-1/3 rpm speed

Frequency Response: Probably 300 to 2500 cps

Total Record Storage Capacity:

Dimensions of Recorder: 8-1/2" wide x 6" high x 11-3/4" deep

Input: 25 ohms

Weight: 15 lbs.

Power Supply: 115 volts 60 cycles 60 watts

Reproducer: Included in recorder

Storage Density:

Reference:

Type | Mechanical |

Recording Process

Description of Process Ink Pen - Paper

(Thompson Products Logarithmic Rectangular Recorder Model ASRI-01)

Geometry Rolled Chart

Time Duration Range Not Specified

Frequency Response 400 to 10,000 cps

Total Record Storage Capacity Not specified

Dimensions of Recorder 60" x 28" x 21"

Input 80 db range 2V full scale at 1,000 cps

Weight Not specified

Power Supply

Reproducer Not specified

Paper Drive Selsyn with 100:1 gear ratio

Resolution Pen position error less than 0.5% of full scale. Chart position error less than 0.1° on the 2° per inch scale

Paper Speed From 2° to 60° per inch

Maximum Pen Speed 13" per second

Maximum Pen Travel 7-29/32

Storage Density

Reference:

B. Acoustical Recording Energy Systems: In these systems acoustical energy is applied to the recording material, and produces the change in state of the record. Principal types of systems are:

1. Material Removed from Record
    a. Ultrasonic Cutting Stylus
    b. Sonic Cutting Stylus

2. Record Material Displaced
    a. Ultrasonic Embossing Stylus
    b. Sonic Embossing Stylus

3. Record Material Changed in Physical State
    a. Contact Stylus - Vibration Sensitive Record - Physical Change in State
    b. Contact Stylus - Chemical Change in State
    c. Focussed Ultrasonic Beam - Vibration
        (1) Generated by Electromechanical Resonator
        (2) Generated by Corona Discharge (Ionophone)
        (3) Generated by Gas Explosions

General Criteria - Acoustical Systems
    a. Ungrooved or Pregrooved Blanks
    b. Stylus Motion - Vertical or Lateral
    c. Rheology of Record Materials
    d. Type of Stylus Drive

C. Optical Recording Energy Systems: In these systems optical (light) energy is applied to the recording material, and produces some change in state of the record. Principal types of systems are:

1. Latent Image Produced on Record
    a. Light Beam from Single Fixed Source
        (1) Source Intensity Modulated
            (a) Incandescent Lamp
            (b) Gas Discharge Lamp
            (c) Cathode-Ray Tube
            (d) Electric Arc or Spark
            (e) Luminescent Phosphor
                ((1)) Type of Exciting Energy
        (2) Beam Intensity Modulated
            (a) Mechanically varied Optical Elements
                ((1)) Successive Apertures
                ((2)) Mechanical Shutter
            (b) Electrically varied Optical Elements
                ((1)) Kerr Cell (Faraday Effect)
                ((2)) Electron or Ion Bombarded Oil Film
                ((3)) Solid-State Light Amplifier
                ((4)) Photoelectron Emitter and Luminescent Screen

(3) Beam Position on Record Varied
  (a) Mechanically Positioned Optical Elements
    ((1)) Moving Mirror
      ((a)) Type of Mirror Driving Energy
    ((2)) Moving Lens
      ((a)) Type of Driving Energy
(4) Source Color Modulated
  (a) Electrical Modulation
    ((1)) Variable Current to Filament
    ((2)) Variable RF Frequency to Glow Lamp
    ((3)) Multicolor CRT Phosphors
  (b) Magnetic Modulation
    ((1)) Multicolor CRT Phosphor Selection
(5) Beam Color Modulated
  (a) Variable Transmission Filter(s)
    ((1)) Type of Filter Actuation
  (b) Selection of Multiple Filter Elements
    ((1)) Type of Selection Process

b. Light Beams from Multiple Fixed Sources
  (1) Source Intensity Modulated
    NOTE: Most of categories in a. can be repeated here, with addition of systems using multiple-digit codes such as PCM employs.

c. Light Beams from Multiple Moving Sources
  (1) Source Intensity Modulated
    NOTE: Most of categories in a. can be repeated here, with addition of more complex codes such as can be achieved with multiple-gun CRT sources, etc. Here, formation of letters and numerals can be included.

2. <u>Visible Image Produced on Record</u>
  a. Light Beam from Single Fixed Source
    (1) Luminescent Phosphor Record
    (2) Direct Printing Photo Materials not Requiring Processing
      NOTE: Many of the systems in 1. may be used to excite these records.

3. <u>Electrical Charge Image Produced on Record</u>
  NOTE: In addition to above categories, the element of a two-dimensional scanning of the record by a portion of its own system can be introduced since tubes such as the Farnsworth Image Dissector can produce the record on a mosaic, etc.

4. <u>Chemical Change Produced in Record</u>

<u>General Criteria - Optical Systems</u>

a. Coding System
  (1) Variable Area
  (2) Variable Density
  (3) Variable Color
  (4) Combinations of Multiple Sources

b. Optical Element Drive
   (1) Electromagnetic
   (2) Piezoelectric
   (3) Mechanical
   (4) Electrostatic
c. Record Materials
   (1) Sensitized Film
   (2) Sensitized Paper
   (3) Sensitized Plates
   (4) Photoemissive Surface
d. Record Processing After Recording
   (1) Type of Processing Energy
e. Spectral Sensitivity
   (1) Of Light Source
   (2) Of Record Material
   (3) Of Optical System Elements
f. Light Source Characteristics
   (1) Frequency Response
   (2) Power Requirements
      (a) AC or DC Excitation
      (b) RF Excitation
      (c) Efficiency
   (3) Brightness
g. Type of Light Modulation Energy Supply
h. Response of Record to Signal
   (1) Response Time
   (2) Persistence or Permanence
   (3) Linearity
      (a) Linear
      (b) Logarithmic
      (c) Vector (Tristimulus Diagram)
   (4) No. of States per Element of Area

Type **Optical**

Recording Process

Description of Process Light Beam - Photosensitive Record

Mirror deflected by galvanometer type movement

NOTE: Charts need no development or fixing; cannot be exposed to bright light.

Geometry Strip Chart 60 mm. wide x 15 meters long

Time Duration Range 150 seconds at 100 mm./sec. to 500 min. at 0.2 mm./sec.

Frequency Response Upper limit varies from 1 to 570 cycles/sec.

Total Record Storage Capacity Resolution not specified

Dimensions of Recorder Not specified

Input 8 - 4,700 ohms in various models

Weight Not specified

Power Supply 220 volts 50 CPS

Reproducer None specified

Light Source High pressure mercury source (0.3 x 0.3 mm^2). Brightness 10^5 Stilb

Light Power Supply 86 - 100 watts, 16 - 24 V.D.C. Ignition 650 V.A.C.

Ignition Time Several minutes Price $1,025.00

Maximum Trace Velocity 10 meters/sec.

Maximum Sensitivity 1 mm. deflection for 0.03 μa. across 4700 ohms or for 0.038 mv. across 8 ohms

Chart Drive Synchronous Motor Maximum No. Channels 4

Storage Density

Reference: Hartman and Braun A-G, Frankfurt/Main, Germany.
Model RLT4 "Lumiscript".

D. Thermal Recording Energy Systems: In these systems thermal energy (including infrared radiation not handled by optical means) is applied to the record. Principal types of these systems are:

1. Material Removed from Record
    a. Evaporation of Record Material
        (1) By Stylus Point
        (2) By "Flame" Stylus
            (a) Gas Flame
                ((1)) From LPG Container
                ((2)) From Chemically Generated Gases
            (b) Heat from Electrical Discharge
        (3) By Electrical Coil Stylus
        (4) By Infrared Radiation
            (a) From Heated Stylus
            (b) From Radiant Energy Source
        (5) By Heated Gas Stream

2. Material of Record Displaced
    a. By Stylus Point
    b. By "Flame" Stylus
        (1) Gas Flame
            (a) From LPG Container
            (b) From Chemically Generated Gases
        (2) Heat from Electrical Discharge
    c. By Electrical Coil Stylus
    d. By Infrared Radiation
        (1) From Heated Stylus
        (2) From Radiant Energy Source
    e. By Heated Gas Stream

3. Change in Physical State of Record
    a. Color Changes
    b. Changes in Magnetization

General Criteria - Thermal Systems
    a. Ungrooved or Pregrooved Blanks
    b. Stylus Motion
        (1) Vertical
        (2) Lateral
    c. Type of Stylus Drive
        (1) Electromagnetic
        (2) Electrostatic
        (3) Piezoelectric
        (4) Hydraulic
        (5) Mechanical
    d. Records Processed or Unprocessed After Recording
    e. Method of Heating Point Stylus
        (1) Chemical
            (a) Localized Combustion
            (b) Exothermal Non-Combustion Reaction

(2) Electrical
(a) Type of Energy Modulation
f. Thermal Record Materials
(1) Chemically Treated Paper
(2) Synthetic Plastic Materials
(3) Metal Foils
g. Method of Providing Heated Gas Stream

E. Electrical Recording Energy Systems: These systems apply electrical energy directly to the record material. Principal types of systems are:

1. Material Removed from Record
a. By Corona Discharge
(1) Puncturing of Film Record
(2) Erosion of Record Surface
b. By Spark Discharge
c. By Low Voltage Current Flow
(1) Generation of Heat in Record
(2) Migration of Ions in Record
d. Attraction of Charged Particles from Record

2. Material Added to Record
a. Attraction of Charged Particles to Record
(1) Single Stage Process (Smoke Printing)
(2) Two-Stage Process (Xerography)

3. Record Material Displaced
a. By Corona Discharge
b. By Spark Discharge
c. By Low Voltage Current Flow

4. Record Material Changed in Physical State
a. Latent Image Produced in Record
b. Color Change in Record
c. Change in Index of Refraction of Record
d. Charge Induced on Record
(1) Dielectric Record
(2) Conducting Elements on Dielectric Record
e. Bi-Stable Ferroelectric Elements
f. Electrets

General Criteria - Electrical Systems
a. Ungrooved or Pregrooved Blanks
b. Stylus Motion
c. Type of Stylus Drive
d. Record Processing Required
e. Method of Creating Electrical Energy Output
f. Frequency of Output Voltage (Carrier)
g. Type of Output Modulation
h. Type of Record Material

Type **Electrical**

Recording Process

Description of Process: Rotating Helix Electrode - Electrosensitive Paper

Geometry: Helix marking perpendicular to direction of paper travel

Time Duration Range: 1 hour operation for 90 feet of paper

Frequency Response: ______

Total Record Storage Capacity: ______

Dimensions of Recorder: ______

Input: ______

Weight: ______

Power Supply: ______

Reproducer: ______

Writing Rate: 300" per second

Resolution: 0.3" paper travel for 300" writing

Storage Density: ______

Reference: Bulletin Alfax Paper and Engineering Company

NOTE: Multiple blades or platens and multiple helices can be used for multi-channel recording.

Type **Electrical**

Recording Process

Description of Process: Fixed Stylus - Current Sensitive Paper

Geometry: Fixed Stylus - Strip Chart

Time Duration Range: 3/4 hour to 8 day per 100-foot roll

Frequency Response: One event per second for 3/4 hour unit; one event per minute for 8 day unit.

Total Record Storage Capacity:

Dimensions of Recorder: Approximately 5" x 2" x 4"

Input:

Weight: Not specified

Power Supply: 110 volts 60 cycles

Reproducer: Not specified

Number of Channels: 2 on 0.4" tape up to 30 on 5-1/2" tape

Storage Density:

Reference: Alden Electronic and Impulse Recording Equipment Company catalog

F. <u>Magnetic Recording Energy Systems</u>

1. <u>Material Removed from Record</u>
   a. By Attraction of Magnetic Particles from Record

2. <u>Material Added to Record</u>

3. <u>Record Material Displaced</u>

4. <u>Record Material Changed in Magnetic State</u>
   a. Orientation of Magnetic Domains - Thin Layer
      (1) Variable Density Type
      (2) Boundary Layer Type
   b. Magnetization of Static Elements
      (1) Bi-Stable Magnetic Cores
      (2) Multi-Stable Elements (Barkenhausen)

<u>General Criteria - Magnetic Systems</u>
   a. Record Geometry
      (1) Drum
      (2) Sheet
      (3) Disc
      (4) Tape
      (5) Wire
   b. Type of Magnetic Field Modulation
   c. Method of Applying Magnetic Field Energy
   d. Type of Record Material
      (1) Oxide Coated Plastic
      (2) Homogeneous Wire
   e. Type of Coding
      (1) Return to Zero Systems
      (2) Non-Return to Zero Systems
   f. Type of Playback Head
      (1) Output Amplitude Proportional to Flux of Record
      (2) Output Amplitude Proportional to Tape Speed

Type | Magnetic |

Recording Process

Description of Process Magnetic Tape

Ampex Model 350

Geometry Tape - Reels 10-1/2" diameter x 1/4" wide

Time Duration Range 32 minutes to 4 hours, 16 minutes

Frequency Response 30 to 15,000 cps +2 db

Total Record Storage Capacity

Dimensions of Recorder Approximately 20" x 40" x 20"

Input 600 ohms balanced or unbalanced

Weight 84 lbs.

Power Supply 110 V 50 or 60 cycles at 2.7 amperes

Reproducer Included in Recorder

Signal to Noise Ratio 70 db to 50 db depending on tape speed

Flutter and Wow 0.2 to 0.3% depending on tape speed

Starting Time 0.1 second

Stopping Distance Less than 2" from 15" per second speed

Playback Timing Accuracy ±0.2% (±3.6 seconds in 30 minutes)

Rewind Time 40' per second

Storage Density

Reference:

Type **Magnetic**

Recording Process

Description of Process Magnetic Belt - FM Carrier Recording

Ampex Model 700

Geometry Magnetic Belt 4" wide x 40-1/4" long

Time Duration Range 5 seconds; tape speed 7.5" per second ±0.5%

Frequency Response 1-1/2 to 3-1/2 cps (-3db) 3-1/2 to 300 cps (±1 db)

Total Record Storage Capacity ____

Dimensions of Recorder 20" x 16" x 70"

Input 26 Channels 1 V rms across 100,000 ohms; 45 to 50 db above noise

Weight 242 lbs.

Power Supply 42 amps at 12 V dc

Reproducer Included in Recorder

Output 1 V rms across 1,000 ohm line

Harmonic Distortion Less than 1% rms total at peak recording level

Time Alignment Interchannel Misalignment Does not Exceed 1 millisecond

Storage Density ____

Reference:

Type | Magnetic |

Recording Process

Description of Process Bi-Stable Magnetic Cores

Alden Products Co., Static Magnetic Memory Model 5100RA

Geometry

Time Duration Range For Minimum Signal/Noise Ratio Pulse Rise Time Should Be 5 Microseconds

Frequency Response Can Handle Up To 30,000 Pulses Per Second

Total Record Storage Capacity One Bit Per Unit

Dimensions of Recorder 1-5/8" x 1-5/8" x 1"

Input

Weight

Power Supply Driving Tube Must Deliver Peak Plate Current of 150 ma

Reproducer

Storage Density

Reference:

Type **Magnetic**

Recording Process

Description of Process Magnetic - Wire (Miniphon)

Geometry Wire 11.8 in./sec. 0.002" diameter

Time Duration Range .25 to 2.5 hours (with different record spools)

Frequency Response 200-4000 cps

Total Record Storage Capacity

Dimensions of Recorder 4-3/8" x 6-5/8" x 1-3/8"

Input Crystal Microphone

Weight 2.125 lbs.

Power Supply 1.5 V A Battery, 30 V B Battery, 9 V Motor Battery

Reproducer Same as Recorder

Output 500 ohms

Motor Battery Life 24 hours

Rewind Speed 2.5 times record speed

No. of Channels 1

Storage Density

Reference:

G. Electronic Recording Energy Systems: In these systems energy is applied to the recording medium by electrons (and for completeness the definition is expanded to include other elementary charged particles) which have acquired energy by acceleration from an electric field - normally in a vacuum. Principal types of systems are:

1. Marking of Record in Vacuum
   a. Latent Image - Film Record
   b. Charge Image - Secondary Emission by Record
   c. Charge Image - Accumulation of Charge by Record
   d. Photosensitive Record - Charge Image
   e. Bombardment of Record by Radioactive Ions
   f. Chemical Reaction of Record with Incident Ions

2. Marking of Record in Air
   a. Charge Image - Exterior of Dielectric Bombarded by Electrons

   General Criteria - Electronic Systems
   a. Type of Coding System
   b. Method of Producing Accelerating Field
   c. Source of Charged Particles
   d. Record Processing After Recording
   e. Response of Record to Signal
      (1) Response Time
      (2) Persistence or Permanence
      (3) No. of States Per Element of Area

H. Electromagnetic Recording Energy Systems: The recording media for these systems are sensitive to electromagnetic radiation. Two sources are excepted, visible light and radiation from nuclear disintegrations, since optical and nuclear techniques differ radically in practice from techniques of handling electromagnetic energy.

NOTE: After review of possible systems in this category, it appears desirable to include the few possible systems under other categories (e.g. under nuclear systems for gamma rays and electrical or optical systems). Until very short wavelengths are reached, electromagnetic fields are not capable of sufficient resolution to be very useful. It is true that very short waves (overlapping infrared wavelengths) have been produced, but these are presently derived from weak harmonics of reflex klystrons, with very low power conversion efficiency. Combinations of electric and magnetic fields may be quite useful, but these are not strictly electromagnetic systems.

I. Nuclear Recording Systems: In these systems energy derived from a nuclear source is applied to the recording medium. This classification does not include radioactive materials transferred to the record by mechanical or other means. Principal types of nuclear systems are:

1. Latent Film Image Produced on Record
   a. Nuclear Emulsion Record

(1) Natural Radioactive Source
  (a) Alpha Particle Emitters
  (b) Neutron Sources
  (c) Beta Ray Emitters
  (d) Gamma Ray Emitters
    ((1)) Moving Stylus in Contact with Record
    ((2)) Nuclear Energy Beam from Single Fixed Source
      ((a)) Intensity Modulation of Beam by Signal
        (((1))) By Mechanically Positioned Absorber
        (((2))) By Electrically Varied Aperture

b. Other Nuclear-Sensitive Emulsion Records

c. Non-Emulsion Records - Latent Image

2. <u>Radiation Damage Produced in Record</u>

3. <u>Radiant Energy Produced in Record</u>

4. <u>Electrical Charging of Record Elements</u>

5. <u>Chemical Effects Produced in Record</u>

<u>General Criteria - Nuclear Systems</u>

a. Type of Coding System
b. Radioactive Element Drive
c. Types of Record Materials
d. Record Processing After Recording
e. Nuclear Source Characteristics
f. Type of Nuclear Beam Modulation
g. Nuclear Beam Modulation Energy Supply
h. Response of Record to Signal
  (1) Response Time
  (2) Persistence or Permanence
  (3) Linearity
  (4) No. of Physical States per Element
i. Type of Reading Energy

J. <u>Chemical Recording Energy Systems</u>: As defined these systems apply energy to the recording material primarily in chemical form. The original means of bringing chemical energy to the record may involve mechanical transport, but the end effect is a chemical reaction.

1. <u>Solid Added to Record</u>
  a. Etching or Corrosion of Record Surface
    (1) Unselected Record Surface
    (2) Chemically Treated Record Surface
  b. Color Change of Record Surface
    (1) Color of Applied Material Changed
    (2) Color of Record Material Changed

2. <u>Liquid Added to Record</u>
  a. Type of Chemical Reaction Produced

(1) Oxidation
(2) Reduction
(3) Polymerization
(4) Depolymerization
(5) Bond Formation
(6) Bond Disruption

b. Physical Reaction Produced
(1) Formation of Gas Bubbles

3. Gas Added to Record
(Similar to 2.)

4. Contact of Catalyst with Record
a. Latent Image Produced in Record

5. Removal of Chemical from Record

General Criteria - Chemical Systems

a. Ungrooved or Grooved Blanks
b. Stylus Motion - Vertical or Lateral
c. Stylus Drive
d. Record Processing After Recording
e. Chemical Source Characteristics
f. Type of Chemical Stream Modulation
(1) Reagent Injected into Gas or Liquid Stream
g. Chemical Carrier Stream Energy Supply
h. Response of Record to Signal
i. Type of Reading Energy
j. No. of Stable States per Element of Area

VI. Critical Evaluation: With all the factors to be considered, one may still reduce the recording problem to elementary questions of how to mark the record and how to drive it. Ignoring such refinements as coding, one might review principal sources of marking energy as follows:

A. Hypothetical Problem: Provision of a subminiature, rugged, recording device which can be used with a variety of input units in a simple manner. The recorder should be extremely straightforward in design, with a minimum of adjustments, but information need not be instantly readable from the record by eye. The reader can be as complex as desired, and one reader can be used to service many recorders.

Some tentative specifications may be set up:

1. Duration of Recording: At least 30 minutes.
2. Frequency Response: 0-2500 cycles per second.
3. Total Storage Capacity: About 10^7 bits.
4. Power Supply: Self-contained.
5. Weight: Not more than 1 pound.
6. Dimensions: Not greater than 3/4" x 4" x 5".
7. Input: 1 volt across 600 ohms (rms).
8. Accuracy: 2% of full scale.

B. Problem Discussion: With severe space and weight limitations, the power supply for recording and scanning energy is a critical factor. In this case possible principles of use for recording may first be examined to find those with the lowest energy requirement. Because of the limitations of this study, review will be made only of possible optical, nuclear, and chemical systems of novel types which might fulfill the requirements.

C. Possible Optical Systems: Photographic film is available in color with a resolving power of about 60 lines per mm. and in black and white with 135 lines per mm. for microfile and more than 1,000 lines per mm. for high resolution plates. The exposure time or light intensity requirement increases for higher resolution film, so that one best compromise exists between the maximum number of bits per square inch which can be stored, and the energy required per bit of information.

Possible storage density on microfile is about 10^7 bits per square inch, so that one square inch can meet our rough specification. However the size of an element of area is about 0.0003 inch, and mechanical positioning to this accuracy would be difficult to realize in production.

Light sources constitute something of a problem in such recording. Incandescent sources have poor frequency response and low efficiency. Glow discharge sources have low brightness. Although a few new types of sources have been developed in recent years, there is a great deal of promise for new ideas.

One system which might offer promise would use the old "Crosley tuning indicator" principle, where the length of glow discharge in a long, thin light source was made proportional to signal amplitude. This would eliminate mechanical motion of film, and would lend itself to a sampling technique where the lamp was pulsed only at intervals according to the signal. Since motion of the leading edge of a light source is involved, conversion of analog to digital information might be achieved, or a multiplicity of colors might be worked out.

An alternative system is use of the "glow transfer" principle now used in counter tubes. If each electrode represents a "decade" of voltage values (i.e. electrode #1 represents 0.01 to 0.1 volt; #2, 0.1 to 1.0 volt; etc.), then a single tube becomes a 10 per cent recorder over a wide range of values. Its image could be directly focussed on film.

Still another system would use a binary code wherein each glow lamp represented one binary digit. With six lamps, sixty-four different values can be registered, giving an accuracy of better than 2 per cent of full scale.

Mechanical systems of interrupting or moving light beams do not look attractive from the energy standpoint, except for the fact that transistor amplifiers now allow more efficient driving of low impedance systems than previously. The very fact that mechanical systems are relatively low impedance systems seems to imply appreciable power requirements.

Electronic means of generating light are attractive, although development costs may be relatively high. The "glow modulator" type of tube for sound on film recording presently has high power requirements, although frequency response is quite good. So far as is known, no attempts have been made to miniaturize this type of recording element.

To date, record materials not requiring processing have not been found with high sensitivity. A search along these lines might be useful, although record processing might be made so convenient as not to constitute a serious difficulty.

D. Possible Nuclear Systems: Supplying the recording energy by nuclear sources is attractive from the standpoint of power supply requirements. One basic form of recorder might involve a moving stylus where the point is composed of sufficient radioactive material to make a developable trace on a film chart at the highest writing speed required.

A system of this sort, involving mechanical motion, might be capable of attaining the desired frequency response, even if contact with the record is essential. Small galvanometer elements can be vibrated over limited amplitudes up to rather high frequencies, and if a collimated beam of nuclear radiation could be attained with small mass, the system might be feasible. Necessary amplitude of motion is of course a function primarily of beam width.

So many radioactive materials are available that it is desirable to make a detailed review of this subject.

E. Possible Chemical Systems: Suppose that the record in a system consisted of a spool of nylon thread with diameter just sufficient to insure a reasonable margin of mechanical strength. (Glass fiber reinforcing might assist in this respect, if feasible.) If this thread could be marked (recorded on) in some manner with greater resolution or with less power requirement than is possible for magnetic wire, a useful system might result.

One conceivable marking system might involve directing a stream of a suitable chemical gas against the thread. Resolution in a magnetic system is limited partially by the "granularity" of the record and partially by the area into which sufficient lines of magnetic flux can be concentrated. The same sort of limitations might apply to the "nylon thread" system, with resolution limited by the area into which a suitable gas flow could be concentrated. It seems possible that more energy per unit area could be obtained from a chemical gas stream, even allowing for flow effects caused by motion of the thread.

Chemical reactions for this purpose might be studied, with emphasis on marking gases which could be stored in liquefied form in a small pressure chamber. Modulation of the gas stream might be achieved by a tiny, high speed valve, or by small amplitude motion of the stream outlet. (In the latter event, recording only of "axis crossings" seems to be a natural feature.) Bromine may be a possibility.

Sources of chemical energy for marking are attractive from the standpoint of power supply considerations. The energy per unit volume which can be stored chemically is normally higher than can be stored electrically. The chemical fuels are of interest, but thought should be given to "high energy" materials such as explosives, as well. Other violent or reactive chemicals might be useful for chart recording on ordinary paper when used in place of ink. Of course special materials (e.g. dyes) might be incorporated in the record material. Prospects for low granularity of records appear encouraging. Charged cartridges of pressurized gases should be able to be handled as easily as batteries.

The possibility of using only a catalyst to affect a chemical reaction which might then take place in the record medium is of interest because a stylus point of catalyst material might need replacement only occasionally. This would assist in reduction of power supply requirements.

F. Record Geometry and Scanning: Regardless of the type of recording energy used, a method of scanning the record must be selected, as well as the record geometry.

The most practical commercial recording form seems to be the belt as used by Dictaphone (See Appendix D). If 10 square inches of belt surface is needed, the length and width of a "square" belt can be 1.75 inches. Present Dictaphone belts have a width of 3.5 inches and a total area of roughly 42 square inches.

A miniature belt chart record might first be visualized as a belt having a diameter of 3 inches and an equal width - perhaps with sprocket holes for indexing purposes. The belt geometry allows good tracing with linear motion of the recording head, and a helical track, using the area rather effectively. On this basis it would be necessary to store 9×10^6 bits in an area of 27 square inches, or 3.3×10^5 bits per square inch. The linear dimension of a bit is .00175 inch, so that the speed of the belt will need to be about 8.8 inches per second. For a 1 inch circumference driving drum, this would correspond to about 510 rpm. The power requirement for 1/2 hour at this rate might be excessive. A clockwork motor might be hard-pressed to supply this much energy.

Drive: The Esterline-Angus chart recorder uses a spring clock in some models, and will drive a rather large chart and take-up mechanism at speeds up to 6 inches per minute for as long as 4 hours, almost the equivalent of 48 inches per minute for 30 minutes. The Esterline-Angus escapement design is not new, and modern techniques might bring the drive speed of a much smaller chart (less take-up mechanism) up to perhaps 100 inches per minute for 30 minutes, while reducing size and weight.

Thus, 1.67 inches per second seems reasonable, and this is within a reasonable range of a belt diameter which does not place too severe tolerance requirements on the mechanical system.

Another good form of geometry is the wire (or thread, as previously mentioned). The "Miniphone" recorder can achieve a response of 4000 cps with 11.8 inches per second of 0.002 inch diameter steel wire. Experience at SwRI indicates that tungsten wire with a diameter of 0.0002 inch might be handled successfully from the mechanical standpoint. If chemical or optical marking of this wire could be achieved with a resolution of 100 lines per mm. or 2500 lines per inch, then a tape speed of 2 inches per second would be necessary for 2500 cycles at two bits per cycle. For 30 minutes, a length of 3600 inches or 300 feet would be needed; this would occupy a volume of $(\pi)(.0001)^2(3600)$ or roughly 10^{-4} cubic inch. A minimum spool diameter of perhaps 0.75 inch would be needed to avoid crimping the wire around a sharp bend.

G. General: In examining all possible systems to arrive at the better prospects, it is necessary to develop weighting factors for the important criteria. This raises many questions:

Consider the factor of resolution. This is involved with the minimum area or volume in which one or more bits of information may be stored. Yet the interrelation of limitations on resolution and those on area cannot be avoided. A high resolution system might be realized, for example, by causing the deposition of atoms of various stable isotopes to be arranged in a crystal in a certain way. The number of bits per atom would depend on the number of stable isotopes which could be detected by the beam of exploring energy (reading energy), or by the amount of energy available for creating the isotopes initially. Since the wavelength of an energy beam is always a measure of its energy level, it is fair to assume that high resolution will be associated with a high energy level. This does not necessarily mean a high power input if the energy is efficiently used.

VII. Bibliography: While a bibliography was recently published by Hollander, it does not contain data on many of the basic principles necessary to evaluate recording processes. Energy conversion principles are not treated well in any known papers. With the budget limitations of this present study, it was not possible to conduct a proper literature or patent search, but this should certainly be done. In particular, a careful review of ASTIA items should be made.

APPENDIX A

Energy Conversion Processes and Recording

For basic analysis it is necessary to consider recording as an energy conversion process. Energy from an information source plus (in most cases) energy from local power supplies are directed to a volume element of the record, and it must be assumed that in all cases that element represents a higher energy level when it stores information. Reading must direct a second quantity of energy to the element of the record.

There is, therefore, an energy conversion efficiency factor which must describe one of the most fundamental properties of a recording process. In addition, the resolution of a process must be closely associated with the volume required to store the smallest amount of energy which can be detected (in a given time, and with a given noise figure) by the reader. Thermodynamic concepts of entropy and energy should be explored specifically in this connection.

APPENDIX B

Communications Theory and Recording

D. K. C. Macdonald[1] suggests that the entropy of a system be regarded as a measure of its overall state, while information should be regarded as an incremental quantity characteristic of a transition or possible transition from one state to another. Then in communications

$$I_{12} = -\Delta S_{12}$$

where ΔS_{12} is the change in entropy.

Starting with knowledge of the statistical structure of all possible messages to be recorded, and the requirements for message readout, it is possible to design a recording system which is neither too elaborate nor too simple for a very high percentage of possible messages. Even as O. H. Schade developed "equivalent bandwidth" concepts for optical elements of TV systems, so will it be possible to treat mechanical tolerances and other fundamental system limitations in such a manner that individual elements are not overdesigned.

[1] JAP May 1952.

APPENDIX C

Mechanical Tolerances in Recording

For any recording system involving mechanical motion, a limiting factor in resolution, recording time, or other performance variables is mechanical tolerance. The familiar example of mechanical precision has been the ruling engine for diffraction gratings, which has required large mass, isolation from vibrations, thermal stability, aging of metal parts, and other extreme care in construction to realize the capabilities of resolution within optical dimensions. Lately, elaborate feedback systems have been used to correct for some process variables.

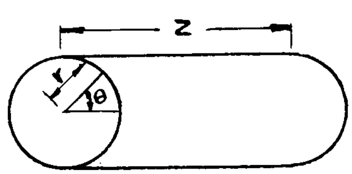
Extremely compact recording systems must be so designed as to minimize the effects of mechanical variations and to use ordinary fabrication methods. For this reason, careful study should be given to systems not requiring mechanical positioning of elements, or which can incorporate very simple servo correction systems. At the same time, data should be obtained on the realistic limits of present shop practice, where servo controls of machines may raise ordinary standards. Little attention seems to have been paid to the limitations imposed on recorders by these factors.

APPENDIX D

Record Geometry

Since it is possible to use three-dimensional spaces to store information, these should be considered in a general analysis. However, the great majority of existing recording media use the third dimension only incidentally or not at all. The common forms of records, and the two- and three-dimensional spaces they occupy, are listed in Table II which follows.

Practical Form of Record	Equivalent Solid	Scanning Axes	Equivalent Area
1. Wire	Cylinder	Z	Rectangle
2. Belt	Cylinder	θ,Z	Rectangle
3. Cylinder	Cylinder	θ,Z	Rectangle
4. Disc	Cylinder	r,θ	Circle
5. Tape	Parallelopiped	Z	Rectangle
6. Chart	Parallelopiped	y,Z	Rectangle
7. Sheet	Parallelopiped	y,Z	Rectangle
8. Magnetic Core Matrix	Parallelopiped	x,y,Z	--
9. Mobius Strip	?	?	?



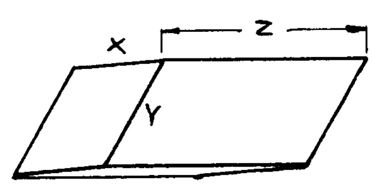


Table II

Solid Geometry of Records

An analysis of the maximum recording space that can be made available with specified limitations can be made using the principles of analytic geometry. For example, if the "maximum dimension" of the record (for a given storage capacity) is critical, a drum may be preferred to a disc. Using only one side, a drum has a surface area of πDW square inches, where D is the drum diameter and W is the width. If W = D (for the smallest maximum dimension), then the area is πD^2. A disc with the same maximum diameter D has an area only of $\pi D^2/4$, so that the drum has four times the disc area.

On the other hand, if a "thin" package is desirable (with one small dimension) the disc and belt may be compared. In a volume of, say, 1" x 4" x 5", the largest disc would have an area (one side) of $\pi D^2/4 = 4\pi$. A belt running on two pulleys of diameter d = 1" and w = 5" could have a separation, S, of pulley centers of 3", and its length L would be $L = 2S + \pi d$, or $(6 + \pi)$ inches. Thus the belt area would be $(6 + \pi)5$ or $30 + 5\pi$ inches^2.

Scanning Geometry: In two-dimensional cases, it is possible to scan a given area in many ways. Some common types of scanning are:

1. Single Line Scan
2. Parallel Line (Raster) Scan
3. x-y Scan
4. Parallel Circle Scan
5. Spiral Scan
6. PPI Scan
7. Sound Track (Variable Area) Scan

Decision as to the most efficient scan for a given recorder design has usually been dictated by record drive problems. Since the reader must be made to follow the same path as the recorder in many systems, a continuous rather than an intermittent path has often been preferred. This does not necessarily make most efficient use of the area. For example, the constant pitch spiral used in disc recording separates all tracks by the minimum amount necessary to achieve a certain cross-talk figure, so that storage density is sacrificed for simplicity.

Mark Geometry: The shape of an individual mark made on the record by the recording "stylus" is not simple. For example, in an embossing process such as the plastic belt "Dictaphone" system, the width of the groove may be less than the stylus width because of the elasticity of the material. As the stylus plows through the record there is a "bow wave" ahead of the stylus which modifies the trace of the stylus in some way.

The "mark" in a flying-spot scanner recording, say, on film may be quite complex. O. H. Schade studied cosine-squared and exponential aperture response factors since the distribution of light in a cathode-ray tube spot is far from uniform over a circular area. Fringing effects modify the pattern of a magnetic flux gap.

Resolution of any recording process is degenerated by the effective geometry of the mark on the record. The usual type of mark is a "spot" or a "slit," ideally. For each type of recording system the mark geometry must be a major factor in evaluation.

APPENDIX E

Record Materials

A study of record materials must be made independently for each type of recording energy. The sensitivity of a material to this energy is a vital factor in energy economy, and each material may have an equivalent "noise figure" of its own, depending on the dynamics of the recording process.

The number of energy levels or stable states of an element of record area offers a potential opportunity to improve recording efficiency very substantially. Color film can store as many elements as can be recognized by the optical reading system. It is possible to visualize the equivalents of "colors" in magnetic or chemical or nuclear systems. This property of record materials should be carefully explored.

Processing of records after recording should also be explored. This apparent disadvantage to practical operations may nevertheless afford very substantial economies in expenditure of recording energy. Such processing could actually be performed in the recorder itself, by applying uniform energy per unit area, at less overall energy expense than if signal energy alone is used. This is because the conversion of power supply energy to signal energy is often extremely low.