PAT WALTER

TG

EIGHTH MEETING

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EIGHTH TRANSDUCER WORKSHOP

22-24 April 1975

WRIGHT PATTERSON AFB
DAYTON, OHIO

TELEMETRY GROUP
INTER-RANGE INSTRUMENTATION GROUP
RANGE COMMANDERS COUNCIL

KWAJALEIN MISSILE RANGE
WHITE SANDS MISSILE RANGE
YUMA PROVING GROUND

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EIGHTH TRANSDUCER WORKSHOP

22-24 April 1975
WRIGHT PATTERSON AFB
DAYTON, OHIO

TRANSDUCER COMMITTEE
Telemetry Group
Range Commanders Council

Edited by
Pierre F. Fuselier, General Chairman

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INTRODUCTION

The Eighth Transducer Workshop was held in Dayton, Ohio, from 22 to 24 April 1975. It was sponsored by the Transducer Committee of the Telemetry Group, Range Commanders Council. The General Chairman was Pierre F. Fuselier of Lawrence Livermore Laboratory.

Workshop logistics were executed by a volunteer crew as follows:

Patrick L. Walter, Chairman Transducer Committee
Sandia Laboratories

Colonel Brien D. Ward, Welcoming Address, Commander
Air Force Flight Dynamics Laboratory
Wright Patterson AFB

Charles E. Thomas, Accommodations and Arrangements
Host, Wright Patterson AFB

Theresa Hanshaw, Registration

Jack Schmermund, Audio-Visual; both of Wright Patterson AFB.

Workshop program duties were also performed by a volunteer crew, as follows:

Pierre F. Fuselier, General Chairman, Lawrence Livermore Laboratory

Dayle E. Fitzgerald, Technical Secretary, Lawrence Livermore Laboratory

Session Chairmen:

Henry S. Freynik, Jr., Lawrence Livermore Laboratory

Garland N. Rollins, NASA Langley Research Center

Paul S. Lederer, National Bureau of Standards

Peter K. Stein, Arizona State University

John S. Hilten, National Bureau of Standards

Patrick L. Walter, Sandia Laboratories.

The traditional discussion format was observed. Workshops are just what the name says; everyone should come prepared to contribute something from his knowledge and experience. In a workshop the attendees become the program in the sense that the extent and enthusiasm of their participation determine the success of the workshop.

Participants had the opportunity to hear what their colleagues have been doing and how it went; to explore areas of common interest and common problems; to offer ideas and suggestions about what's new and what's needed in transducers, techniques, and applications.

GOALS OF THE WORKSHOP

To bring together people who use transducers; to air out problems and maybe come up with some solutions; to identify areas of common interest; and to provide a communication channel among the community of transducer users. Some examples are:

1. Improve coordination of information regarding transducer standards, test techniques, evaluations, and application practices among the national test ranges, range users, range contractors, other transducer users, and transducer manufacturers.

2. Set up special sessions so that people with measurement problems in specific areas can form subgroups and stay on to discuss them after the workshop conclusion.

3. Solicit suggestions and comments on past, present and future Transducer Committee efforts, and towards providing some standardization in the area of transducer signal conditioning amplifiers.

4. Provide task definition to the NBS Inter-Agency Transducer Project for transducer R & D for FY 76 and 77 supported through NAVAIR and national test range funding.

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China Lake, CA 93555

Antenna Systems

Data Multiplex

Recorders and Reproducers

Transducers
  Transducer Subcommittee

Transmitter/Receiver

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William D. Anderson
Naval Air Test Center

Elvis Skidgel
I. E. D. Conic

Earl Cunningham
Ectron

TRANSDUCER COMMITTEE OBJECTIVES

OBJECTIVES: This committee will inform the Telemetry Group (TG) of significant progress in the field of telemetry transducers; maintain any necessary liaison between the TG and the National Bureau of Standards and their transducers program or any other related telemetry transducer efforts; coordinate TG activities with other professional technical groups; collect and pass on information on techniques of measurement, evaluation, reliability, calibration, reporting and manufacturing; and recommend uniform practices for calibration, testing and evaluation of telemetry transducers.

RECOGNITION OF SPECIAL EFFORT

For various reasons, such as travel funds restrictions, work schedules and other factors, some participants went beyond the usual excellence in professional responsibility that marks the Transducer Workshops. This recognition is in appreciation of that extra effort.

Session 1	Speaker Mills Dean, III, attended at his own expense.
Session 2	Session Chairman Garland Rollins retired in February, but continued his Workshop duties on his own time.
	Speaker William Callis attended at his own expense.
Session 3	Paul Lederer was drafted as Session Chairman just 2 weeks before the Workshop.
	Speaker William Shay had only 3 days' notice to condense an extensive test report.

No doubt there were others on the program and in attendance who also contributed an extra measure, and to all of those the rest of us extend our thanks.

CHANGES IN AGENDA

Substitutions, alterations and deletions in the oral presentations were caused principally by the widespread restrictions on travel funds and by imperative duties at work.

SESSION ONE: M. A. Hatch, Jr., spoke on "Strain Sensitivity of Pressure Transducers in a Dynamic Environment." C. W. Olsen was detained at work.

SESSION TWO: Larry Sires substituted for Larry Josephson on "Fuel-Air Explosive Blast Measurement."

Joseph J. Dolis substituted for J. M. Cassanto on "R/V Flight Test Pressure Instrumentation Techniques."

W. Paulson and J. Nuhfer were unable to secure travel approval. Session Chairman Garland Rollins summarized their paper, "Collection of Environmental Data for the HARPOON Missile Program in USS PEGASUS (PHM-1)."

SESSION THREE: Paul Lederer took over as Session Chairman for Joe Haden, who was unable to secure travel approval.

Murray Rosenbluth was unable to secure travel approval. Paul Lederer summarized his paper, "Telemetry Instrumentation for Acceleration Track Test System."

James Morrison experienced two test schedule revisions in the week before the Workshop, so that his paper, "An Instrumentation System for Making Measurements in a High Explosive Environment," was not given, but he was present.

William Shay presented his paper, "HSM, a Measurements Engineering Challenge," on very short notice due to the circumstances just related.

SESSION FOUR and SESSION FIVE went as planned.

SESSION SIX was so badly riddled by loss of personnel unable to secure travel approval that the complete revised list of participants is given here and in the Minutes of Session 6. The Session Chairman and the subject matter remained as shown on the original agenda.

Paul Lederer, National Bureau of Standards (NBS),
IRIG 106, "Transducer Standards"

William Anderson, Naval Air Test Center (NATC),
IRIG 118, "Transducer Based System Calibration"

"Proposed Standard Terminology for Telemetry Transducer Amplifiers,"
Patrick Walter and Frederick Schelby, Sandia Laboratories
William Anderson, NATC

William Anderson, NATC
"Directory of Transducer Users, July 1973"

Paul Lederer, NBS
"Interagency Transducer Project Activities"

Charles Thomas, Wright-Patterson Air Force Base
"Future Task Definition for NBS"

AGENDA

EIGHTH TRANSDUCER WORKSHOP

SPONSORED BY:

Transducer Committee of
the Telemetry Group,
Range Commanders Council

22-24 April 1975

Definition of the Transducer Workshop

History:

The Workshop is sponsored by the Transducer Committee of the Telemetry Group, an Inter-Range Instrumentation Group (IRIG) of the Range Commanders Council. The seven previous meetings, beginning in 1960, were held at 1- to 3- year intervals at various U.S. Government installations around the country.

People:

Attendees are working-level hardware people who must solve real-life problems and are strongly oriented to the practical approach. Their field is making measurements of physical parameters using transducers. Test and project engineers should attend for education on the true complexity of transducer selection.

Subjects:

These include practical applications of transducers, conditioners and readouts, considered separately and in systems. Engineering tests, laboratory calibrations, development and evaluation all are potential applications involving present problems. Test controls and experimental methods used to assure valid data are essential elements in these applications. Measurands include force, pressure, flow, acceleration, velocity, displacement, temperature and others.

Emphasis:

1. The practical approach.

2. Strongly focused on transducers and related instrumentation used in measurements engineering.

3. Ratio of discussion papers to presentation is high.

4. Open and universal discussion; problem solving through knowledge sharing. Session chairmen use speakers as a panel to stimulate discussion.

Goals:

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4. Provide task definition to the NBS Inter-Agency Transducer Project for transducer R&D for FY 75 and 76 supported through NAVAIR and national test range funding.

General Chairman:

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Livermore, CA 94550

(415) 447-1100 X 8665

PRELIMINARY PROGRAM

Monday, 21 April 1975

2000 Social hour, courtesy of the Transducer Committee. All attendees welcome.

Tuesday, 22 April 1975

0730 Registration.

0830 Welcome: Col. Brien D. Ward, Commander, Air Force Flight Dynamics Laboratory, Wright Patterson AFB

Introductions:

Charles Thomas, Dynamics Test Group Leader, Wright Patterson AFB.

Pat Walter, Chairman, Transducer Committee of TG, RCC.

Pierre Fuselier, Chairman, 8th Transducer Workshop.

0900 Session 1: Transducers––Their Construction and Application.

Chairman:

Henry Freynik, Measurements Engineer, Lawrence Livermore Laboratory.

Panel Members and Papers Briefs (10 minutes each):

Robert Bunker, Kirtland AFB, "Piezoelectric Polymer Instrumentation."

Bert Dennis and Billy Todd, Los Alamos Scientific Laboratory, "Transducer Technology for Deep Borehole Geothermal Environments."

Thomas Piper, Aerojet Nuclear, "Variable Reluctance Displacement Transducer Compensated to 650°F."

Willard Smith, NASA Ames "A Six-Component Strain Gage Balance for Helicopter Rotor Testing."

C. W. Olsen, Lawrence Livermore Lab, and M. A. Hatch, Jr., EG&G, "Strain Sensitivity of Pressure Transducers in a Dynamic Environment."

Mills Dean, III, Naval Ship R&D Center, "Miniature Pressure Gage for Aerodynamic and Hydrodynamic Research Investigations."

1010 Break.

1020 Session 1 open discussion, with speakers sitting as a panel. "Boo-Boos," as time permits.

1200 Lunch.

1330 Session 2: Transducer Measuring Systems and Their Calibration.

Chairman:

Garland Rollins, NASA Langley.

Panel Members and Papers Briefs (10 minutes each):

Larry Josephson, Naval Weapons Center, "Fuel-Air Explosive Blast Measurement."

Tom Rodgers and Jerry Wright, Eglin AFB, "Transducer Applications in Airborne Instrumentation."

J.M. Cassanto, General Electric, "R/V Flight Test Pressure Instrumentation Techniques."

W. Paulson and J. Nuhfer, Naval Ship Weapon Systems Engineering Station, "Collection of Environmental Data for the HARPOON Missile Program in USS PEGASUS (PHM–1)."

Charles Federman, William Walston, John Ramboz, of NBS, "Shock Calibration of Accelerometers."

William Callist, Newark AFS, "Measurement System Control Through Periodic Correlation."

1440 Break.

1450 Session 2 open discussion, with speakers sitting as a panel. "Boo-Boos," as time permits.

Wednesday, 23 April 1975

0830 Session 3: Transducer Signal Conditioning.

Chairman: Joe Haden, Holloman AFB.

Panel Members and Papers Briefs (10-minutes each):

Frederick Schelby, Sandia Laboratories, "Miniature Transducer Amplifiers Development for Telemetry Applications."

Darrell Harting, Boeing Aerospace, "A System for Measuring Static Strains to 1500°F."

Murray Rosenbluth, Picatinny Arsenal, "Telemetry Instrumentation for Acceleration Track Test System."

James Morrison, Lawrence Livermore Laboratory, "An Instrumentation System for Making Measurements in a High Explosive Environment."

P. L. Coleman, Systems, Science and Software, "A Particle-Velocity Gage for Ground Motion Studies."

0940 Break.

0950 Session 3 open discussion, with speakers sitting as a panel. "Boo-Boos," as time permits.

1130 Lunch.

1300 Tour of Air Force Museum.

1800 No-host social hour at hotel.

1830 Dinner at hotel.

1930 Session 4: Manufacturers' panel.

Chairman: Peter K. Stein, Professor in Measurements Engineering, Arizona State University.

Panel members:

BLH ELECTRONICS
ENDEVCO
KULITE SEMICONDUCTOR
KAMAN SCIENCES
NATIONAL SEMICONDUCTOR
SCHAEVITZ ENGINEERING
STATHAM INSTRUMENTS
SUNDSTRAND DATA CONTROL
VALIDYNE ENGINEERING
ROSEMOUNT ENGINEERING
KISTLER–MORSE

Thursday, 24 April 1975

0830 Session 5: Information-Utilization and Sources.

Chairman: John Hilten, National Bureau of Standards.

Panel Members and Papers' Briefs (10 minutes each):

Peter K. Stein, Arizona State University, "Information and Information Conversion: Some New Thoughts on the Subject for Measurement Engineering Purposes."

M. J. Kroll and J. P. Carrico, Bendix Research Laboratories, "A Transducer Information Center,"

Dale Rockwell, Navy Metrology Engineering Center, "Update on Transducer Standards Prepared Since the Seventh Transducer Workshop."

0900 Session 5: Open discussion, with speakers sitting as a panel.

0940 Break

0950 Session 6: Implementation of Workshop Goals and Transducer Committee Aims.

Chairman: Pat Walter, Transducer Committee Chairman, Sandia Laboratories.

Panel: Transducer Committee Members.

1000 Charles Thomas, AFFDL, IRIG 106 "Transducer Standards."

1010 Kenneth Cox, NWC, IRIG 118, "Transudcer Based System Calibration."

1025 Joe Haden, HAFB, "Proposed Standard Terminology for Telemetry Transducer Amplifiers."

1040 Paul Davis, NATC, Telemetry Group, "Directory of Transducer Users, July 1973.

1050 Paul Lederer, NBS, "Interagency Transducer Project Activities Report."

1120 Leroy Bates, NSMSES "Future Task Definition for NBS."

1200 END OF WORKSHOP.

GENERAL INFORMATION

The Eighth Transducer Workshop will be held 22, 23 and 24 April 1975 at the Biltmore Towers Hotel in the center of Dayton, Ohio. The hosting agency is Wright Patterson Air Force Base.

Registration

The registration fee is in two parts: a written "Boo-Boo" of 1 page or less, and $10.00 by check, money order, or cash (no purchase orders can be accepted).

A "Boo-Boo" can describe any measurement attempt that went astray, with the objective of learning from our errors and keeping our feet on the ground. It should be something generic, rather than common human oversight; something that can be learned from. The tone should be relaxed and with a sense of humor. The "Boo-Boo" should be anonymous and must not embarrass any person, organization, or company.

Advance registration is highly desirable. Please use the enclosed registration form, include your "Boo-Boo" and a check or money order for $10.00, payable to the Eighth Transducer Workshop, and mail by 4 April 1975. The registration fee covers coffee or soda water and doughnuts, bus round trip to the Air Force Museum, the Wednesday evening fixed-menu dinner at the hotel, and a copy of the minutes of the workshop. Late registration will be provided at the Workshop registration desk in the hotel. Present your "Boo-Boo" at the desk also.

Hotel Accommodations

The official hotel for the Workshop is the Biltmore Towers, 210 North Main Street, Dayton, Ohio, 45459. The telephone number is (513) 223-2161.

Special rates have been set for Workshop attendees and will apply if you state on the enclosed reservation card, or state at time of registration in person, that you are attending the Eighth Transducer Workshop. Send in your reservation card early to be sure of getting a room; the special rates are $12.00 single or $14.00 double. Requests for room reservations should be mailed by 11 April 1975.

All sessions will be held in the Cotillion Ball Room.

No formal program will be provided for wives; however, they will be most welcome at the Social Hour on Monday and on the Air Force Museum tour Wednesday. Shopping tours should be very convenient, with the downtown location of the hotel.

Format and Background

The traditional discussion format will be observed. Workshops are just what the name says; everyone should come prepared to contribute something from his knowledge and experience. In a workshop the attendees become the program in the sense that the extent and enthusiasm of their participation determine the success of the workshop.

Participants will have the opportunity to hear what their colleagues have been doing and how it went; to explore areas of common interest and common problems; to offer ideas and suggestions about what's new and what's needed in transducers, techniques, and applications. A few manufacturers, selected to represent a fair sampling of transduction methods and measurands, have been invited to the Eighth Transducer Workshop. Give some thought (and write it down!) to the questions, comments and topics you want to present to them, and make a copy to give the girls at the registration desk on Tuesday morning.

Our final session of Thursday morning is quite as important to the attendees as to the panel members. Please come prepared to contribute your opinions, ideas and recommendations as to the past, present and future tasks that these groups have accomplished or should undertake.

We will act as intermediaries to help individuals and small groups to get together on Thursday afternoon to discuss specific problems in measurement areas uniquely interesting to them.

Additional Information

May be obtained from the General Chairman or:

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EIGHTH TRANSDUCER WORKSHOP

22-24 APRIL 1975

(List of Attendees)

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EIGHTH TRANSDUCER WORKSHOP

OPENING REMARKS

Charles E. Thomas of Wright Patterson Air Force Base:

My name is Charles Thomas and I work in the Air Force Flight Dynamics Laboratory out at the Base. At the present time I am running a Branch of the Laboratory's Vehicle Dynamics Division--the Dynamics Technology Applications Branch. My Branch is deeply involved in instrumentation technology, transducers, calibrations, data acquisition, reduction and analysis. I am pleased that I was asked to open our workshop here in Dayton.

To welcome you to Dayton and to kickoff the Transducer Workshop, we are fortunate to have with us the Commander of the Flight Dynamics Laboratory, Colonel Brien D. Ward. Colonel Ward came to us last year from the Office of the Secretary of Defense in the Pentagon. Prior to that time he was a Deputy Program Director for the A-10 airplane here at the Aeronautical Systems Division of the Air Force Systems Command. He was a fighter pilot with the 56th Air Commando Wing, stationed in Thailand. He is a graduate of West Point, and holds Master's Degrees in Mathematics and Aeronautical Engineering as well as the Doctorate in Control Systems Engineering from UCLA. As we say in the Laboratory, "let's not kid the Chief."

Gentlemen, Colonel Ward.

Colonel Brien D. Ward, Commander, Air Force Flight Dynamics Laboratory, Wright Patterson Air Force Base:

Colonel Ward welcomed the participants and stated that Wright Patterson Air Force Base has many kinds of laboratories and kinds of activities that use transducers of all sorts--for instance, almost 1,000 people work on programs which require making measurements on aircraft, missiles, and wind tunnel models.

He remarked that the transducer community worked in several areas useful to his Agency--development of evaluation and calibration techniques was one example and another one was the standardization of both components and methods.

He said that maximum utilization of all resources is one of the goals, resources of all kinds--human, material, and facilities. He pointed out that cost effectiveness had become of paramount importance due to the effect of continued inflation over the years.

Colonel Ward congratulated us on our agenda and the objectives of this Workshop. He wished he could join us in some of the sessions because he thinks the transducer business is fascinating. He wished us success and hoped that we would remember the Workshop with as much pleasure as Wright Patterson Air Force Base takes in acting as host to the Workshop.

Patrick Walter, Transducer Committee Chairman, Sandia Laboratories:

Walter filled us in with some background on who sponsors the Workshop: what is now called the Range Commanders Council, an association of 13 national test ranges formed in 1951. This association has been responsible for establishing standards in telemetry which are universally used.

Walter outlined the structure of this tri-service organization. The chain starts with the Range Commanders Council which is implemented by an Executive Committee with delegates from all the ranges. Under it is the Telemetry Group which has several working committees; the Transducer Committee is one. The Telemetry group, among other things, is responsible for maintaining currency of documents 106, "Telemetry Standards," and document 118, "Test Methods for Telemetry Systems and Subsystems."

Most people still call these the IRIG standards. The subcommittee is charged with keeping the Telemetry Group posted on developments of transducers, especially those useable for telemetry. One way of keeping up is to hold Workshops such as this one to get feedback from the transducer community. Secondly, the Transducer Committee interacts with the Transducer Projects Group at NBS, sets tasks for them and suggests areas of needed inquiry and experimentation. Attendees will be asked to contribute their ideas in these areas at the Thursday morning session.

Pierre F. Fuselier, Workshop Chairman, Lawrence Livermore Laboratory:

Fuselier thanked Col. Ward for his welcoming remarks and Charles Thomas for making all the physical arrangements necessary. He also thanked Transducer Committee members and the Session Chairmen for their help in this Workshop. He solicited comments from the attendees to be given at the Thursday morning session to the Transducer Committee and to the NBS Interagency Transducer Projects Group.

The format is that of a Workshop. We learn from each other and the success of this meeting depends on participation of everyone here in the discussion that follows after all the talks for the session are given. Participation by manufacturers in the discussion periods is encouraged. Recognition was given to those who contributed to the program from a sense of professional duty, at their own time and expense in some cases.

NOTES ON THE SESSIONS

The traditional format of the Transducer Workshop was observed. Each paper presentation was limited to 10 minutes and all papers in a session were given sequentially.

Authors then sat as a panel to spark the discussions and to answer questions and receive comments on their work. Participation in the discussions was extensive and productive.

The discussion summary reproduced here at the end of each session was taken from shorthand notes and tape recordings in an effort to capture the interactive spirit of the Workshop. Transcription and editing were done by Dayle Fitzgerald, Technical Secretary, and Pierre Fuselier, General Chairman, both of Lawrence Livermore Laboratory.

SESSION I

TRANSDUCERS — THEIR CONSTRUCTION AND APPLICATION

Henry Freynik, Chairman

PIEZOELECTRIC POLYMER INSTRUMENTATION

Robert B. Bunker

Air Force Weapons Laboratory
Kirtland AFB, N. M.

for

EIGHTH TRANSDUCER WORKSHOP

Sponsored by:

Transducer Committee of
the Telemetry Group,
Range Commanders Council

22-24 April 1975

PIEZOELECTRIC POLYMER INSTRUMENTATION

Robert Bunker

Air Force Weapons Laboratory
Kirtland AFB, N.M.

ABSTRACT

A preliminary evaluation of a new piezoelectric polymer gage developed by the National Bureau of Standards has been performed. Improvements in materials and in polarization techniques have led to the development of polymers with significant piezoelectric activity. These materials can be used to make many kinds of instruments for measuring dynamic stress and shock loading. Piezoelectric sensors consisting of a sandwich of two thin polarized polymer sheets have been fabricated. When stress is applied to the opposite faces of the sensor, it functions as a stress gage: when an inertial mass is added, it functions as an accelerometer. These sensors are not brittle and are not likely to be damaged by shock, and are not affected by common solvents. Thin (.002 to .010 in) sheet flexible plastic gages provide diameter to thickness ratios greater than 90 which makes them suitable for soil stress gage applications. Hydrostatic calibration shows the gage linear with applied stress. Dynamic tests performed at room temperature illustrate good dynamic performance. Elevated temperature tests show the charge stress sensitivity changes with temperature and point to an area of needed improvement. Typical stress gage and accelerometer performance records for ground motion demonstrate the application and potential value of this material for satisfying a significant free field soil measurement need.

SOIL STRESS AND MOTION

The conventional approach to the problem of making soil motion measurements consists generally of placing a transducer in a canister, placing the canister in a drill hole and backfilling with grout. It is apparent that regardless of the differences in density, acoustic velocity, modulus, etc., between the foreign materials and the native soil, the transducer/canister/grout column system will eventually reach an equilibrium velocity with the soil.

In comparing the transducer motion with the motion of the undisturbed soil, the primary distortion in the transducer motion would occur in the early time immediately after stress wave arrival, and would depend upon the severity of the mismatch in physical properties and the actual dimensions of the canister and grout column. This currently accepted approach in fielding ground motion instrumentation is used, not because it is the best approach, but because it is a practical way of placing instrumentation at depths greater than a few feet below the surface. By taking care in selecting canister and grout materials and keeping minimum dimensions on the drill hole diameter, the effects of property mismatches with the soil can be maintained at an acceptable level. Generally, reasonable matches of density and sound velocity will give good results.(1)

The problem of making stress measurements in soil is altogether different because the different modulus of the inclusion (the transducer package) perturbs the stress field itself, insuring that the "sensed" stress will be different than the undisturbed free field stress. While it might be possible to obtain reasonable modulus matches in the elastic range of the soil it would be futile to attempt to match the non-linear behavior of the soil at higher stresses. One can hope to match only two or three of these properties at a time. It is hopeless to try to solve the problem by matching physical properties given the inhomogenities of a given soil and the wide range in properties of various geologic materials. Analysis of soil stress gage designs indicates that overregistration (stress due to the inclusion of the gage in ratio to the true stress) is a function of the stiffness of the gage relative to the soil and the relative dimensions of the sensitive area of the gage.(2)(3) From this

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(1) Ingram, J. K.; "Development of a Free Field Soil Stress Gage for Static and Dynamic Measurements."

(2) Peattie, K. R. and Sparrow, R. W.; "The Fundamental Action of Earth Pressure Cells," Journal of Mech & Phys of Solids 1954, Vol 2, pp 141-151, Pergamon Press Ltd, London.

(3) Monfore, G. E.; "Analysis of the Stress Distributions In and Near Stress Gages Embedded in Elastic Solids," Structural Research Laboratory Report No. SP-26, June 1950; US Department of the Interior, Bureau of Reclamation, Research and Geology Division, Denver, Colorado; Unclassified.

analysis, it has been concluded that the gage should be several times as stiff as the surrounding material and should have a sensitive center element that measures stress only over 30 to 50 percent of the total area, with a diameter to thickness ratio of 20 or better.[(4)(5)] If the modulus of the gage is kept high and the diameter to thickness ratio is large, the gage will respond linearly even though the modulus of the soil changes. The problem, therefore, of variations in soil modulus with stress (elastic-plastic response), or of variations between different geologies, can be overcome simply by designing a high modulus, center sensing package, having a large diameter to thickness ratio.

In meeting the design and placement requirement for a suitable soil stress gage, it would appear that the criteria for soil motion measurements are also satisfied. Meeting the stress gage criteria implies that the stress field is minimally perturbed by the presence of the gage; it can be concluded that the same approach to gage packaging and placement could be used for both soil stress and motion measurements.

Tests of various gages in sand and clay point to the use of a placement technique causing a minimum disturbance of the soil around the gage. This will cause minimum overregistration to occur.[(6)] Probably the best method of placement is one requiring no recompaction. However, since even with the best of techniques variation in overregistration will occur, it is recommended that dynamic calibrations be made using the field placement techniques together with as large a sample of the native material as possible.[(7)]

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(4) Loh, Y. C.; "Internal Stress Gages for Cementitious Materials," Proceedings of the Society of Experimental Stress Analysis, Vol II, No. 2, 1954.
(5) Selig, E. T.; "Stress Gages," AFWL TR 66-51, KAFB, New Mexico, September 1966.
(6) Hadala, P. F.; "The Effects of Placement Method on the Response of Soil Stress Gages," Tech Report No. 3-803, November 1967; US Army Engineer, Waterways Experimental Station, Vicksburg, Mississippi.
(7) Simmon, K. B.; "Dynamic Evaluation of Soil Stress Gages," AFWL TR 68-141, University of New Mexico, CERF, February 1969.

STRESS TRANSDUCER SPECIFICATIONS

Some desirable characteristics for stress transducers are listed:

- Linearity and hysteresis are desired to be less than 1 percent.
- Compensated temperature less than 1 percent per 100°F over the span of 30° to 85°F.
- Linear range of operation within 1 percent 0 - 5000 psi.
- Excitation 9 - 15 volts nominal
- Output 0 - 5 volts
- Acceleration sensitivity normal to diaphragm not to exceed .05 psi/g
- Natural Frequency >50 kHz
- Response time (to a step input) <10 x 10^{-6} sec.
- Cross axis sensitivity <5 percent of full scale output when subjected to a 1000g dynamic input or 5000 psi static pressure.
- The gage should be acoustically matched to the medium in which it is contained. (The acoustic impedance is the product of the density and the acoustic velocity.)

THE POLYMER AS A SENSOR

Polymer research has demonstrated that piezoelectric characteristics result when a plastic sheet material simultaneously undergoes the application of a high intensity electric field and pressure. One of the more energetic materials is polyvinylidene fluoride (PVF_2). Sheets of this material are poled by being charged between plates of a hot (60°C) press (800 N/m^2) while simultaneously subjected to an electrical field of 6 x 10^5 V/cm, and then cooling the polymer through the glass transition temperature with the field still applied.(8)(9) Polarization is the process of bringing about a partial separation of electrical changes of opposite sign in a body by the superposition of an external field. This is a vector quantity representing the dipole moment

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(8) Cohen, J., Edelman, S., and Vezzetti, C.F.; "Pyroelectric Effects in Polyvinyl Fluoride," Nature Phys. Sci 233, 12 (6 September 1971).
(9) Pfister, G., and Ablcowitz, M. A.; "Dipole Reorientation in Polyvinylidene Fluoride," Xerox Rochester Corporation Research Center, Rochester, New York, 21 September 1973.

per unit volume of a dielectric medium. Piezoelectric effects have also been shown to be a natural result of the rolling process for polymers; however, large increases in piezoelectric activity result by heating and applying pressure in the presence of a strong electric field.[10][11] This change in properties is somewhat analogous to the change in magnetic permeability that occurs when a ferromagnetic material is raised in termperature then cooled through the curie point in a strong magnetic field.[12] One researcher in this field feels that the PVF_2 can more precisely be defined as a ferroelectric polymer.[13]

The piezoelectric polymer sensors possess potential advantages over piezoelectric ceramics and crystals because they can be made lighter, thinner and cheaper, and are less likely to be damaged by shock since they are not brittle. Being somewhat chemically inert they are not affected by oil and water or by other common chemical solvents. Sheets of polymer as thin as .001 in. are much thinner than are commonly available with ceramics or crystals. Sensors are fabricated from thin poled polymer sheets with evaporated metal electrodes on both faces. These sheets are cemented or fused into a sandwich, with like charges of the poled sheets placed together so that charges of the same polarity appear on the inner faces. The center conductor of a coaxial cable is connected to the evaporated metal electrodes of these inner faces, and the shield of the cable is connected to the evaporated metal electrodes of the outer faces. Connected in this manner, all exposed surfaces are at ground potential and the signal potential inside the sensor is shielded. When pressure is applied to the surfaces, electrical output will be proportional to the stress. If an inertial mass is attached to the polymer sandwich and the gage is accelerated, its response will be as an accelerometer.[14] There are a variety of applications for this sensor, limited only by the imagaination and ingenuity of the user.

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(10) The Piezoelectric Effects in Polymers, NBS Technical News Bulletin, January 1972.

(11) Bergman, J. G., Jr., McFee, J. H., and Crane, G. R.; "Pyroelectricity and Optical Second Harmonic Generation in Polyvinylidene Fluoride Films," Applied Phys Ltr, Vol 18, No. 5, 1 March 1971.

(12) Bozorth, Richard M.; Ferro Magnetism, pp. 112-133, D. Van Nostrand Co., Princeton, New Jersey, 1951.

(13) Bergman, J. G., Jr., p. 203.

(14) Cohen, J., Edelman, S., p. 233.

The National Bureau of Standards provided the Air Force Weapons Laboratory with several five inch diameter gages 0.01 inches thick, with configurations as shown in Figure 1. These gages consisted of two sheets of poled polymer aluminized on their inner and outer surfaces and with positive charge bearing faces touching. These gages had capacitances of 0.014 μF and resistances > than 100 megohms. Hydrostatic pressure linearity tests were run and the charge pressure sensitivity was determined, as shown in Figure 2. For these tests and these gages, a charge pressure sensitivity of 184 $pC/lb/in^2$ was demonstrated to be typical. Figure 3 represents data from dynamic tests at ambient temperature. The polymer and the Norwood reference gages compared within 3 pct. Data in Figures 1 through 3 are from CERF conducted tests.[15] Results of elevated temperature tests by Baum are shown in Figure 4. A temperature sensitivity of 0.0167 mv/psi/°C (.6% change in sensitivity per degree centigrade) was found. It should be noted that, after placement, soil stress gages in soil do not encounter more than ±5 degree variations in temperature. Since calibrations can be made at the expected temperature, gage temperature compensation is not required for the configuration tested.

FIELD TEST OF POLYMER GAGES

From the above initial test results, it appeared that the polymer gage had sufficient potential to warrant further development. Work was therefore, initiated to field test three polymer gages: a stress gage, an accelerometer, and a pressure gage, in a large scale high explosive test by the AFWL. Because of the thinness (.002 and .007 inch) and difficulty in handling it, a thin aluminum backplate (5.5 inches diameter by .060 inch thick plate) was used to support the sensing elements for the stress and airblast pressure gages. The diameter to thickness ratio, even with the backing plate, was 90:1.

A polymer gage was packaged as an accelerometer by attaching an inertial mass (tantalum foil) to one surface of the gage, and bonding the other surface to a recessed area in an aluminum plate. A cover plate isolated the polymer from the stress field. Motion of the gage package results in a stress-induced output proportional to the inertial mass and the magnitude of the acceleration encountered. Because of the low output of the accelerometer, which resulted from the use of a much smaller sensor area and a small inertial mass, an

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(15) Bulchram, R. L.; "Evaluation of Piezoelectric Polymer Soil Stress Gage," CERF University of New Mexico, AFWL TN 74-016, October 1974.

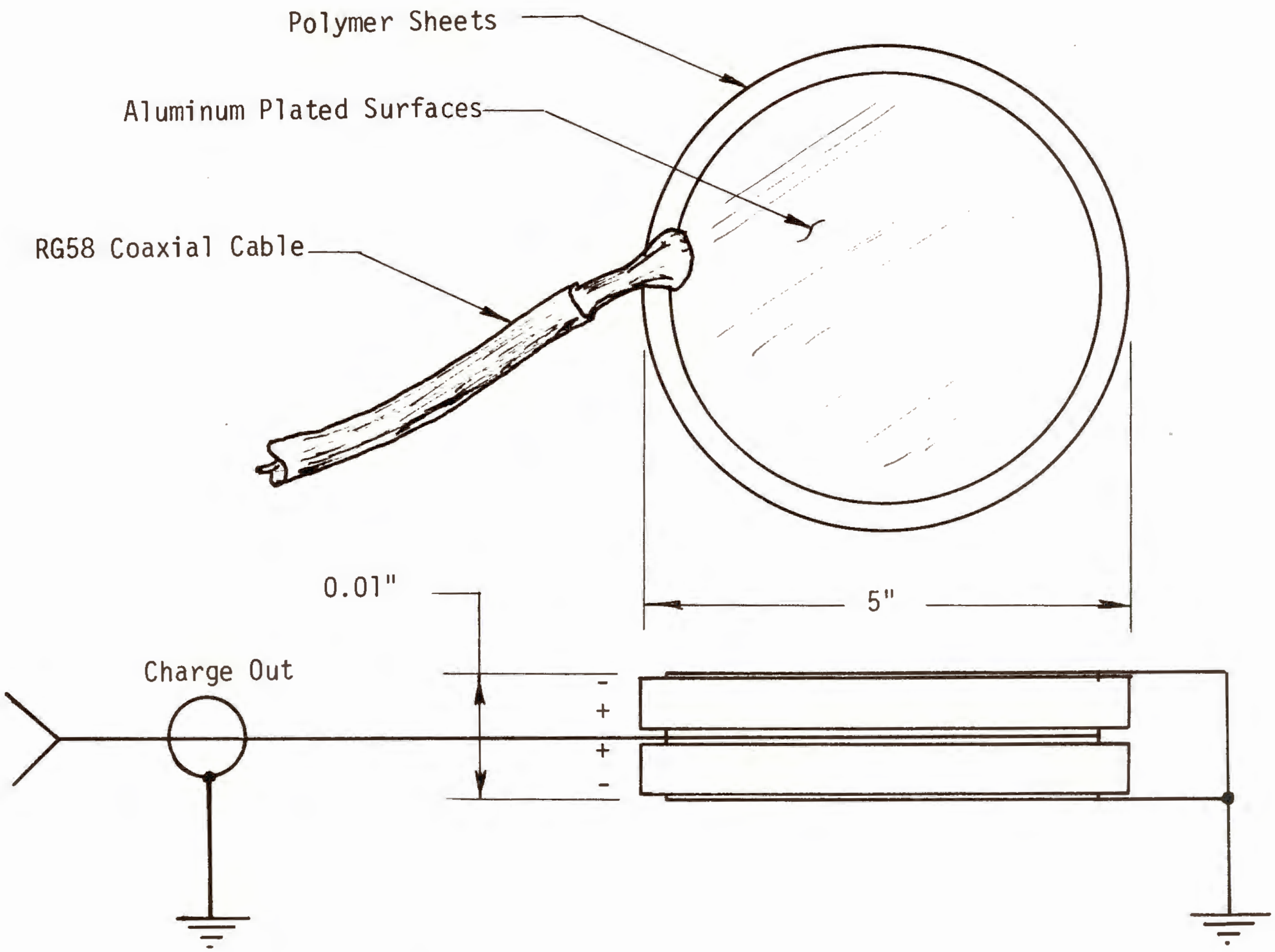

Figure 1. NBS Polymer Soil Stress Gage.

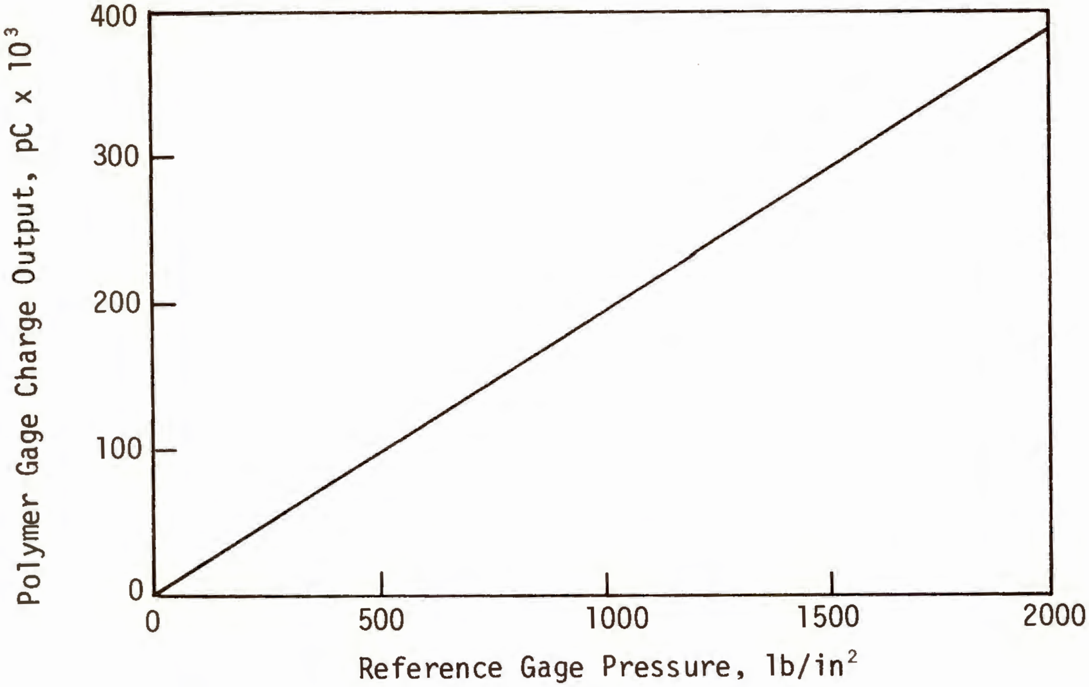

Figure 2. Hydrostatic Loading Curve.

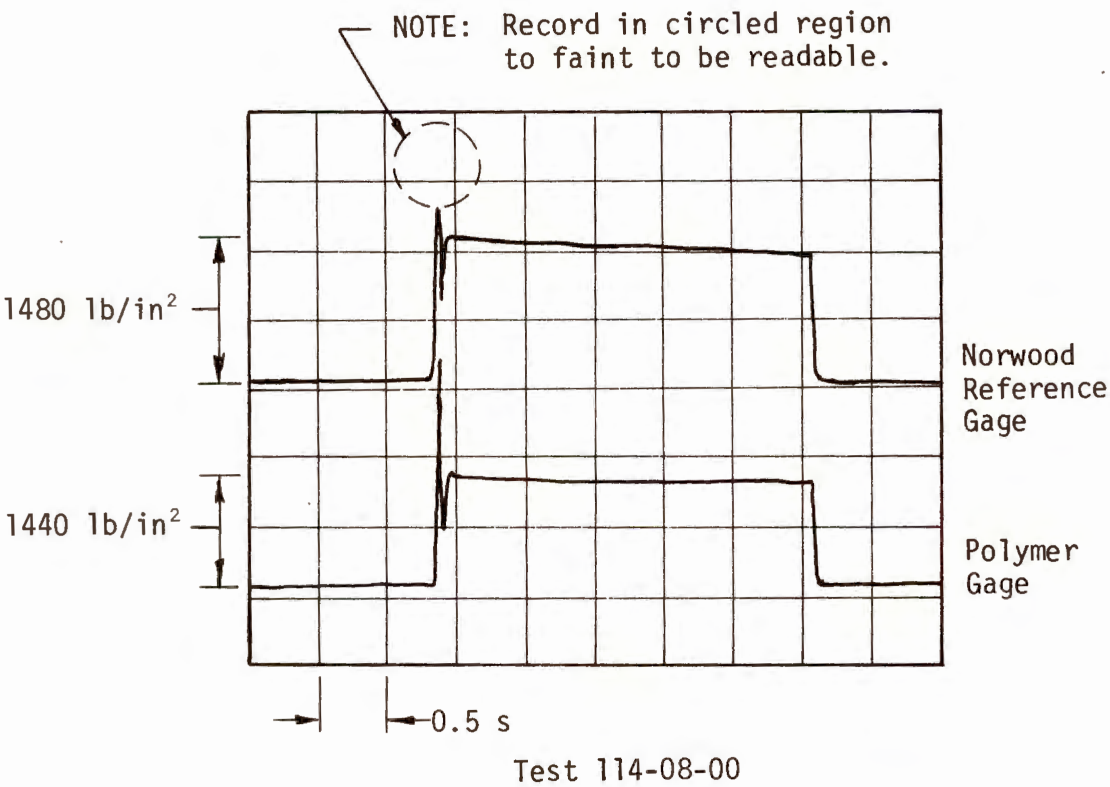

Figure 3. Typical Ambient-Temperature Test Data.

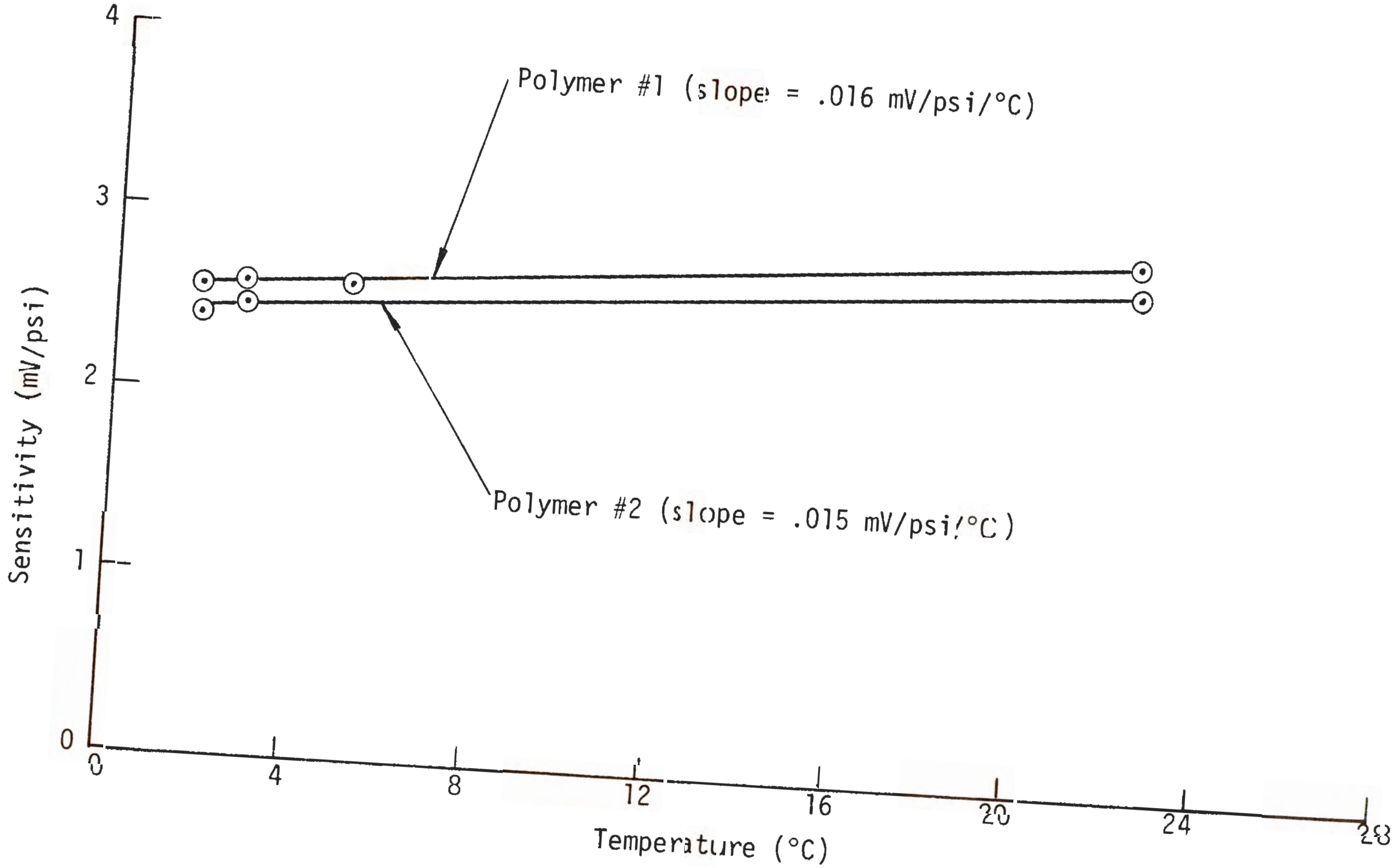

Figure 4. Polymer Temperature Sensitivity.

Intersil Corporation Type ICL8007AC operational amplifier in series with a buffer amplifier was used to provide signal amplification. The buffer amplifier was required to permit the operational amplifier to operate in a favorable gain range of 10 to 20, with the overall design gain being approximately 60. The stress gage fielded as an air pressure sensor was submerged in a pharmaceutical gelatin. The purpose of the gelatine was to provide hydrostatic pressure to the sensor while protecting it from debris impact and attenuating the high frequency components of explosive loading.

Results from the large scale field test were discouraging. The accelerometer was not fielded because it had excessive output from bending and shear even though the anisotropy of the piezoelectric material should normally result in little or no shear sensitivity.[16][17] An investigative work by Baum at the CERF, University of New Mexico, indicates that the adhesive used to bond the polymer sheets together could introduce significant signals when subjected to shear. The blast pressure gage provided an excellent initial waveform; however, the peak pressure was high by approximately a factor of two when compared with other blast pressure measurements. This amplitude discrepancy may be attributable to spurious output due to stretching and/or bending. The soil stress gage cable failed just after arrival of the stress pulse.

FURTHER DEVELOPMENT EFFORTS

Because of the shortcomings uncovered in our initial design and in the field test results, several steps to improve gage performance were taken. The first step was to request that the Bureau of Standards review polymer fabrication techniques for eliminating bending effects and shear sensitivity. The Bureau was also asked to see if the upper useful temperature limit could be increased. The second step taken was to review the methods being used in the application of the polymer as a sensor. It was decided that a complete understanding of the polymer shear sensitivity probably is not required if the gage can be isolated from shear loads. Pure bending of the polymer also seems to introduce undesired outputs. Two possible approaches were considered for elimination of bending signals. First, the gage was to be isolated in such a manner that bending loads could not be transmitted to the sensitive

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(16) Fukada, E., Takshita, S.; Japan J. Appl. Phys 8, 960 (1960).
(17) Kawai, H.; Japan J. Appl. Phys 8, 975 (1969).

element. Secondly, the polymer gage configuration as manufactured with respect to geometry and charge generation in bending might be improved so that the net charge output from the tension element in one half of the gage and the compression element in the other half of the gage would be minimized. This would require that the gage be mounted so that it could bend only about its neutral axis or that it be supported in a manner which would prevent the transmission of bending loads, such as a foam rubber member in a cavity filled with a pressure transmitting fluid. The gage packaging problem is then one of providing isolation from undesired inputs while maintaining faithful preservation and transmittal of desired inputs.

In considering gage packaging the best approach found was to support the polymer in a high resistivity, low viscosity fluid contained in a thin flat package made up of a stainless steel ring and two thin sheets of stainless steel. A small, 3 inch diameter polymer with the same voltage sensitivity as the larger gages was used. The fluid in which the polymer was immersed was to provide isolation from all loads except the hydrostatic fluid pressure which would be the same as the soil pressure if the package was thin and flat with a diameter to thickness ratio at least of 20.

A major concern in any system designed for field use is with the field calibration of the end-to-end system. For field calibration purposes the use of the reciprocity technique is recommended.(18)(19) In applying this technique, an additional polymer element can be bonded to the stress sensing polymer and driven by an amplified signal from an oscillator. This results in a charge-induced mechanical input into the polymer. The output signal can be related to the amplitude of the known input calibration signal and to a known stress level through laboratory calibration of the gage. Two soil stress transducers designed by Bolt Beranek & Newman Inc. (BBN) of Cambridge, Massachusetts were acquired by AFWL for evaluation. The first gage tested was 1/8 inch thick and 5 inches in diameter. The polymer was suspended between stainless steel plates on neoprene sheets to isolate the polymer from bending and shear inputs.

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(18) Bouche, R. R., and Ensor, L. C.; "Accelerometer Calibration with Reciprocity Standards," Measurements and Data, July-August 1970.
(19) Trent, H. M.; "The Absolute Calibration of Electromechanical Pickups," Journal of Applied Mechanics, 15 pp 49-52 (1948).

The gage provided a linear output with stress. The impulse response obtained indicated a rise time on the order of 10 to 20 μs (see Figure 5). The frequency spectrum of this impulse response function has its 3 db point at approximately 16.5 kHz (Figure 6). The reciprocity technique, incorporated into the gage utilizing a ceramic crystal driver, functioned well and, thus, provides the capability for in-place calibration. Additional testing is currently underway at the AFWL.

CONCLUSIONS

The polyvinylidene fluoride polymer shows considerable potential for use as the active sensing element in a variety of ground motion and stress measuring transducers. Work is continuing at the AFWL to develop, particularly, a soil stress gage which is not sensitive to bending or shear stresses. A number of design concepts which appear capable of satisfying all objectives are being explored.

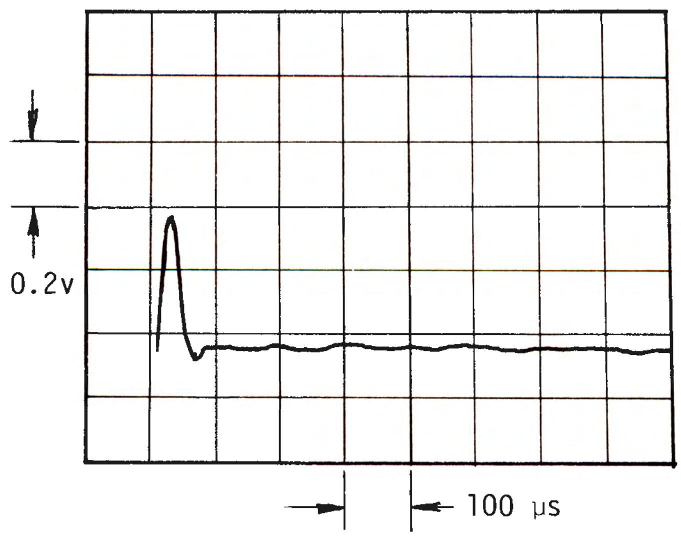

Figure 5. Impulse Response-Polymer Gage #1.

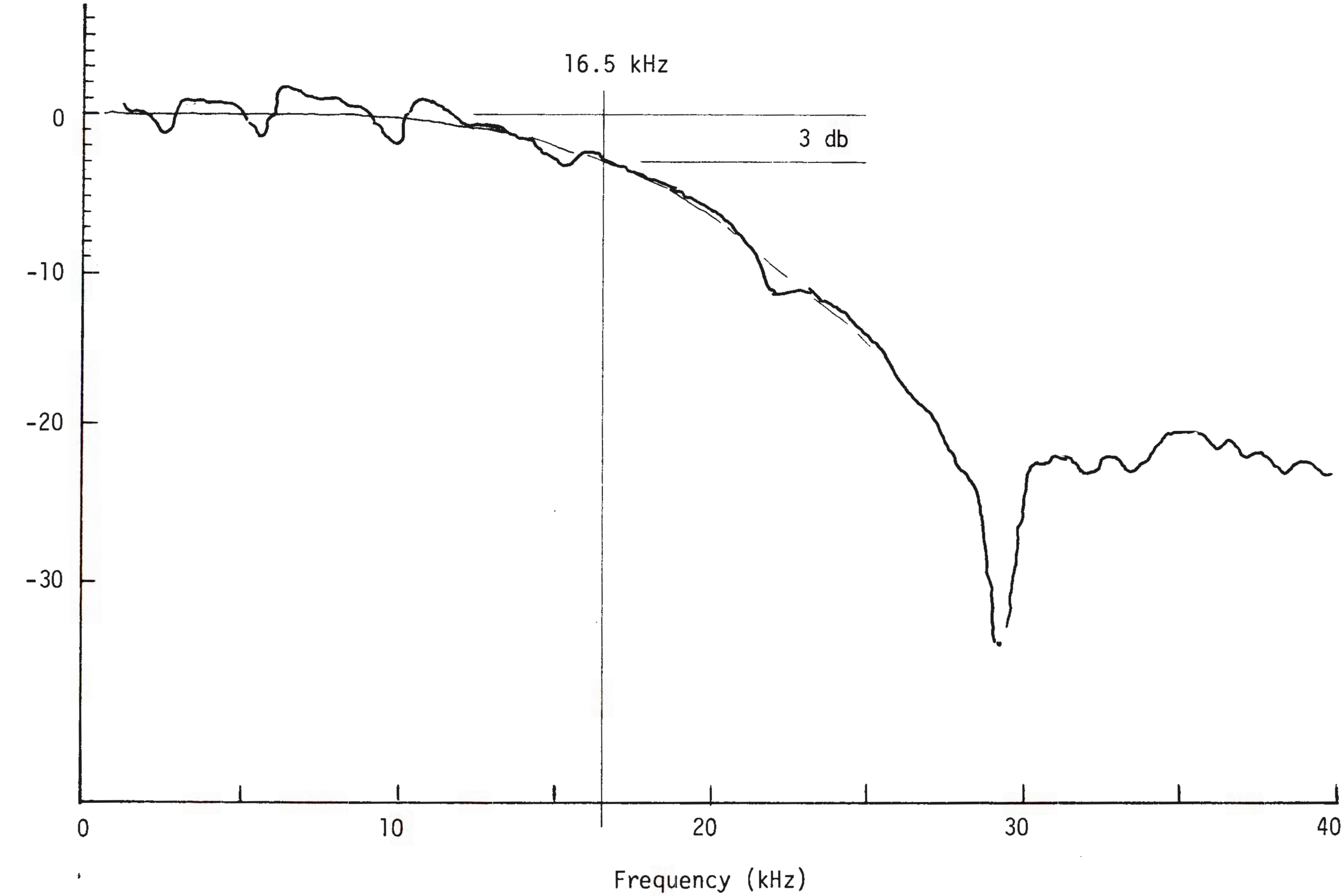

Figure 6. Frequency Spectrum of Impulse Response of Soil Sensor (Polymer #1).

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TITLE: TRANSDUCER TECHNOLOGY FOR DEEP BOREHOLE GEOTHERMAL ENVIRONMENTS

AUTHOR(S): Bert R. Dennis and Billy E. Todd

SUBMITTED TO: 8th Transducer Workshop

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TRANSDUCER TECHNOLOGY FOR DEEP BOREHOLE GEOTHERMAL ENVIRONMENTS*

by

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(For presentation at the 8th Transducer Workshop in Dayton, Ohio on April 21-24, 1975.)

This work was done under the auspices of the United States Energy Research and Development Administration.

TRANSDUCER TECHNOLOGY FOR DEEP BOREHOLE GEOTHERMAL ENVIRONMENTS

by

Bert R. Dennis
Billy E. Todd

ABSTRACT

Hydraulic-fracturing experiments, as a part of the Los Alamos Dry Hot Rock Geothermal Energy Program, were conducted in the Jemez Mountains 40 miles (60 km) west of Los Alamos, New Mexico on the western rim of the Valles Caldera. Pressurization was accomplished in a 2040-m-deep borehole in the Precambrian basement rock at a bottomhole temperature of 145°C. Instrumentation was designed to measure breakdown and crack-extension parameters in the borehole. *In situ* measurements of pressure, temperature, and acoustic velocities required brute-force techniques in the high-pressure, high-temperature environment during long-term tests of up to 12 hours. Special armored logging cable of high-temperature Tefzel, enclosing shielded pairs, provided communication between a downhole instrumentation sonde and a recording facility at the surface. Lack of suitable downhole signal conditioning limited the number of data channels that could be employed for the *in situ* measurements.

INTRODUCTION

Research in fundamental geophysics at the Los Alamos Scientific Laboratory (LASL) is directed toward an understanding of the nature and physical behavior of geothermal reservoirs through studies conducted at the Fenton Hill test site on the Jemez Plateau as part of the LASL Dry Hot Rock Geothermal Energy Program.[1] A deep exploratory hole (GT-2) has been drilled to an intermediate depth of 2042 m (6700 ft) where the bottomhole temperature is 147°C. Extensive studies were made during drilling to evaluate and improve the drilling program in a variety of geological formations for future geothermal-energy systems.

In addition to drilling and coring studies during the drilling phase of GT-2, a series of borehole thermal measurements was planned to study temperature gradients and heat flow in a region of abnormally high geothermal gradient due to the recent volcanic activity in the Jemez Mountains. Extensive thermal measurements were conducted in a previous exploratory hole (GT-1) over a period of approximately 1 year, and indicated that the region was one of high temperature gradient and heat flow, and that rock temperatures above 200°C could be expected at depths less than 3048 m (10,000 ft). The temperature-logging program initiated for GT-2 was planned to investigate anomalous changes in apparent heat flow as a function of depth, and periodic variations in temperature which might result from formation of convective cells in water-filled holes.

Temperature-measuring techniques, including both experimental and analytical methods, were developed to achieve optimum bottomhole thermal measurements.[2] It was necessary to obtain a realistic bottomhole temperature in a reasonably short period of time in a borehole that had recently been perturbed by drilling. Experimental field use of various types of geophysical apparatus and techniques for making measurements in a deep geothermal well, at high temperatures and hydrostatic fluid pressures, was undertaken. Downhole sensors housed in sondes capable of withstanding the temperature and pressure were designed to insure maximum accuracy and resolution of measured parameters.

Upon completion of the drilling phase of GT-2, a series of hydraulic-fracturing experiments was conducted in the open (uncased) portions of the borehole extending 1165 m (3821 ft) into the crystalline rock. Development, field testing, and application of improved downhole pressure- and acoustic-sensing equipment were pursued for spatial delineation and energy characterization of cracking events associated with hydraulic fracturing. Investigation of rock-parameter changes produced by changing stress conditions in the granitic crystalline rock during pressurization, fracturing, and relaxation events was conducted to determine original stress conditions and subsequent stress variations. Instrumentation was designed to measure breakdown pressure of the rock, crack-extension pressure, and shut-in pressure for each fracture. Measurements were made to determine the principal tectonic stress and the leak-off rate of the fracturing fluid. High-temperature downhole geophones, properly coupled to the rock formation, were intended to monitor acoustic signals generated by the cracking events and to determine the feasibility of mapping the crack as it formed. The development of techniques to field the borehole transducer array and achieve competent low-level signal reception at a surface recording station required high-temperature, properly-shielded instrumentation cable capable of withstanding the fracturing pressure and preventing the hydraulic fluid from penetrating the steel armor and leaking from the pressurized system. The high temperatures encountered in the fracture zones prohibited the use of downhole electronic packages. Information from the downhole instrumentation array was complemented with a series of surface measurements to insure complete coverage of the hydraulic-system parameters.

Following the series of hydraulic fractures in the 1828-m (6000-ft) zone, a second drilling phase was begun to deepen the hole to 2895 m (9500 ft), reaching temperatures in excess of 190°C. Future experiments at this depth and temperature will challenge the state-of-the-art measurement techniques.

IN SITU BOREHOLE TEMPERATURE MEASUREMENTS

The drilling program initiated for Geothermal Test Hole No. 2 (GT-2) allowed for extensive coring in the Precambrian granitic rock followed by *in situ* temperature measurements in the air-drilled dry borehole. An integral part of the temperature measurement program was to optimize the time interval (at depth) required to extrapolate to an accurate and realistic bottomhole temperature. Since the least thermally disturbed region of rock at any time during the drilling operation would be at the bottom of the borehole, a temperature sonde was designed and fabricated that would allow a thermistor probe to be positioned over the core stub left at the bottom of the hole following core recovery (Fig. 1). The sonde would be lowered through the center of the drill string and the core bit raised 3.05 m (10 ft) off the bottom. The thermistor probe, mounted in a spring-loaded thermally insulated collar, would come to rest on top of the 100-mm-long core stub. The Teflon collar was designed to take up the weight of the probe and cable and gently bring the fragile thermistor assembly into intimate contact with the rock surface (Fig. 2). The sonde was lowered into the hole employing a seven-conductor (NO. 20 AWG) Tefzel-insulated, armored well-logging cable. The temperature was measured by recording the thermistor resistance (including line resistance) directly on a digital data-logging system outputting on a teletype printer (Fig. 3). The digital ohms converter employed a six-digit readout with an accuracy of $\pm 0.02\%$ of full scale or $\pm 0.004\%$ of the actual reading. Corrections were made for line resistance and the data converted to temperature using the following thermistor-calibration equation.

$$\text{Therm Assembly No. 151: Temp } ^\circ\text{C} = \frac{2152.9}{\log 38.97(R-156)} - 300.$$

The borehole was cased through the sediments and volcanics to a depth of 772.7 m (2535 ft), so that the casing extended 45.7 m (150 ft) into the Precambrian granitic rock.[3] The first bottomhole

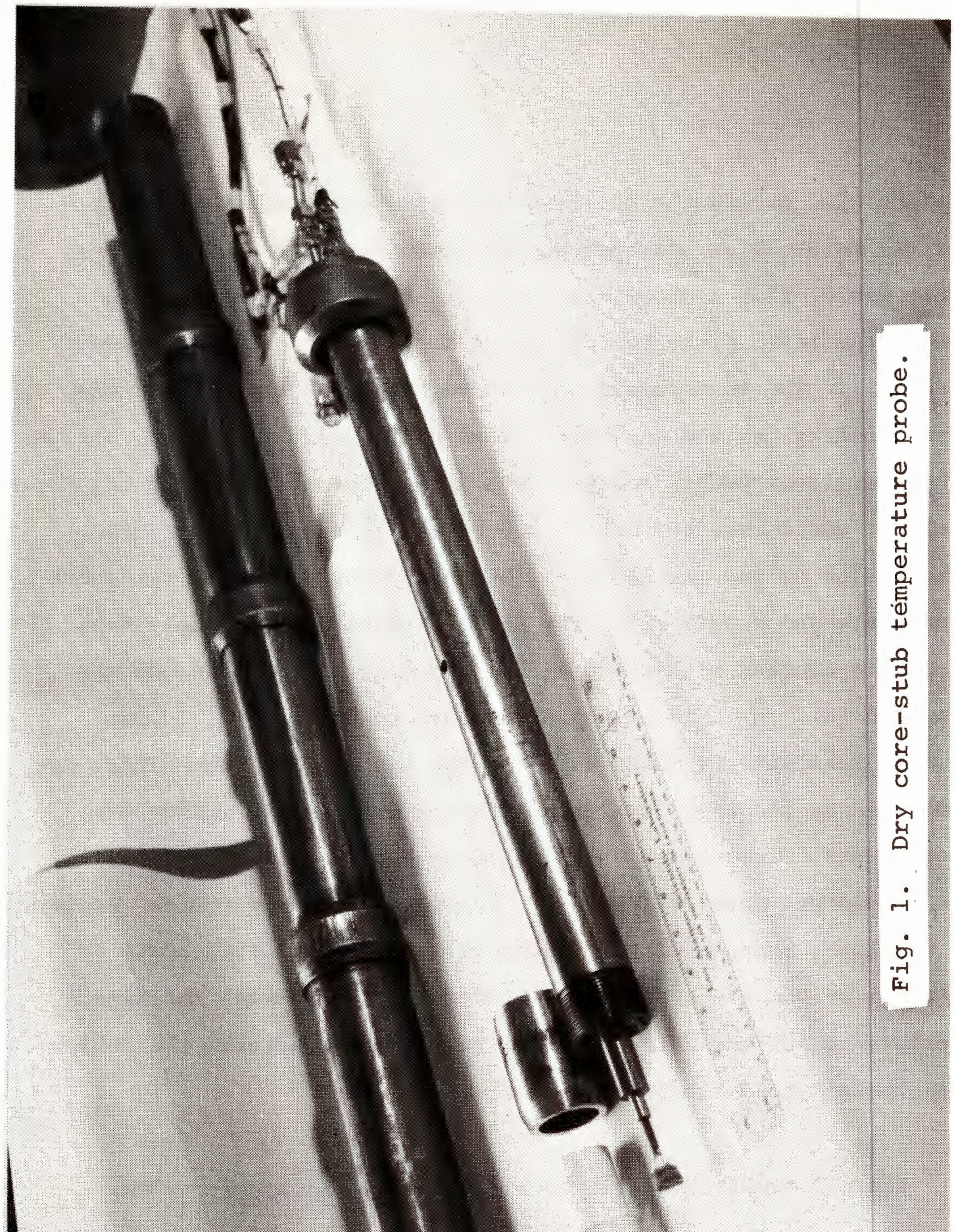
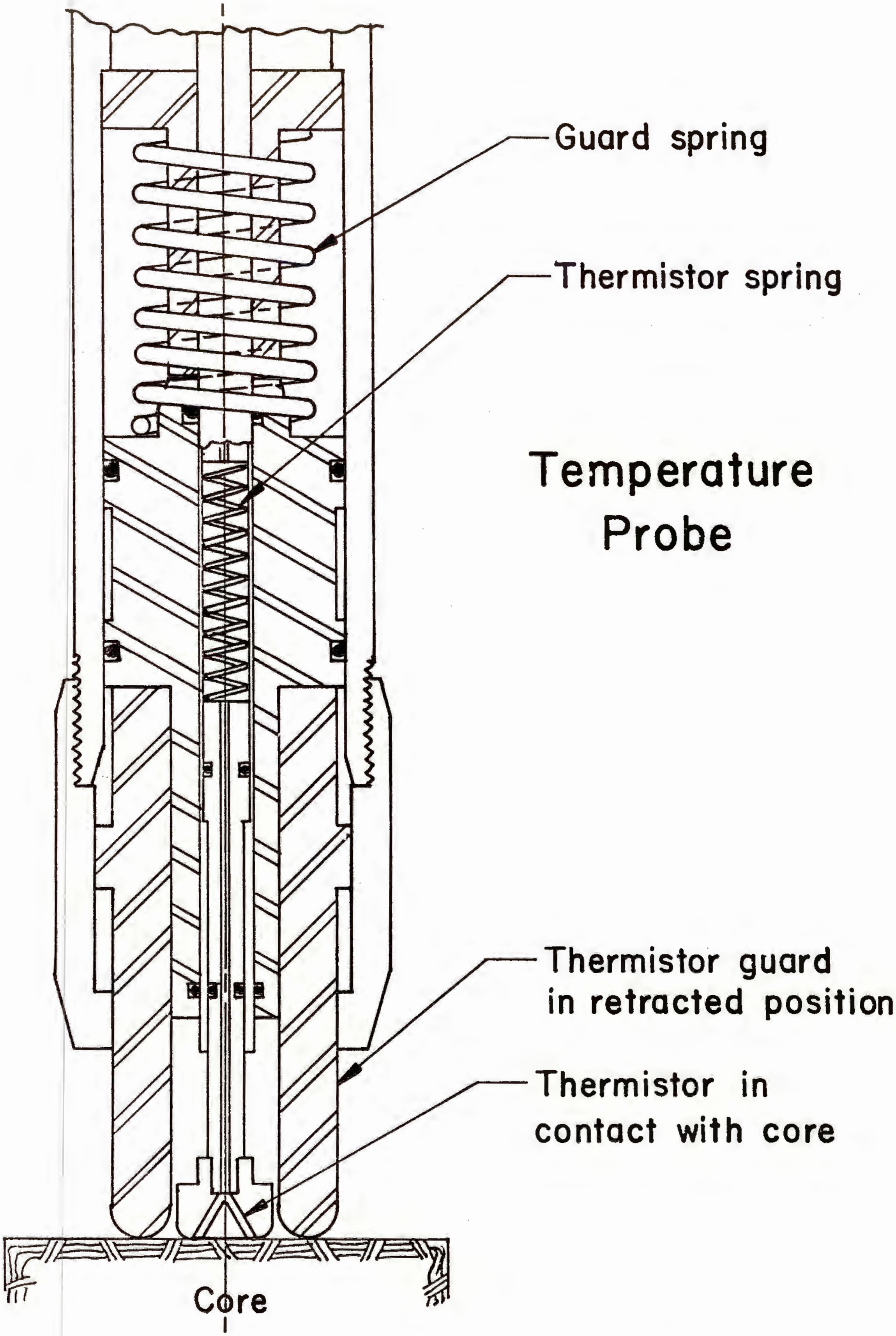


Fig. 1. Dry core-stub temperature probe.



Fiq. 2. Temperature-probe thermistor assembly.

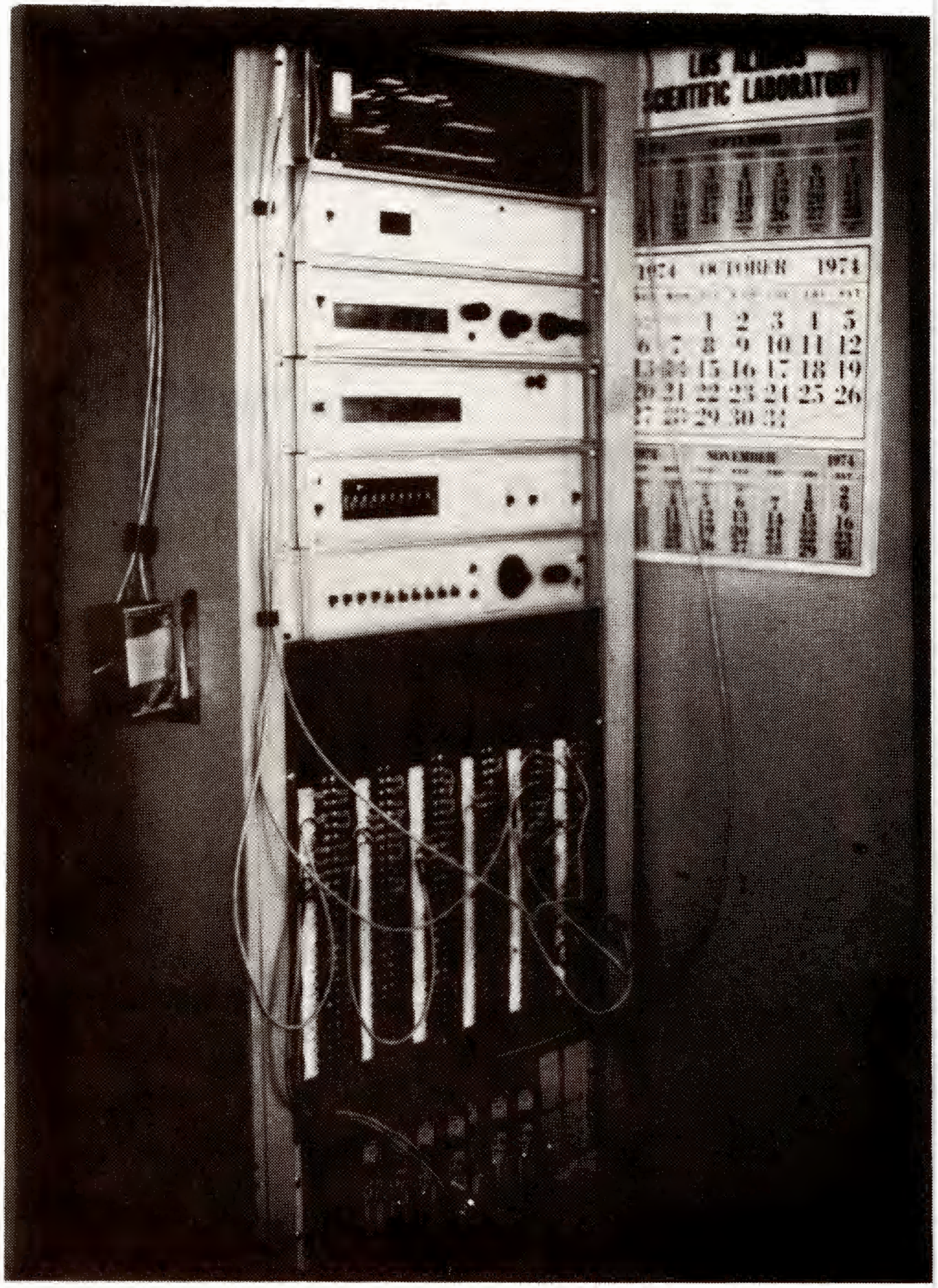


Fig. 3. Digital data-logging system.

temperature measurements were made at a depth of 789.4 m (2590 ft). Once the probe was on bottom the temperature was read continuously in order to observe the approach to the equilibrium state that would eventually be reached. It was not practical to allow the temperature sonde to remain on-bottom for extended periods of time waiting for all effects of drilling perturbations to subside because of the high cost of an idle drilling rig and crew on location.

Three subsequent measurements were made at depths of 866.8 m (2844 ft), 964.4 m (3164 ft), and 1055.8 m (3464 ft). The data are shown in Fig. 4, where the bottomhole temperature is plotted vs the time that the probe was on bottom. It is quite obvious from the first set of measurements that 1 hour of data was not sufficient for extrapolating to a realistic bottomhole temperature. The third set of bottomhole measurements, at 964.4 m (3164 ft), led to the suspicion that moisture was condensing on the massive probe, forming a pool on the bottom of the hole, and starting to boil. It appeared that water was seeping into the borehole, and this suspicion was confirmed by the next set of measurements at 1055.8 m (3464 ft), when the hole was found to contain large amounts of water at the boiling point. Subsequent logging of the borehole revealed the presence of aquifers in the granitic zones that communicated with a water-bearing zone in the Madera Formation above the granite. Attempts were made to cement these zones but were only partially successful in sealing off the large water source.[3] Therefore, the air-drilling (dry-hole) program was abandoned, and drilling was resumed using water and mud, as had previously been done in the volcanics and sediments.

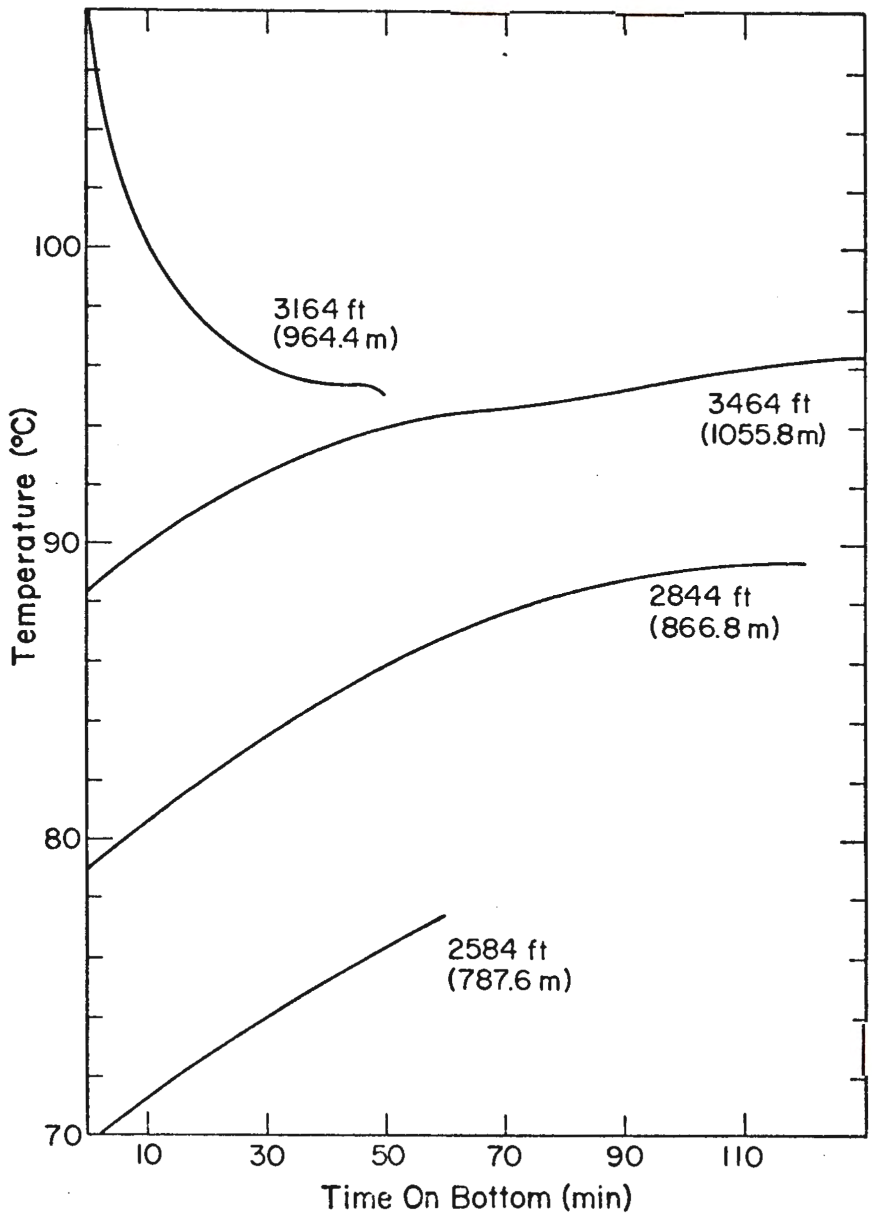


Fig. 4. GT-2 bottomhole temperature, dry-core probe.

A new probe was designed to log temperature in the fluid-filled hole and measure the bottomhole temperature. This new probe required a much longer residence time at the bottom of the hole because the fragile thermistor probe, protected in a metal cage, did not come into intimate contact with the bottomhole rock (Fig. 5). Prior to each temperature run, the borehole was circulated for at least 1 hour with clean water to remove all mud and drill cuttings that could settle to the bottom and insulate the instrument from the rock surface. During the sonde insertion, the thermistor probe was switched into one leg of a four-arm bridge circuit and the output plotted on a strip-chart recorder as a function of depth. The resistance span of the bridge was calculated to minimize non-linear characteristics of the thermistor. This resulted in the temperature interval (ΔT) being restricted to ranges of 50°C. A maximum error of 4% at the high end of the interval was realized using this technique. However, the concern at this time was to detect anomalies rather than to measure absolute temperature. As the sonde approached the drilled depth it was stopped at several points and allowed to come to thermal equilibrium before touching bottom. This technique greatly reduced the temperature perturbation when the massive probe finally reached the bottomhole rock surface. During this phase of the log, the thermistor was switched back to the digital ohms converter for maximum accuracy and resolution.

The results of the borehole temperature logging are shown in Fig. 6. The effects of the aquifers are clearly shown on the

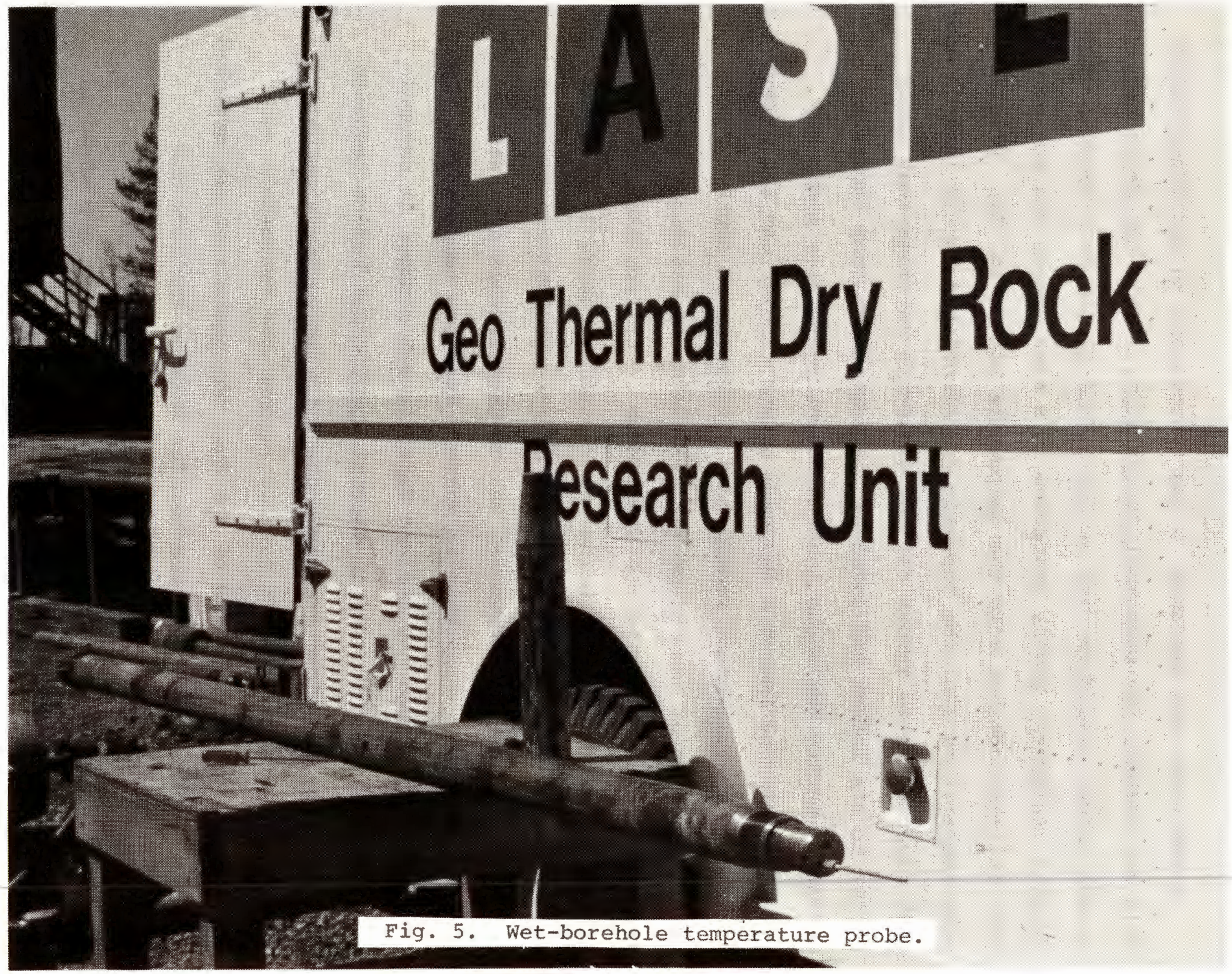


Fig. 5. Wet-borehole temperature probe.

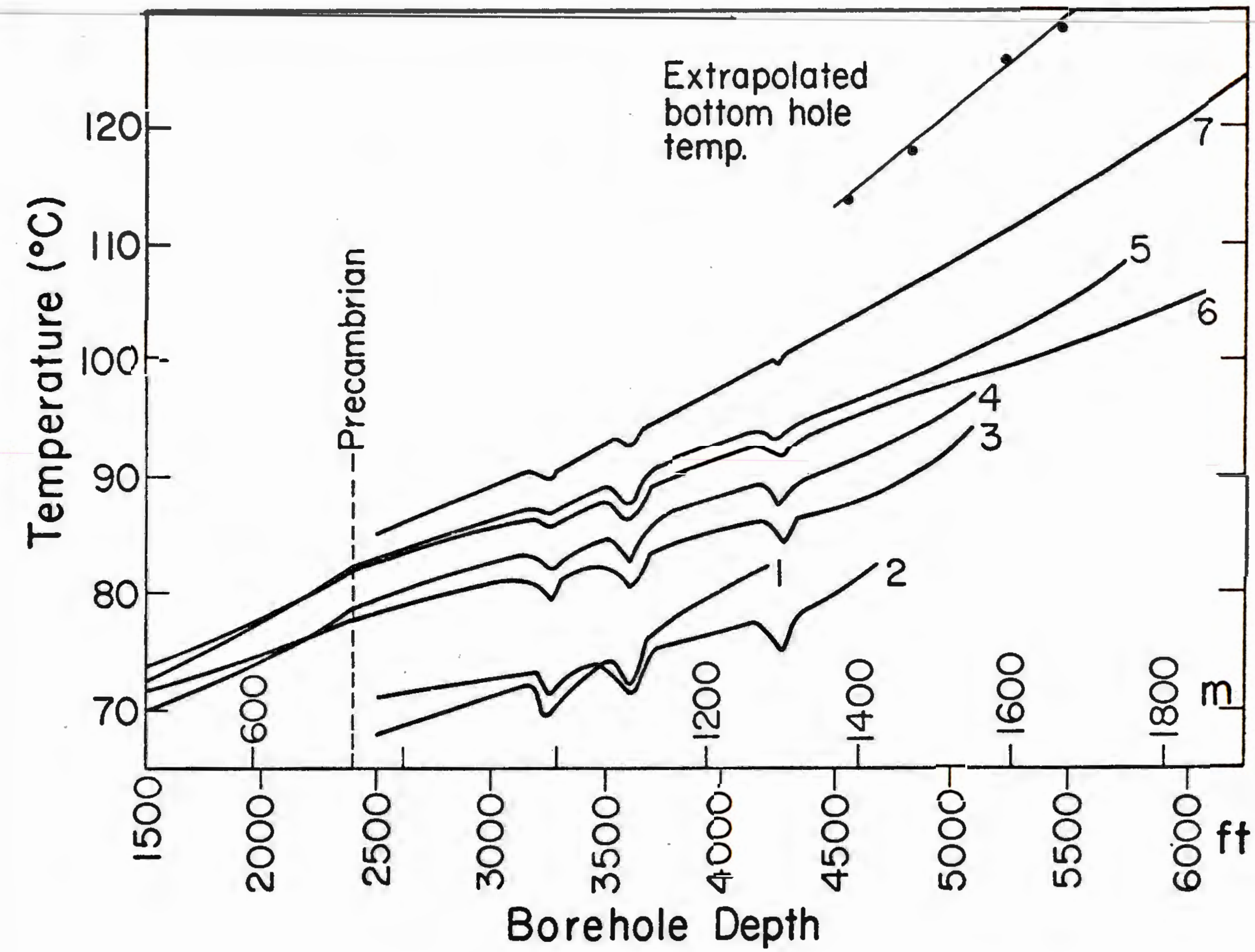


Fig. 6. GT-2 borehole temperature log.

initial logs. As hoped, the perturbations from these zones dimished with time. Thermal recovery of the borehole is shown by the continuing increase in temperature for each successive logging run and with the elapsed time between the logging run and the termination of circulation prior to that run (e.g., Runs No. 1 and 2 and Runs 5 and 6). Information concerning each logging run is given in Table I.

TABLE I

BOREHOLE TEMPERATURE-MEASUREMENT PARAMETERS

Run	Date	Bottomhole Depth (ft)	Bottomhole Depth (m)	Circulation Time Lapse (h)	Time on Bottom (h)	Extrapolated* Temperatures (°C)
1	6-9	4551	1387	12	21	113.58
2	6-13	4835	1474	6	30	117.78
3	6-19	5233	1595	6	48	125.66
4	6-25	5480	1670	10	32	128.35
5	7-3	5988	1825	19	36	135.63
6	7-6	6156	1876	10	48	138.57
7	9-2	6485	1977	10	17	142.9

**Reference 2.*

The continuous temperature log was terminated at least 100 ft above the bottom of the hole to allow the probe to reach thermal equilibrium at that point. The upswing in temperature near the end of each run as the sonde approached the bottom of the borehole results from the fact that this part of the hole was the least disturbed thermally by circulation of the drilling fluid. The method used to determine the extrapolated bottomhole temperatures (plotted in top right-hand corner of Fig. 6) is described in Ref. 2. Several temperature logs were recorded in the volcanics as well as in the Precambrian rock. Note the change in thermal gradient (slope) when the probe entered the granitic rock at 732 m (2404 ft).

One more thermal study is of interest. Following this first drilling phase in GT-2 a series of hydraulic-fracturing experiments took place. Various openhole packers from several manufacturers were employed to seal off designated areas in the open hole for pressurization in predetermined zones. All of the packers failed in one manner or another during the fracturing attempts. The use of packers in the open hole was finally discarded and plans were made to cement a section of pipe in the borehole which would accept a hook-wall (casing) packer and thus isolate the desired zone. Previous experience with costly cementing jobs in the upper sections of the borehole[3] prompted a careful examination of the thermal properties of the selected zone between the 1920-m (6300-ft) and 1981-m (6500-ft) levels where the section of pipe was to be cemented. The temperature probe was lowered to 1951 m (6400 ft) and the temperature recorded during a 5-hour circulation period with a flow of water of 9 bbl/min or 1438 liters/min (380 gpm). During this cooling period, the temperature was reduced from 126.9°C to 92.7°C (Fig. 7), for a ΔT of 34.2°C. At this time the flow was terminated and thermal recovery was measured for an additional

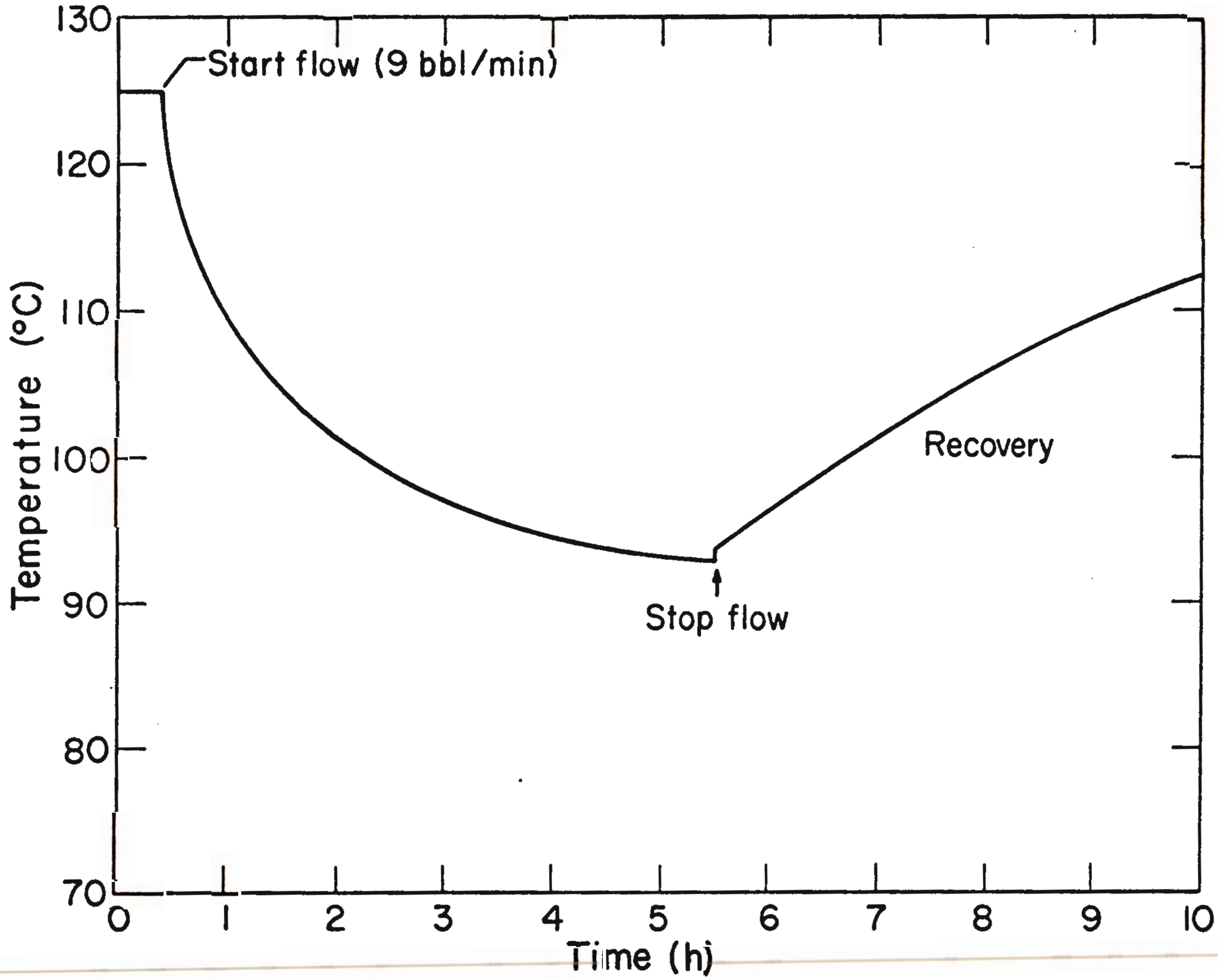


Fig. 7. Circulation and thermal recovery.

4.5 hours. The information was most beneficial in determining the proper cement mix to be used as well as describing additional thermal properties of the borehole.

HYDRAULIC-FRACTURE EXPERIMENTS

Following the drilling and logging operations in GT-2, a series of hydrology experiments was performed to determine the prefracture permeability of the Precambrian rock in the open-hole section of the borehole.[4] The rate of fluid loss from a dry-rock geothermal energy system is largely dependent on the permeability of the rock that contains the system. Results from these hydrology studies confirmed the low permeability of the granitic rock, and preparations were made to carry out hydraulic-fracturing experiments in the open hole. The fracturing experiments were designed to determine fracture-initiation (breakdown) pressure, fracture orientation, fracture-extension pressure, and fluid leak-off rates and to measure the least component of earth stress. The first series of fracture experiments was conducted in six different zones selected from the results of the hydrology studies and the information obtained from the various logs. The zones were selected primarily on the basis of low permeability and few pre-existing fractures.

A straddle-packer assembly was lowered into place in the zone of interest by a high-pressure line (drill pipe) extending to the surface. The packers were "locked" into the open hole formation to seal off the zone to be pressurized. A downhole instrumentation package was lowered inside the drill string via a special armored instrumentation cable. The instrumentation sonde was equipped with a mule shoe (Fig. 8) which mated with a receptacle attached to the upper straddle packer and oriented the sonde. The downhole package (Fig. 9) housed high-temperature instruments including a strain-gauge pressure transducer, 0 to 517.1 bars (7500 psi), compensated over the temperature range of 50 to 200°C. A tri-axis geophone assembly (Fig. 10) was provided to determine fracture orientation, with the two horizontal instruments providing azimuthal information and the vertical component providing vertical location of fracture events. The geophones were designed with a natural frequency of 8 Hz and a coil resistance of 730 ohms. The intrinsic sensitivity was 0.72 V/in./s with 70% damping. A solenoid-actuated water-sample bottle would collect a fluid sample in the fractured zone, and a ball-release solenoid would allow inflation of an impression packer. The impression packer was employed as a back-up system to confirm fracture orientation.

Previous experience with instrumentation cable in geothermal boreholes[5] led to the development of a logging cable fabricated specifically for this application. The cable contained 11 twisted pair (22 conductors) of No. 20 AWG copper insulated with 10 mils of high-temperature Tefzel 260°C (500°F) and wrapped with a Mylar aluminum shield including a drain wire. Each pair was blocked with a silicone compound to maintain cable integrity in the high-temperature, high-pressure environment. The entire conductor assembly was jacketed with a 30-mil Tefzel belt and a nylon braid.

Fig. 8. Instrumentation sonde orientation mule shoe.

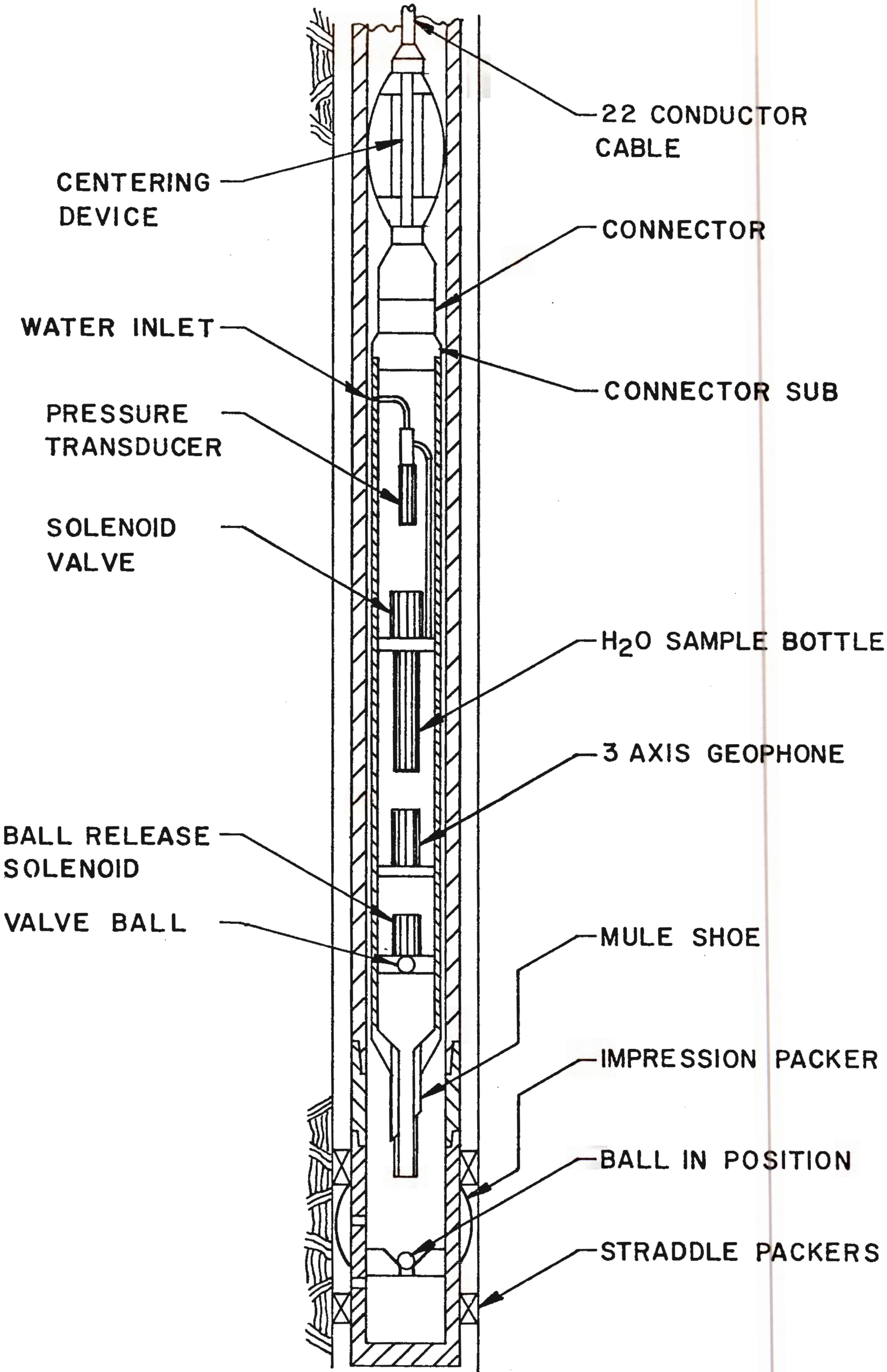


Fig. 9. Downhole instrumentation package, GT-2.

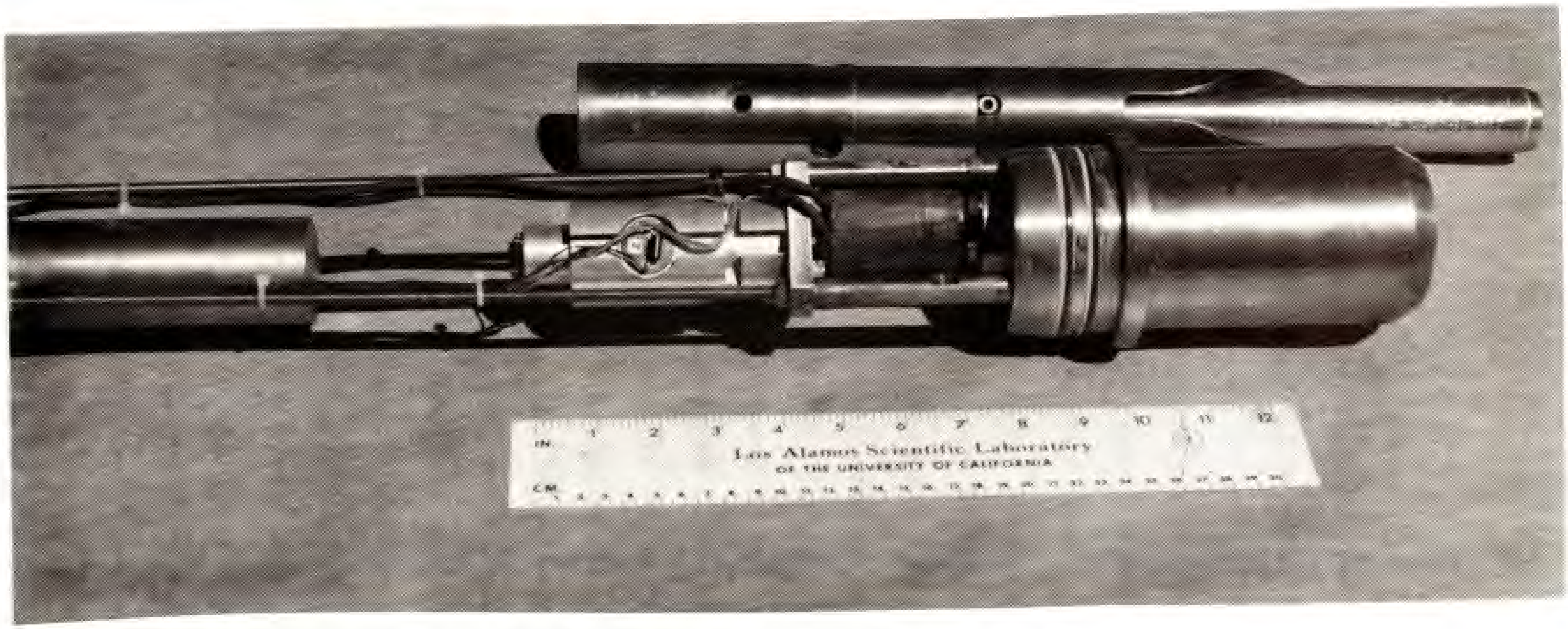


Fig. 10. Downhole tri-axis geophone assembly.

The inner armor was constructed of 36/0.051 special galvanized plow steel and the outer armor of 36/0.058 wire of the same material. Both armors were blocked with a silicone compound (Kalax) to prevent pressurized fluid from extruding into the wire armor and leaking at the surface above a Regan pack off. The cable weight was 460.4 kg (1015 lbs)per 1000 ft (304.8 m), with a breaking strength of 14,968 kg (33,000 lbs). The cable diameter averaged 820 mils. Conductor dc resistance was 10 ohms/1000 ft and capacitance was 35×10^{-9} fd/1000 ft conductor to mate. Insulation resistance was greater than 1000 megohms/1000 ft. The cable was lowered and raised in the borehole employing the off-shore cable hoist shown in Fig. 11.

The first series of pressurization experiments was designed to create relatively small fractures at low pumping rates. The pressurization system (Fig. 12) employed air-pressurized accumulator tanks holding approximately 38 liters (10 gal) of water at a pressure of 344.74 bars (5000 psi). An electropneumatic control valve controlled the fluid flow rates from 4 to 76 liters/min (1 to 20 gpm). During the pressurization test all surface equipment, with the exception of a data-acquisition trailer powered from a nearby power line, was shut down to insure a quiet test location. The reduced surface noise would enhance the reception of downhole acoustic and surface seismic signals generated during the fracture initiation and extension events.

Flow rate during pressurization was measured with a low-velocity, 8 to 76 liters/min (2 to 20 gpm) turbine flowmeter, and total flow was obtained by counting total turbine rotations. Surface pressure

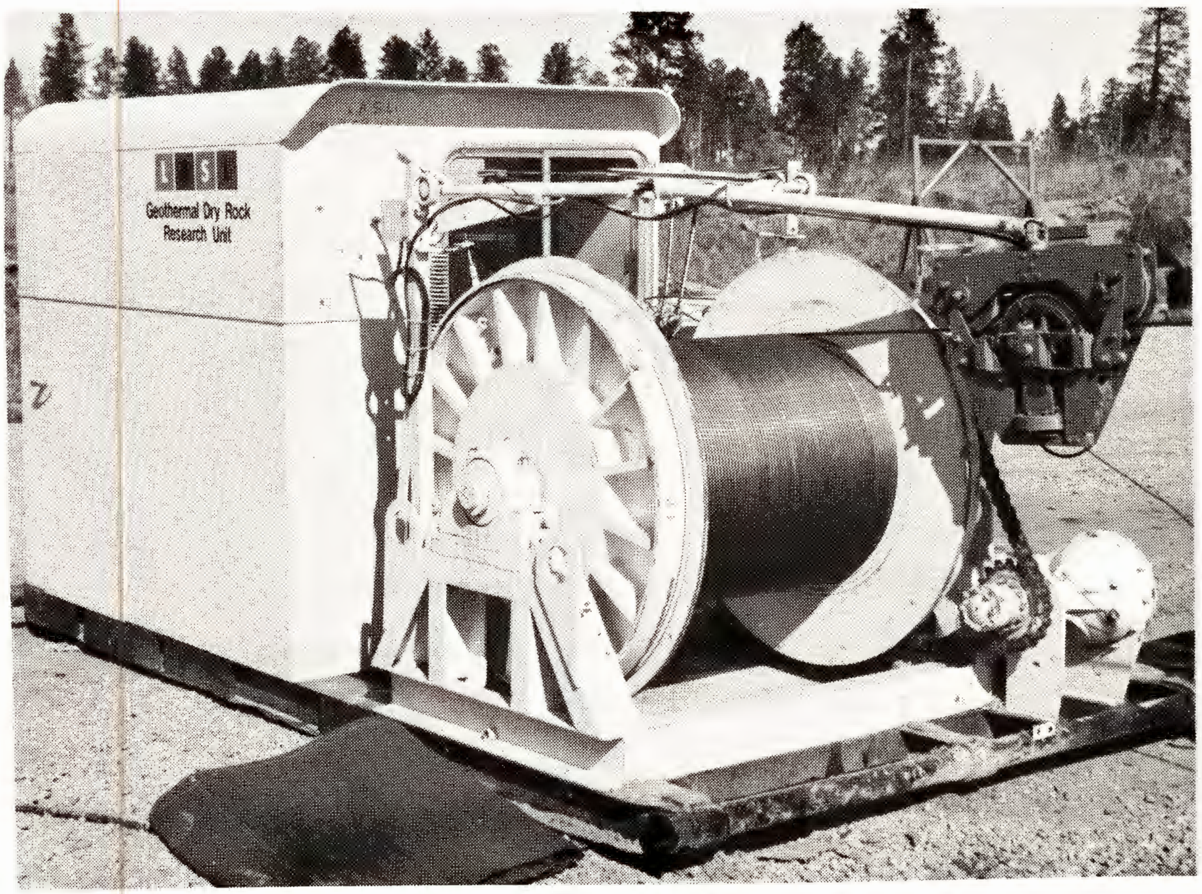


Fig. 11. Instrumentation cable hoist.

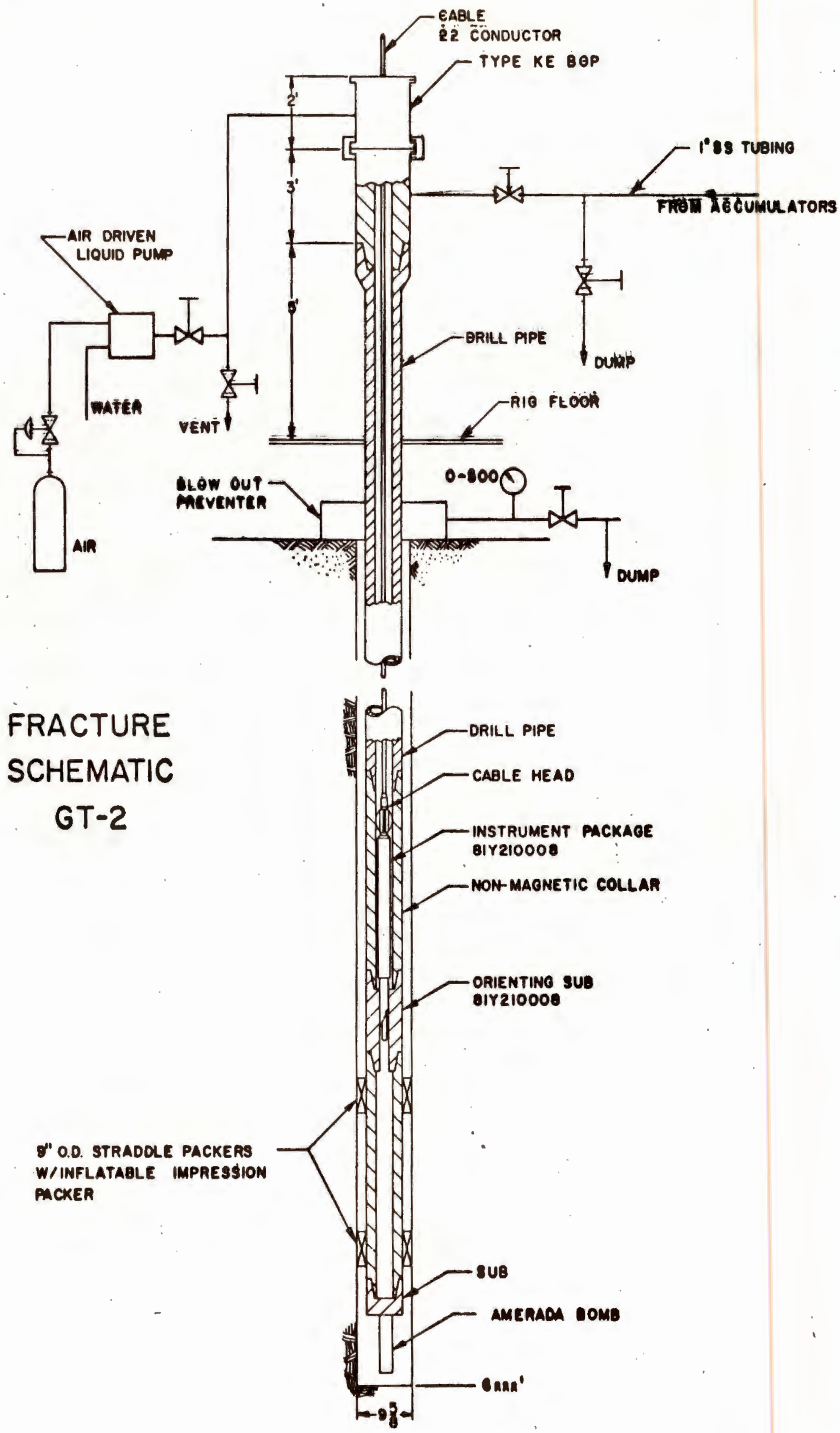


Fig. 12. GT-2 borehole pressurization system.

was measured with a strain-gauge bridge-type pressure transducer, 344.74 bars (0 to 5000 psi). A sensitive pressure gauge, 0 to 1.034 bars (0 to 15 psia), was lowered in the annulus around the drill pipe to measure water level. This measurement became most important when problems were encountered in seating the packers in the open hole. Rapid rise in annulus water level during pressurization tests was a positive indication that the pressurized fluid was leaking around the packers.

Following fracture-initiation and fracture-extension experiments, the flow system was shut in and pressure monitored for several hours to establish fluid leak-off rates. The system was then vented and return fluid measured in a weighing tank instrumented with load cells to determine the amount of water recovered from the collapsed fracture.

Signals from the surface and downhole transducers (as well as from a surface seismic array) were conditioned and fm multiplexed for recording on magnetic tape in an instrumentation trailer (Fig. 13). An online playback system (Fig. 14) was used to display pertinent information during the fracture experiments as a guide in carrying out experimental plans. The data-acquisition equipment employed floating, differential, and guarded techniques to maximize rejection of common-mode signals and improve signal-to-noise ratios. This conditioning technique was necessary to insure transmission of low-level transducer output signals over long lines.

Fig. 13. Data acquisition system.

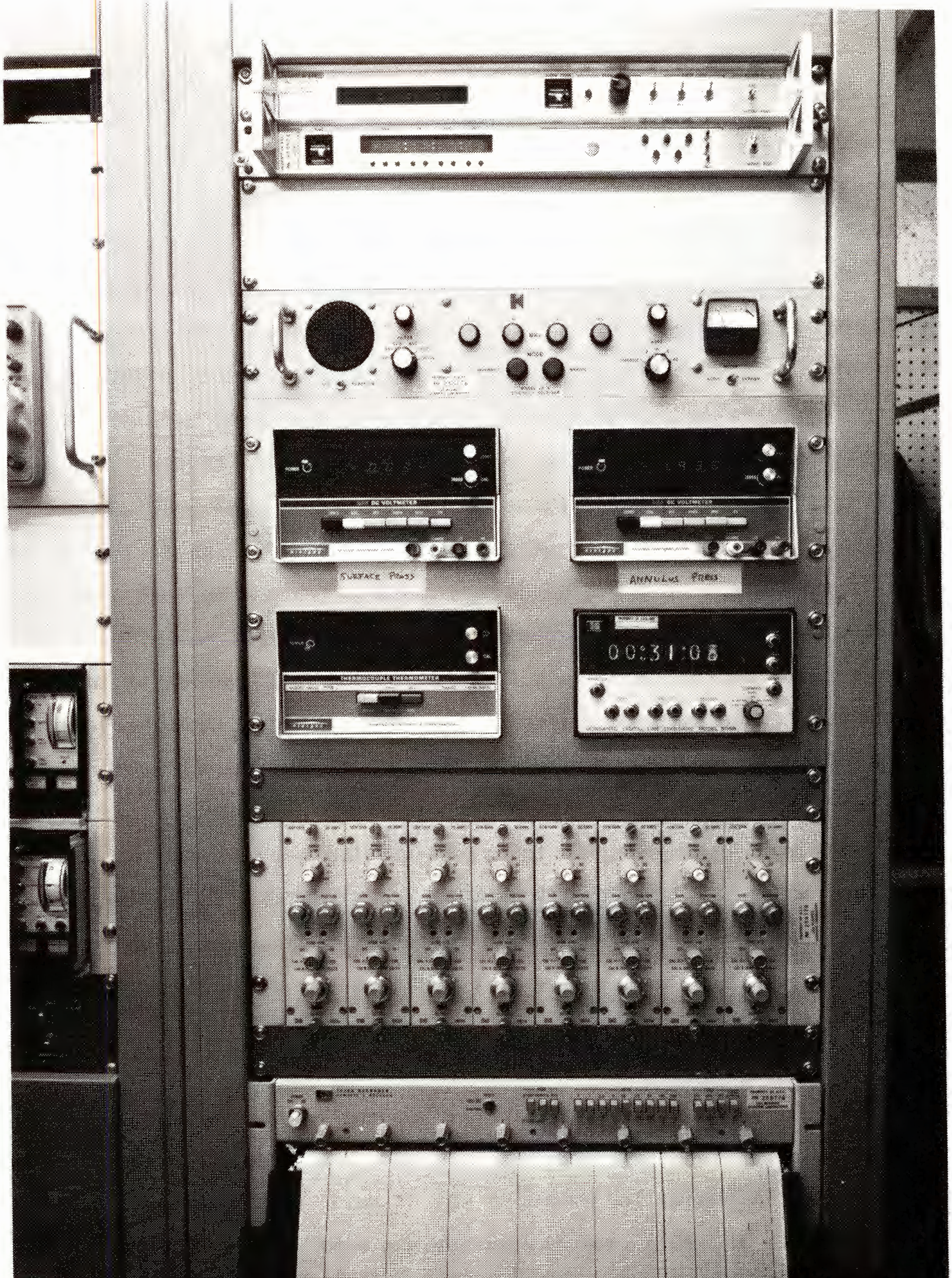


Fig. 14. Online playback station.

EXPERIMENTAL RESULTS

Fracture experiments were carried on in the six zones with a variety of packers from several oil tool companies. All packers failed to satisfactorily seal the open hole during the pressurization tests, as confirmed by the rapid rise in annulus water level. Pressures ranging from 34.45 to 110.32 bars (500 to 1600 psi) above hydrostatic were measured prior to leakage around the packers. Following this frustrating series of experiments it was decided to drill the hole to a depth of 2042 m (6700 ft). A number of diagnostic logs were run in the new section of the hole, including a temperature log extrapolating to a bottomhole temperature of 147°C. Hydrology tests were also made in the new section of hole to determine permeability. At this point, due to the failure of packers to hold in the open hole, it became necessary to cement a liner in place to conduct meaningful fracture experiments. Zone 7 was chosen, between 1981 and 2042 m (6498 and 6701 ft). A high-volume truck-mounted pump was employed to pressurize this zone with pressures up to 172.37 bars (2500 psi) and flow-injection rates of up to 682 liters/min (180 gpm).

Data from the initial pressurization test in Zone 7 are shown in Fig. 15, upper left-hand corner. A total of 398 liters (105 gal) of water was injected into the openhole section in 1 min. The surface pressure increased to 172.37 bars (2500 psi) and leveled off, at which time the system was shut in and the fluid allowed to permeate the rock around the open crack. The system was then vented and fluid recovered. A comparison of the surface

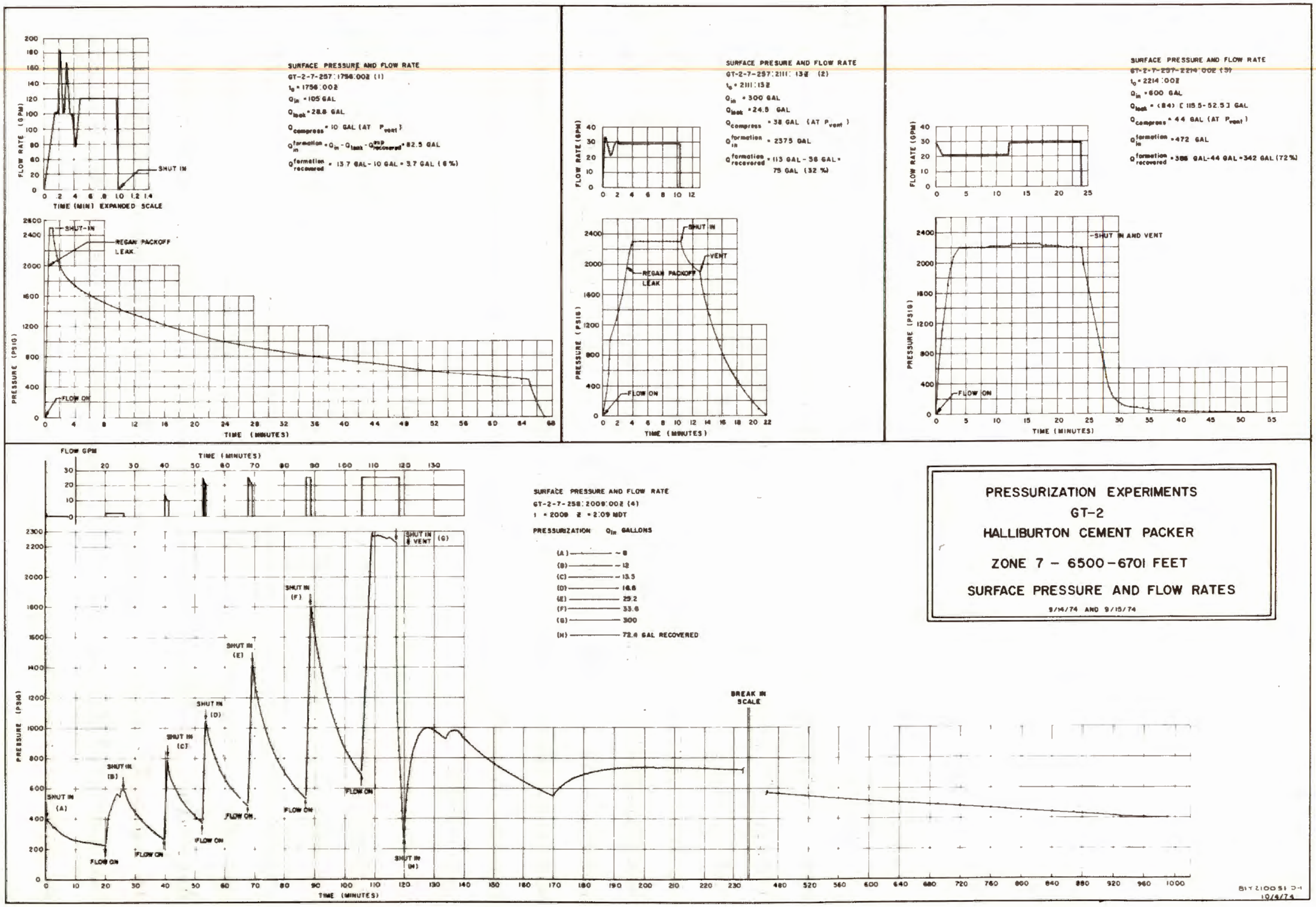


Fig. 15. Zone 7 pressurization experiments.

pressure and the pressure recorded from the downhole gauge is shown in Fig. 16. The downhole pressure transducer recorded a hydrostatic pressure of 185.1 bars (2850 psi) prior to the pressurization experiment. This is in good agreement (0.5%) with a calculated value of 1860 bars (2864 psi) using an overall average water temperature of 50°C.

Following the fracture initiation, several pressurization tests were conducted at low flow rates to reopen the small fracture (162 bars, 2350 psi,and 151.7 bars, 2200 psi), Fig. 15. A series of hydrological flow tests was conducted to study permeation effects in the fractured system (bottom plots, Fig. 15). The small fracture was extended by pumping water into the initial fracture at a maximum pressure of 237 bars (2500 psi) and maximum flow rate of 606 liters/min (160 gpm). A total of 266,625 liters (67,160 gal) of water was pumped into the fracture. The fracture was then propped open with a sand-gel mix.

To complete the fracture experiments in the existing borehole, a designated Zone 8 was chosen in the liner in the interval 1941.6 to 1944.6 m (6370 to 6380 ft). The casing was perforated, the zone pressurized to a maximum pressure of 134.4 bars (1950 psi), and the system shut in. Several experiments were performed to determine the possibility of communication between the fractures in Zones 7 and 8. Preliminary analyses of the data indicate that two separate cracks existed, offset from each other and separated by unfractured rock.

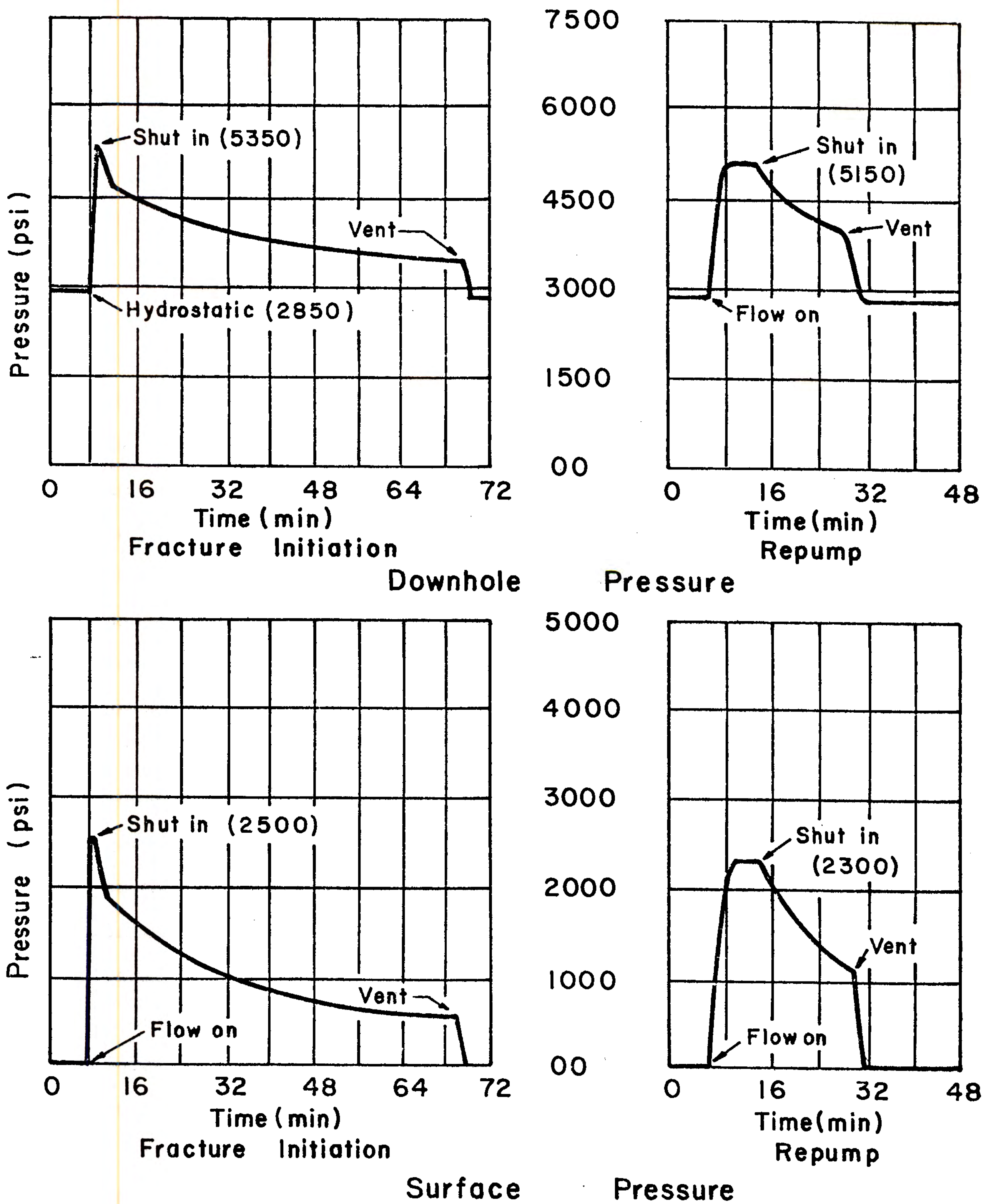
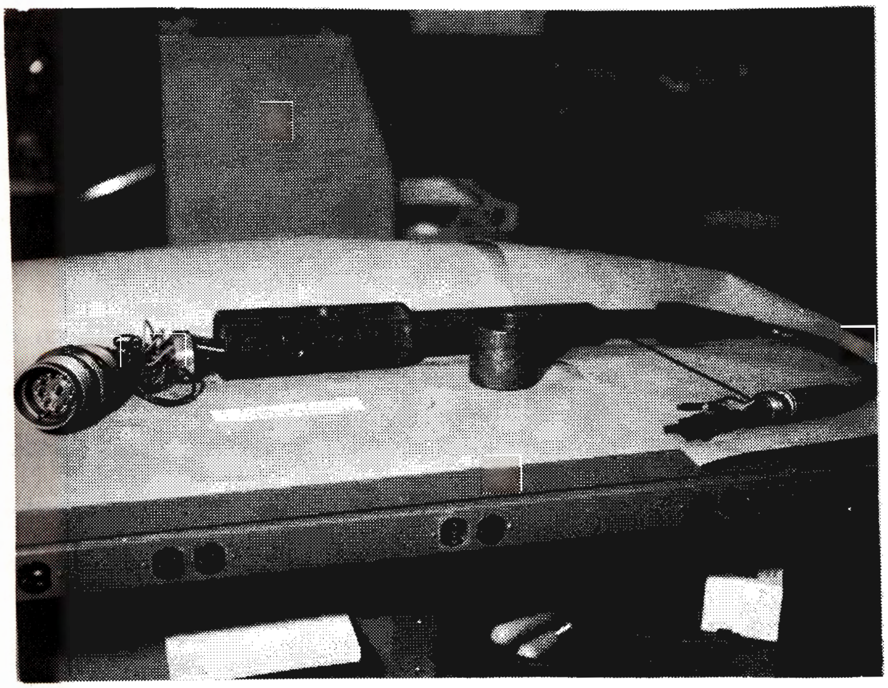


Fig. 16. Downhole and surface pressure measurement.

The fracture experiments were terminated and operations began to deepen the borehole to 2750 m (9000 ft) in order to achieve a bottomhole temperature approaching 200°C. Additional hydraulic fracturing experiments are planned at this depth.

CONCLUSION

Detailed analyses of all pertinent data recorded during the hydraulic fracture experiments is presently in progress and will be the subject of separate reports. In general, the instrumentation systems, including downhole instruments, performed well in the zones selected. Future experiments at the new depth of 2750 m (9000 ft) will impose additional temperature requirements approaching the limitations of downhole components. Problems were encountered during the long-term bottomhole temperature measurements in maintaining cable integrity as the borehole approached 2042 m (6700 ft). The combination of hydrostatic pressure and high temperature over an extended period of time allowed moisture to eventually seep into the cable-head assembly at an interconnecting torpedo and resulted in a breakdown of insulation resistance to ground. A standard seven-conductor, high-temperature (Tefzel-insulated), armored well-logging cable was used for the temperature logs. The cable-head assembly and torpedo (Fig. 17) were constructed of "high-temperature" components commonly used by most well-logging service companies where severe environments are normally encountered only for very short times (approximately 1 hour). The torpedo was designed to accommodate a "quick" disconnect of cable heads in the



field. The cable head was designed to terminate the wire line in a "fishing-bell" housing where the cable would break in the unforeseen event that an instrumentation package should hang up somewhere in the borehole. This design allowed the user to retrieve the cable from the borehole and "fish" out the disengaged sonde. Viton o-rings and insulation boots were employed to maintain a moisture proof assembly and additional protection was provided by packing the head and torpedo housing with a high-temperature silicone grease.

The cable head is expected to become a major concern during the subsequent series of experiments in GT-2 at the 2750 m (9000 ft) depth, due to the high-temperature environment. Design of a cable-head assembly that will eliminate exposure to moisture of the signal leads and retain the fishing-bell housing is in progress at Los Alamos.

The primary objectives of the experiments in GT-2 are to investivate magnitude and direction of the minimum compressive earth stress (S_3) and its variations with depth,[6] to study methods of measuring and possibly controlling direction of crack propagation, and to determine stability of pressurized fractures. These objectives will require the development of downhole instrumentation capable of characterizing hydraulic fracture systems. The development of the downhole instrumentation must emphasize reliability of measuring devices to function properly in high-temperature environments as the temperatures of subsequent geothermal boreholes approach 250°C and exceed the specifications of presently available components.

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VARIABLE RELUCTANCE DISPLACEMENT TRANSDUCER
TEMPERATURE COMPENSATED TO 650°F

By
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VARIABLE RELUCTANCE DISPLACEMENT TRANSDUCER TEMPERATURE COMPENSATED TO 650°F

T. C. Piper

Aerojet Nuclear Co.
Idaho Falls, ID

Abstract

A variable reluctance transducer (VRT) for operation to 650° F in a pressurized water environment and associated signal conditioning electronics are described. Effects such as VRT core hysteresis-loss and core permeability-change are discussed with respect to temperature compensation. The transducer and electronics were designed as a system to yield minimum change in the VRT null and sensitivity with rapid thermal transient. Steady-state null and sensitivity changes of ± .5% and 1.8% of full scale, respectively, were obtained over the 70° F to 650° F temperature range. With the VRT core locked at null a 650° F to 70° F thermal transient amounts to a ± 3% of full scale variation. The output signal variation lasts for about two seconds. The VRT utilizes a single 1/16-inch diameter, three conductor, sheathed cable. Ceramic cement, ceramic insulated wire, and ceramic flame spraying techniques allow it to have large nuclear radiation tolerance as well as the noted high temperature capability.

VARIABLE RELUCTANCE DISPLACEMENT TRANSDUCER

TEMPERATURE COMPENSATED TO 650^{o}F

I. INTRODUCTION

In pressurized water reactor tests, compact instruments for accurate measurement of small displacements in a 650^{o}F environment are often required. In the case of blowdown tests such as the Loss of Fluid Test (LOFT) or Semiscale computer code development tests, not only is the initial environment water at 650^{o}F and 2200 psi but it undergoes a severe transient due to depressurization. The pressure drops from 2200 psi to ambient in a few seconds and the temperature of the coolant drops from 650^{o}F to 212^{o}F. The transducer temperature then heads toward either about 400^{o}F (the vessel temperature after blowdown) or room temperature if emergency core coolant is used. Since the LOFT and Semiscale tests are run just for the purpose of obtaining data during the depressurization, instruments used to obtain the data must not give false outputs induced by the change in environment. Figures 1 and 2 show, respectively, a LOFT ρv^2 probe and a Semiscale drag disk; each utilizes a variable reluctance transducer (VRT) such as described in this paper for indication of the drag-disk location and a torsion bar for drag-disk restoring force. The VRT, in addition to being thermally gain and null offset stable, is fabricated from materials known to be resistant to large nuclear radiation levels and has successfully passed a fast neutron radiation test of 2.7 x 10^{17} nvt without failure.

II. THEORY OF OPERATION

A VRT, being somewhat different than an LVDT (linear variable differential transformer), consists of only two, series connected, cylindrically wound coils. A magnetic core placed on the cylinder axis serves to vary the self and mutual inductances of the two coils which electronically form two legs of a four-arm bridge as shown in basic form in Figure 3. Because thin sections of austenitic stainless steel have little effect on the coil magnetic flux distribution at the drive frequency of 3 kHz, the coil region of the transducer can be hermetically sealed from the environment in which the core of the unit resides.

The theory related to obtaining constant sensitivity and low null-drift versus temperature can be summarized as follows: The transducer's magnetic core hysteresis loss decreases with temperature increase (see Appendix A). For constant current through the transducer, the decrease in hysteresis loss would cause an increase in transducer sensitivity with temperature. By winding the transducer with wire having a large resistance temperature coefficient and shunting this with the appropriate constant ohmage bridge completion resistance (see Figure 3), the increase in sensitivity due to core behavior can be canceled by the decrease in current through the transducer. The shunt resistance effectively bypasses a portion of the constant ac drive current from the drive transformer T_1 (see Appendices A and B for details). Pushbutton switch Sw1 allows the transducer bridge to be resistively

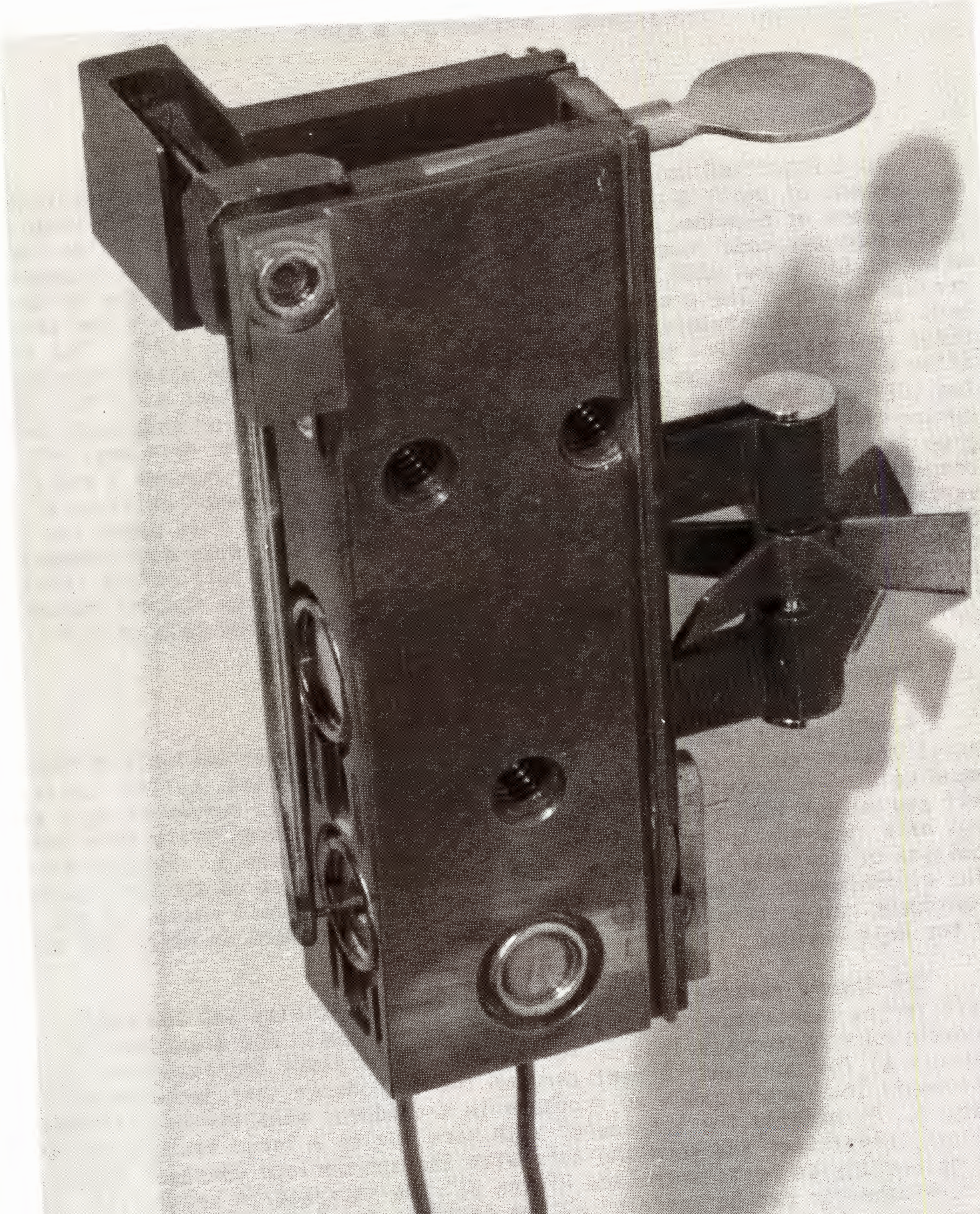


Figure 1

Figure 2

BASIC SCHEMATIC OF ELECTRONICS

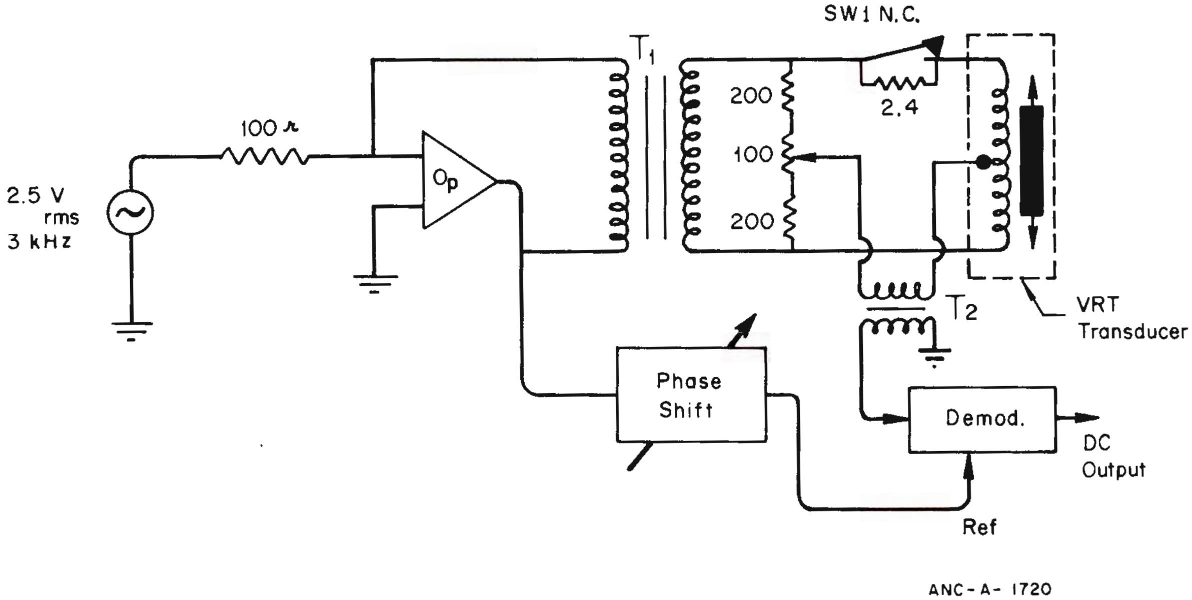


Figure 3

imbalanced so that the reference to the demodulator can be set to that phase where no dc output change occurs when the button is pushed. This makes the output insensitive to thermal-induced resistive imbalances. Because resistive changes are the primary source of bridge imbalance with temperature and particularly of thermal transients, this technique of setting the reference to the demodulator maximizes transducer null-drift stability. Transformer T_1 must be selected to approach ideal transformer characteristics (low series impedance and high shunt impedance) so that it does not introduce phase angle changes or act as a variable shunt on the constant ac current being supplied to the four-arm bridge.

III. MECHANICAL DESIGN

The VRT coil bobbin is shown in Figure 4 with the coil in place. To accomplish this: The 304 stainless steel bobbin is first vacuum annealed to 1800°F to remove any trace of magnetic permeability induced by work hardening in fabrication. The bobbin is next sand blasted and immediately flame sprayed with ceramic to serve as an undercoat for the coil (BHL 215020-H Al_2O_3 rod is used). Platinum wire with ceramic insulation is used for the coil wire. The wire with insulation is .0088" diameter and the bare wire is .007" diameter and is supplied by Secon Metals Corp. of White Plains, New York. Secon Metals Corp. supplies the wire with their type E insulation. The coils are wound on the flame sprayed bobbin in a sense such that the mutual inductance aids the self-inductances when the two center leads are connected together to form the VRT common lead. The ends of the coils are secured in place with Aremco 503 ceramic cement (Briarcliff Manor, New York) as shown in Figure 4, and the coil fired in air to 1500°F to cure the ceramic. After the leads have been gently folded into the hole of Conetic B magnetic shield (Perfection Mica Company, Chicago, Illinois) that is spot welded to the ridge at each end of the bobbin, it is slid into position in the transducer body. The leads are then fished out through a lead connection hole and brazed to the sheathed cable leads which also protrude into the lead connection hole. With the finished connections tucked neatly back into the lead connection hole and cemented into place away from metallic parts with a small amount of Saureisen #8 ceramic cement (Pittsburgh, Pa.), a seal cover is welded into place on the lead connection hole after the cement has cured.

IV. RESULTS

Results of thermal cycling and transient tests on the completed ±0.100-inch stroke VRT are as follows: Sensitivity change from room temperature to 650°F was 1.8% or 0.003%/°F. Zero null remains fixed to within ±0.5% of full scale in the room temperature to 650°F range. With core locked at null and unit plunged horizontally into 70°F water from 650°F heat, transient output variations of about two seconds duration and of ±3% of full scale occurred. Failure to vacuum anneal a VRT bobbin has occurred once or twice and has led to irratic behavior of the VRT versus temperature because the work hardening from machining the bobbin leaves the bobbin with a magnetic permeability greater than unity.

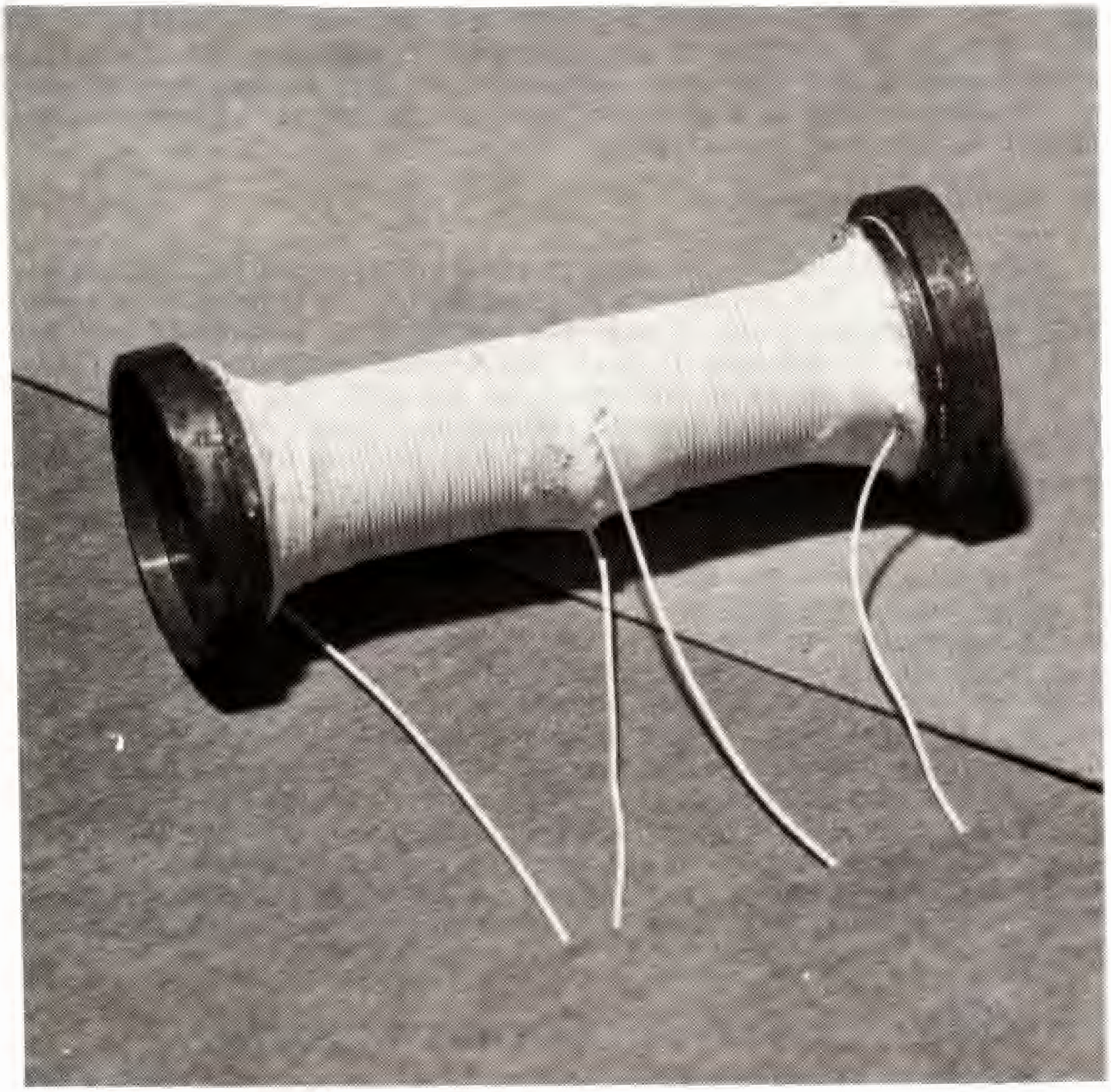


Figure 4

APPENDIX A

EFFECT OF VARIATION IN HYSTERESIS LOSS

The equivalent circuit of Figure A1 can be used to approximate the behavior of a single side of the VRT coil with core in place. Resistance R_2 increases as the hysteresis loss of the core decreases with increasing temperature*. R_1 and X are the coil resistance and reactance for the core in some fixed position. The simple theory outlined in Appendix C shows that moderate changes in core permeability, μ_r, with temperature do not change X significantly. However, the change in R_2 with temperature results in an effective change in the coil reactive component, X_{in}.

$$Z = R + jX_{in} = R_1 + \frac{R_2 jX}{R_2 + jX} = R_1 + \frac{R_2 X^2}{R_2^2 + X^2} + j\frac{R_2^2 X}{R_2^2 + X^2} \qquad \text{(A-1)}$$

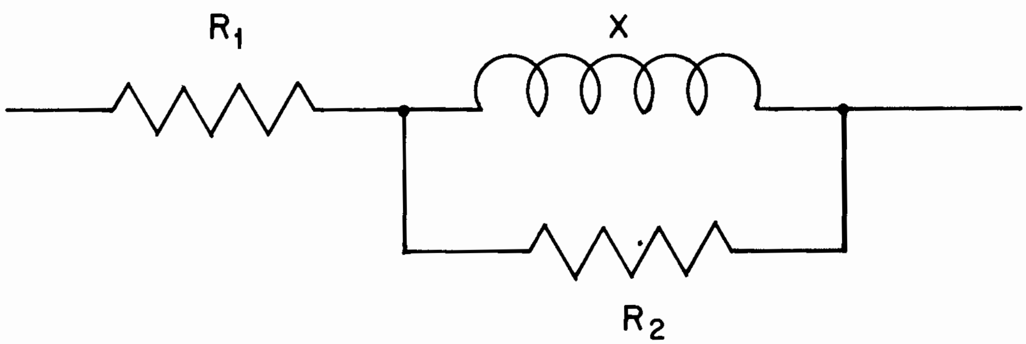
This leads to

$$\frac{\Delta X_{in}}{X_{in}} = \frac{2X^2}{R_2^2 + X^2} \cdot \frac{\Delta R_2}{R_2} \, . \qquad \text{(A-2)}$$

For a 17-4 PH core heat treated H-1100, $\Delta X_{in}/X_{in}$ has been found, by measurement, to equal + 0.068 for a temperature change from 75 to 650°F. This β = 0.068/575°F = 0.00012/$^{\circ}$F, of course, agrees with the increase in sensitivity experienced if a constant current bridge drive is used with no current shunting resistor. Other core materials such as 410 stainless and Remendur were tested and found to have $\Delta X_{in}/X_{in}$ values as large as +0.095 for the same temperature change.

**Actually, R_2 would vary with variations in either hyseresis or eddy-current losses. But for the design presently being described, it was determined (by using slit cores and cores of nonmagnetic 300 series stainless) that eddy-current losses are constant or are insignificant enough that they cause no variation of R_2 with termperature.*

EQUIVALENT CIRCUIT OF "1/2" VRT



ANC-S-5020

Figure A-1

APPENDIX B

MATHEMATICAL FORMULATION OF VRT TEMPERATURE COMPENSATION

Referring to Figure 3 of the text and being informed that at 3 kHz the total transducer imaginary impedance component is only about 3 ohms while the room temperature real impedance component is 30 ohms, analysis of current flow through the shunt and transducer can be done fairly accurately using only resistances.

Let i_c be the constant current from T_1, V be the voltage across T_1, i_2 be the current through the transducer, $R_0(1+\alpha\Delta T)$ be the resistance of the transducer coils, and R_1 the constant resistive shunt placed across T_1. α is, of course, the temperature coefficient of resistance for the wire used in the transducer.

Then

$$R_{11} = \frac{R_1 R_o(1+\alpha\Delta T)}{R_1+R\ (1+\alpha\Delta T)} \quad \text{(B-1)}$$

or

$$V = i_c R_{11} = \frac{i_c R_1 R_o(1+\alpha\Delta T)}{R_1+R_o(1+\alpha\Delta T)} \quad \text{(B-2)}$$

Thus

$$i_2 = \frac{V}{R_o(1+\alpha\Delta T)} = \frac{i_c R_1}{R_1+R_o(1+\alpha\Delta T)} \quad \text{(B-3)}$$

The sensitivity, S, of the system will be

$$S = Ki_2\ (1+\beta\Delta T) \quad \text{(B-4)}$$

where β is the temperature coefficient of the coil inductance caused by changing core hysteresis loss. Let K equal unity. Then,

$$S = \frac{i_c R_1\ (1+\beta\Delta T)}{R_1+R_o(1+\alpha\Delta T)} \quad \text{(B-5)}$$

This can be rearranged to give

$$\frac{S}{i_c} = \frac{1+\beta\Delta T}{1+\frac{R_o}{R_1}(1+\alpha\Delta T)} \quad \text{(B-6)}$$

If $\frac{R_o}{R_1}(1+\alpha\Delta T)$ is a fair amount less than unity in value, the denominator may be brought to the numerator using the approximation $\frac{1}{1+\gamma}\sim 1-\gamma$ for γ<<. Assuming this approximation holds for the R_o, R_1, α, and ΔT involved,

$$\frac{S}{i_c} = (1+\beta\Delta T)\left(1-\frac{R_o}{R_1}\{1+\alpha\Delta T\}\right) \qquad \text{(B-7)}$$

Dropping terms quadratic in ΔT,

$$\frac{S}{i_c} = 1-\frac{R_o}{R}+\Delta T\left(\beta-\frac{R_o}{R_1}\alpha\right) \qquad \text{(B-8)}$$

Clearly, adjusting the R_o/R_1 ratio permits this approximate expression to be made independent of ΔT.

By Appendix A, $\beta = 0.00012/^{o}F$. α, for platinum wire, is $0.002/^{o}F$. R_o = 30 ohms. And, the value of R_1 found experimentally to give minimal change in S with T was 500 ohms.

Checking: 30/500x0.002 = 0.00012. Thus, since this is also the value of β, the ΔT coefficient is zero with the value of R_1 found to give minimal temperature sensitivity. Furthermore, 30/500(1+0.002x575) = 0.129 so γ is <<1, and the approximations made in obtaining Equation (B-8) are valid.

Because of the large temperature coefficient of platinum wire R_o varies from presence of the 500 ohm shunt across this changes the phase of the current through the transducer to vary by only 0.3 degree for the 575^{o}F temperature change. Use of coil wire with a smaller temperature coefficient would have required a smaller value of R_1 and this would then lead to larger changes in the phase of the current through the transducer for the given temperature variation. Constancy of the phase of the current passing through the transducer is, of course, necessary so that the demodulator reference phase need not be adjusted as temperature changes.

APPENDIX C

EFFECT OF VARIATIONS IN CORE U_r ON

VRT SENSITIVITY

Because the demodulator used to process the VRT signal is driven with a reference voltage of phase such that the filtered demodulator output is insensitive to resistive bridge imbalance, the resultant transducer sensitivity is only affected by changes in VRT coil reactance. For a coil with a core but having an appreciable air gap,

$$L = \frac{\mu_o N^2 A}{\frac{\ell - X}{\mu_r} + h - \ell + X + \ell_A} = \frac{\mu_o \mu_r N^2 A}{(\ell - X) + \mu_r (h - \ell + X + \ell_A)} \qquad \text{(C-1)}$$

where μ_o is the permeability of free space, μ_r is the relative permeability of the coil core, 2ℓ is the core length, ℓ is the length of the core in each coil of the VRT at null, X is the offset of the core from this null position, h is the length of each of the two VRT coils, N is the number of turns on each coil, A is the effective area of the ID of the coil, and ℓ_A is a small constant, representing the fact that the coil is not actually too long a solenoid. See Figure C-1.

The VRT, of course, consists of two such coils connected as a half bridge with X negative of the above in the expression for the other coil).

$$\Delta L = L_2 - L_1 = \mu_o \mu_r N^2 A \left[\frac{1}{\ell + X + \mu_r (h - \ell - X + \ell_A)} - \frac{1}{\ell - X + \mu_r (h - \ell + X + \ell_A)} \right] \qquad \text{(C-2)}$$

After separating out the X portion, cross multiplying, and condensing, this becomes

$$\Delta L = \frac{2 \mu_o \mu_r (\mu_r - 1) N^2 A X}{[\ell + \mu_r (h - \ell + \ell_A]^2 - X^2 (\mu_r - 1)^2} \qquad \text{(C-3)}$$

Since X is always small compared to $h-\ell$, the X^2 term in the denominator may be dropped. Compared to $h-\ell$ both ℓ_A and ℓ/μ_r are quite small so Eq(C-3) can be written:

$$\Delta L = \frac{2 \mu_o \mu_r (\mu_r - 1) N^2 A X}{\mu_r^2 (h - \ell)^2} \approx \frac{2 \mu_o N^2 A X}{(h - \ell)^2} \qquad \text{(C-4)}$$

PICTORIAL SCHEMATIC OF VRT COIL AND CORE

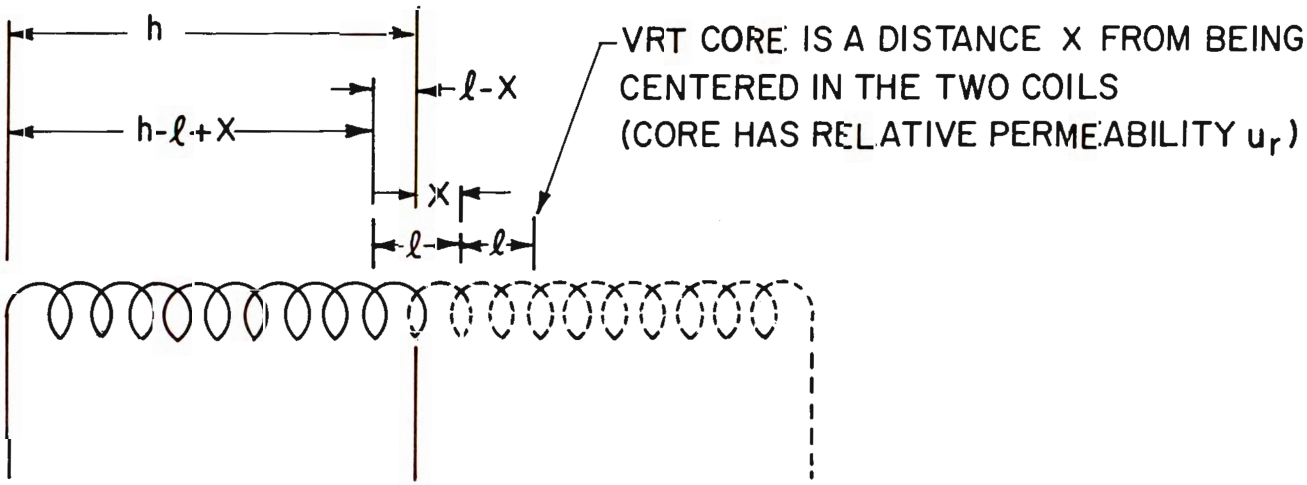


Figure C-1

Using Eq(C-3) for ΔL, the VRT sensitivity is

$$S = \frac{\partial(\Delta L)}{\partial X} = \frac{2\mu_o \mu_r (\mu_r - 1) N^2 A \{[\ell + \mu_r (h - \ell + \ell_A)]^2 + X^2 (\mu_r - 1)^2\}}{\{[\ell + \mu_r (h - \ell + \ell_A)]^2 - X^2 (\mu_r - 1)^2\}^2} \qquad \text{(C-5)}$$

Using $h-\ell >> \ell_A$ and ℓ/μ_r or glancing at Eq(C-4) shows that the approximate value for S is:

$$S \simeq \frac{2\mu_o N^2 A}{(h-\ell)^2} \qquad \text{(C-6)}$$

Performing $\partial S/\partial \mu_r$ on the expression of Equation(C-5) gives an involved expression which reduces, upon using $\mu_r >> 1$, $h-\ell >> \ell_A$, and $h-\ell >> \ell/\mu_r$ to:

$$\frac{\partial S}{\partial \mu_r} \simeq \frac{4\mu_o N^2 A \ell}{\mu_r^{\,2}(h-\ell)^3} = \frac{2S\ell}{\mu_r^{\,2}(h-\ell)} \qquad \text{(C-7)}$$

This may be rewritten

$$\frac{\Delta S}{S} = \frac{2\ell}{(h-\ell)} \frac{\Delta \mu_r}{[\mu_r]^2} \qquad \text{(C-8)}$$

Since a typical value for μ_r is 150, a typical value for $\Delta\mu_r/\mu_r$ is 0.3 for the 575°F temperature change involved, and $2\ell/(h-\ell) \simeq 1.1$

$$\left.\frac{\Delta S}{S}\right|_{typ} = 1.1 \times \frac{.3}{150} = .002 \equiv .2\% \qquad \text{(C-9)}$$

Thus, changes in μ_r do not significantly affect the VRT sensitivity. But, as shown in Appendix A, variations in VRT core hysteresis loss do cause significant values of $\Delta S/S$.

A SIX-COMPONENT STRAIN GAGE BALANCE FOR HELICOPTER TESTING

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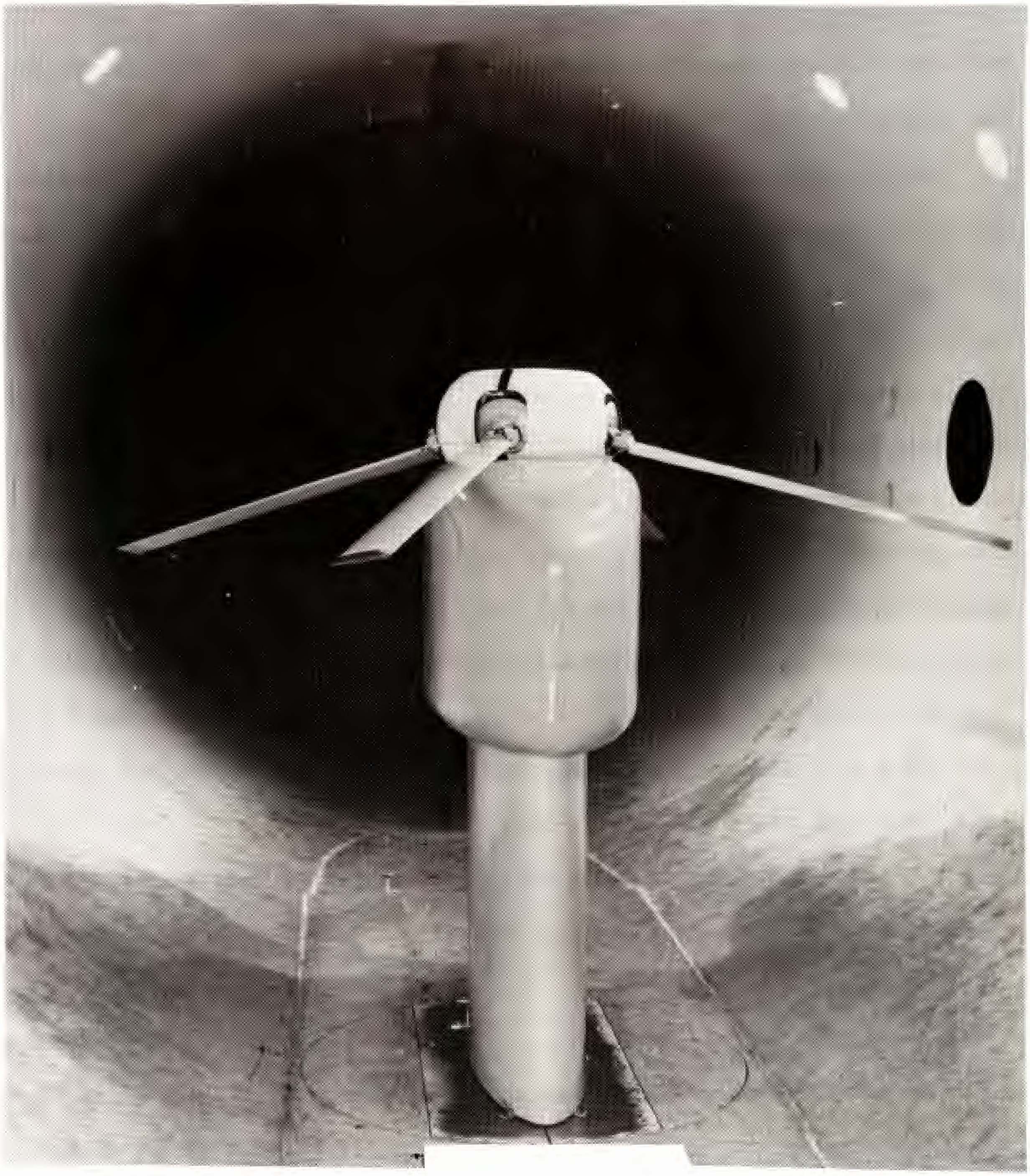
Tests of a reversed velocity helicopter rotor in the 12-foot pressure wind tunnel at Ames Research Center presented us with some rather unusual requirements for a multicomponent force transducer. A new rotor concept that could operate at forward speeds in excess of rotational tip speed was to be tested. A good description of this high speed helicopter principle is given in ref. 1. In addition to the usual collective control and once-per-revolution cyclic control, there is a second swash plate that provides a two-per-revolution cyclic control in that speed-rpm regime where reversed velocity on the retreating blade is a problem. When operating, the two-per-revolution control cycles each blade from maximum to zero lift twice per revolution.

Since the rotor model would be remotely controlled in the tunnel and would not always be at the optimum control setting for speed and rotation rate, it was clear that large cyclic loads and vibration were to be expected; this was borne out in a preliminary test. In this earlier test the entire rotor model, including drive motor and control mechanism was mounted on a conventional Ames-designed wind tunnel balance. Figure 1 shows the model in the wind tunnel with a simple non-metric streamlined fairing covering the drive motor and control mechanism. The top spherical fairing is attached to the rotor hub. In the main test an additional balance was used to measure only the force reactions at the hub of the rotor on the shaft.



Fiqure 1. Helicopter rotor model in the 12-foot pressure tunnel.

The rotor hub balance is the subject of this paper. The balance was attached to the rotor shaft and the rotor hub was then mounted directly on the balance. The balance installation is shown in Fig. 2. Vertical thrust, shaft torque, X and Y forces, and moments about the X and Y axis were measured with the electrical signals carried through slip rings on the shaft. The reference axis, of course, rotates with the rotor.

The primary design requirement was a high natural frequency in order to get valid dynamic data and a fatigue life of 10^7 cycles at the cyclic loads expected. A four-bladed rotor turning at 1680 rpm generates a primary cyclic load of 112 Hz and a third harmonic of 336 Hz. This is the twelfth multiple of the rotational frequency. The estimated weight of the hub and blades to be supported by the balance was 34 kg (75 lb). The real problem was to design measuring elements stiff enough for the required natural frequency yet sensitive to the operating loads. All of this had to be done within a hollow cylindrical space with a 4.1 cm (1.6 in) I.D., a 7.3 cm (2.875 in) O.D. and with a length of 17.1 cm (6.75 in). Maximum expected loads were to be a steady 2.7 kN (600 lb) thrust with a dynamic component of ±1.3 kN (±300 lb), a steady .9 kN (200 lb) X or Y force with ±1.3 kN (±300 lb) dynamic component, and a maximum shaft torque of 113 m-N (1,000 in-lb).

A unique wind tunnel balance design, developed at Ames Research Center (ref. 2), was chosen to measure the rotor loads. This design, based on a hollow cylinder configuration, is both rugged and exceptionally stiff. The balance (Fig. 3) is two concentric cylinders brazed together at both ends with the inner cylinder undercut so the inner and outer cylinders are non-contacting except for the brazed areas. Slots are cut in the outer cylinder adjacent to the brazed areas to form the measuring beams. The heart of this balance is the system of eight beams located in two parallel planes

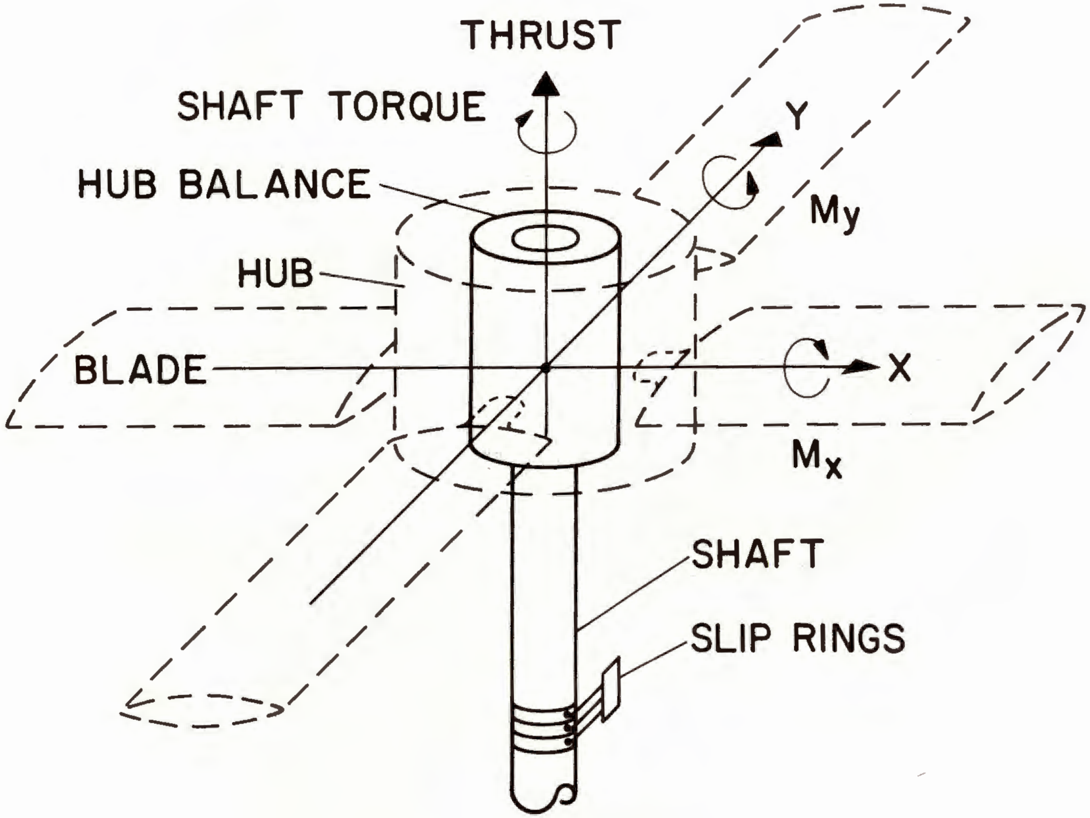


Figure 2. Rotor hub balance installation.

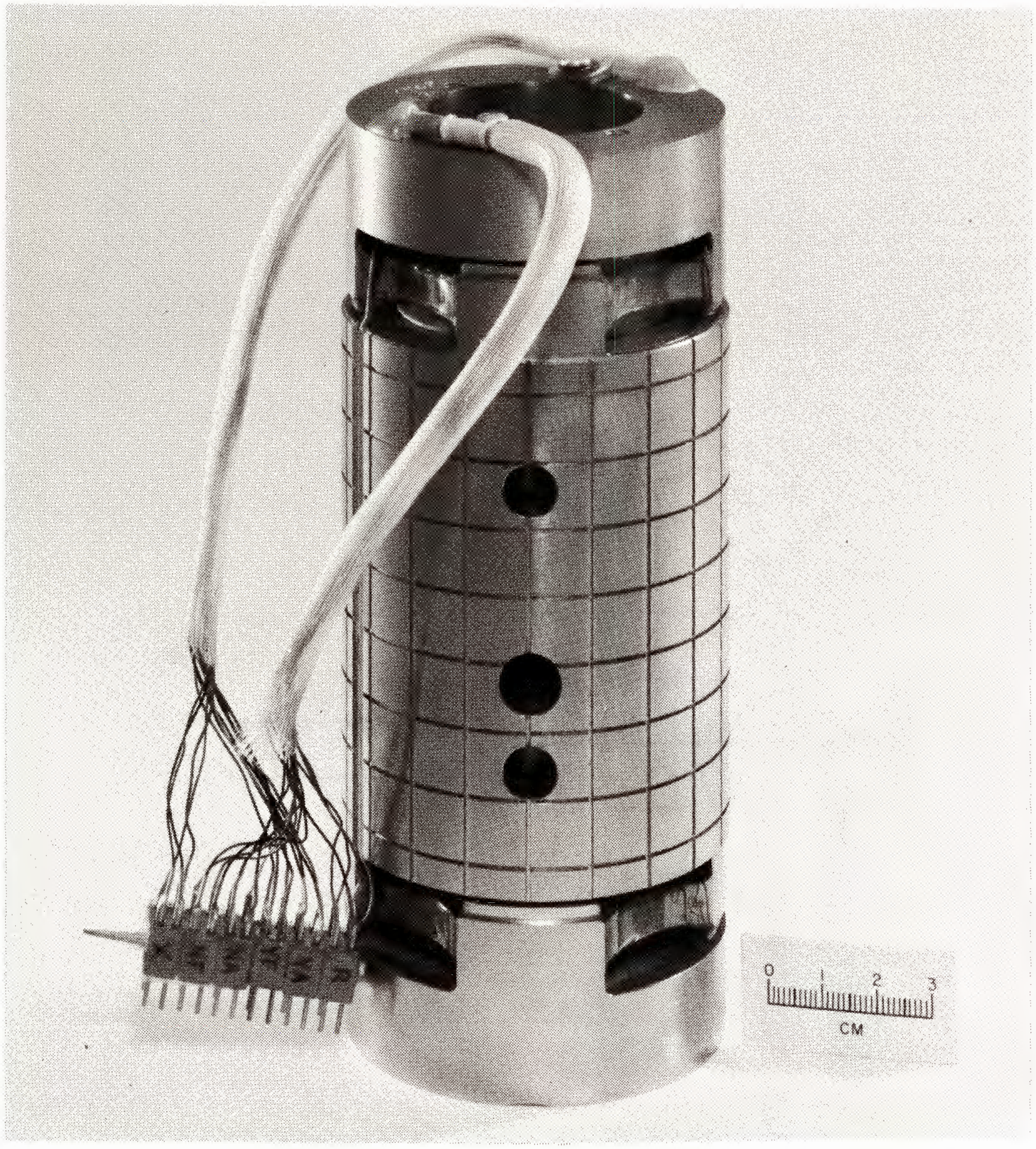


Figure 3. Rotor hub balance.

perpendicular to the longitudinal axis and gaged to measure six components of force and moment. This type of balance is called a two-plane balance. The arrangement of the beams and two cylinders is shown in the section view and cut-away in Fig. 4. The load path is from the rotor hub to the outer cylinder, then through the measuring beams to the brazed connection between outer and inner cylinder, and then to the supporting shaft. In the section view, the non-metric parts are crosshatched; note the hourglass shape of the beams. The outer surfaces of the beams were machined on a mill that used a fly cutter with the same radius as the bore of the outer cylinder. The beams act as symmetrical columns with sufficiently small center sections to measure tension and compression stresses yet preserve maximum stiffness in bending in the thrust direction. A force in the plus X direction puts Beam 2 in tension and Beam 4 in compression. Beams 1 and 3 are put in bending but the compliance ratio between the tension and bending mode of these beams is such that only 5 percent of the load is carried by the beams in bending. Beams 2 and 4 are gaged to measure the X component of force. The total X force is obtained by summing the output from the X strain gage bridges at the two measuring stations and the difference in output times the distance between stations is a measure of the moment about the Y axis. Similarly, Beams 1 and 3 are used to measure the Y force and moment about the X axis.

The two remaining force components are thrust and torque about the longitudinal axis. Both are shared equally by all eight measuring beams. A thrust force displaces the central part of the outer shell causing all eight measuring beams to bend; however, a temperature difference between inner and outer shells will also cause bending of the measuring beams due to thermal expansion. The temperature induced bending at the two stations is equal but of opposite sense and can be cancelled by installing thrust measuring strain


Figure 5. Photo of typical beam.

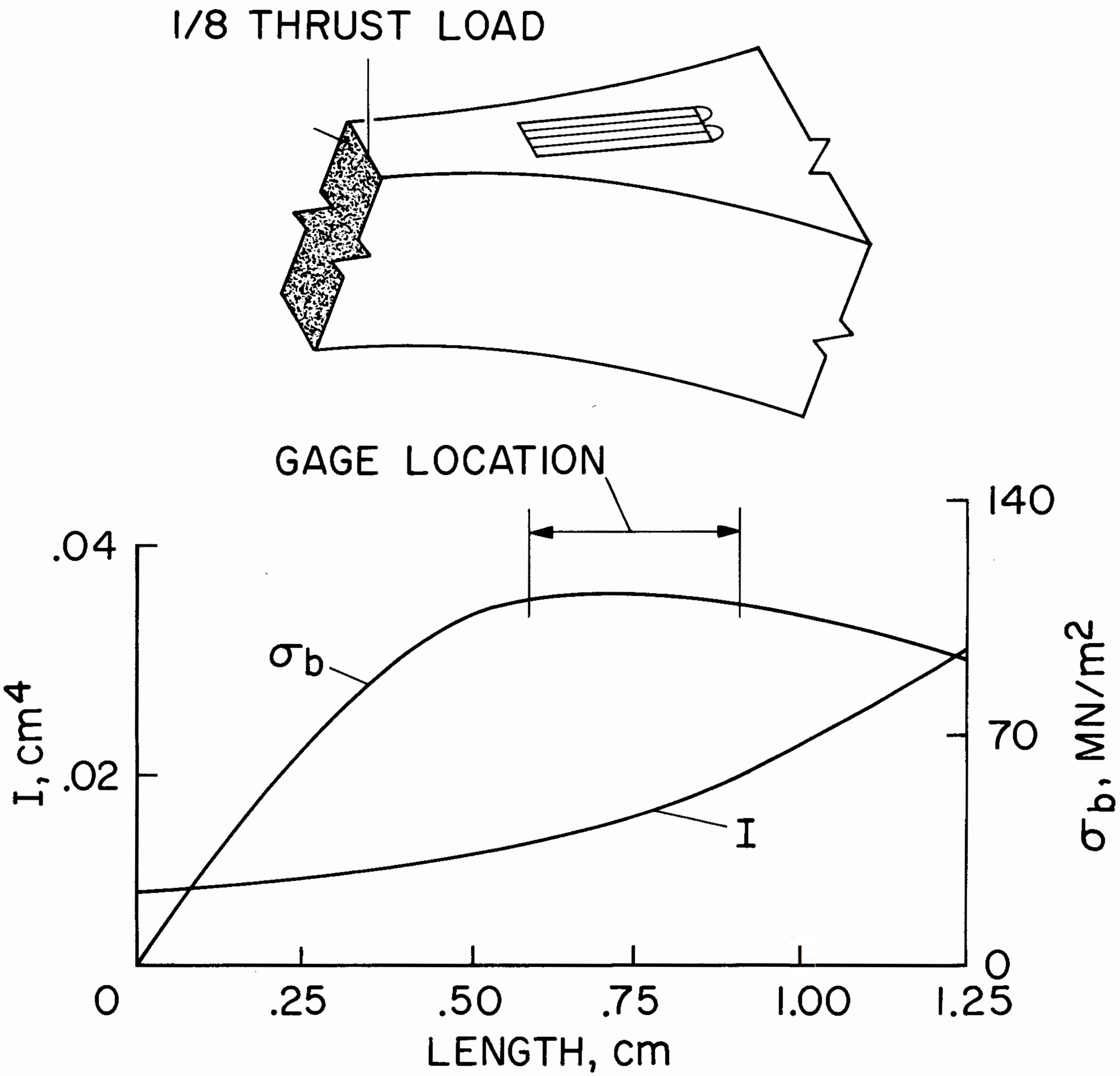


Figure 6. Thrust beam characteristics.

on an IBM 360/67 computer and a second order, least square curve fit was obtained for the primary sensitivity coefficients and for the interaction terms.

As mentioned earlier, the primary design requirement was for a high natural frequency and good fatigue characteristics. The design was compromised in that the measuring beams were stiffer with lower operating stresses than would be used on a normal six-component wind tunnel balance. The trade-off was low output with consequent loss in signal-to-noise ratio.

The most serious performance deficiency was hysteresis at about 0.3 percent of full scale. Source of the hysteresis was probably the braze joints: either a joint with less than 100 percent penetration or possibly just the inelastic property of the braze material. The hysteresis was a problem because of the poor signal-to-noise ratio. A less serious deficiency, because it was repeatable, was the non-linear output. Figure 4 shows that the projections of the outer shell, which are the supports for the measuring beams, are unsymmetrical relative to the centerline of the beams. A force in the X direction, for example, puts Beam 4 in compression and also in bending due to deflection of the eccentric end support. The low compressive stress in these beams and the hour-glass shape — which concentrated the bending stress at the center under the gages — exaggerate this second order effect. The non-linear part of the output averaged about 1.75 percent for this balance.

In conclusion, the design for the rotor hub balance was good and the balance served its purpose; however, it did not have the accuracy of a standard six-component wind tunnel balance. The calculated natural frequency of the balance-rotor system was 377 Hz; therefore, depending on damping ratio, the dynamic data should be good up to the twelfth multiple of the rotational frequency. The balance performed reliably for about 40 hours of operation in a rough wind tunnel test and survived two major model failures. In the last failure the rotor blades went into uncontrolled oscillation caused by a broken push-rod and the shaft hammered heavily against the stops causing extensive damage to the model. The only damage to the balance was the loss of electrical signal from one component.

References

1. Michael L. Yaffee: Advanced Rotor Concept Tested, *Aviation Week & Space Technology*, Aug. 5, 1974, pp. 44-46.
2. John Dimeff, Keith McFarland, Inder Chabra, and Edward L. Conley, "Characteristics of a New Type Balance for Wind-Tunnel Models," NASA TM X-1278, August 1966.

STRAIN SENSITIVITY OF PRESSURE TRANSDUCERS IN A DYNAMIC ENVIRONMENT*

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ABSTRACT

Strain error in pressure measurements is recognized as a trouble source, but seldom is it the major source of error in measurement. In experiments at the USERDA's Nevada Test Site, it has been necessary to obtain dynamic pressure data from inside pipes which are subject to an initial tensile stress of about one-half yield which changes rapidly to failure in a compressive mode.

Static and dynamic data show that representative pressure transducers are subject to strain error and that the error is not only a function of stress in the mounting, but is also dependent on the rotational position of the transducer (about its own axis) as it is ported into the pipe.

Schemes for decoupling the transducer from the pipe without seriously decreasing the burst capability of the installation have been investigated. A mounting using an annular cut-out around the transducer barrel has been devised which significantly decreases strain error and has little effect on the installation integrity or the response to dynamic gas pressure.

Work performed under the auspices of the US Energy Research and Development Administration.

INTRODUCTION

Measurements of dynamic and static pressure in line-of-sight pipes coupled to nuclear detonations are required to provide data on containment of the radioactive debris, to provide design information for future experiments, and to allow comparison with calculated behavior. Parameters other than pressure are also measured but are not within the scope of this paper. The line-of-sight pipe on which the transducers are mounted is generally the weight-bearing member for most of the experimental hardware. The strain in the pipe changes from tension before detonation to compression as the explosion generated shock-wave passes, and has been found to be the source of considerable error. We will illustrate the type of spurious pressure signals observed and outline an investigation and solution of the problem.

MEASUREMENT DESIGN BACKGROUND

Early in the containment diagnostics program, stock transducers (Figure 1A-1) were modified by removing the restricting aperture between the transducer diaphragm and the measurand. The threaded fitting was removed, and the 1.5-in. o.d. transducer case was threaded, as shown in Figure 1A-2. This considerably improved the response-time of the transducer. The 1.5-in. threaded transducers, Figures 1A-2 and 1B, become known as the "Golden Gate Bolts." As time passed, newer, generally smaller, transducer designs were fitted into the 1.5-in. diameter ports with adapters. In a number of instances, the pressure records obtained were suspect for various reasons. In several cases the output appeared to correlate with accelerometer and velocity-gauge data, but differed from normal shock sensitivity. A program of dynamic and static tests has been pursued to investigate the strain sensitivity of various pressure transducers and mounting adapters, and to formulate means of minimizing spurious data.

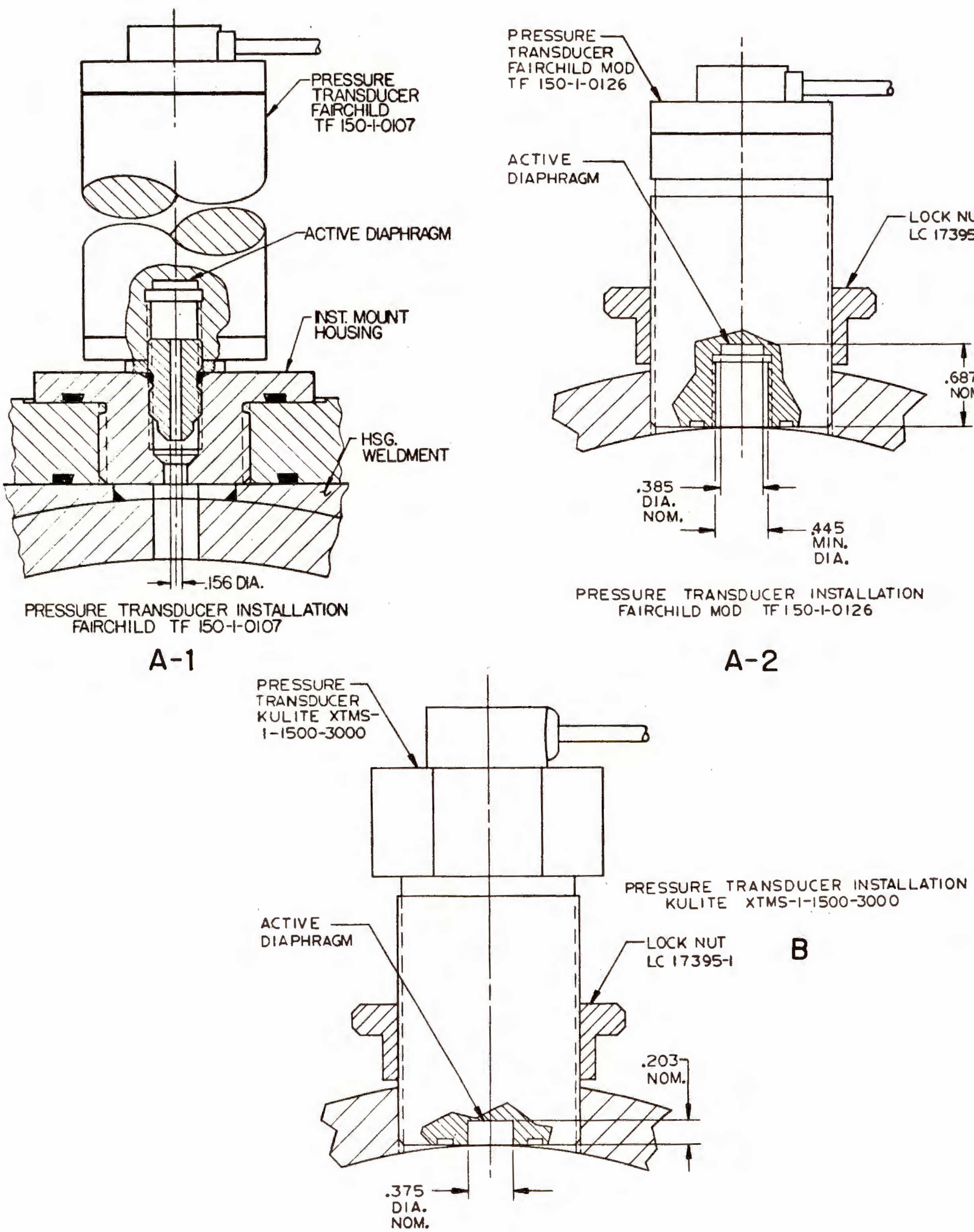
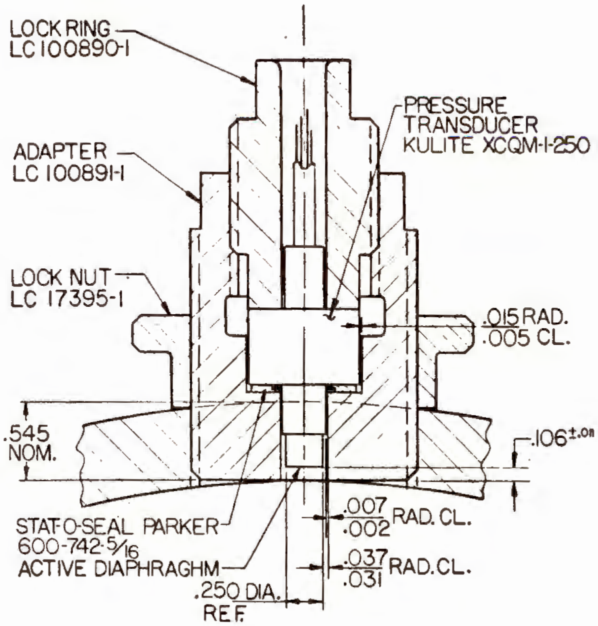
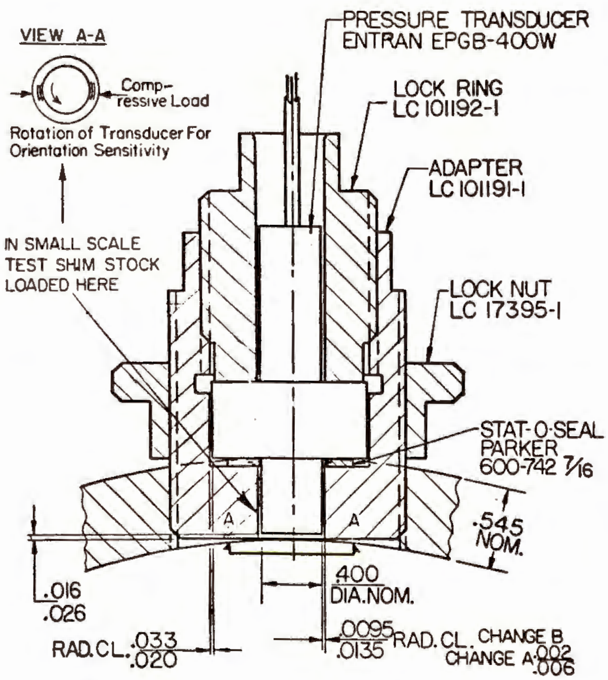


Figure 1. Pressure transducer installations.



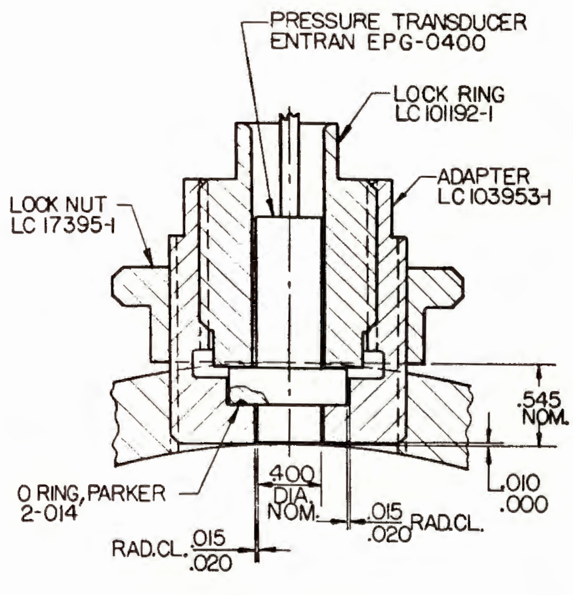
PRESSURE TRANSDUCER INSTALLATION
KULITE XCQM-1-250

C



PRESSURE TRANSDUCER INSTALLATION
ENTRAN EPGB-400WA

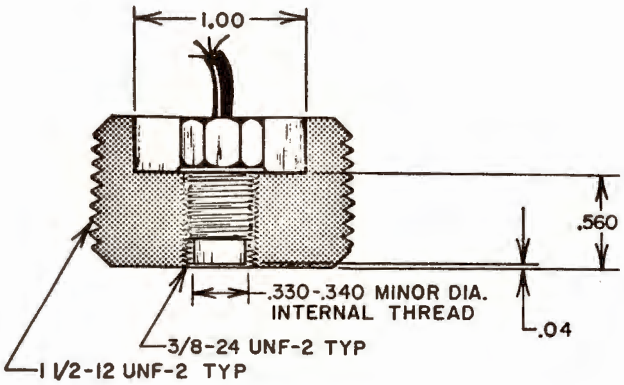
D-1



PRESSURE TRANSDUCER INSTALLATION
ENTRAN EPG-0400

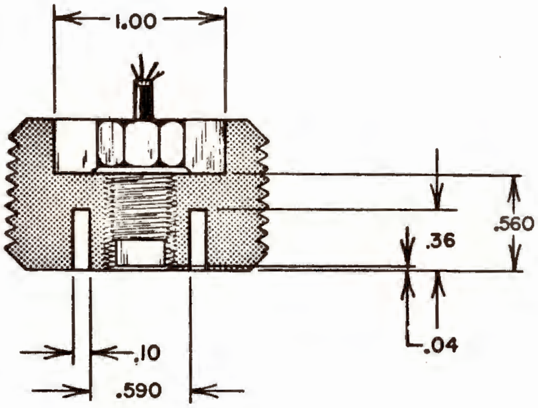
D-2

Figure 1. Pressure transducer installations (continued).



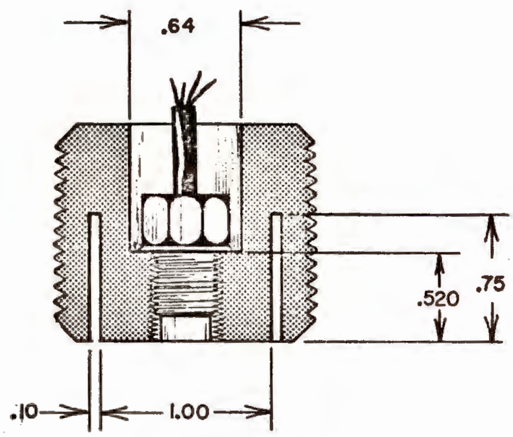
LB102677-1

E-1



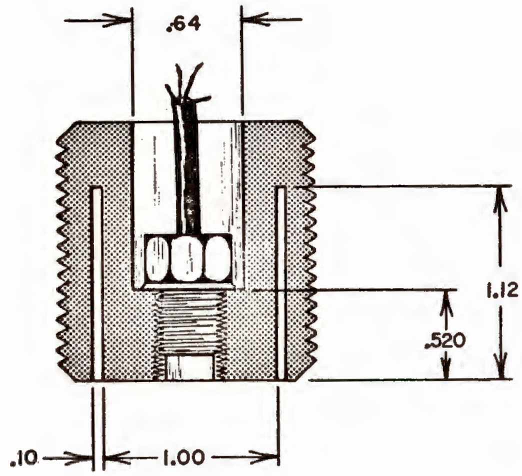
LB102677-2

E-2



LB103241-1

E-3



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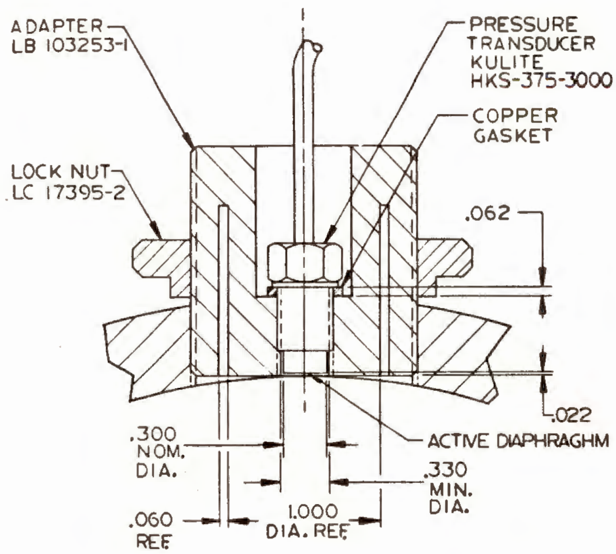
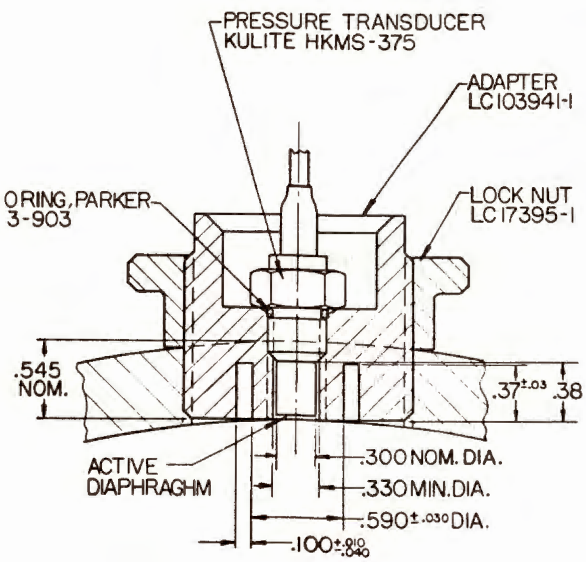
E-4

Figure 1. Pressure transducer installations (continued).



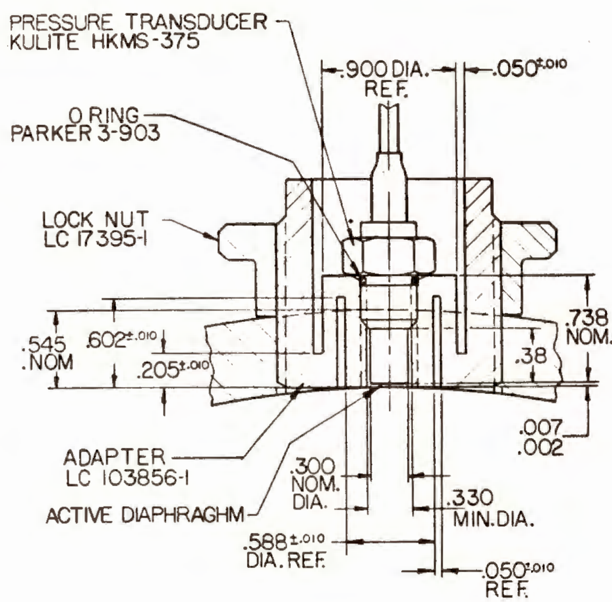
PRESSURE TRANSDUCER INSTALLATION
WITH LB-103253-1 ADAPTER
KULITE HKS-375-3000

E-4



PRESSURE TRANSDUCER INSTALLATION
KULITE HKMS-375
WITH .37 DEEP RELIEF

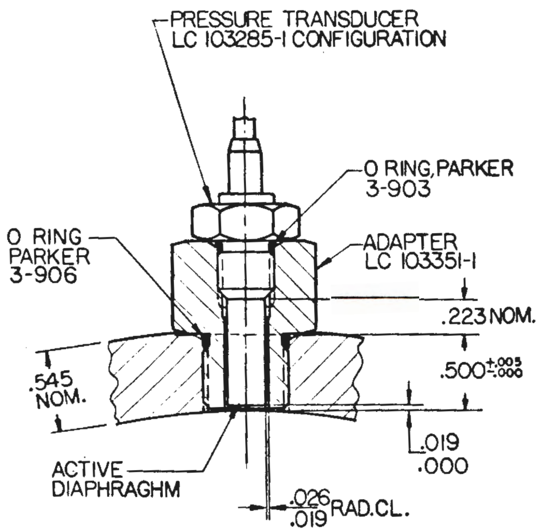
F-1



PRESSURE TRANSDUCER INSTALLATION
KULITE HKMS-375

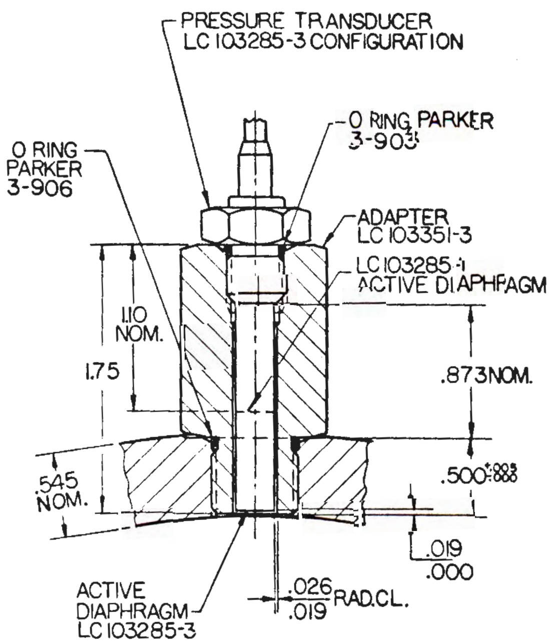
F-2

Figure 1. Pressure transducer installations (continued).



PRESSURE TRANSDUCER INSTALLATION
LC 103285-1 CONFIGURATION

G-1



PRESSURE TPRANSDUCER INSTALLATION
LC 103351-1 CONFIGURATION

G-2

Figure 1. Pressure transducer installations (continued).

DYNAMIC TEST RESULTS

Figure 2 shows the layout of instrumentation on a pipe section used for dynamic studies on two nuclear tests. In each case three pressure transducers and an axial strain-gauge were installed. Table 1 lists the transducer types for each event, and Figures 1B, 1C, and 1E-4 show cross-sections of the transducers and mounting details.

Table 1. TRANSDUCER TYPES FOR TWO NUCLEAR TESTS

Experiment Number 1

Channel	Manufacturer	Model	Range
1 PR B	Kulite	XTMS-1-1500-3000A CV*	0 - 207 Bar
1 PR C	Kulite	XCQM-1-250-1000A CC**	0 - 69 Bar
1 PR E-4	Kulite	HKS-7-375-3000A CV	0 - 207 Bar
1 SG	Micro Measurements	EA-06-250AE-350	

Experiment Number 2

Channel	Manufacturer	Model	Range
2 PR B	Kulite	XTMS-1-1500-3000A CV	0 - 207 Bar
2 PR C	Kulite	XCQM-1-250-1000A CC	0 - 69 Bar
2 PR E-4	Kulite	HKS-7-375-3000A CV	0 - 207 Bar
2 SG	Micro Measurements	EA-06-250AE-350	

**Constant voltage four-arm bridge*
***Dual constant current two-arm bridge*

Details from the first test show clearly that some designs are very susceptible to case strain.

Figure 3 shows data plots from channels 1 SG, 1 PR B, 1 PR E-4, and 1 PR C. All plots have the same time base intervals and are meant

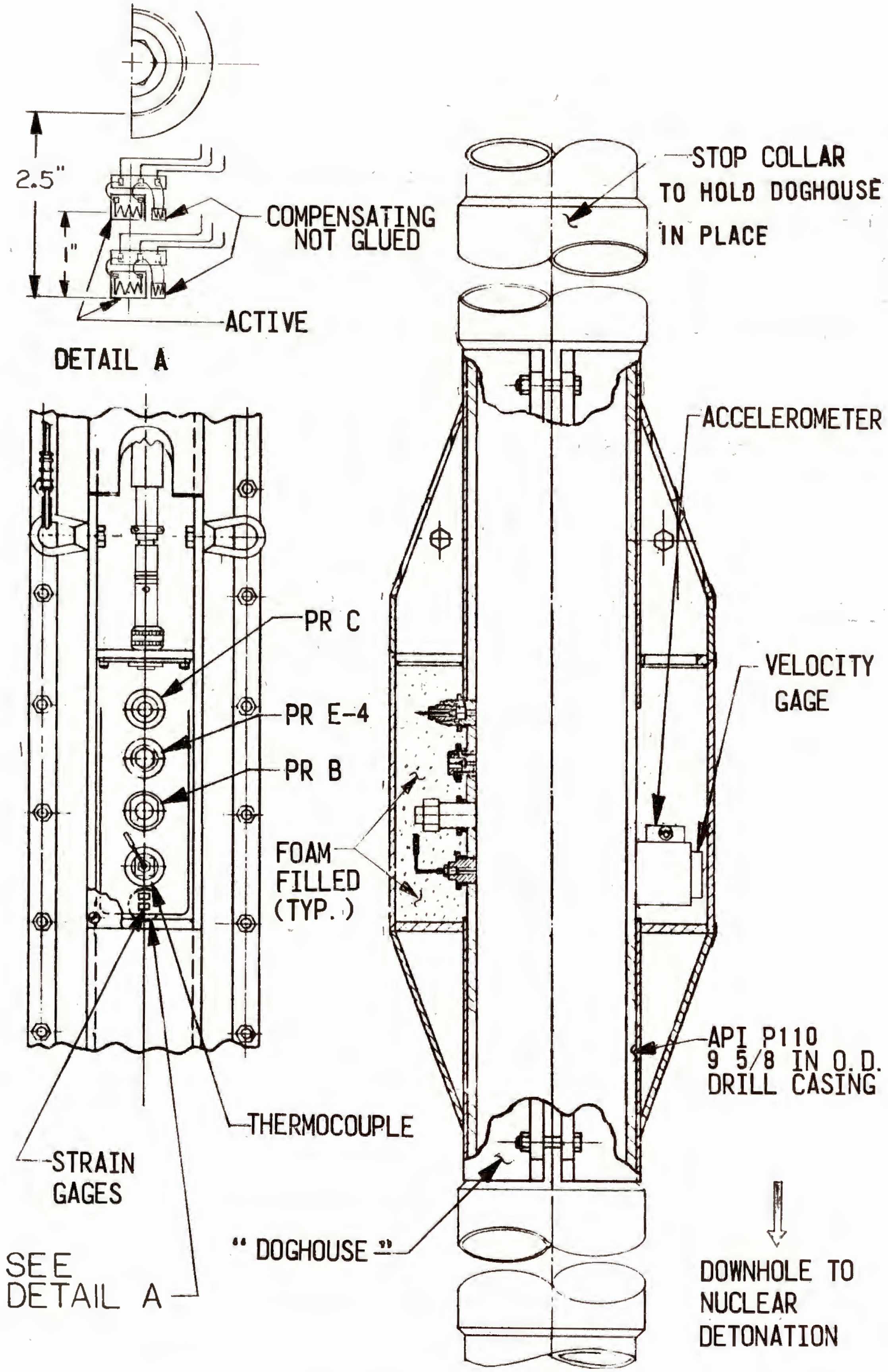


Figure 2. Instrumentation layout for pipe section.

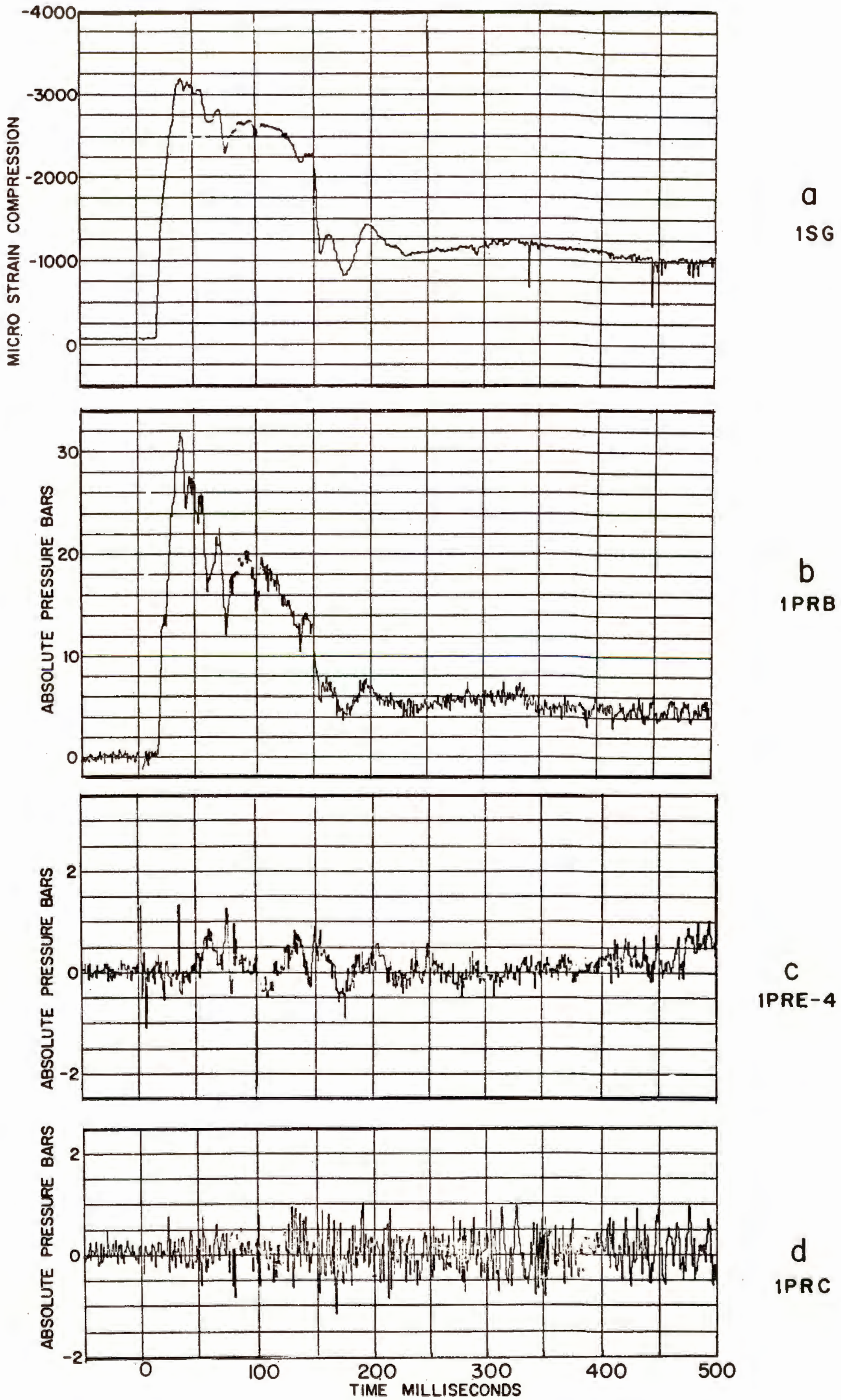


Figure 3. Test data from Nuclear Test No. 1.

to provide a means for reader comparison. The strain-gauge output (Figure 3a) shows a peak compressive strain of -3190 $\mu\varepsilon$ (relative to the pre-zero-time level) occurs at 40 milliseconds.

The signal output from channel 1 PR B is in form quite similar to the output of 1 SG. A false peak output of 32 bars was caused by coupling the pipe strain onto the active element of the pressure transducer. This transducer did not have an isolation gap and was screwed directly into the pipe. The change in residual signal output of .6 bars beyond 500 milliseconds is less than the .8 bars indicated by 1 PR E-4, as discussed below. After the transducer has been affected by high levels of strain, it is difficult to say which data are good and which are not.

Some minor strain effects are indicated by 1 PR E-4. The peak output due to strain was about .6 bars, and the output returned to the base line. The residual output not due to strain, which started at 475 milliseconds, was .8 bars. The strain effects are noticeable between 0 and 250 milliseconds. The strain effects are minor, however, considering the pipe strain present. Installation 1 PR E-4 is screwed into an adapter which has a 1.12-in. deep annular gap to provide strain isolation. The adapter is screwed directly into the pipe as shown in Figure 1E-4.

Data from installation 1 PR C indicates no effects due to pipe strain. The transducer also does not indicate the slight pressure increase that the other transducers indicate. There is no reason to believe this channel did not function (or did function, for that matter).

The Golden Gate Bolt design of 1 PR B is clearly inappropriate where-ever significant pipe strain can be expected. The strain isolation technique used on the 1 PR E-4 type of transducer worked, but should be further developed. The XCQM-type transducer and adapter system used as 1 PR C appeared to be quite insensitive to strain.

The second nuclear experiment again shows a definite correlation between pipe-strain-induced signals and transducer-strain isolation. The strain-gauge output trace is shown in part a of Figure 4. A peak compressive strain of about -445 $\mu\varepsilon$ (relative to the pre-zero-time level) occurs at 57 milliseconds and is followed by another compressive strain of about -438 $\mu\varepsilon$ at 231 milliseconds.

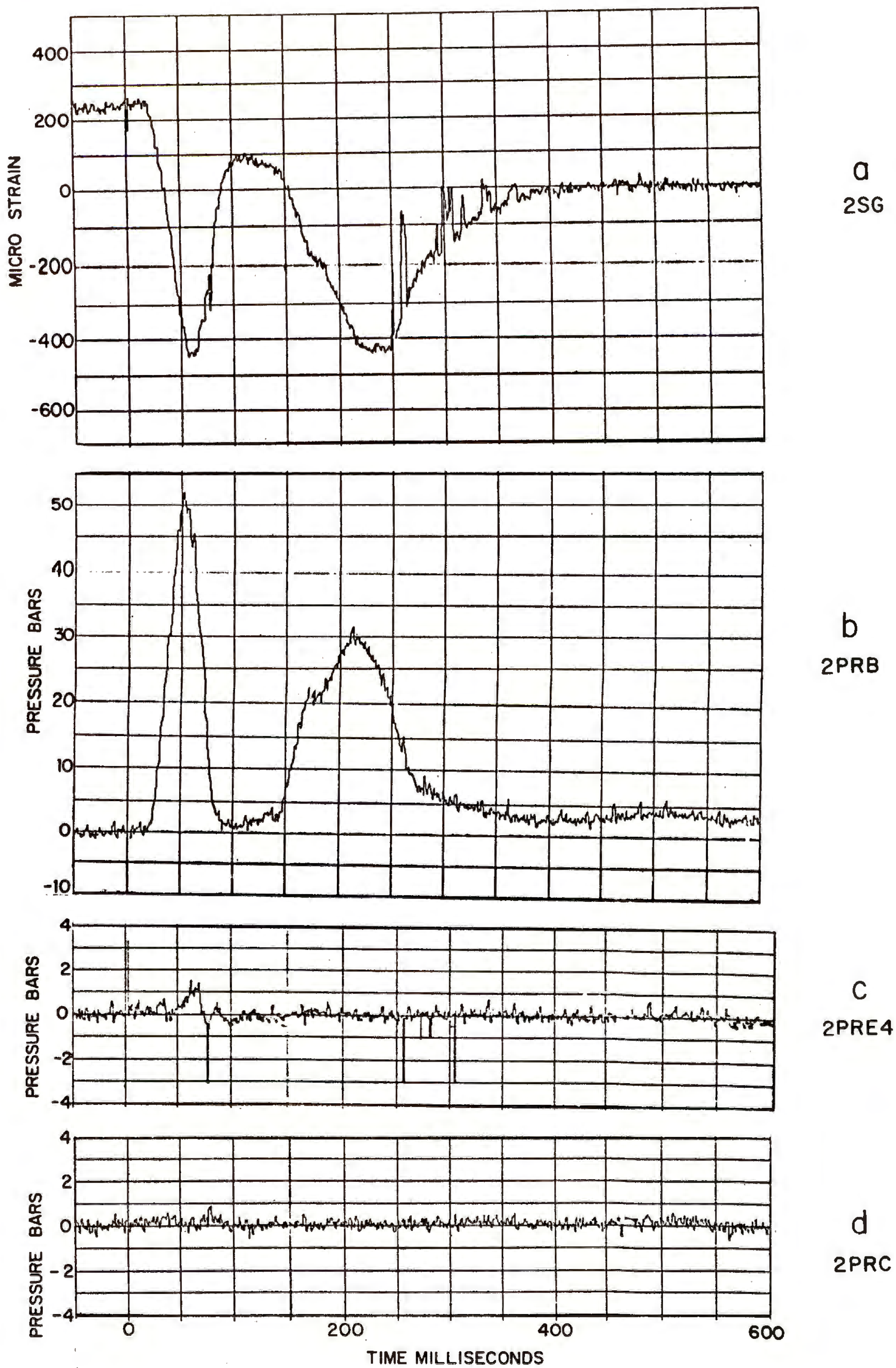


Figure 4. Test data from Nuclear Test No. 2.

Part b of Figure 4 is the output trace of the 2 PR B pressure transducer and very nearly follows the trace contours of the strain gauge. This transducer does not have an isolation gap and is screwed directly into the pipe. The output of this transducer indicates a pressure of 52 bars. This trace pulse shape is not too confusing, but the second pulse caused by the second strain is much harder to differentiate from a pressure caused pulse. Without the strain gauge data available to help with the analysis, it would be difficult to say what happened. Time, costs, and necessary data channel requirements preclude the continuous use of strain gauges to validate pressure data, so it is necessary to have the transducer elements isolated from pipe strain.

Figure 4 (part c) is the output trace of 2 PR E-4 which indicates a possible but very slight pipe strain effect of ~1.5 bars. The effect is temporary and would not normally interfere with analysis. Because the strain levels measured are much lower than normally incurred, the design will be further tested.

Figure 4 (part d) is the output trace of 2 PR C and indicates no strain effects. The XCQM transducer configuration has been specified in the past; recent transducer purchases, however, have been of the 2 PR E external configuration. Further tests are planned for the 2 PR C type of transducer adapter, although a transducer from a different vendor (Figure 1D-2) will be used to better evaluate the adapter design.

The Golden Gate Bolt-design transducer used on channel 2 PR B is very sensitive to case strain and should not be used where pipe strain is expected. The 2 PR E-4 adapter design may not be adequate to eliminate the effects of high pipe strain, hence, a new isolation concept is planned. It is important that this transducer type be effectively isolated because its use is increasing. The 2 PR C adapter worked well.

Attention will be given to the transducer-adapter installation in future experiments to further evaluate the strain isolation capability of the adapter.

Summarizing, Experiments 1 and 2 clearly point out that the Golden Gate Bolt type of transducer should not be used where pipe strain can be expected. Although magnitude and polarity depend on orientation, the strain sensitivity is still very highly independent of orientation. Data show its use should be severely restricted.

The XCQM-type transducer and adapter combinations provide the best strain isolation. Further tests of this combination are planned, but there is no reason to expect any adverse results.

The HKMS-type transducer and the isolation gap adapter provide a high level of strain isolation. The case sensitivity levels are acceptable, but further development to reduce the sensitivity is continuing.

A new adapter has been designed which will incorporate the use of the HKMS-type transducer, and will employ a high adapter isolation concept. Figure 1G-1 and 1G-2 are cross section sketches of this new design. Present plans are to squeeze-test the adapter and to field an adapter-transducer combination during the Spring of 1975.

STATIC TESTS

Small-Scale Investigation

Small-scale laboratory tests have been made by placing the 1½-in. threaded adapter (with transducer installed) between two matching drilled and tapped blocks (0.50-in. thick). These blocks were then loaded directly in compression in a 20,000-lb universal test machine. This process yielded several results.

(1) A definite case strain sensitivity in the designs shown in Figure 1B through E was found (design A was no longer available for pipe tests when squeeze testing started).

(2) A direct relationship between case load (stress) or hole deformation and case sensitive transducer output was demonstrated (see Figure 5, parts a and b). Thread clearances affect this measurement.

(3) Transducer rotational orientation relative to the direction of the compressive force was found to effect the response to case loading. Tensile effect would be from Poisson compression of the hole 90° from the principal load axis. (See Figure 6, parts a through e.) It should be

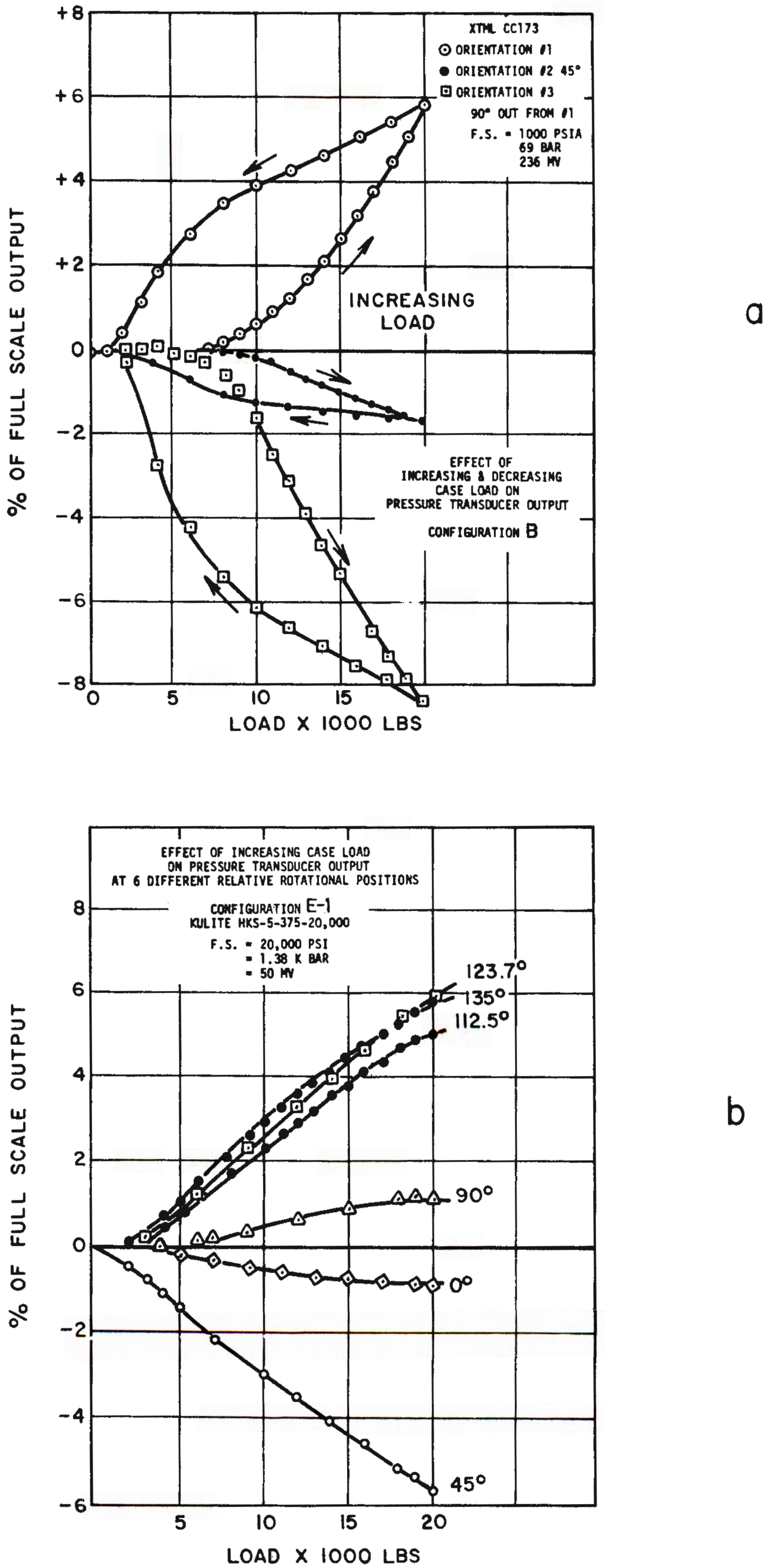
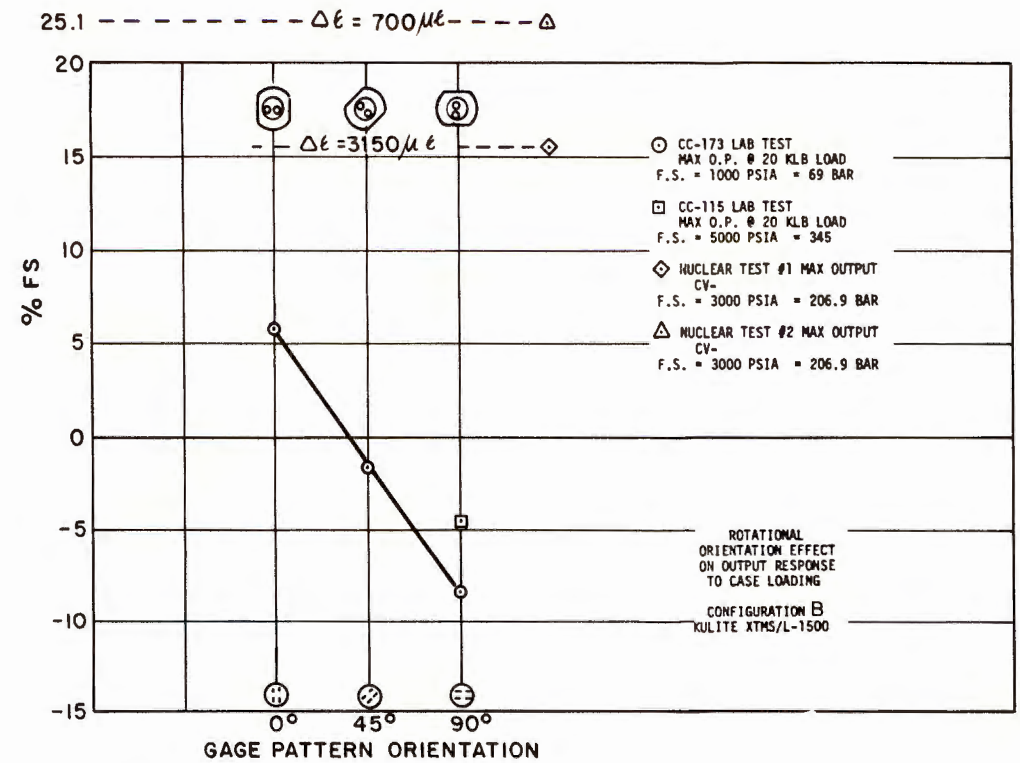
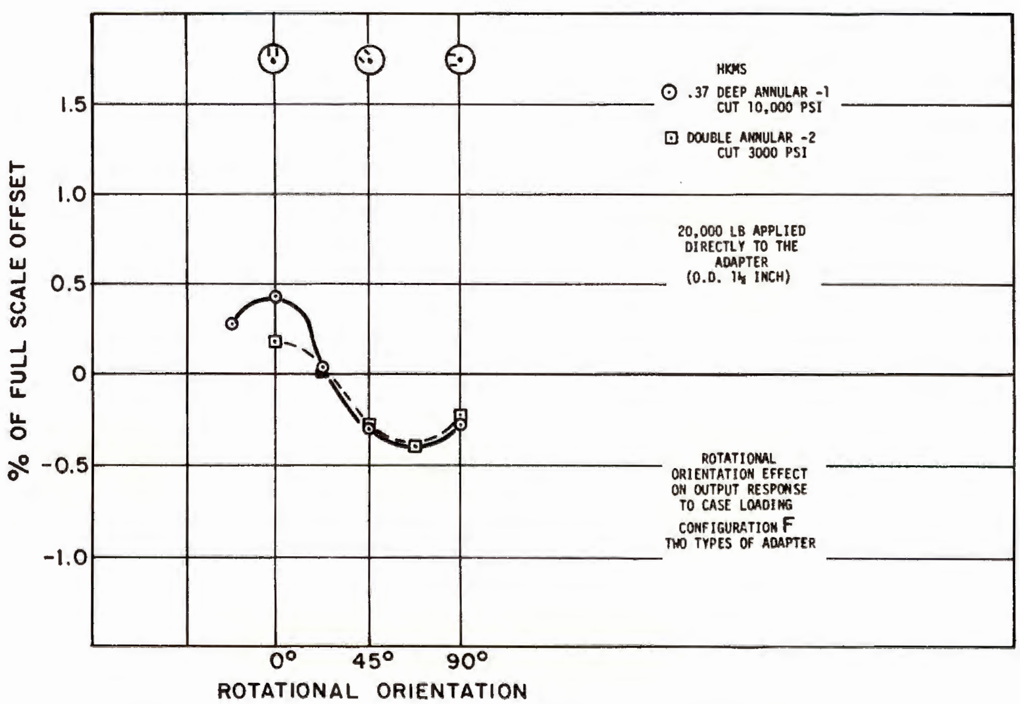


Figure 5. Effect of increasing case load on pressure transducer output.



a



b

Figure 6. Transducer rotational orientation, with respect to the direction of the compressive principal load, effect on output as a response to case loading of 20,000 lb.

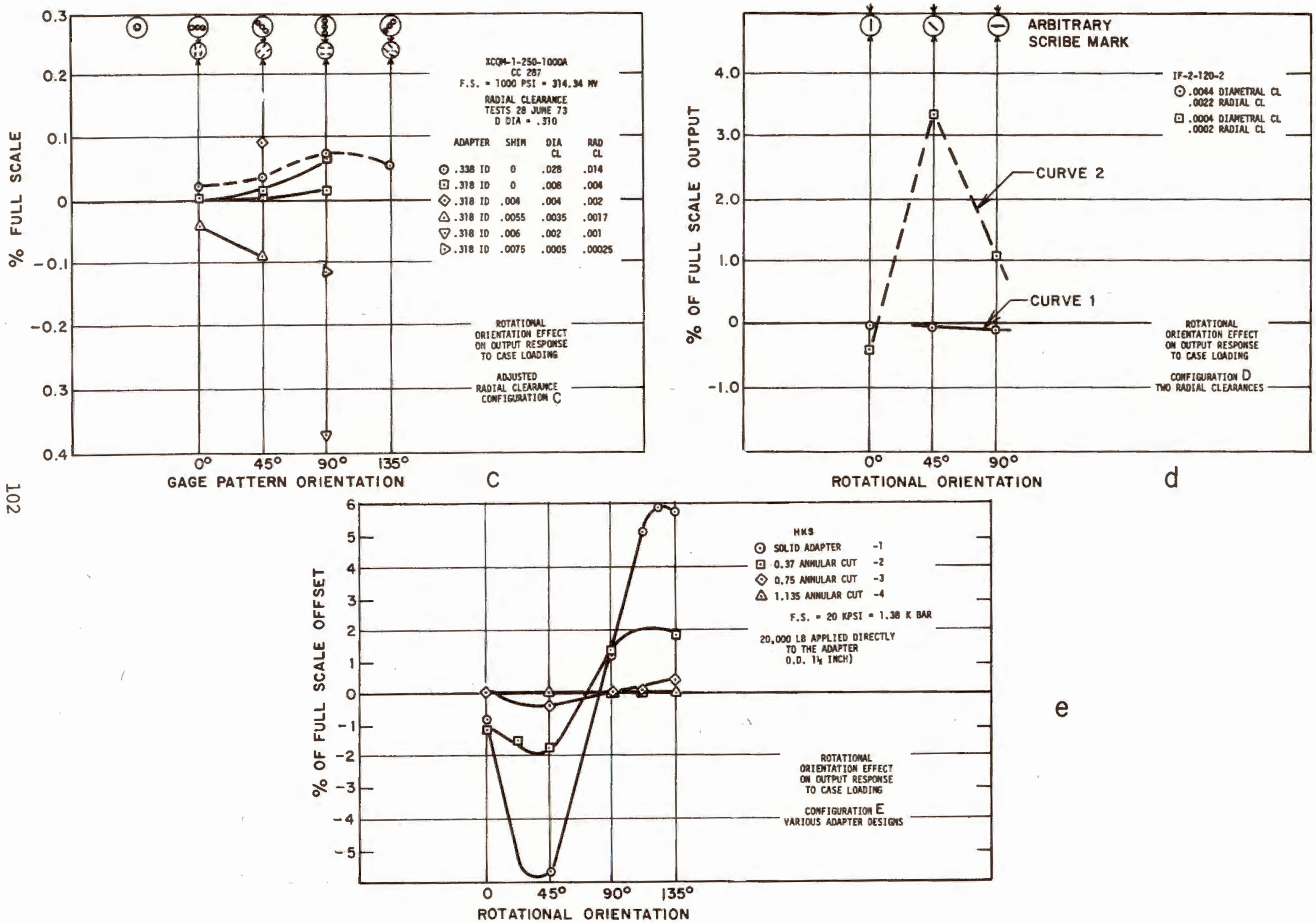


Figure 6. Transducer rotational orientation, with respect to the direction of the compressive principal load, effect on output as a response to case loading of 20,000 lb. (continued).

mentioned that "negative pressures" have been seen in nuclear test data corresponding with these small-scale data. Also note that a smaller output accompanied a larger compressive strain. A comparison of 1 PR B and 2 PR B maximum outputs is shown in Figure 6, part a. No doubt this is due to the difference in orientation of the two units, which unfortunately was not recorded.

(4) The effect of radial clearance is shown in Figure 6, part d. Curve 1 shows the outputs with 0.0022-in. radial clearance as on the nuclear experiment. The laboratory apparatus could not distort the adapter sufficiently to cause detectable output, so two pieces of .002-in. thick shim stock were inserted one on each side to help reduce the clearance around the diaphragm as shown in Figure 1D-1, view A-A. Curve 2 shows the output of the unit with 0.0002-in. radial clearance. These data indicate that: (a) the 20,000-lb machine is incapable of providing actual pipe loads on the adapter, (b) smaller diaphragms are less susceptible to case sensitivity (smaller hole deflection and stouter adapter), and (c) the 0.404-in. to 0.410-in. i.d. adapter must have deformed in the field experience at least .0044 in. on the diameter and in the laboratory at least .0004 in. on the diameter.

(5) A confirmation of the required amount of isolation as shown in Figure 6, part e (compare also Figures 1E-1 through 1E-4).

It should be noted that these tests become more ineffective as the adapters become more rigid and the diaphragms smaller as shown in Figure 6, part b. The small-scale tests indicate where a problem may exist, but they do not provide nearly the force required to test the design to field conditions.

Full-Scale Investigation

Because of the uncertainties involved in small-scale testing and study of underground nuclear experimental data, a full-scale test has been initiated using a universal test machine capable of 3×10^6-lb tension and compression.

The full-scale test is designed to answer questions on the amount of interdependence of the following design variables for guidance in new transducer/mounting designs: (1) hole diameter, (2) radial clearance, (3) vertical distance of transducer thread from stressed wall, and (4) internal transducer design.

Other questions to be answered are the following: (1) what are the strain levels that occur around holes of various size at known loads, (2) what is the amount of hole deformation under experimental conditions (during routine pull testing of the pipe, the 1½-12 UNF class 2 threaded holes yield enough to require retapping; the 9/16-UNF-18 class 3 threaded holes do not require rework), and (3) what is the amount of deformation of the adapter at the inner and outer pipe wall when under actual experimental conditions.

It is planned to install the transducer/adapter combinations shown in Figures 1B, 1C, 1D-2, 1C-2, 1E-4, 1F-1, 1F-2, 1G-1 and 1G-2 in standard 9 5/8-in., .545-in. wall AP1 P110 drill casing. These installations will be carefully arranged so that each transducer is oriented with its most strain-sensitive axis parallel with the longitudinal pipe axis.

SUMMARY

In our experience with small and large scale laboratory testing, as well as with actual underground nuclear testing, it has been shown that the best mounting strain decoupling is achieved using the "floating" principal shown in Figures 1C, 1D-1 and 1D-2. The non-threaded transducer is firmly clamped in place in an axis vertical to the planes of any stresses which could be transmitted to its case. Radial clearance must be provided, along with almost total flexibility and sealing in the plane of the major stresses.

It was found that threaded transducers require a deep annular groove (depth greater than two times the mounting thickness as shown in Figure 1E-4). In each of the designs mentioned above, the decoupling adapter is complex, and it is difficult to effect a vacuum seal at the 1½-in. thread.

The design shown in Figure 1G-1 was provided to overcome the vacuum seal problem, to upgrade the pressure capacity, and to reduce the installation cost. The smaller port design should prove to be adequate to decouple the transducer from mounting strain. Should the design shown in Figure 1G-1 be inadequate, the design in Figure 1G-2 was devised to provide additional decoupling by moving the transducer thread further from the pipe wall. This lengthening must be done with caution, however, to keep from introducing mechanical shock sensitivity and fluid dynamic effects from high flow, fast rise time pressure pulses. If the 1G-2 configuration proves inadequate, use will be made of a combination of the 9/16-in. 1G-1 type pipe port with a non-threaded transducer (such as the configuration shown in Figure 1C and 1D).

Data will be gathered through proper instrumentation of the full scale test specimen, which will help in designing effective small scale tests and ultimately in designing transducer installations for underground nuclear experiments.

The configurations discussed here can be applied to any situation in which a pressure measurement is required under conditions where mounting strains may produce erroneous data.

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
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MINIATURE PRESSURE GAGE (FOR USE IN AERODYNAMIC AND HYDRODYNAMIC RESEARCH INVESTIGATIONS)

by

Mills Dean, III
Central Instrumentation Department

ABSTRACT

A miniture pressure gage has been developed for use in aerodynamic and hydrodynamic research investigations. The gage is completely waterproofed, has a flush diaphragm, and is easily mounted. Its small size allows the gage to be placed at the actual measurement site, where full advantage may be made of its high natural frequency.

The gage is manufactured from beryllium copper alloy and consists of a main body or housing and a rear cover plate which is cemented in place. A diaphragm type strain gage is cemented to the gage's diaphragm area. A "junction box" area is created to allow the gage wires to be joined to the leads which connect the gage to external instruments. If needed the sensitivity of the gage can be easily increased by a type of lapping technique to reduce the thickness of the gage diaphragm (i.e., a gage which produces full output for an input pressure of 200 psi can be made to produce full output for a 25 psi input).

INTRODUCTION

This paper discusses the development of a miniature flush diaphragm pressure gage used in a variety of experimental hydrodynamic and aerodynamic tests at the Naval Ship Research and Development Center (NSRDC).

BACKGROUND

The development of a flush mounting pressure gage evolved from the need to measure bow and keel line pressures of ship models slamming in simulated heavy seas. Originally a number of commercial miniature pressure gages were purchased. They were very small and flat and seemed ideal for the application. However, they were not waterproof. A method of waterproofing and mounting was worked out (see Figure 1a) and used with fair success for a number of years. This method consisted of cementing the pressure gage to a small brass coupon the width of the gage. Machine or wood screw holes were located on each end of the gage. To flush mount the gage the wood hull of a ship model was carefully cut out to fit the pressure gage. The connecting lead wires were sealed where they penetrated the hull.

NEED FOR IMPROVED PRESSURE GAGE

Over several years of use, some of the failures of the original type of gage were traced to cathodic corrosion of the small interconnecting lead wires. The corrosion was due to gradual

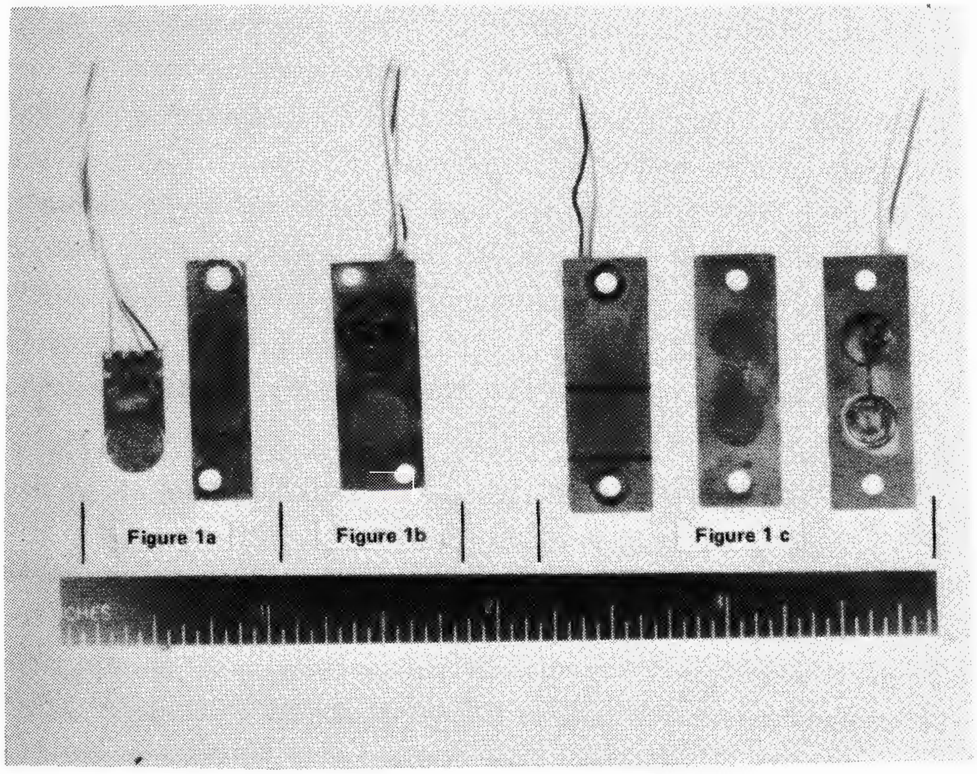


Figure 1

Figure 1a – On the Left is a Non-waterproofed Commercial Pressure Gage. Next to It Is a Brass Coupon on Which the Gage Is to be Mounted and Waterproofed.

This Combination was the Forerunner of the Bikini Gage.

Figure 1b – The Intermediate Design Pressure Gage.

Figure 1c – The Bikini Gage.

The Face of the Gage is the Third item from the right. The Two Pieces on the Right Form the Housing and Rear Cover Plate.

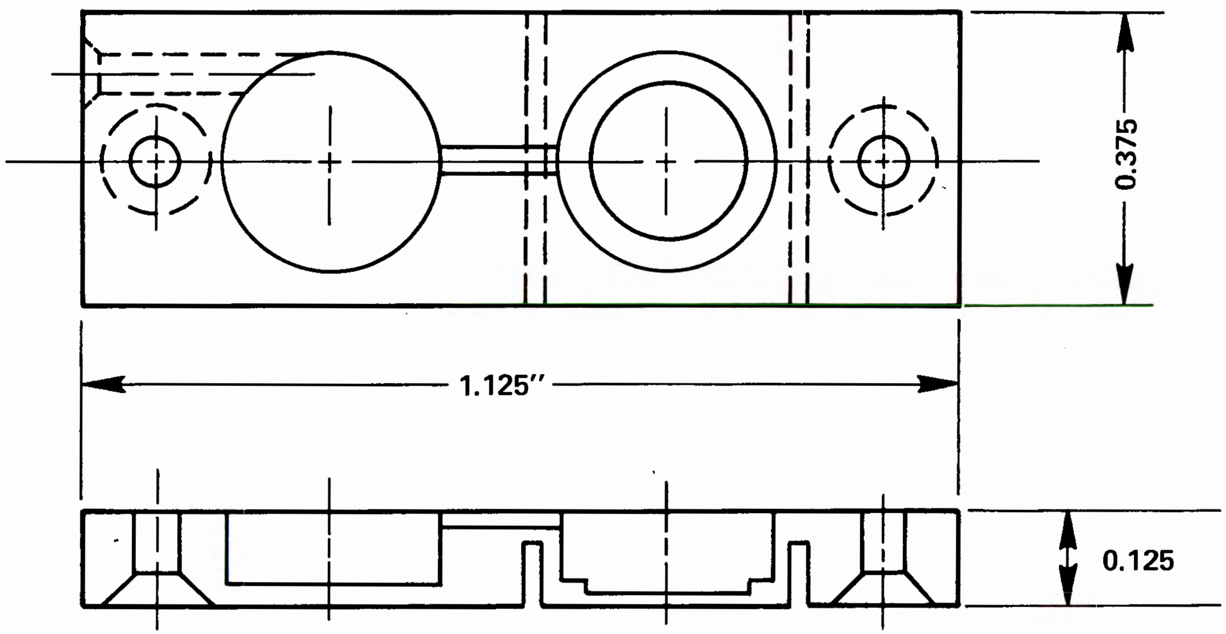
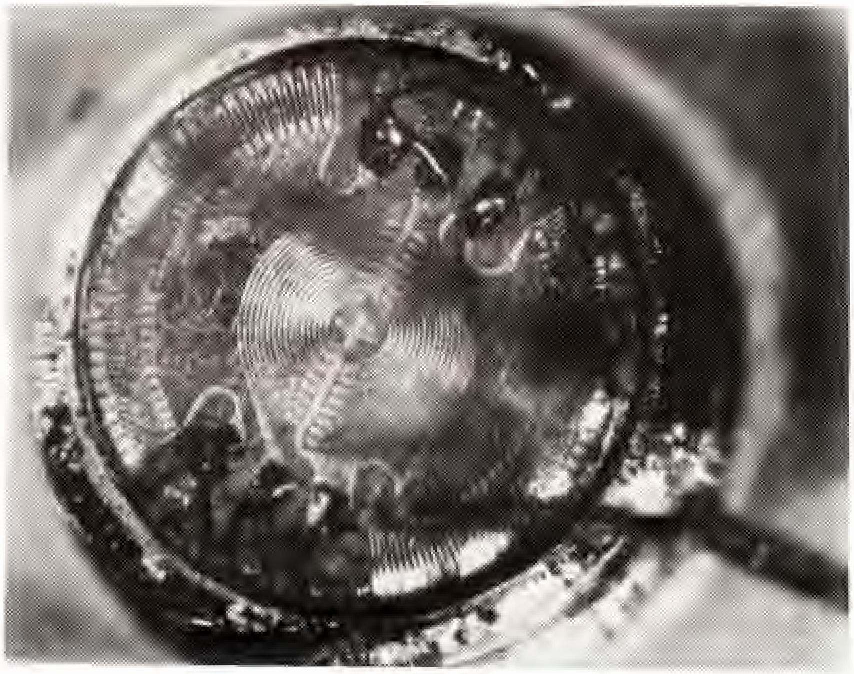


Figure 3 – Details of the Bikini Gage

(Adapted from NSRDC Engineering drawing
E-3076-1)



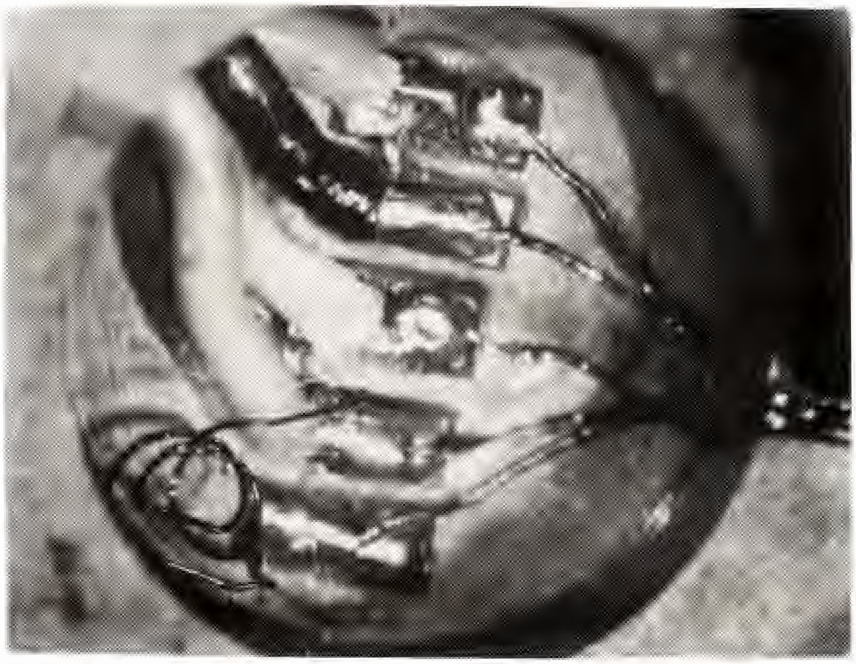


Figure 4 – The Two 1/4-Inch-Diameter Cylindrical Chambers are Pictured Here in Magnified Form

(The top photograph shows the foil strain gage elements. The lower views show the "Junction Box." The 1 mil bridge balance wires in lower left corner.)

Design variations of pressure gage housings are almost limitless. Figure 5 shows a circular housing of tapered cross section. This configuration is used for its streamlined flow characteristics.

CALIBRATION

Static calibrations show that the BIKINI gage has good linearity and repeatability. Figure 6 contains data from the calibration of six 30 psi BIKINI gages. Figure 7 shows data from the same group of gages when calibration pressures in the range 0 to −14 psig were used.

Dynamic calibration of the BIKINI gages were carried out using a Type D-142 dynamic calibrator developed by the Navy Metrology Laboratory, Pomona, Calif. This system creates a pressure step change on the face of the gage using helium gas. A 10 psi BIKINI gage has been found to have a natural frequency in the range of 10–15 kHz.

Since BIKINI gages with full scale ranges greater than 10 psi have thicker diaphragms, it is expected that these higher range gages will have natural frequencies much higher than 15 kHz. However, this could not be verified by using the D-142 calibrator, since this system has an upper frequency limit of 15 kHz.

The gage is satisfactory for ship model impact tests with a one millisecond pressure rise time.

CONCLUSIONS

The development of the BIKINI pressure gage has led to more accurate and reliable pressure measurements in aerodynamic and hydrodynamic research investigations. The features of the gage are its: compact size, light weight, moderate cost, high natural frequency, and waterproof case. Approximately 150 of these gages have been constructed during the past three years.

ACKNOWLEDGMENTS

The original development of this pressure gage was made possible through the encouragement of Aden Langford. Continuation of this work was stimulated further by Charles D. Bradley and Robert T. Schwartz. The expert calibration was conducted and data furnished by F. Edward Frillman. I am also indebted to many others at NSRDC who have helped make the BIKINI gage a success.

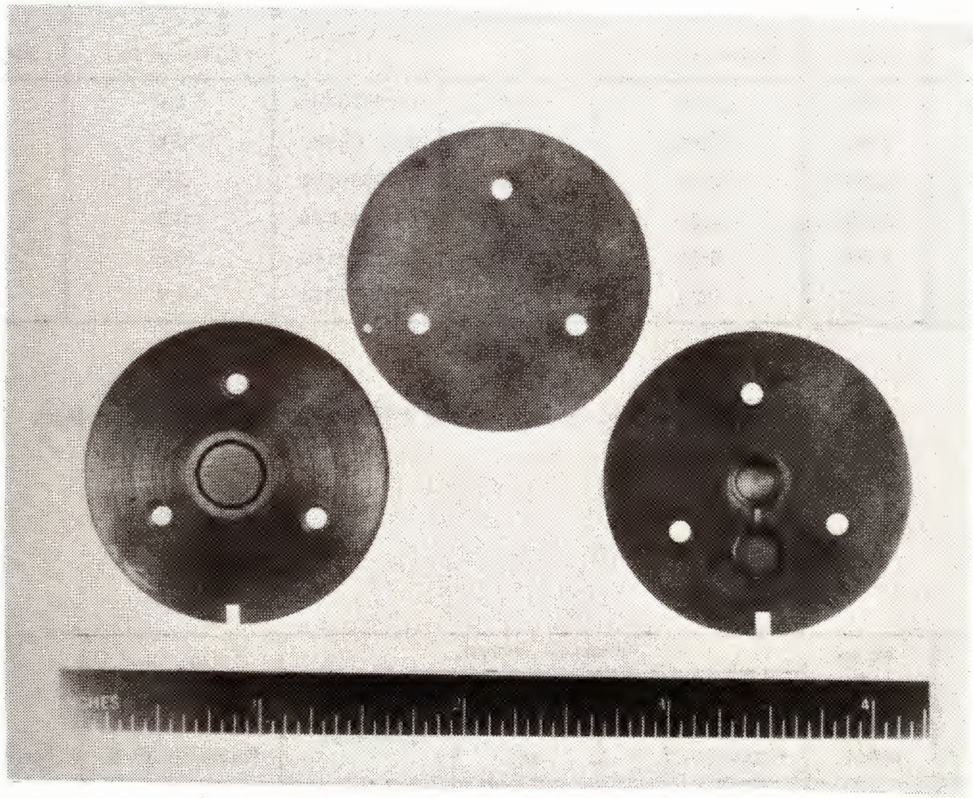


Figure 5 – Elox Machining Allows a Wide Choice of Pressure Gage Housing Designs

(On the left is the face of a tapered cross section gage. It is ¼" thick at the center and tapers to a circular feather edge. Also pictured is the rear cover plate, top center. On the right is a rear view of the chambers.)

Bikini Gage Serial	30 psi F. S. Output mV/V	Linearity Analysis			Zero Offset Percent of F. S.	Zero Shift Percent of F. S.
		Maximum Deviation Percent of F. S.	Standard Deviation psi	Correlation Coefficient		
248	2.246	0.84	0.15	0.99988290	4.4	0.4
249	2.457	0.54	0.09	0.99996343	0.4	0.0
257	2.292	0.33	0.06	0.99998154	3.5	0.5
258	2.375	0.21	0.04	0.99999149	0.2	0.1
259	2.321	0.26	0.04	0.99999149	3.5	0.6
260	2.529	0.39	0.07	0.99997740	1.7	0.6

Figure 6 – Zero to Plus Thirty PSI Bikini Gage Calibration Data

Bikini Gage Serial	−14 psi F. S. Output mV/V	Linearity Analysis			Zero Offset Percent of F. S.	Zero Shift Percent of F. S.
		Maximum Deviation Percent of F. S.	Standard Deviation psi	Correlation Coefficient		
248	−1.117	0.30	0.0249	0.99998523	10.6	0.6
249	−1.143	0.11	0.0090	0.99999805	0.8	0.7
257	−1.011	0.40	0.0329	0.99997402	6.1	0.4
258	−1.066	0.15	0.0126	0.99999620	0.0	0.5
259	−1.015	0.50	0.0443	0.99995307	7.7	0.3
260	−1.131	0.21	0.0189	0.99999148	4.6	0.5

Figure 7 – Thirty PSI Bikini Gage Calibrated from 0 to −14 PSIG

TERMS USED IN FIGURES 6 AND 7

1. Let (a) $y' = a\,x + b$ be the straight line which minimizes the mean square error between any straight line and the experimental data points (x_n, y_n).

   (b) $n = 1, \ldots, N$ and

   (c) N be the total number of data points

2. The standard deviation S_y, is defined as:

$$S_y = \sqrt{\frac{\sum_{n=1}^{N} (y'_n - y_n)^2}{N}}$$

3. The sample Correlation Coefficient:

$$\gamma = \frac{\frac{1}{N}\sum_{n=1}^{N} x_n\, y_n - \left(\frac{1}{N}\sum_{n=1}^{N} x_n\right)\left(\frac{1}{N}\sum_{n-1}^{N} y_n\right)}{\sqrt{\left[\frac{1}{N}\sum_{n=1}^{N} x_n^2 - \left(\frac{1}{N}\sum_{n=1}^{N} x_n\right)^2\right]\left[\frac{1}{N}\sum_{n=1}^{N} y_n^2 - \left(\frac{1}{N}\sum_{n=1}^{N} y_n\right)^2\right]}}$$

is a measure of the quality of the fit of the experimental points to a straight line. If all the experimental points fit a straight line $\gamma = \pm 1$.

4. Zero offset – is the electrical unbalance at zero pressure. The zero offset is expressed in percent of full-scale pressure.

5. Zero shift – is the shift between the initial zero pressure reading (before the calibration begins) and the zero pressure reading when the calibration has been completed. Zero shift is expressed in percent of full-scale pressure.

6. Maximum Deviation is determined from

$$\text{Delta } Y_{max_{1 \leq n \leq N}} = \max \left| y_n - y_n \right|$$

The maximum deviation is expressed in percent of full-scale pressure.

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SESSION I

DISCUSSION SUMMARY

Session Chairman: Henry Freynik

Papers: Bunker, Dennis and Todd, Piper, Smith, Olsen and Hatch, Dean

DISCUSSION:

Bruce Wilner, Becton, Dickinson Electronics: One question for two speakers, Mr. Bunker and Mr. Piper. Both did not indicate precisely what the required time constants were, whether they had to go down to steady state on the measurements, and how fast the response had to be on the other hand.

Robert Bunker, Kirtland AFB: First of all, on soil stress gages we have been using a charge amplifier with the device, and the time constant is around 40-60 secs. We do like to go that low, and we can calibrate the device under hydrostatic pressure.

Thomas Piper, Aerojet Nuclear Company: The upper limit on my device is about 300 Hz with the carrier frequency of 3 kHz.

Patrick Walter, Sandia Laboratories: I have a question for Mr. Bunker, Mr. Piper, Mr. Smith, and Mr. Dean, at least. Why did you become transducer manufacturers yourselves rather than pose the problem to industry?

Bunker: Basically, in looking at the piezoelectric devices that are on the market the Q is quite high. The polymer has some internal friction and some damping associated with it. It looks like the transduction element will be very inexpensive. Many people in the transducer manufacturing business are not willing to leap into a totally untried and unproven field to produce a transducer. As a result of the initial work we have done, we have started to deal with some manufacturers, and after seeing the potential, they are willing to move in that direction.

Another area oftentimes neglected is one of calibration. Starting off on our own we could incorporate in a piezoelectric device a down-hole calibration scheme using the reciprocity approach. It is possible to use another polymer bonded to the first as a driver. You can drive the sensor polymer and establish an in-situ kind of calibration. I think the idea and the principles must be addressed before you can throw a job out to the manufacturers.

Willard Smith, NASA, Ames: We at Ames do use commercial wind tunnel balances for most of our applications. Sometimes we do specialized tests that require a development program to build a balance. In this particular case I wanted to experiment with my hour-glass beam.

Thomas Piper, Aerojet Nuclear: In the case of the variable reluctance transducer (VRT) it is true there are quite a few vendors. You might have noticed in the slides that the VRT is an integral part of the transducer, and in some cases the turbine, etc., are all built in. It is very difficult to get a vendor to work with you and do the whole thing in this sort of effort. Furthermore, the VRT manufacturers had not worked out the compensation scheme that we used and which was very important to the operation of the unit.

Mills Dean, III, Naval Ship R & D Center: One reason for our in-house work is, of course, we are there. That means a lot to the test engineer. Speaking of boo-boos, about 10 years ago our hydrodynamicists decided to go to industry and get the one universal, ideal pressure gage that would make all their measurements. The contract was awarded to a west coast company to build this ideal pressure gage. To my surprise, I was invited to go along and witness the water tunnel acceptance tests, so we arrived in California, and sure enough, there was a nice little sting with a silhouette where the pressure gage was mounted, and they said, "Is there anything further before we close up the tunnel and fill it with water?" I said, "Let's just check strain direction and make sure everything is working. Just press on the diaphragm there." They said, "But you won't get any output." Dean: "But isn't it a pressure gage?" Them: "Yes." Dean: "Well, where's the diaphragm?" They said, "Oh, that's inside the annular hole." Apparently the contract had been worked up such that it did not require a flush diaphragm pressure gage. We had just bought a pressure gage that we could not use. That's another reason why we do in-house work.

John Carrico, Bendix Research Labs: Mr. Bunker, we are thinking of investigating polymer diaphragms. What sort of diameter-to-thickness ratios can you make these polymers?

Bunker: It is possible to cut the polymer in just about any diameter you like. We have been working with 2-mil to 10-mil material. It is all available. If you like a larger diameter, work with it as big as you like. The Navy is considering the possibility of using a polymer on the external surface of a submarine sonar device. It hasn't developed to that large a state yet, but at least it is one consideration that the Bureau is working on.

Carrico: I'm thinking of one application as a deflection diaphragm. What material is it again?

Bunker: Polyvinylidene fluoride. It looks like thin mylar sheets, 1-mil to 20-mils thick.

Carrico: How is it mounted?

Bunker: Epoxy bond in some cases, depending on the application. If you don't want to influence the strain sensitivity, you can use different adhesives, such as rubber cement, epoxy, etc. It does have strain sensitivity.

Carrico: You used it in the piezoelectric mode and looked at the piezoelectric phenomenon. Have you ever considered vibrating it and looking at changes in the resonance mode? (Bunker: Yes.) That would change with pressure?

Bunker: It should change with pressure, and if you had an inertial mass, it will certainly change considerably.

Carrico: Have you tried those experiments?

Bunker: We have tried this with an inertial mass, and we did run into a strain sensitivity problem. A thin, flat piece of this material, about 1 cm in diameter without any diaphragm on it has a 600 kHz natural frequency. Strain compensation is necessary. We are using two pieces of polymer that are poled and then fused together at the edges. We bond one half on the under side of a plate and the other half on the top side of the plate. Each piece of polymer is loaded with an inertial mass. The two pieces of polymer can be wired to get compensation and shear sensitivity on the diaphragm and twice the output. I might add that the applications are probably limited only by the genius of the person making the measurement, but you have to give consideration to all the factors.

Henry Freynik, Lawrence Livermore Lab: When you measure pressure in a line-of-sight pipe, what is the working fluid?

John Kalinowski, EG&G: The media immediately surrounding the nuclear explosion is vaporized to such an extent that it becomes the principal constituent of the gas. Therefore, the gases are generally vapors of silicon dioxide, water and iron. Temperature, luminosity, and ionization of the gases are also measured in addition to the pressure measurements.

Freynik: The designs you are thinking of using have progressively longer and longer cavities. Do you anticipate problems of ringing?

Melton Hatch, EG&G: We had noticed problems with the original designs, and that's why the 1-1/2 in. size is an adaptation from an old transducer where the diaphragm was located about 3/4 in. up into the transducer body and separated by a #4 AN fitting. The requirements of our measurements changed from a low speed measurement to a much higher speed measurement, so there was a lot of making do with what we had on hand. We have tested all the configurations shown in gas guns. We are just about ready to test the latest design in a gas gun to see what effects we may have from ringing due to possible resonant cavities.

Allen Diercks, Endevco: The material you are talking about sounds vaguely similar to what some people call Electrets. Can you identify the source material?

Bunker: I think this material probably does not fall in that category. I'm not the world's best expert in this line. I suggest, if you really want to identify the material and polymer chain and alignment of the dipoles, that you contact Seymour Edelman at the Bureau of Standards. I do feel he is probably most familiar with that particular material.

Diercks: We made a study of Electret materials and discovered that the sensitivity decayed relatively rapidly with time. Did you experience the same effect with your material?

Bunker: No. The material after poling does drop off slightly, but after a short period remains constant. It has been observed over a period of a year or so and it is constant over that period of time.

Terry Trumble, Wright-Patterson AFB: About 2-1/2 years ago we had a contract with Seymour Edelman to develop piezoelectric sensors. There will be a report forthcoming and will be available for the attendees as soon as released by NBS. Edelman did a tremendous amount of work on that particular material which turned out to be the most stable. He was able to stabilize it to 450°F without any appreciable change in properties. We developed the material for the purpose of fire detection. We found out that it was an extremely fine piezoelectric device. It was very sensitive to the opening and closing of doors, so we had to hermetically seal the device. Anyone interested in the report can send me his name and I will send him a copy.

Wilner: On the frequency response of your small sensors you said that these sensors had been tested in a helium shock tube or shock tube equivalent. Isn't that going to be wildly different than the frequency response in a water environment where the water loads the diaphragm?

Dean: About a factor of three different. The hydrodynamicists feel that in slamming studies it is really an air block on the hull, not so much water.

Wilner: Of course with a lot of white water you're getting more into measurements on white water, which is a complete mix.

Dean: You're looking at foam.

Wilner: Those are complex problems.

Dean: Yes, it does alter the characteristics, but I don't know anyone who has built a calibrator. Paul Lederer, do you know of anyone who has tried to calibrate the gage in the mix? (Lederer: No.)

Freynik: I have a question for Bert Dennis on the actual temperature measurement. I had an opportunity to read your paper, and you push a thermister against the bottom of the hole. You had rather long time constants of hours, and I was wondering how the heat was conducted into the thermister. Were you losing heat down the thermister leads? How did you get the thermister up to the temperature of the rock? Did you depend on conduction from the rock at the tip? Or did you have a convection process going on from the sides of the hole that heat up several feet of the length of the probe?

Bert Dennis, Los Alamos Scientific Laboratory: We designed the probe initially to put the thermister in as intimate contact with the rock surface as possible. We did use a little foil that pressed on the core stub. This core stub stuck up 10 cm off the bottom of the hole. The hole bottom is the least thermally disturbed area during the drilling phase. Before the temperature measurement was made we circulated water in the hole for one hour to get rid of drilling chips and sediments on the bottom. We found that sometimes it would take 30 hours after starting the measurement before we could extrapolate a good temperature off the rock.

Walter: I have a question on strain sensitivity of pressure transducers. There is a strain sensitivity test for accelerometers, and there is always a question of what it really means or how it equates to the real world, but at least there is a comparison there that manufacturers can specify to. We have no such thing for strain gage transducers, although there are indications that some designs are much more sensitive than others. I would be interested in comments on this subject.

Lederer: The base strain sensitivity test in ISA standards refers to piezoelectric accelerometers, not strain gage accelerometers. We have not done anything on strain sensitivity in regard to strain gage based pressure or acceleration transducers. It never really occurred to any of us or to the people we are dealing with that there was really a problem. Steve Rogero, any comment? (Rogero: No.)

Peter Stein, Arizona State University: I think that the work done by the group Mr. Hatch represents is perhaps more significant than it might appear. If strains in the pipe are apparently reflected in changes in diaphragm strain, the calibration of the transducer should also change. Have you done any work on that? It wouldn't really much matter if it were a piezoelectric transducer or a resistance strain gage transducer. Both would be strain sensitive but by different amounts. We ran across similar problems for vibration sensitivity of pressure transducers sometime ago.

We have always buried a transducer next to the one doing the measuring, but only part way through the pipe wall, simply as a record to find out whether or not we were recording something extraneous to the problem. In your case limited channel capacity will not let you do that. I think the strain relief annulus is a simple, ingenious type of solution that really ought to be sold as an accessory to all pressure transducers for measurements in environments where large strains are present.

Hatch: The adapter incorporating the annular groove is rather expensive. In our case anything put down-hole is a one-shot deal, so the expense is of some importance. As Pete Stein mentioned, the solution of putting strain gages on the pipe next to every transducer is something we can't do everytime because of wire-cost and channel-cost consideration. I think in any test design one has to evaluate the total situation to be sure you are not picking up some undesired signals. In our case we have to be careful that we don't get any resonance frequencies due to the annular groove or any extraneous problems due to a shock coming off the edge of that groove.

This is both a static and a dynamic pressure measurement we are attempting to do here. Therefore, we do shock tube testing of the transducer installation. I favor the floating design somewhat over the annular groove. The cost of the adapter with a deep annular groove is around \$50-\$70. The cost of the floating adapter is about \$50-\$70 also because it is in two pieces. The cheaper version of the floating adapter, the last one shown, cost about \$5 in production.

Richard Taylor, Wright Patterson AFB: Mr. Dean, is your pressure transducer a strain gage type in a bridge configuration?

Dean: Yes, it is a standard gage made by Micro Measurements. BLH has a comparable unit with four active arms designed to pick up the highest bending moments of diaphragm deflection. We use the smallest gage made that has a four-arm Wheatstone bridge. I have a sample here.

Joseph Dolis, General Electric: In your presentation you talked extensively about temperature environments of 160-250°C. What was the pressure environment at those levels?

Dennis: The hydrostatic pressure was 1200 psi at 6700 feet. To initiate fracture in the rock, we pressurize an additional 2000 psi. Once fracture was initiated we could reopen the fracture with a pressure of about 1800 psi.

Fuselier, Lawrence Livermore Laboratory: Were the different components of the balance read out as single active gages or completed as full bridge?

Smith: All four legs were complete bridges.

Fuselier: Is that kind of instrumentation called a sting balance?

Smith: It is a variation, but looks very much like a sting balance. This particular design could be used in several ways. In this case it really wasn't a sting balance. It went over a shaft rather than mounting on the end of a sting.

Fuselier: Is it called a sting balance because it mounts on a projection into the wind tunnel air stream?

Smith: The sting is mounted typically on supersonic airplane models. The model of this particular jet airplane has a tail pipe hole. It is very convenient to mount the model with the sting extending into the tail pipe. The balance rotates on the end of the sting, and you have a valid aerodynamic model with no strut interference.

Fuselier: Three questions I'll ask all at once. Are the transducers still being manufactured in-house or by a commercial supplier? The other two: How do you calibrate transducers basically and also for temperature effects?

Piper: We are still manufacturing transducers in-house. It has been a very short period of time since we started. Usually we start looking for vendors as soon as we see that there is a fairly sizeable quantity requirement. Commercial vendors are not likely to become involved in small requirements. I guess the question centers on whether we could implement a commercial vendor's VRT into this fairly distinct type of instrument. Making the leads integral is fairly difficult to do. The vendor would have to do the whole job and for a limited quantity that's not likely.

The actual calibration of drag disks is done in-place where they are used in experiments. We usually know the flow path in the steady state and we make velocity-versus-output recordings and also drift-down measurements in the flow to see that operation is normal and to get zero offset in output versus flow. Temperature sensitivity is tested before delivery to the customer. The unit is mounted in the top of an autoclave, subjected to the 2200 psi pressure, brought up to 650°F and the output observed. If anything abnormal is seen, the unit would be rebuilt or the trouble found and corrected.

I didn't get a chance to state the results we achieved with this unit. We had the sensitivity remain constant from room temperature to 650°F within 1.8% of full scale or 0.003%/°F. Zero null remained fixed within ± 0.5% of full scale in the same temperature range. The unit withstood plunging it from 650°F into 70°F water with a ± 3% of full-scale output occurring during this extreme shock.

Stein to Hatch: Have you tried to calibrate the transducer as it is being squeezed in the test fixture?

Hatch: No, we haven't done that. The only thing I can say is that I assume the transducer has been compromised. You can never tell because some transducers in some orientations in the pipe produce no response from the squeezing. That doesn't mean that the diaphragm hasn't been affected in some way such that it does not respond to pressure as it normally would.

Bunker: I have a question about the application of your transducer in that environment. The question is associated with the content of the thing you're trying to measure. Is it possible that you have a loading of the diaphragm with other than a gas? That is, the density of the material could run from dust particles to fiberized iron or whatever. What does that pressure represent when you read it?

Hatch: First of all, the pressures are side-wall pressures. We can't get into looking at total or stagnation pressures. In all cases, as far as we know, they are all gas pressures. John, would you like to make any comments on that?

Kalinowski: We usually are talking about natural gases such as carbon monoxide and carbon dioxide. The iron fibers normally stay high enough up in a region where those fibers are cooled down and we don't have a deposition problem on the diaphragm. We do use shields to help protect from debris of any sort impinging on the diaphragm. As Mel mentioned, we are in a side wall and recessed 0.02 inch so we don't get any reflection into the diaphragm. So you can say we are working from a low density to a not too high density of material.

We use other types of instrumentation--ion gages and others--to tell us what the gas is and whether it is in an ionized or a plasma state. We use thermocouples to tell us the temperature. We use photocells to tell us the luminosity to compare that with temperature. So we have a good idea what the gas looks like and what it is, but we usually stay up in a region where we don't have to worry about direct device debris.

Phil Coleman, Systems, Science and Software: Have you observed any zero-shift in polymers?

Bunker: No. Basically, if you dc coupled and if you looked at long time constants, you should be able to see that sort of effect. In the applications we have made we didn't observe measurable changes in dc output. Considering that the time constants are in the period of 40-60 secs, we did fairly well.

Coleman: What was the level, 10% or 1%?

Bunker: It is difficult for me to put a number on that, but I would say within a few percent.

Darrel Harting, Boeing Aerospace, to Dennis: Have you made enough measurements to conclude what the lifetime of power stations might be?

Dennis: As I mentioned when I showed the slide of the LASL concept, theoretically cooling of the rock near the injection well would set up thermal stresses and crack the rock perpetually. The cracks would extend into the formation of deeper and hotter rock. If this is the case, then a thermal well will last 100 years. If thermal stress cracking does not take place, life of the well will probably be 20 years. One feature I might point out is that if the well had a 20-year life, it would be relatively simple to move to the other side of the power plant and sink another well and continue operation with the same surface facility. Then, by the time the second well had cooled down to where it was inefficient, you could go back to the original well which would have heated up again during the 20-year rest period.

Eldine Cole, Kaman Sciences: What useful range of stress levels do you anticipate that your devices are good for?

Bunker: When we observed strain sensitivity of the material, we had it fastened to a diaphragm. The diaphragm had a sensitive area about 3 in. in diameter. We were looking at bending of the diaphragm. I don't recall exactly the numbers to use. I think it was about 40 microin. of deflection per 1000 psi being applied. You will have to convert that yourself.

Freynik: I would like to ask Willard Smith to discuss the metal selected for his balance--why he chose that particular metal and how he machines and heat treats it.

Smith: We used 15-5 stainless steel for the metal. We chose it because it has good elastic properties and a simple heat treatment that is essentially distortion free. It is interesting you should ask about heat treatment. This particular balance is brazed together so that it acts like a solid balance. That theoretically eliminates the hysteresis you would get in a compound balance with mechanical joints. We didn't quite eliminate hysteresis in this balance. The purpose of the brazing was to eliminate any mechanical motion. Heat treatment and brazing were done in one operation. We nickel plated areas to be brazed, used a copper braze, brought the balance to 1900°F braze temperature (this also anneals 15-5), cooled to room temperature, then brought it back to 900°F for 1 hour, then cooled to room temperature. This H-900 heat treatment produces 180,000 psi yield strength. It was a very simple, neat, combined heat treatment and braze.

Wilner: What is the response of your balance to thermal gradients? It is a couple of inches long, and the heat source and sinks are separated. How does it respond to heating in the middle and cooling on the outside surfaces?

Smith: That is a good question and an astute observation. The way the strain gage bridges are hooked up we have to have pairs of gages on opposite sides of the balance. Fortunately, there is axial symmetry in the balance so we don't need to consider gradients across the balance. There very well may be a temperature gradient where the inner cylinder and outer cylinder could be at different temperatures. That should not affect X or Y output nor should it affect shaft torque output. It would directly affect the thrust output. We gaged both measuring stations, then we added the two outputs in parallel. The thermal gradient effect on one bridge at one measuring station would be equal and opposite to the thermal gradient effect on the other measuring station. Therefore the signal would cancel.

Howard Grant, Pratt and Whitney Aircraft: What was the purpose of the soil stress measurement you were making?

Bunker: In the testing work that we are doing we are trying to simulate nuclear environments with high explosives to test missile systems. It is necessary to know the stress-strain relationships that occur under dynamic conditions. We also measure ground motion accelerations and velocities.

The session concluded with the reading of selected boo-boos and an anecdote from the magazine "Sound and Vibration" editorial.

SESSION II

TRANSDUCER MEASURING SYSTEMS AND THEIR CALIBRATION

Garland Rollins, Chairman

FUEL-AIR EXPLOSIVE BLAST MEASUREMENT

Larry H. Josephson

Naval Weapons Center
China Lake, CA

Abstract

During the development of Fuel-Air Explosive (FAE) weapons, it is necessary to measure their blast output in order to evaluate their effectiveness and to determine the influence of design changes. A brief description of the FAE blast environment is given and the requirements this places on the measuring system in order to obtain adequate data for weapon development. The system that has evolved at the Naval Weapons Center for measuring FAE blast is described. The topics covered include transducer selection, transducer mounts and signal conditioning. Some of the problems that have been encountered over the years are discussed as well as the solutions that have been implemented.

A new blast arena has been installed on one of the aircraft ranges in order to measure the blast performance of FAE weapons under realistic operational conditions. The incorporation of design features based on previous experience are discussed.

FUEL-AIR EXPLOSIVE BLAST MEASUREMENT

by

Larry H. Josephson
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Introduction

The use of Fuel-Air Explosives (FAE) in free air is a relatively recent development. A distinction needs to be made between an explosion caused by the ignition of a flammable fuel-air mixture in a confined space and a free air FAE. Most accidental fuel-air explosions are deflagrations, although they may accelerate to a detonation under proper conditions of confinement. FAE, as defined here, is a reaction that is initiated as a detonation and the detonation propagates throughout the fuel-air mixture. Because the reaction is initiated as a detonation, confinement is not required and operation in free air is feasible. This mechanism has been weaponized.

In order to evaluate the effectiveness of FAE weapons it is necessary to measure the blast overpressures both inside the detonating fuel-air mixture and in the blast decay region outside the detonable region. The FAE weapons currently under development or already in the inventory all rely on explosive dispersion of a liquid hydrocarbon fuel to form the fuel-air mixture. As a result of this process most of the fuel is still in the liquid phase rather than the vapor phase and the fuel-air mixture that is detonated is actually an aerosol of fuel droplets in air. Detonation of this aerosol cloud is initiated by a separate high explosive charge which is usually positioned within the aerosol or FAE cloud, as it is called.

The FAE Blast Environment

The detonation pressures obtained from all the hydrocarbon fuels tested to date have varied between 250 psi and 350 psi. The positive phase duration is determined largely by the physical size of the FAE cloud, or rather, the distance the relief wave has to travel to relieve the pressure. The longest positive phase durations measured to date within the FAE cloud have been about 25 msec. Longer durations have been measured well outside the FAE cloud.

Because the aerosol clouds are not homogeneous it is difficult to predict the direction the detonation wave will be traveling at any given transducer location. Thus the actual peak pressures measured within the detonating cloud will range from the side-on pressure (~300 psi) to the pressure obtained on normal reflection (~2,000 psi). The local perturbations in the detonation front that result from the cloud inhomogeneities disappear rapidly in the blast wave that is transmitted into the air outside the aerosol cloud. Thus the direction of the blast wave outside the fuel-air cloud can be predicted with good accuracy.

Transducers positioned within the detonating cloud are subjected to a large heat pulse, both radiative and convective. If the transducers being used inside the cloud require thermal shielding, precautions must be taken to insure that the shielding is not removed by the relatively high velocity flow that follows the detonation front.

By their design, FAE weapons produce few metal fragments and, therefore, judicious placement of the transducers will usually eliminate any need to shield them from fragments.

Measurement System Requirements - Transducer

As stated above, maximum pressures on the order of 2,000 psi can be encountered on within-cloud measurements. This would imply that transducers with a 2,000 psi capability are required. In actual practice, however, when the transducers are mounted flush with the surface and the FAE clouds are formed in contact with the surface, peak pressures in excess of 1,000 psi are seldom observed. Thus transducers with a lower pressure range are often acceptable and may in fact be preferred, depending on the type of data desired. It has been observed that pressure pulses in excess of 500 psi are usually spikes. That is, the amount of time that the pressure is above 500 psi is very short, usually less than 0.1 msec. If one is evaluating the military effectiveness of a weapon the measure of interest is usually the impulse, or the area under the pressure-time curve. If a 2,000 psi pressure transducer is used to insure catching any pressure spikes, the resolution of pressures below the 100 psi level is usually reduced, yet most of the impulse is obtained from that portion of the pressure-time curve that lies below 100 psi. Therefore, less error is usually introduced into the measure of interest, i.e., impulse, by using a measuring system designed for 1,000 psi, or even 500 psi, in order to obtain better resolution of the lower pressures and accept any inaccuracies in the measurement of the peak pressure. Two precautions have to be observed, however, if this is done. One is to insure that the transducer will not be damaged by the maximum pressures it can be exposed to. The other is to insure that none of the signal processing equipment is driven into saturation by a high peak pressure, or, if it is, that the recovery time is short enough that the data is not biased significantly.

Following the same rationale, i.e., impulse rather than peak pressure is the primary measure of interest, the FAE working party of the JTCG/MD has recommended a minimum system frequency response of 20 KHz for measuring FAE blasts. This is not fast enough to give good resolution of the narrow pressure spikes mentioned above but does give good resolution of the remainder of the pressure time history. In order to give a faithful reproduction at 20 KHz the lowest natural frequency of the transducer should be on the order of 100 KHz or higher. Systems with higher frequency responses have been used but the ratio of 5:1 between transducer natural frequency and desired system response should be maintained.

Since pressure pulse durations on the order of 50 msec have been recorded outside the cloud the measuring system needs to have good low frequency response. It is recommended that the low frequency roll-off be no higher than 2 Hz with 1 Hz or lower being desired.

Two other characteristics of the transducer that are always desirable in blast measurement are low thermal sensitivity and low acceleration sensitivity, although proper shielding and mounting can do much to minimize perturbations due to these effects.

Measurement System Requirements - Transducer Mounts

The transducer mount is as important in obtaining good blast data as selecting the right transducer. The primary function of the mount, of course, is to hold the transducer in the proper position.

In order to minimize displacement of the mount by blast loading a large mass is desirable. Also, a good rigid coupling to the mass is desirable to minimize vibrations. Other desirable features of a transducer mount are that it provide electrical isolation, protect the cables leading to the transducer, and minimize distortions of the blast wave.

Figures 1, 2 and 3 show examples of transducer mounts that have been used at the Naval Weapons Center (NWC). Most measurements have been made with the flush mounts shown in Figures 1 and 2. The lead bricks with the Teflon inserts have been found to provide good electrical isolation and excellent vibration dampening. Care has to be taken when mounting pencil probes to insure that the mount does not provide a reflecting surface for the blast wave. This is why the probe is projected well in front of the basic mount in Figure 3. The pencil probes are typically used only outside the cloud where the blast wave direction is known and thus the peak pressures are usually below 100 psi.

Measurement System Requirements - Signal Conditioning

The frequency response requirements for the signal conditioning portion of the measurement system are the same as listed above under transducers. That is: a high frequency capability of at least 20 KHz and a low frequency roll-off below 2 Hz. One system used for blast measurement at NWC has a frequency response of 100 KHz, yet a transducer with a natural frequency of 250 KHz is used on most tests. To maintain the proper relationship between system frequency response and transducer natural frequency a low pass filter is used on playback.

On most test setups it is desirable to be able to adjust the gain of the signal conditioning equipment so that the expected pressure will give close to full scale response.

Another factor that must be considered is the capability of recording pressures over fairly long lines. Line lengths used at NWC have varied between 500 and 1200 ft. Two basic types of instrumentation systems are currently being used at NWC to measure FAE blasts. Both use piezoelectric transducers. One system uses charge amplifiers which are located at the instrumentation bunker; the other system uses piezoelectric transducers with built in impedance converters with just the power supply located at the instrumentation bunker. Both give satisfactory performance although the charge amplifier system, because it is a high impedance system, requires that more care be taken during test setup. The charge amplifiers, however,

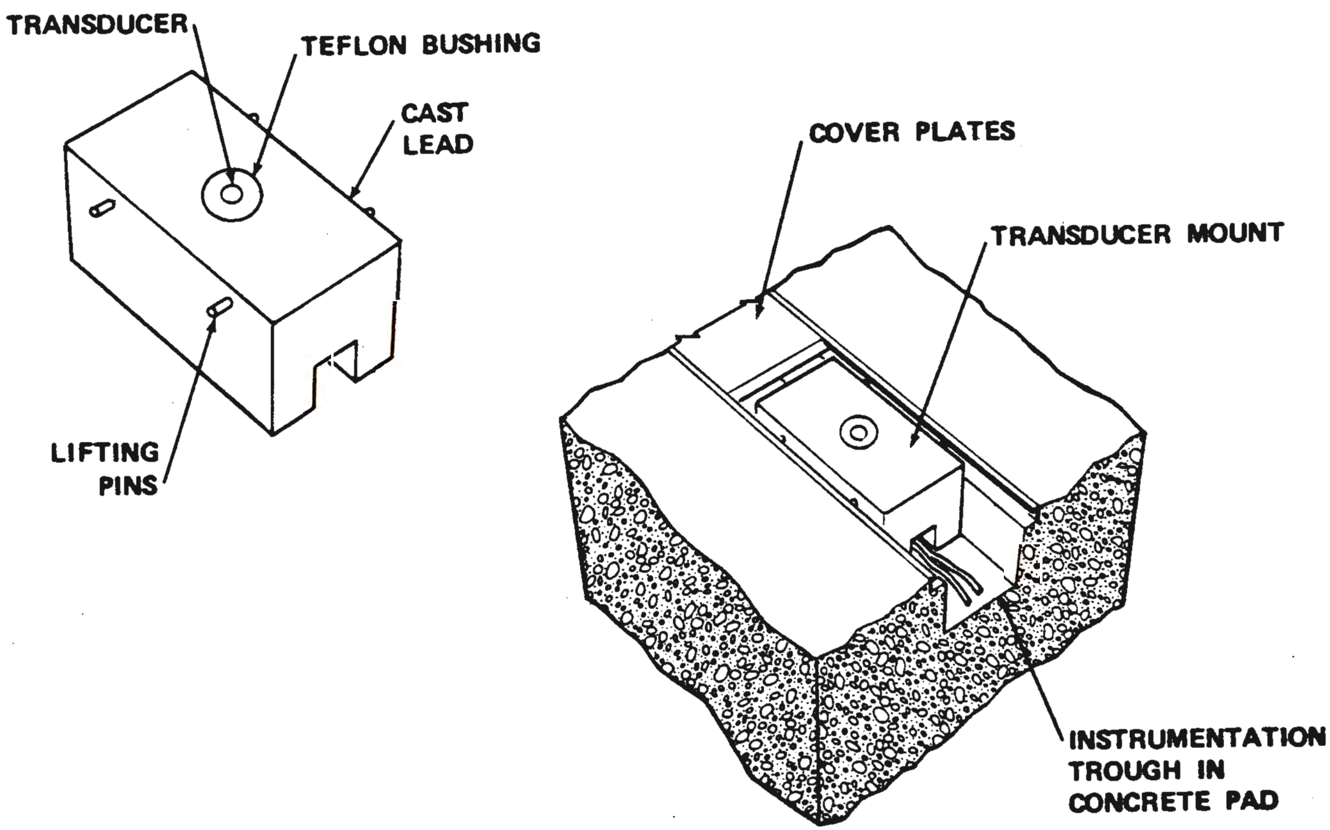

Figure 1. Transducer Mount for Static Test Site.

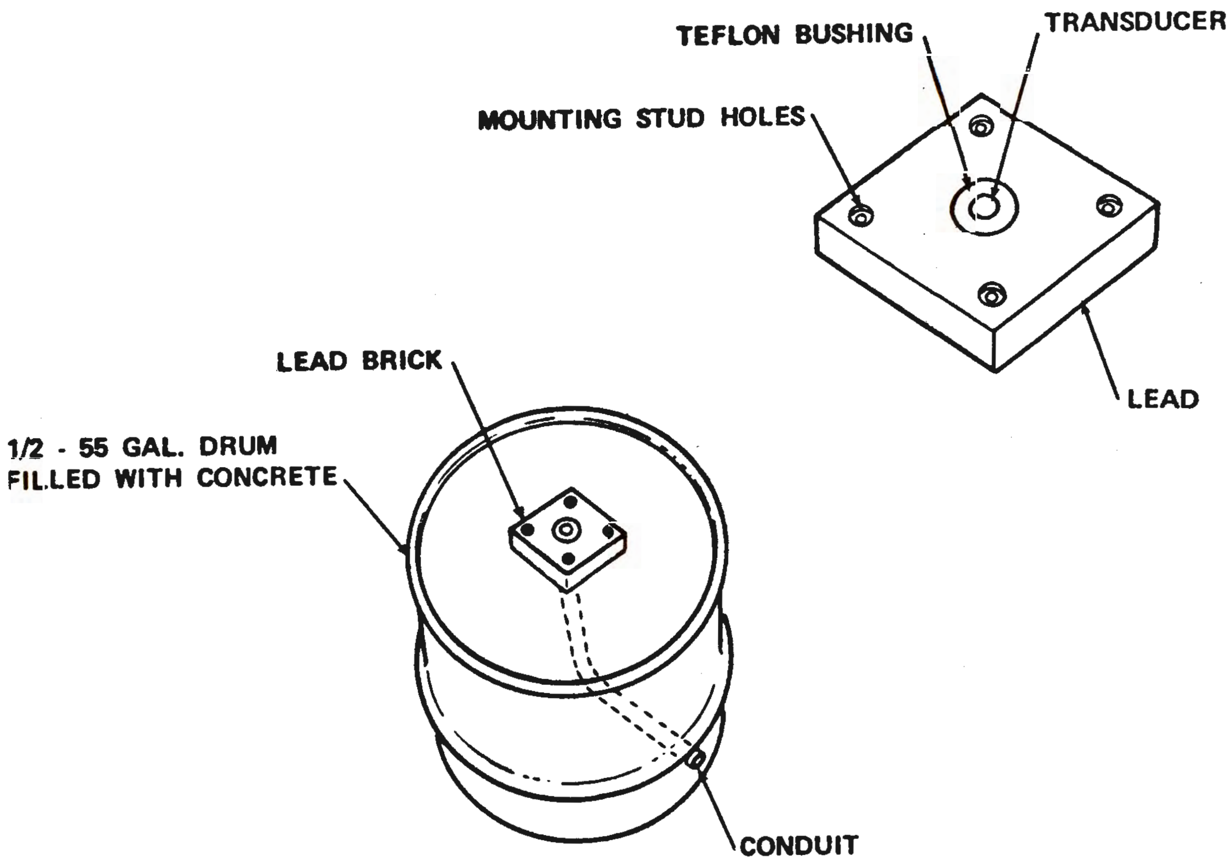

Figure 2. Transducer Mount for Field Use.

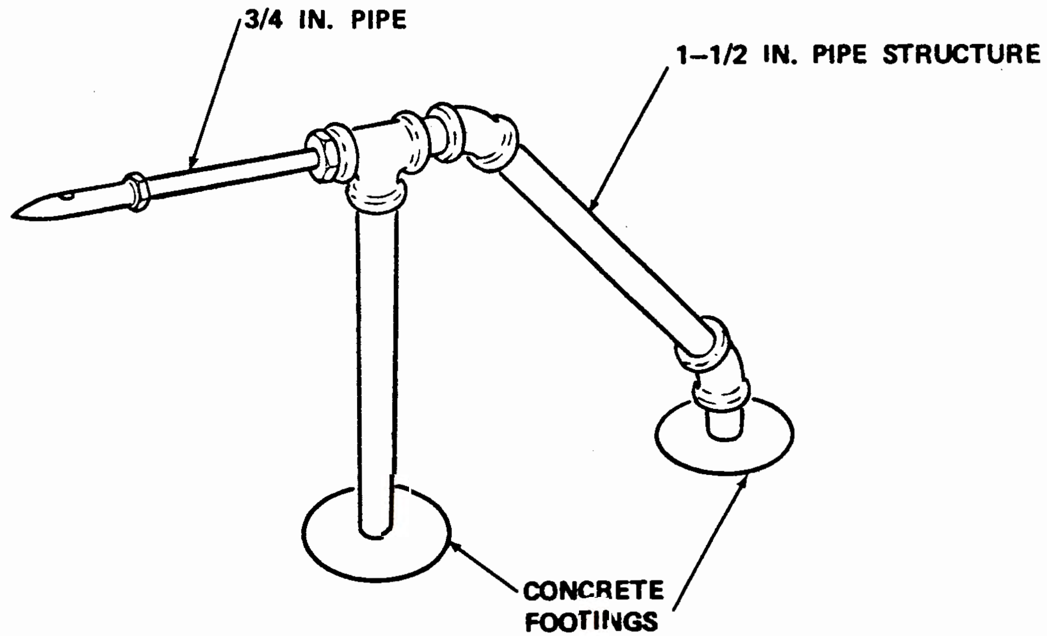

Figure 3. Pencil Probe Transducer Mount.

provide greater flexibility in matching the gain to the anticipated signal level than does the impedance converter system.

The charge amplifier system is used at a permanent static test site that has a concrete test pad (Figure 4). Great flexibility in the signal conditioning system is required at this site because of the large variety in the tests conducted there. The impedance converter system is used on an air drop blast test arena (Figure 5). The inaccuracies involved in delivering a weapon to the target require that each channel in the system be set up to measure the maximum expected pressure, so little flexibility is required, although a large dynamic range is desirable.

When evaluating weapon effectiveness it is frequently necessary to take the blast range to the target rather than the target to the blast range. Since the basic instrumentation is readily portable, i.e., charge amplifiers or power supplies and tape recorders, all that is needed to make a portable system is an instrumentation van to mount the equipment in and portable transducer mounts.

Operational Sequence

The same operational sequence is used with portable systems as with the system at the permanent test site. First, the transducers are screened on a shock tube. This is not a calibration but a check to see that the transducer is functioning properly. The most common fault detected is ringing well below the stated natural frequency. Other faults detected are slow rise times or rapid drop off of the signal. This type of screening is conducted with all new transducers and periodically thereafter.

The pressure calibrations are done with the transducer connected to the appropriate instrument channel. In this way the complete channel is calibrated, not just the transducer. It would be desirable to do all calibrations with a shock tube so that the transducer is exposed to a pressure pulse that has the same rise time as the pressures to be measured experimentally. A practical way to do this with a portable system has not been found. Several different calibrator designs have been used at NWC in an attempt to simulate as closely as possible the desired pressure rise. The calibrators currently used at NWC are basically rapid opening valves giving pressure pulses with a few milliseconds rise time. Pulses with this rise time do not excite the ringing modes detected with a shock tube and therefore this type of calibration cannot be depended upon for detecting faulty transducers.

When the transducers are installed in their mounts three precautions must be observed. The transducers must be tight in their mounts so that they do not vibrate independently of the mount, all electrical connections must be clean, and all electrical connections must be tight. Loose and/or dirty electrical connections are a common source of noisy signals. Clean connections are particularly important with charge amplifier systems. The oil from a thumb print can measureably degrade the signal with these high impedance systems.

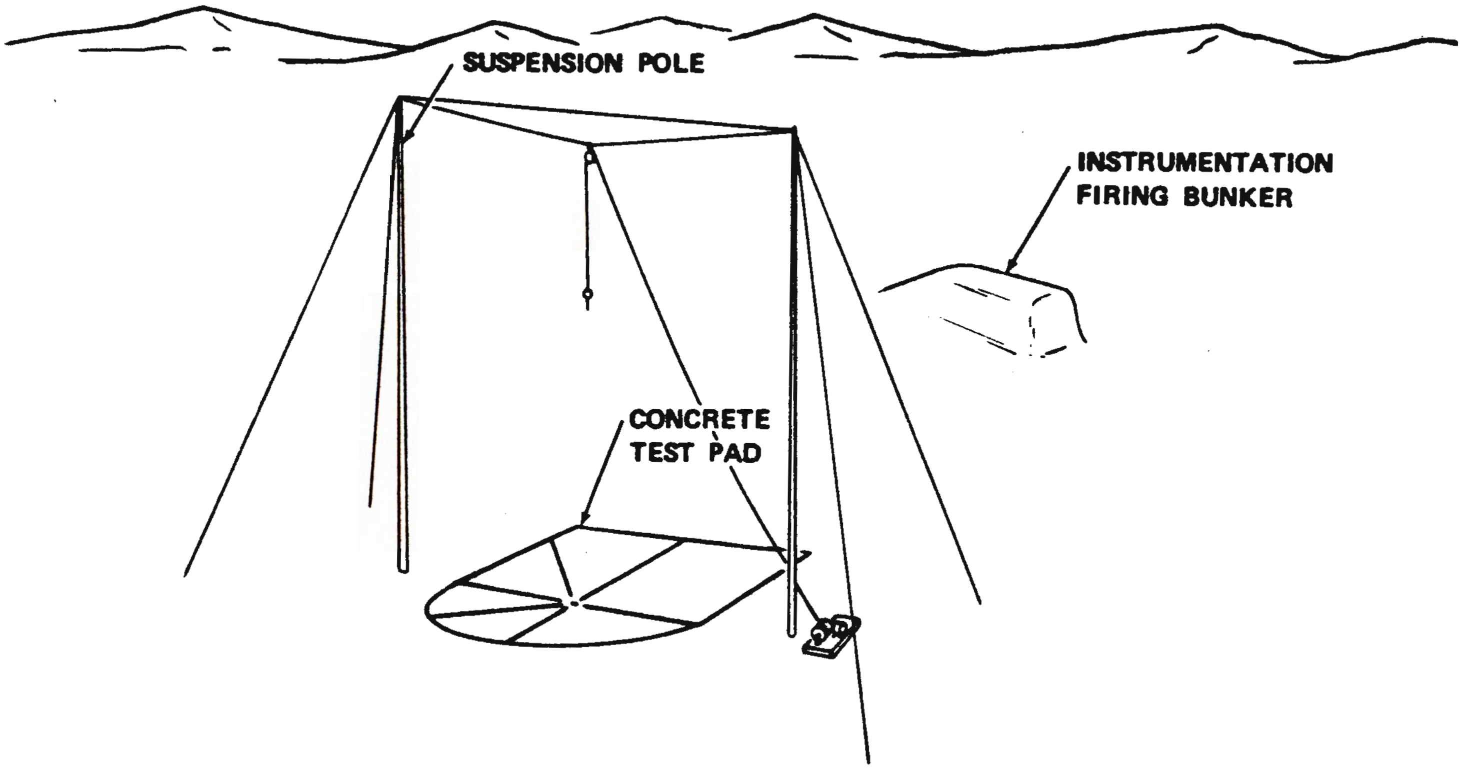

Figure 4. FAE Static Test Site.

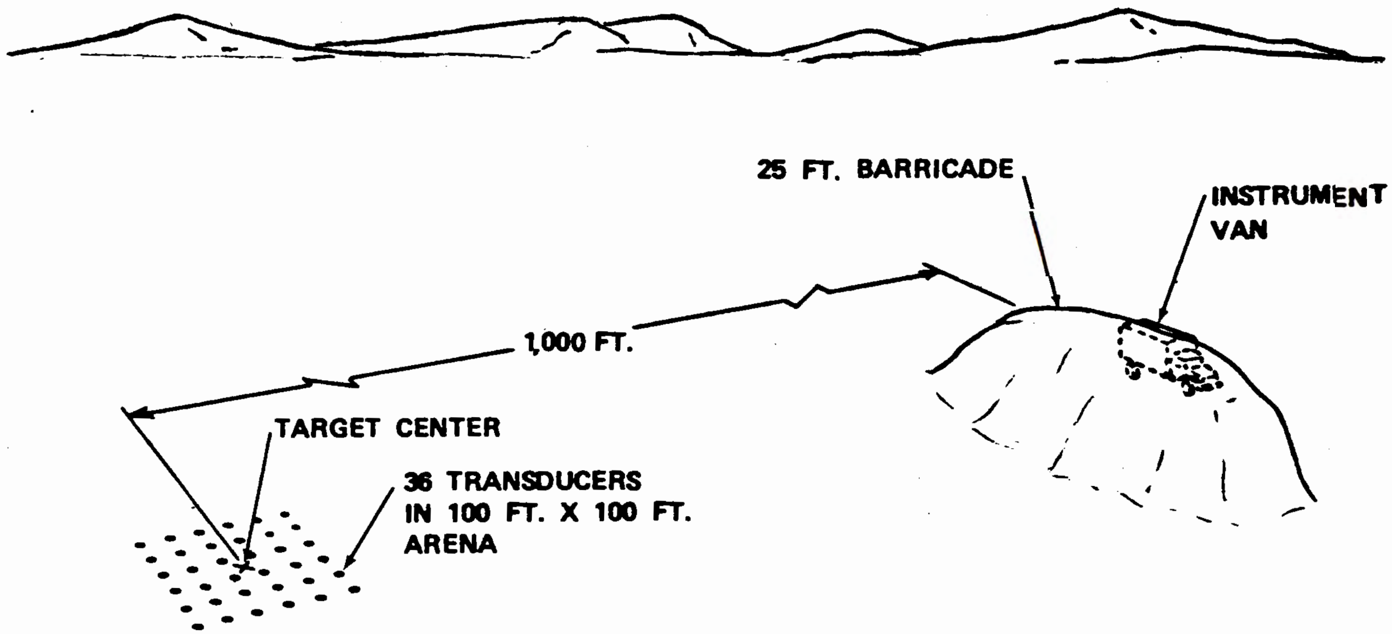

Figure 5. FAE Air Drop Test Site.

The wires should always be positioned away from the blast source, that is, the blast wave should reach the transducer first. All movement of the wires should be prevented if possible.

After the transducers are installed in their mounts the thermal shielding should be applied. Black plastic electricians tape is used for most applications at NWC. For within cloud measurements on the larger devices an additional layer of tape is used along with a spray coating of reflective paint. Silicone grease and RTV rubber have been used by others with good success. However, experience at NWC indicates that an opaque layer is required to eliminate any radiative effects below the shielding layer.

Just prior to the actual test shot the functioning of each channel is verified by tapping lightly on each transducer. Never use a hard object such as a screwdriver to do this. Even though the transducer is tapped lightly, extremely high local stresses are developed at the point of contact and a cracked crystal can result. Tapping with the index finger or some other soft object works fine.

Summary

In summary, the following statements can be made:

1. Select a transducer based on the parameter of most interest.
2. Make sure the signal processing system is compatible with the transducer.
3. Calibrate the complete system.
4. Use solid mounts.
5. Make sure all connections are clean and tight.
6. Use adequate thermal shielding.

TRANSDUCER APPLICATIONS IN AIRBORNE INSTRUMENTATION

By

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TRANSDUCER APPLICATIONS IN AIRBORNE INSTRUMENTATION

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Abstract

The development of modern airborne weapon systems requires constant attention to numerous factors having an effect upon flight safety and ordinance delivery accuracy. The evolution of higher speed aircraft, with increased ordinance carrying capability and more diverse ordinance shapes, has created the requirement for more precise analytical and empirical description of the store separation phenomena. Inflight measurements must be made to realistically account for hardware dynamics and aerodynamic loading effects on stores which cannot be simulated.

Several systems have been designed and fabricated by the Airborne Instrumentation Branch, Engineering Division, ADTC, to obtain the pertinent physical parameters that affect stores upon their separation from an aircraft.

These systems have required the unique application of standard types of transducers and the manufacture of some unique transducers to obtain some standard measurements. Various modes of signal conditioning and recording have been utilized: low level signal amplification, large signal buffering, time division multiplexing, frequency multiplexing, airborne magnetic recording and telemetry. The complexity of the transducer applications is compounded by the rigors of collecting data in the airborne environment.

TRANSDUCER APPLICATIONS IN AIRBORNE INSTRUMENTATION

INTRODUCTION: Prior to the development of high performance jet aircraft the separation of a munition from an aircraft was not of great complexity. The slower aircraft of yesterday, combined with the scenario of relatively high altitude, formation flight munitions release caused few problems during the actual separation of the munition.

Today's modern fighter type aircraft, however, attempt to deliver munitions at high speeds (which approach and occasionally exceed the speed of sound) while performing various maneuvers. As a result, the safe release of munitions from an airborne vehicle becomes a subject of significant interest and study. This concern is not confined solely to the unguided or "dumb" bomb but also includes the newer guided or "smart" bomb. In the past a very limited body of data has been available on the magnitude and variations of forces and delays inherent in an aircraft/weapon release system under dynamic conditions. This data must be available before the extent of associated weapon delivery errors and their contribution to system accuracy and weapon effectiveness can be determined.

Thus instrumentation has been developed to determine the quantitative history of critical parameters during the release of munitions from various fighter type aircraft.

BACKGROUND: Munitions are carried aboard aircraft by attaching them to mechanisms known as racks. These racks serve the purpose of stabilizing the munition while the aircraft is in flight and releasing the munition at the receipt of a command. The munition is secured by movable "hooks" inside the rack that are inserted in "lugs" on the munition. Stabilization is accomplished by rack appendages known as "sway brace pads" (Fig 1 & 2), which contact the munition at four points.

The release of a munition from an aircraft is accomplished by the firing of

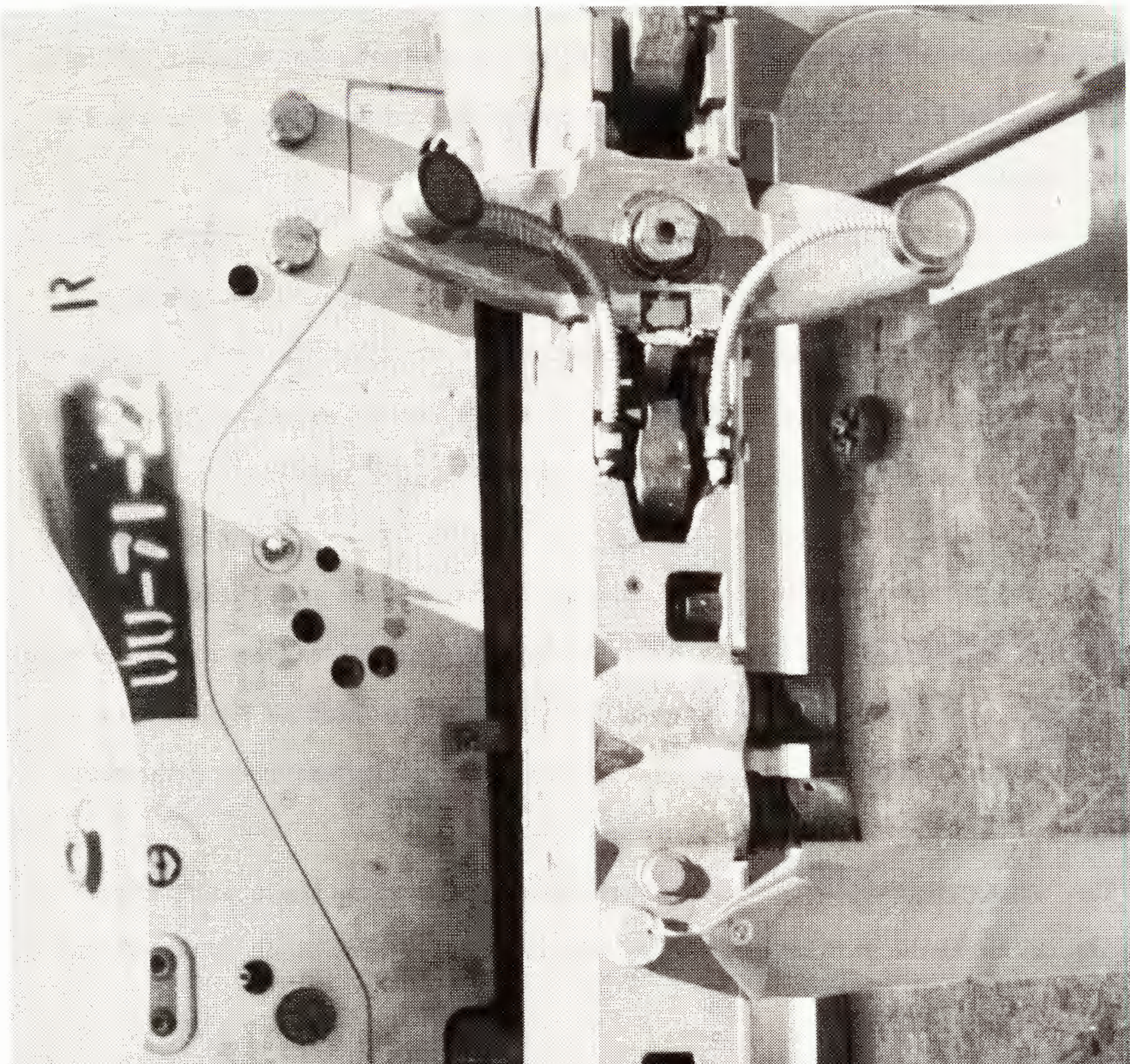


Figure 1

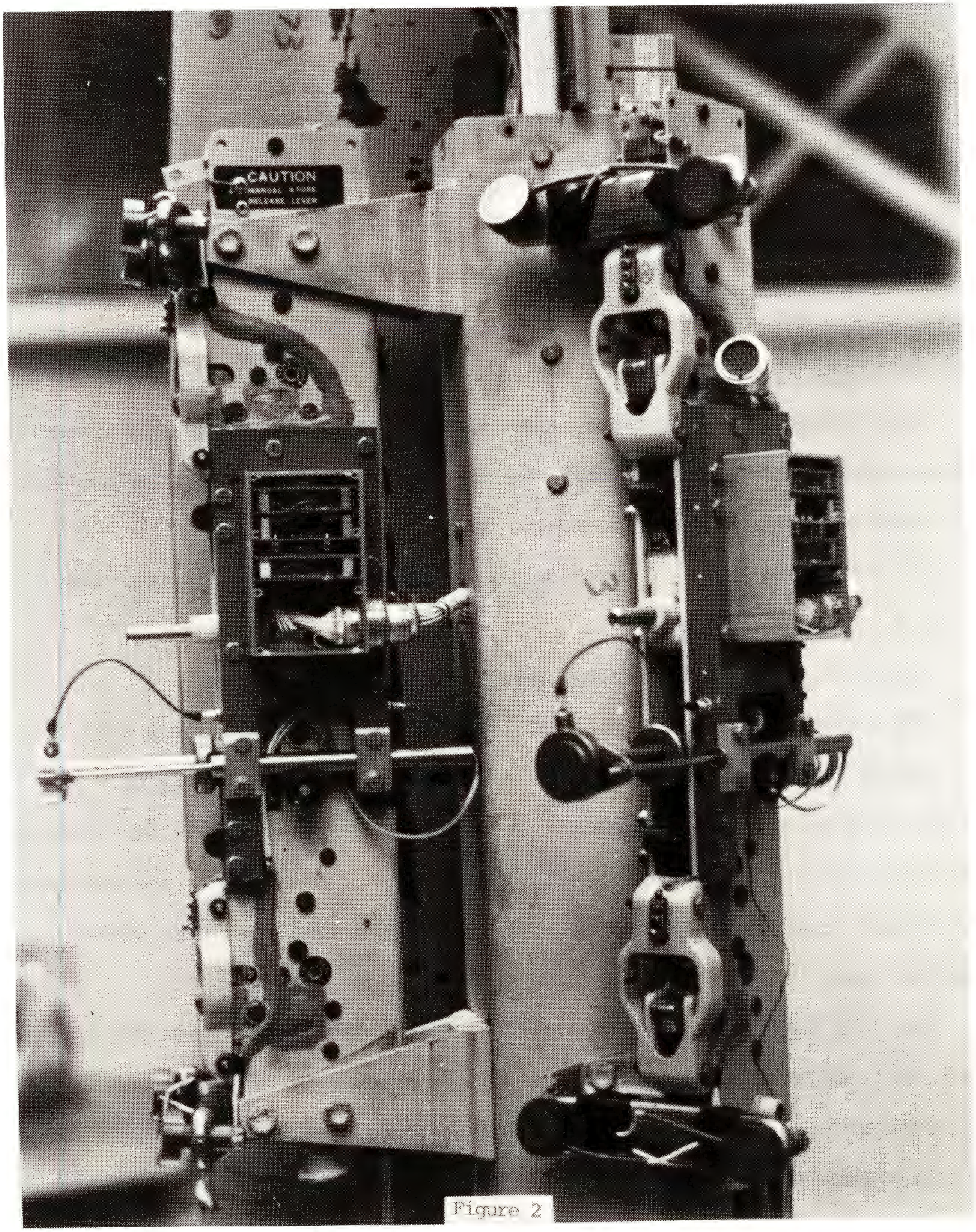


Figure 2

an explosive, gas-generating charge within this rack. This gas enters a cylinder where a piston driven mechanism removes the retaining hooks from the munition lugs and "simultaneously" pushes the munition away from the aircraft (Fig 3). Variations in the burn rate of this charge affect all release functions of rack.

The munition separation characteristics (displacement and attitude) are determined by the forces acting upon the munition before and during the separation phase. The reaction to these forces determines not only the safe separation but also influences the ballistic trajectory of the unguided munition.

THE INSTRUMENTATION:

THE TRANSDUCERS - The basic measurements being made are pressure, strain, displacement (linear and digital) and force. Common and unique applications of transducers are utilized to obtain the required data.

The following types of racks have been instrumented and will be referenced throughout the paper:

MAU-12B/A - A single munition capability (Fig 1 & 4).

TER-9 (Triple Ejector Rack) - A three munition capacity (Fig 2 & 5).

MER-10 (Multiple Ejector Rack) - A six munition capacity (Fig 6). The first instrumentation was installed in a TER-9 rack during Nov - Dec 1970 and has been continually upgraded. Additional units of these racks are now being fabricated to satisfy the test requirement demands that have been levied against them.

PRESSURE MEASUREMENTS - The pressure profile developed within the ejector foot cylinder by the exploding charge is obtained by modifying the top of the cylinder to accept a piezoelectric pressure transducer. (Each rack is individually machined to accept the transducers into the cylinder and to allow clearance for electrical connection.)

TER-9
NOMINAL RELEASE TIME DELAYS

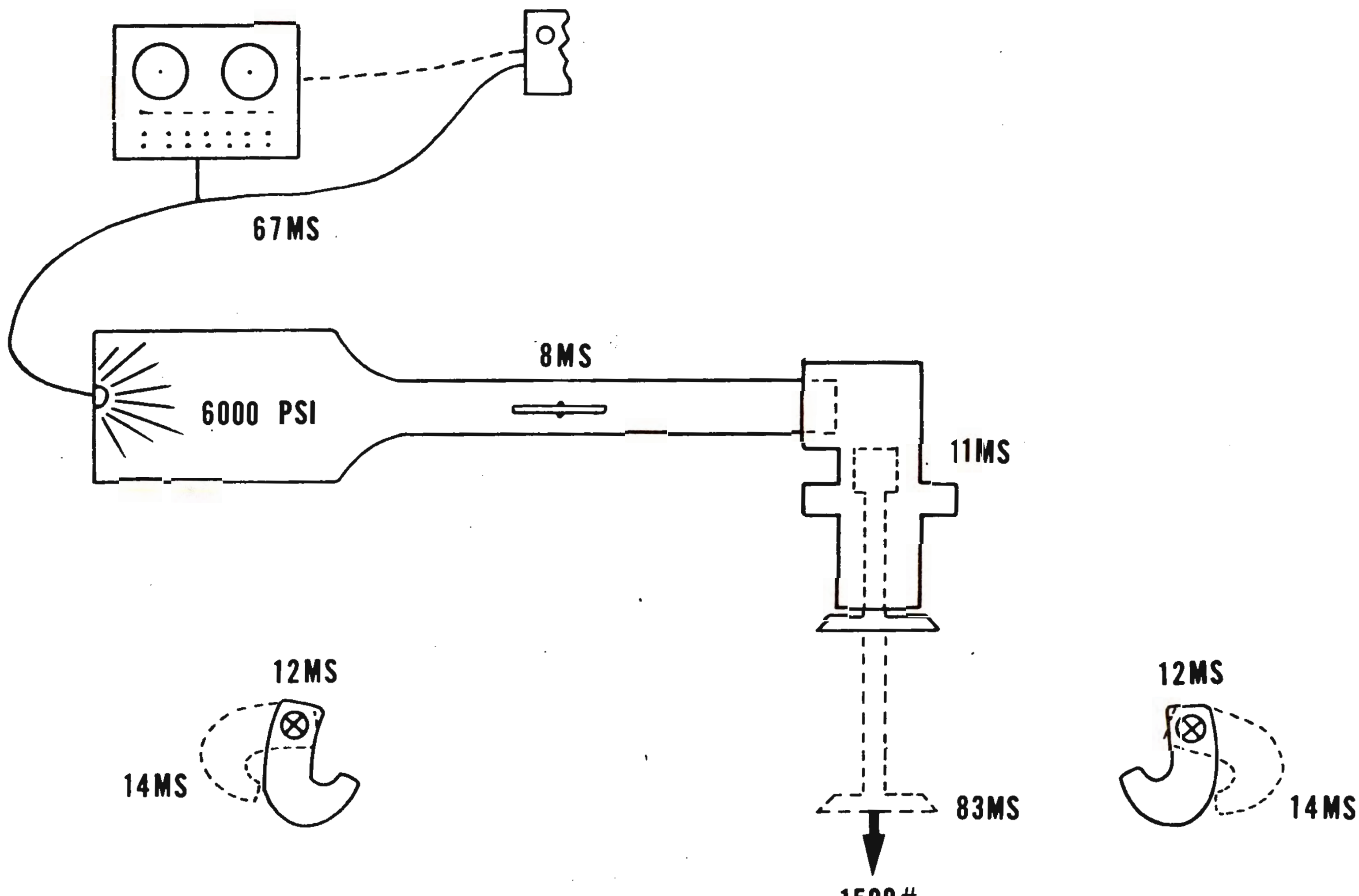


Figure 3

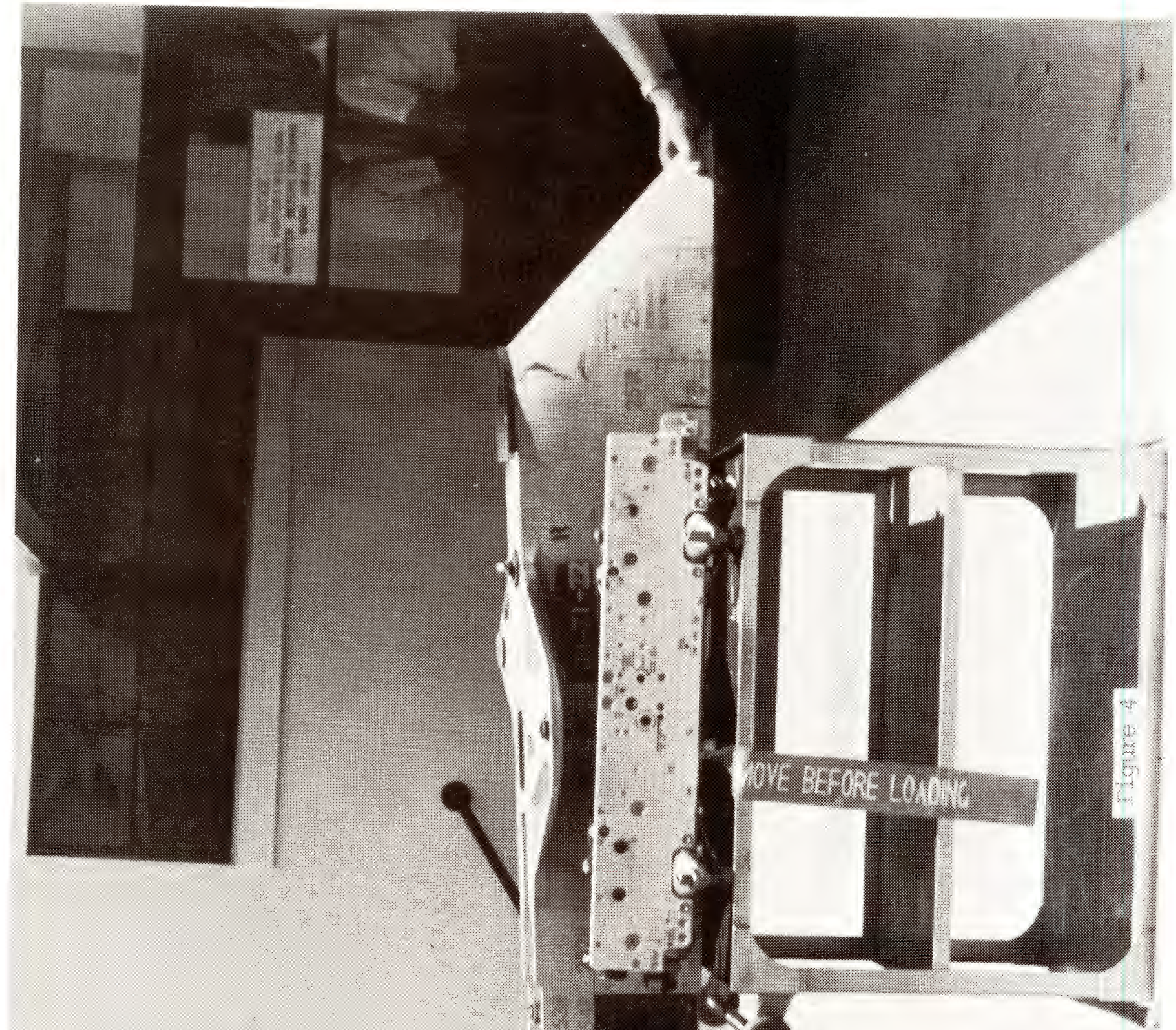


Figure 4

Figure 5

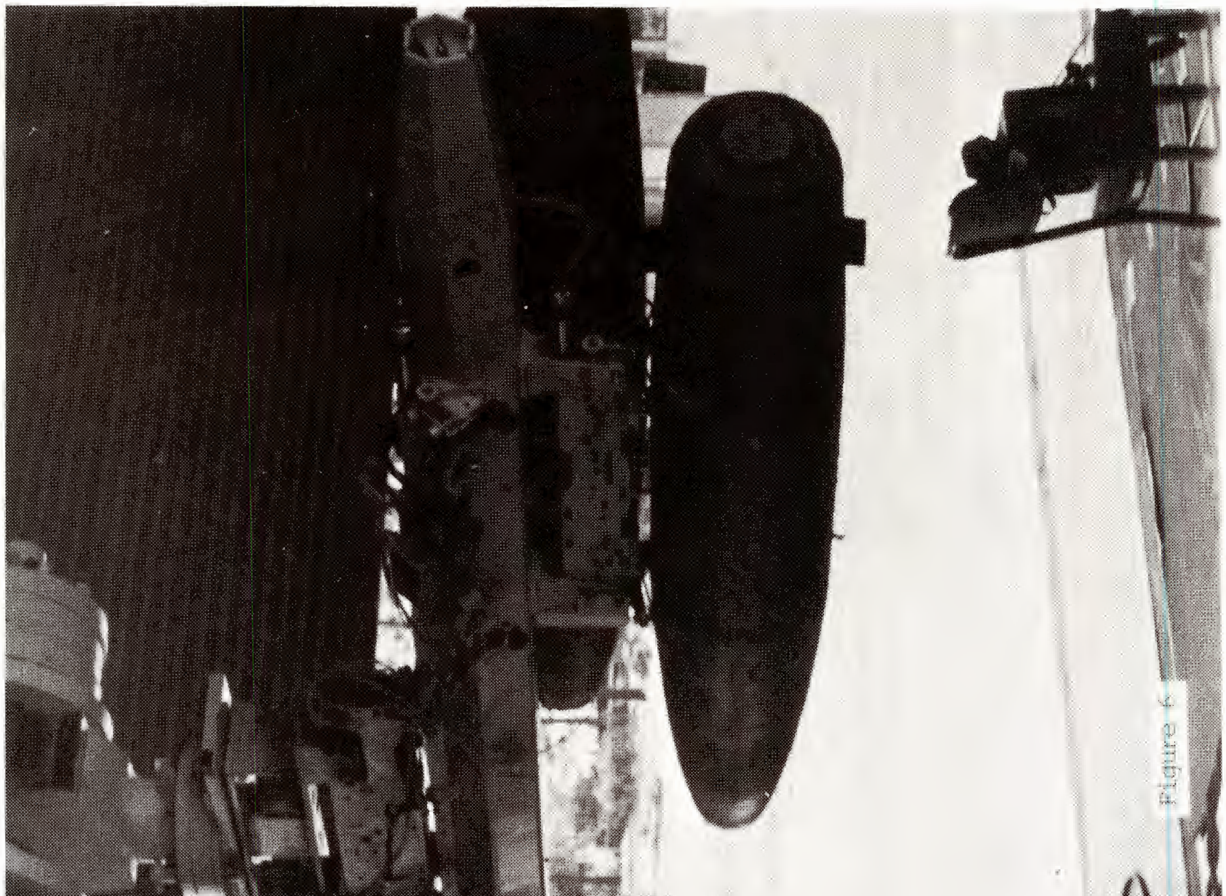


Figure 6

Typical values for peak pressure is 6000 psi using an ARD 863-1 cartridge while ejecting a 250 pound store (Fig 7). Cylinder volume is not significantly affected by the transducer as a virtually flush mounting is achieved (Fig 8).

Difficulties were initially encountered in obtaining this pressure data. Heating caused by the hot gases in the cylinder caused erroneous outputs until an acceptable ablative coating could be found. Pressure profiles obtained after applying black electrical tape as ablative coatings are as shown in Fig 7. The pressure transducers now being used are supplied with an ablative coating of GE Type 580 silicon rubber already on the sensing surface.

STRAIN MEASUREMENTS - Initially strain measurements on the various racks were taken on the hooks and sway brace arms. The purpose of the strain gauges on the sway brace arms was to indirectly determine the loading placed on the munitions by the pads. This method has now been replaced by the use of load cells as the pads themselves (Fig 1 & 2). This configuration of the load cell was specially developed for use on these bomb racks. The intended effect is to exactly replace the normal sway brace pad with the load cell such that direct reaction forces between the pads and the bomb may be read with minimal influence on the data by the instrumentation. Reaction forces obtained with the load cells is shown in Fig 11.

The strain gauges on the hooks are oriented to obtain the loading of the hooks by the bomb during carriage and release. Data can be obtained during aircraft maneuvers to determine rack structural loading limitations in certain munition delivery modes (Fig 9). Typical data obtained from these gauges is shown in Fig 10.

DISPLACEMENT - Motion measurements are made on the various racks to determine the time history of the mechanical component operation. Microswitches are installed to detect the first motion of the linkage which

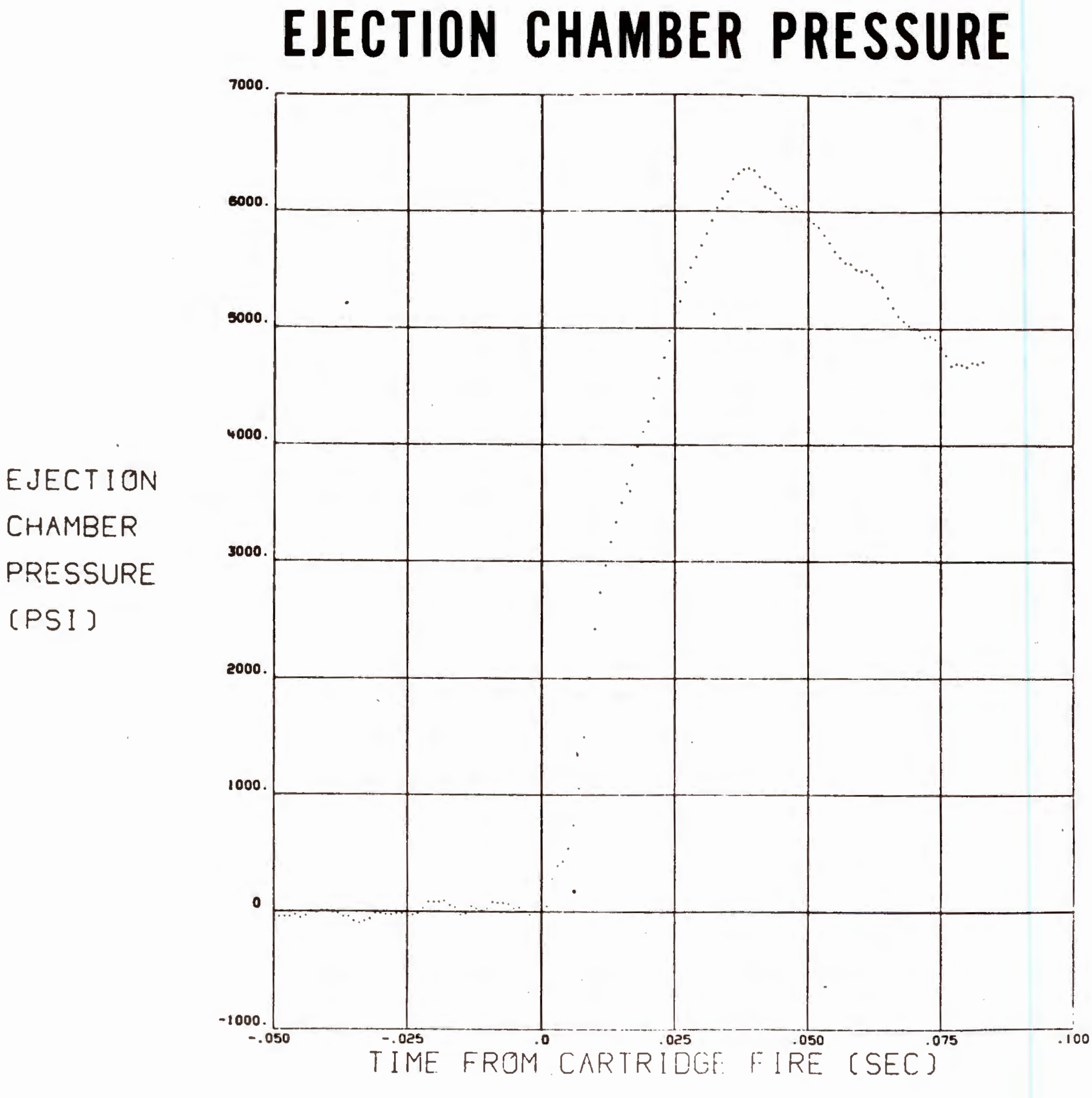

EJECTION CHAMBER PRESSURE
EJECTION CHAMBER PRESSURE (PSI)
7000.
6000.
5000.
4000.
3000.
2000.
1000.
0
-1000.
-.050
-.025
.0
.025
.050
.075
.100
TIME FROM CARTRIDGE FIRE (SEC)

Figure 7

TER-9 EJECTOR PISTON,POTENTIOMETER ASSEMBLY

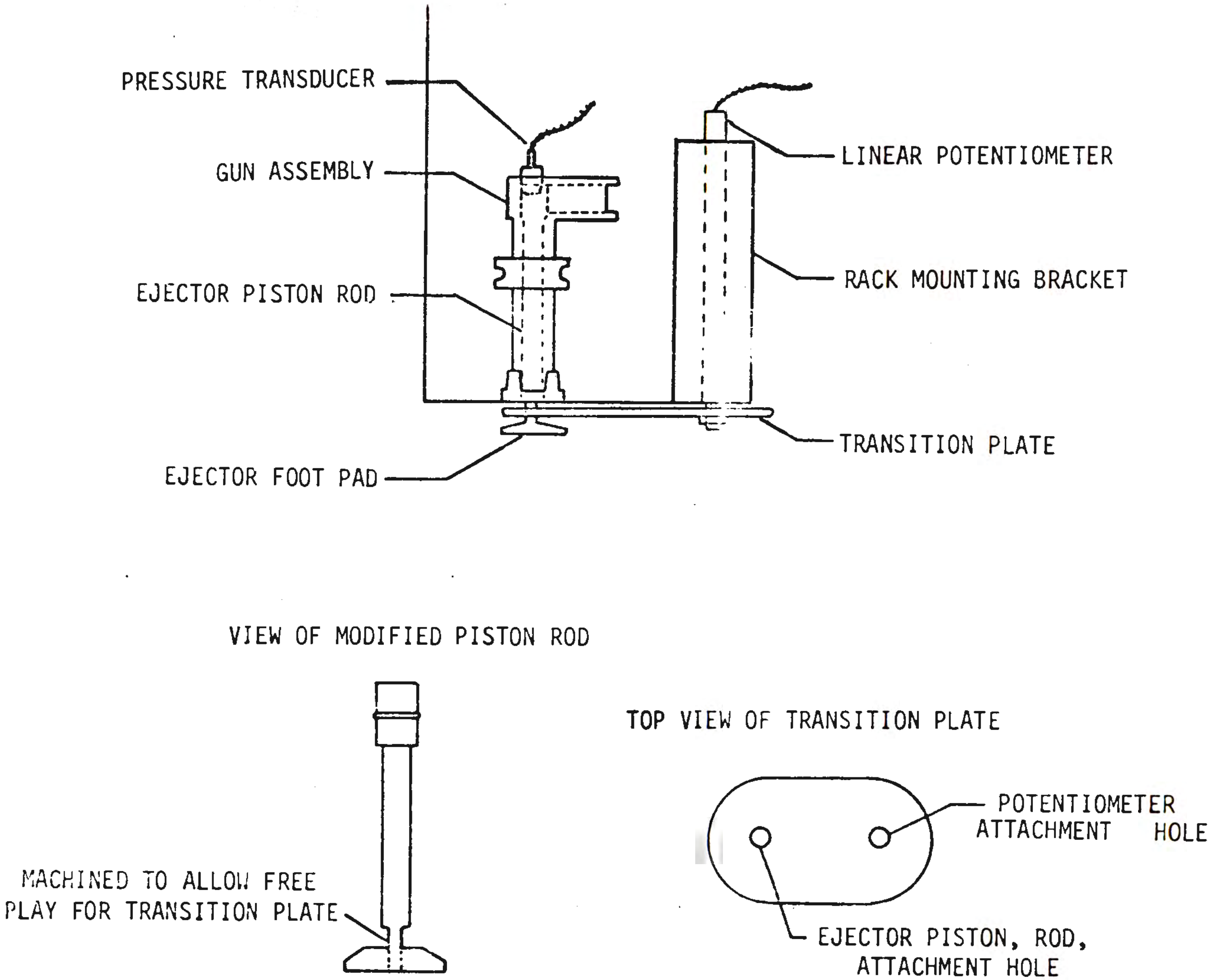
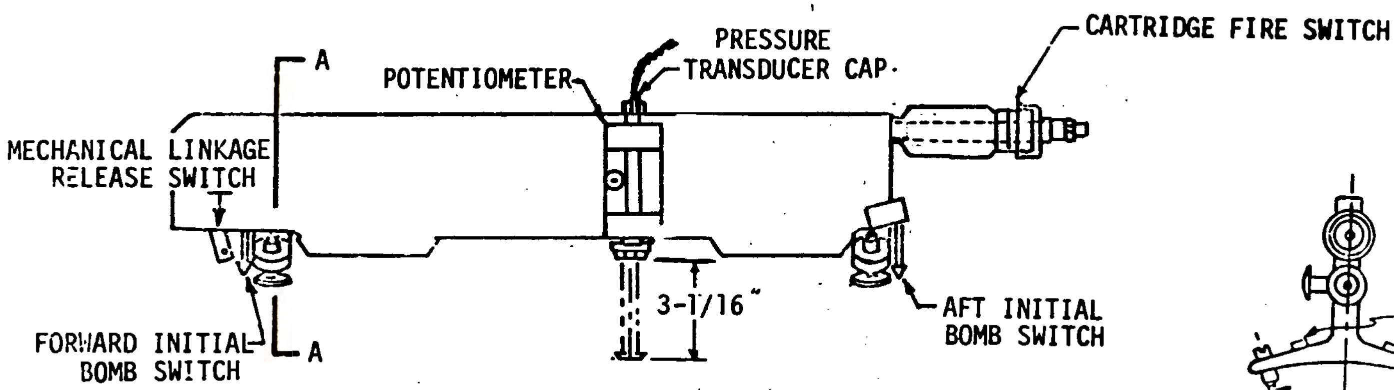


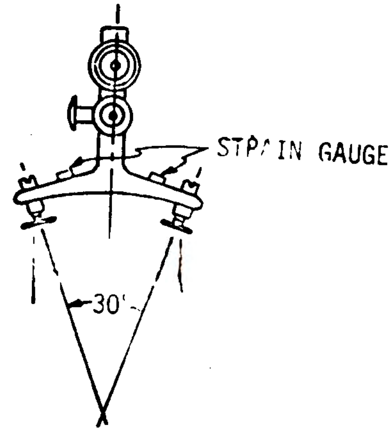
Figure 8

TER-9/CLASS

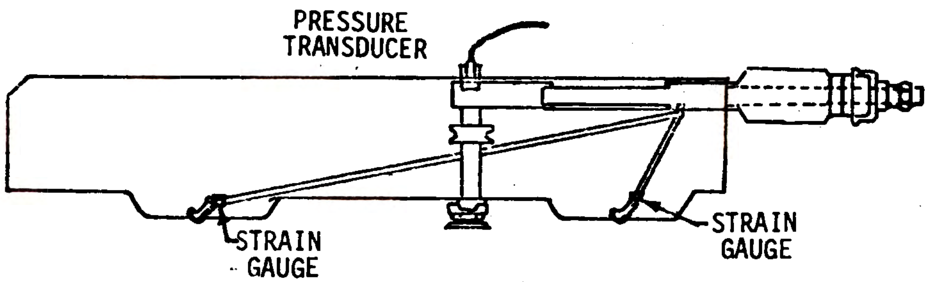
INSTRUMENTATION



EXTERNAL INSTRUMENTATION



VIEW A-A



INTERNAL INSTRUMENTATION

Figure 9

HOOK LOADING

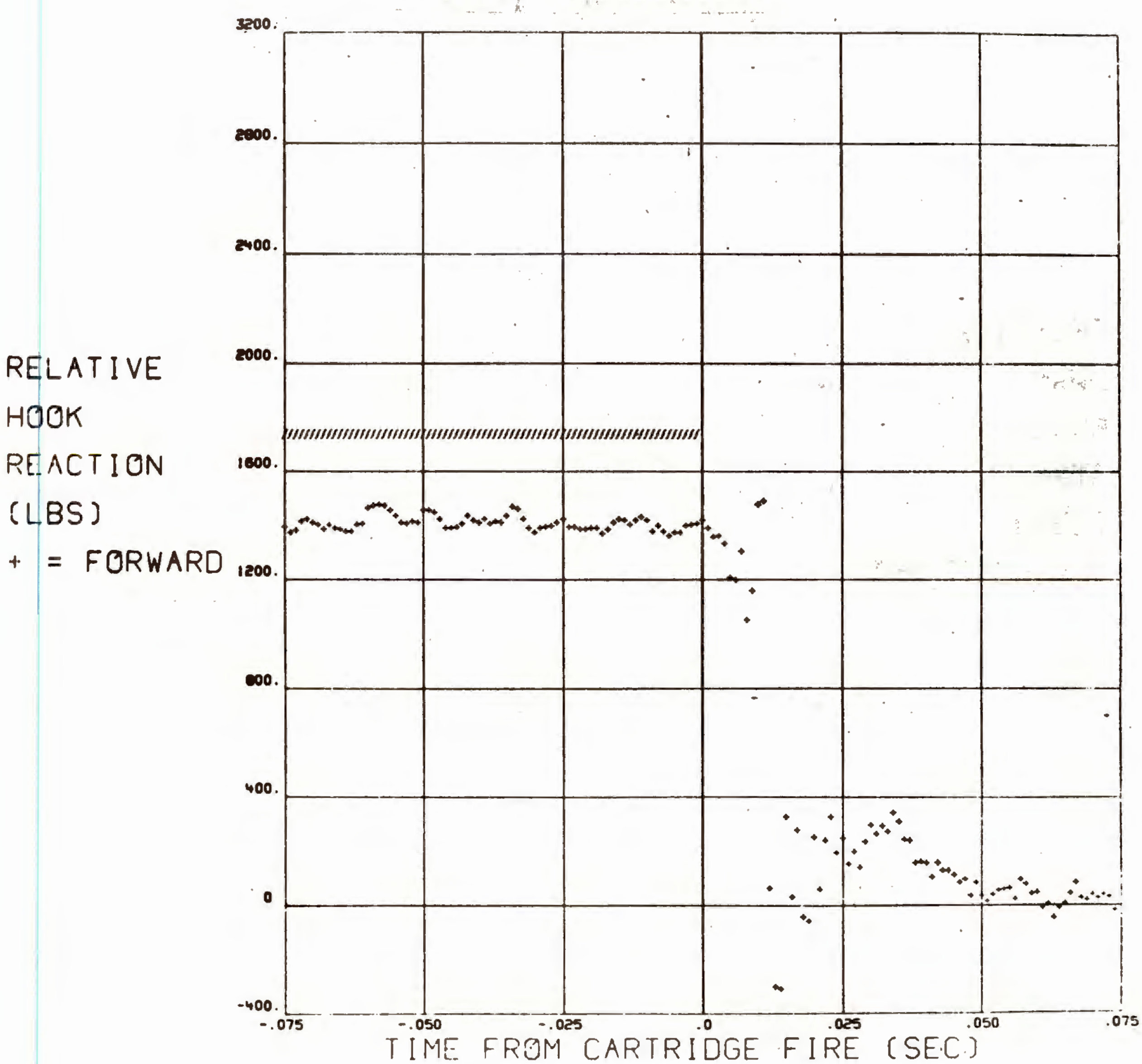


Figure 10

SWAY BRACE LOADING

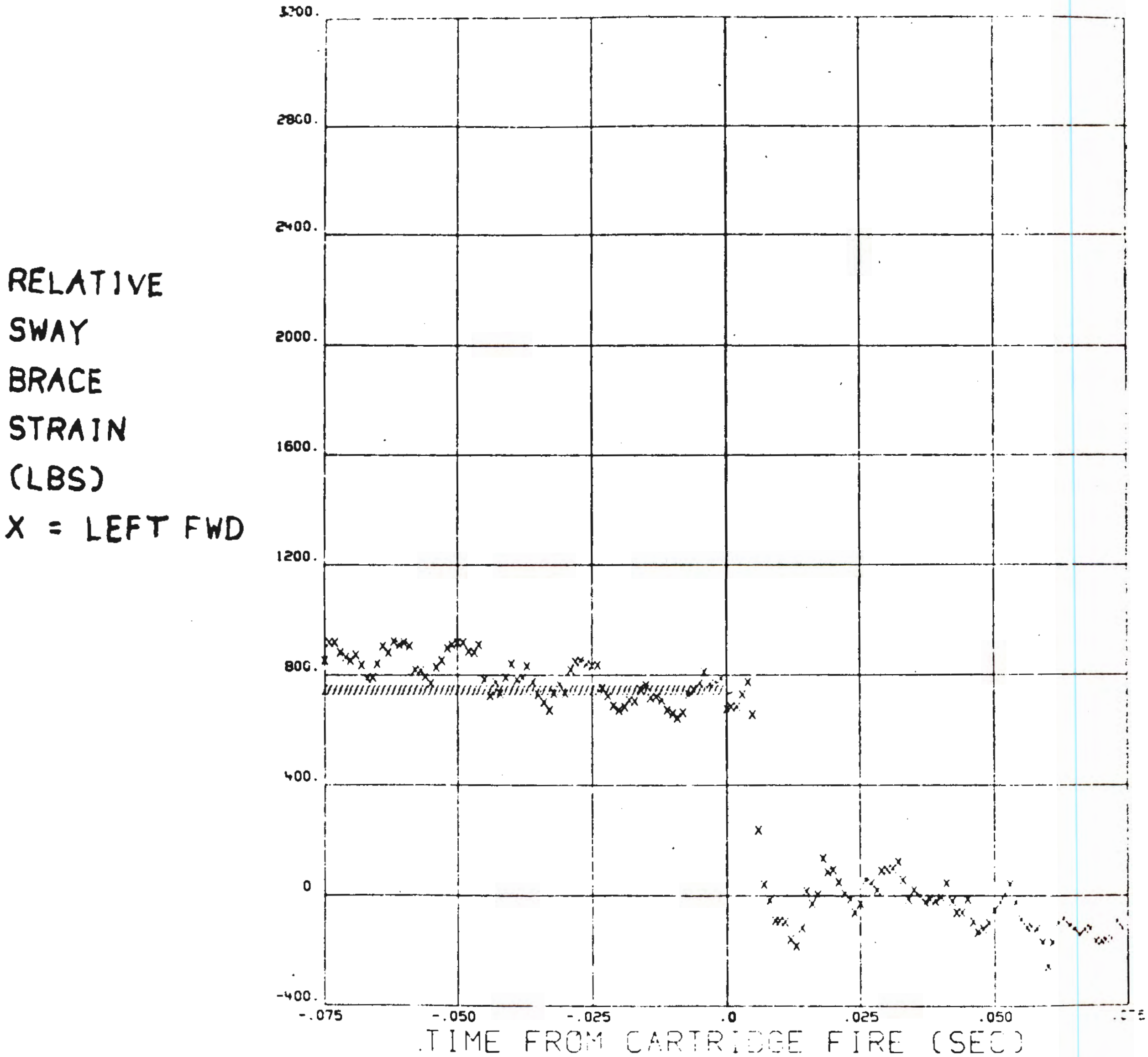


Figure 11

disengages the rack hooks from the bomb lugs. Switches are also installed which give indication as to the moment of the first downward motion of the bomb relative to the rack (Fig 5 & 9). Special machine work had to be accomplished to mount these sensing switches to obtain the required data without interfering with normal rack operation.

Linear potentiometers are attached to the ejector piston foot to give an analog record of its motion (Fig 2, 8, 12 & 13). Precise machining and mounting techniques were necessary to allow the mounting of this potentiometer. Any slight variances in alignment of the potentiometer and the ejector piston arm will cause destruction of the potentiometer or interfere with proper operation of the ejector foot mechanism.

FORCE - In an attempt to determine the actual force being delivered to the bomb by the rack ejector foot a piezoelectric load cell was mounted on the base of the foot (Fig 2 & 12). This rather unique application presented some mechanical and electrical interface problems.

The mounting method and size of the load cell was chosen so as to preserve the structural integrity of the ejector foot and to duplicate the shape and magnitude of the surface area which actually contacted the bomb and delivered the ejection force. Obviously some means of delivering the electrical signal from the transducer to the signal conditioning was necessary. Experiments with various schemes finally resulted in a loop of conductor being used which is long enough to allow full travel of the ejector foot. While the ejector foot is in the "UP" position the excess wire forms a bow in the wind stream and presents no operational problems (Fig 2 & 12).

THE SIGNAL CONDITIONING, MULTIPLEXING NETWORKS AND RECORDING MEDIA - On the single store rack, MAU-12B/A, all of the previously mentioned data is gathered for the one mechanism, is conditioned and telemetered to a ground

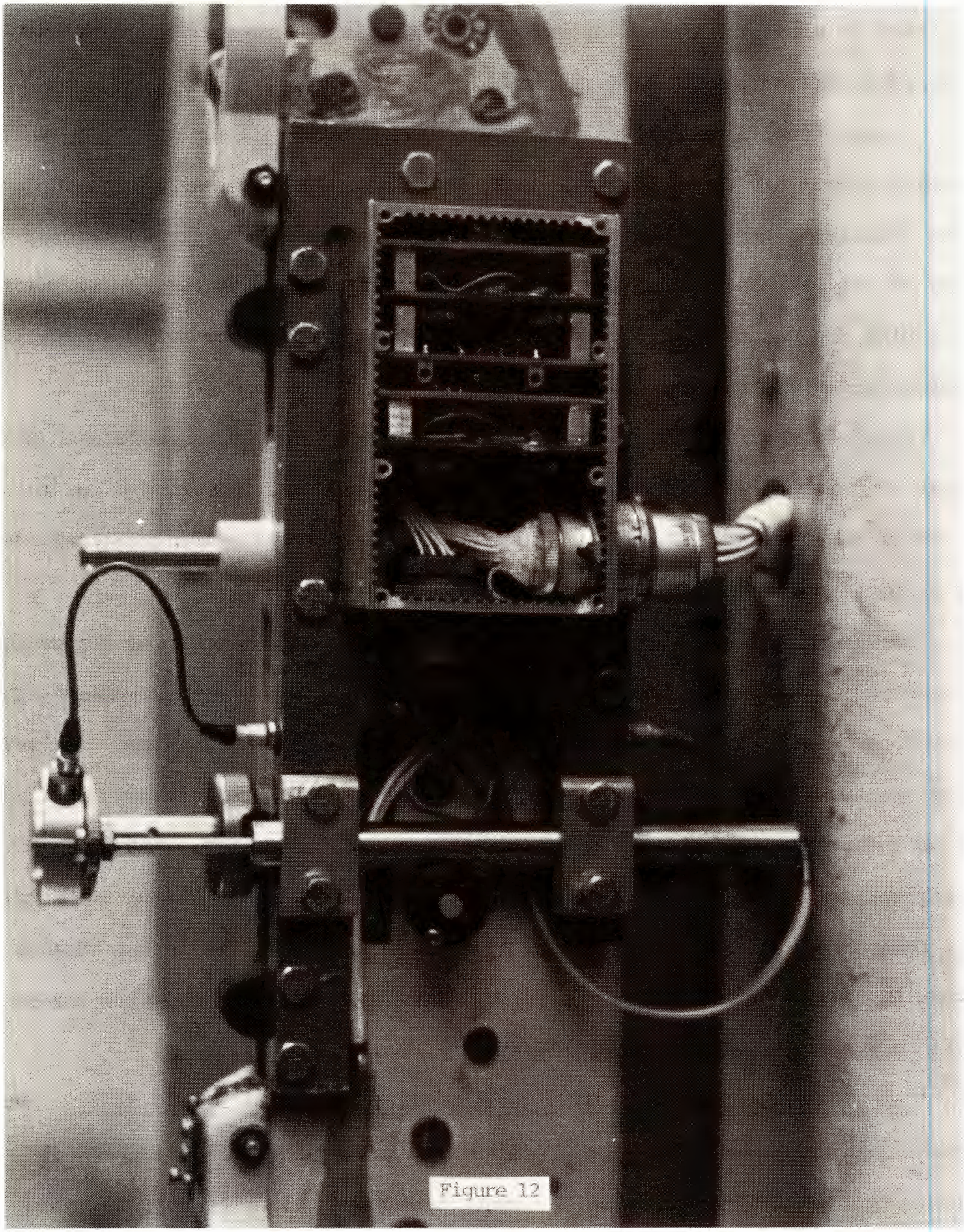


Figure 12

EJECTOR FOOT DISPLACEMENT

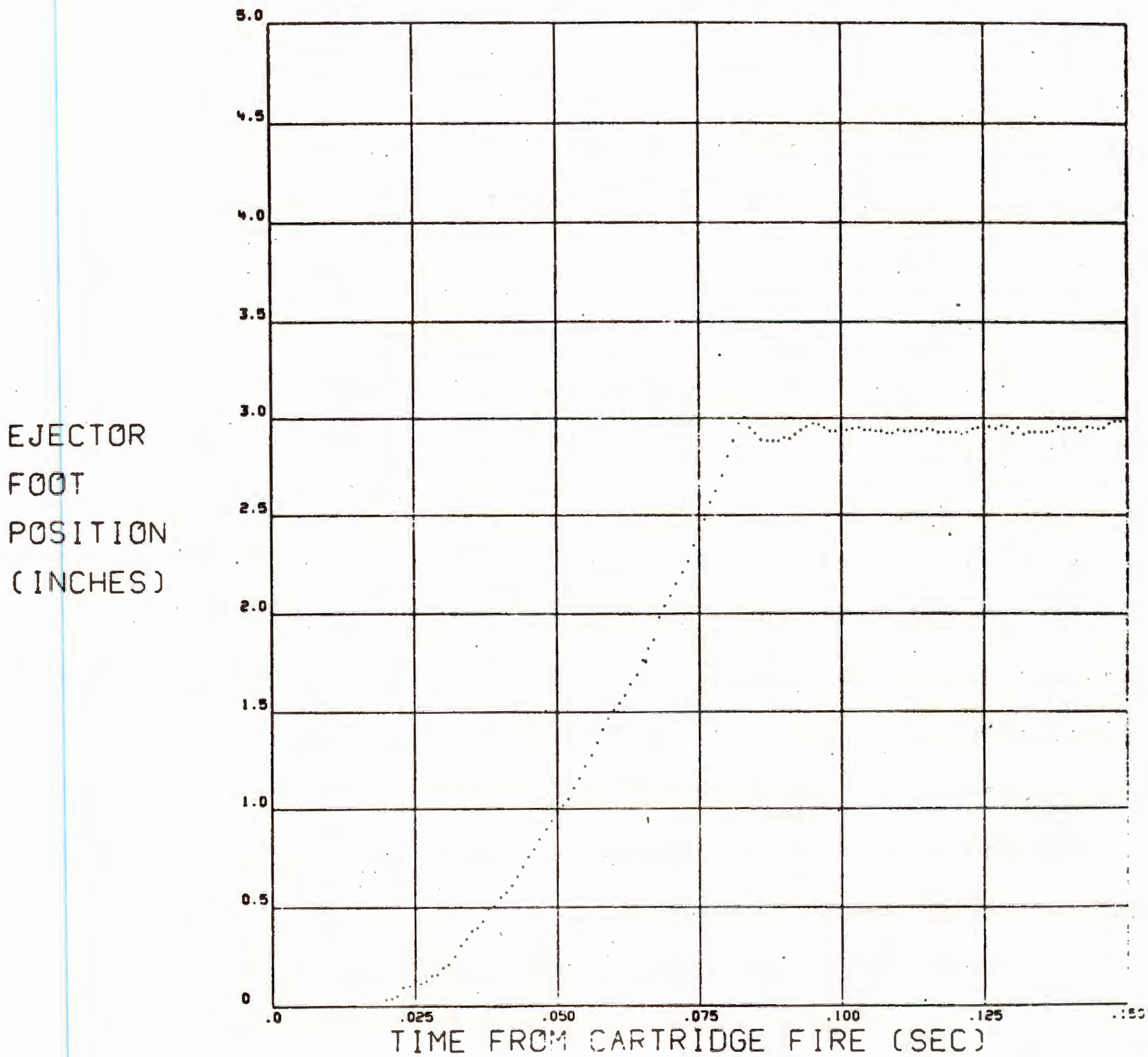


Figure 13

receiving site. A FM/FM system is employed utilizing constant bandwidth oscillators, IRIG Channels 1A - 13A. All low level signals are amplified utilizing operational amplifiers. All high level logic is scaled as necessary (Fig 4 & 14). The composite signal is recorded at the test range site with real time of day being recorded on a separate channel. "Quick-look" capability is utilized at the range site to assure proper system operation. Total demultiplexing is accomplished within the ADTC Mathematical Laboratory and all parameters are quantized against the time of day.

For the multiple station racks (TER-9A and MER-10A) a time multiplexing scheme was utilized to prevent the duplication of signal conditioning networks. Logic circuitry within the racks is monitored to determine which of the various bomb stations will be functioned. The multiplexers are then configured to allow data from the individual sensors on that station to be routed to the signal conditioning networks. As each successive station is prepared for bomb jettison, the multiplexers switch to accept that station's sensors' outputs.

In an early configuration of the MER and TER systems, an on-board tape recorder was utilized to store the data for eventual reduction (Fig 6 & 15). This approach was taken to allow use of the instrumented racks where ground telemetry receiving sites were non-existent or had limited capability. A disadvantage of this approach was that the recording system was housed inside a "dummy bomb" on one of the rack stations, thus preventing the carriage of a full load of jettisonable munitions.

The current configuration replaces the on-board recorder with a FM/FM telemetry system, which is contained entirely within the main-frame of the rack (Fig 4 & 14). Extensive telemetry receiving capability within the ADTC test ranges allow data acquisition with this system in all projected system use profiles.

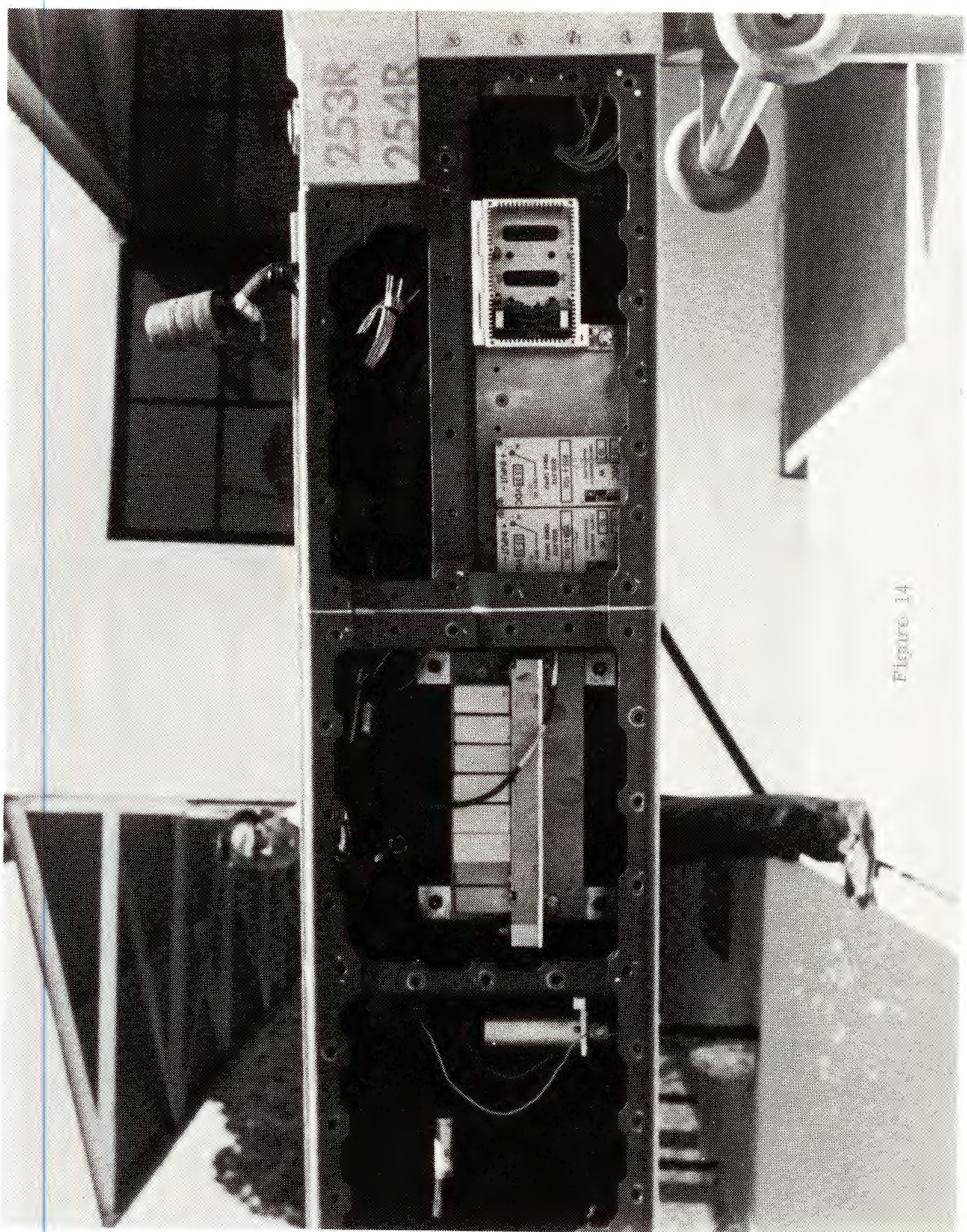


Figure 14

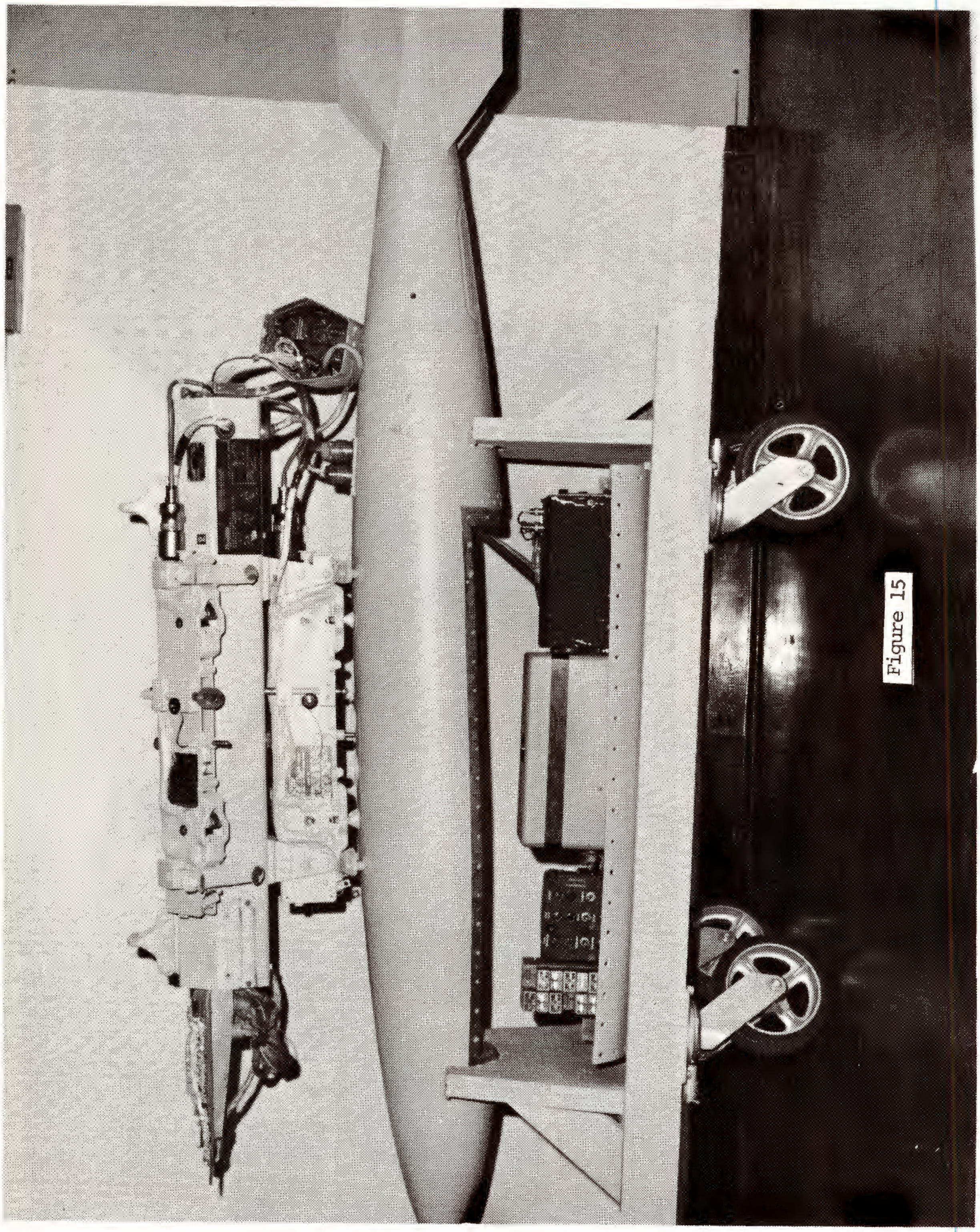


Figure 15

THE DATA AND ITS USE - Several efforts are now in progress at ADTC that are utilizing the data acquired with these instrumentation systems. These programs are attempting to determine: The safety criteria for release of munitions; the structural loading of racks during delivery tactics; the definition of rack performance characteristics; variations in rack parameters that may affect munition ballistics; correlation of computer prediction programs for release parameters with those actually obtained in-flight.

This assembly of individual transducers into an operational data acquisition system is a viable example of the continuing use of transducer technology in the airborne instrumentation discipline.

TECHNICAL INFORMATION SERIES

NO. 75SDR0008

TITLE R/V FLIGHT TEST PRESSURE INSTRUMENTATION TECHNIQUES

AUTHOR J. M. CASSANTO

Paper presented at the 8th Transducer Workshop in Dayton, Ohio, April 22-24, 1975.

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Re-entry & Environmental Systems Division

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SUMMARY R/V flight test pressure instrumentation techniques currently in use by GE-RESD have been reviewed. This review is being provided so that experimenters within the scientific community can take advantage of recent state of the art flight and ground test pressure measurement techniques developed/evolved at GE during the past few years. Flight and ground test data dealing with steady state and fluctuating pressure measurements are presented. Four basic areas have been addressed in the paper: 1) pressure port diameter/erosion effects, 2) pressure tubing diameter/length effects, 3) preflight calibration of pressure transducers, and 4) acoustic (fluctuating pressure) measurement techniques. Recommendations are made in each area for optimizing flight test pressure measurements. This paper will be presented at the 8th Transducer Workshop to be held in Dayton, Ohio, April 22-24, 1975.

KEY WORDS R/V Flight Pressure Data, Pressure Sensors, Steady State Pressure Data, Fluctuating Pressure Data

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I. INTRODUCTION

Flight test pressure data are required to meet Re-entry Vehicle (R/V) mission objectives.

The prime purpose of flight test pressure data are to:

- Determine the inflight pressure distribution to determine and/or verify the predicted forebody and base drag components of total drag (steady state forebody and base pressure data required)

- Verify flow field predictions for trajectory regimes of maximum heating or maximum axial/lateral loading (steady state forebody pressure data required)

- Determine the altitude of onset of boundary layer transition (steady state base pressure data required)

- Determine the boundary layer noise level on the frustum for verification of structural analysis (acoustic/fluctuating pressure data required)

The purpose of this paper is to present a "state-of-the-art" assessment of flight test pressure instrumentation techniques currently in use by GE-RESD. This assessment is provided to the 8th Transducer Workshop so that other experimenters within the scientific community can take advantage of the recent flight and ground test pressure measurement techniques developed/evolved at GE-RESD within the past few years. It should be noted that the scope of this paper encompasses the pressure measurement system from the pressure port to the pressure transducer. This paper will deal in four basic areas:

1. Pressure port diameter/erosion effects
2. Pressure tubing diameter/length effects
3. Pre-flight calibration of pressure transducers
4. Acoustic (fluctuating pressure) measurement techniques

II. RESULTS/DISCUSSION

The following section will consist of ground and flight test data that illustrate current flight test problem areas, and recommended solutions/pressure measurement techniques.

A. PRESSURE PORT DIAMETER/EROSION EFFECTS

Pressure port diameter for wind tunnel applications has a negligible effect on steady state forebody data; however, port diameter has a significant effect on flight test pressure data particularly in turbulent flow. Figure 1 shows ground test wind tunnel data on a slender cone that illustrates that the measured steady state pressure level is invariant with port diameter ranging from 0.030 to 0.240 inch. It is known, however, that R/V flight vehicles with ablative heat shields will experience pressure port erosion in turbulent flow and that port erosion can cause erroneous pressures to be recorded (Ref. 1). In addition, ground test data on simulated pressure port erosion geometries has demonstrated that port erosion effects can lower the measured steady state pressure levels by 25 percent with the lowest pressures corresponding with the largest erosion area (Fig. 2).

Rocket exhaust ablation tests at the Malta facility on full scale frustum heat shields (Fig. 3) have indicated that pressure ports that do not erode produce a constant pressure during the run while ports that do erode will produce a lower pressure (Figs. 4 and 5). In addition, pressure port erosion has been found to be a function of port diameter and heat shield material. It has also been found that phenolic and epoxy heat shield materials appear to be more prone to pressure port erosion effects than carbon and graphite materials. In general, Malta ground test data have indicated that large diameter pressure ports (0.060 to 0.120 inch) are more prone to experience erosion effects than small diameter ports (0.025 to 0.060 inch).

Recent R/V flight test data on a slightly blunted slender sphere cone R/V configuration have tended to support these ground test results. Figure 6 presents flight test pressure data from the aft end of the frustum for an R/V with 0.060 inch diameter pressure ports. The early part of the flight ($h < h_1$) represents laminar flow and the flight pressure data can be seen to be in good agreement with the predictions. However, the latter part of the flight is representative of turbulent flow ($h \sim h_1$ to h_2); the measured pressure data start to diverge and are

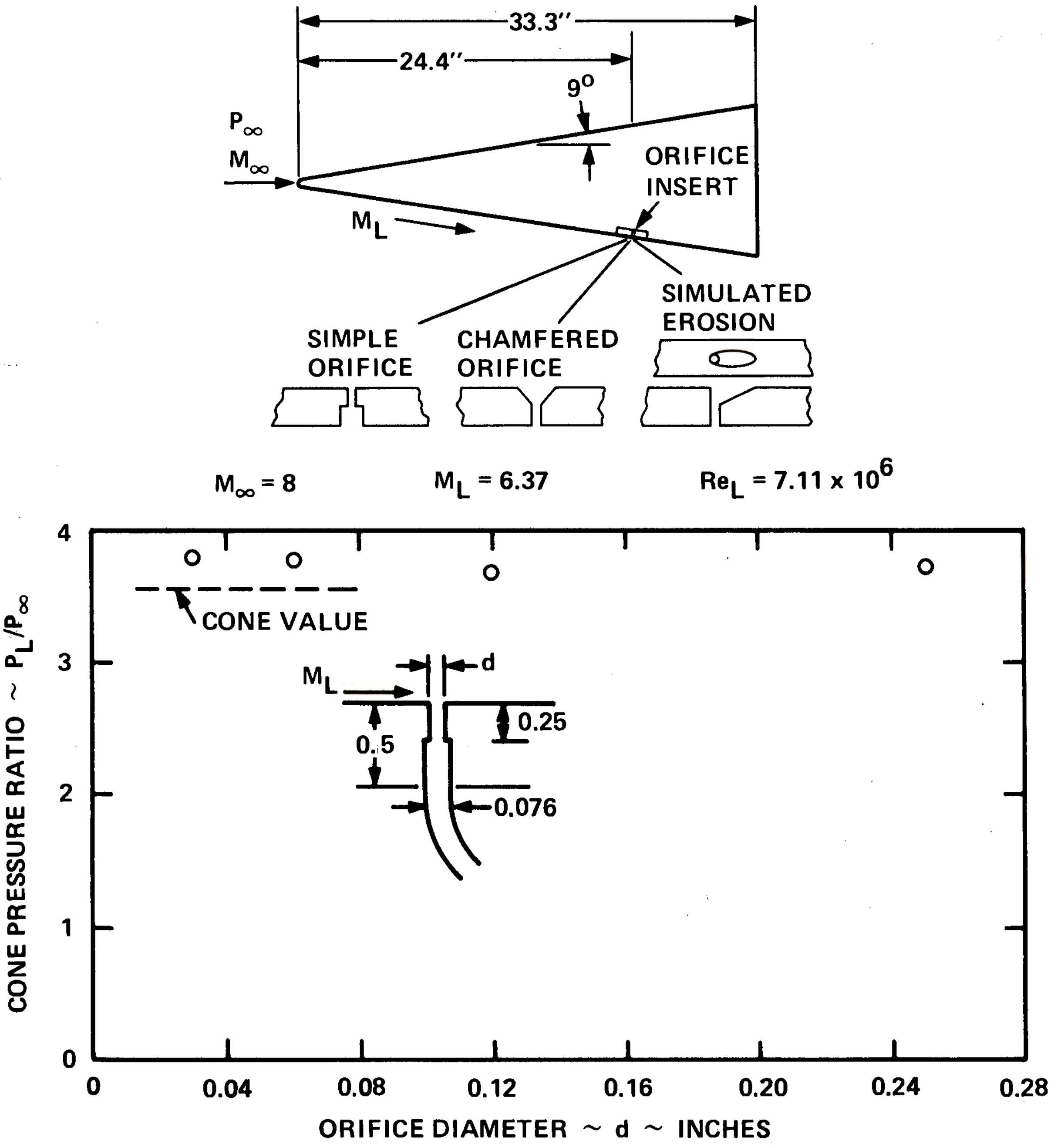
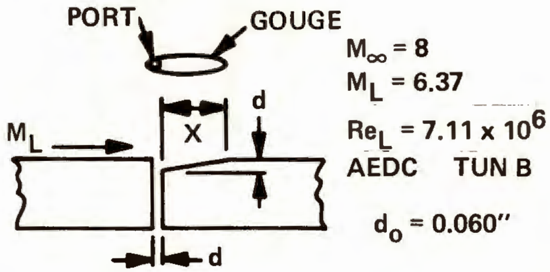


Figure 1. Effect of Orifice Size on Measured Pressure, AEDC Wind Tunnel Data.



SYM	X/d_o	d	CONFIGURATION
○	0	0	SIMPLE ORIFICE ~ 0.060″
□	3.79	0.038″	MINOR EROSION
△	7.61	0.076″	MAJOR EROSION

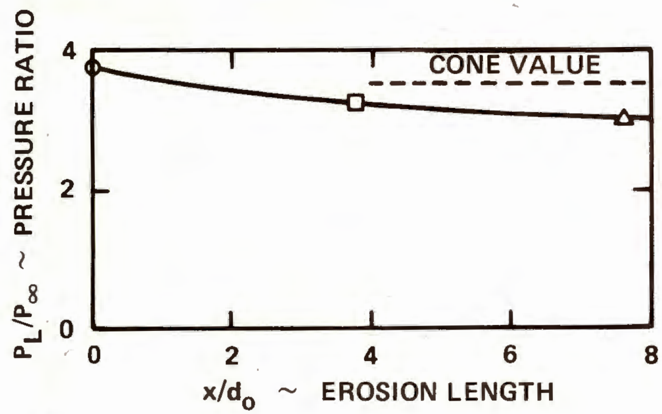


Figure 2. Effect of Simulated Erosion on Measured Pressure.

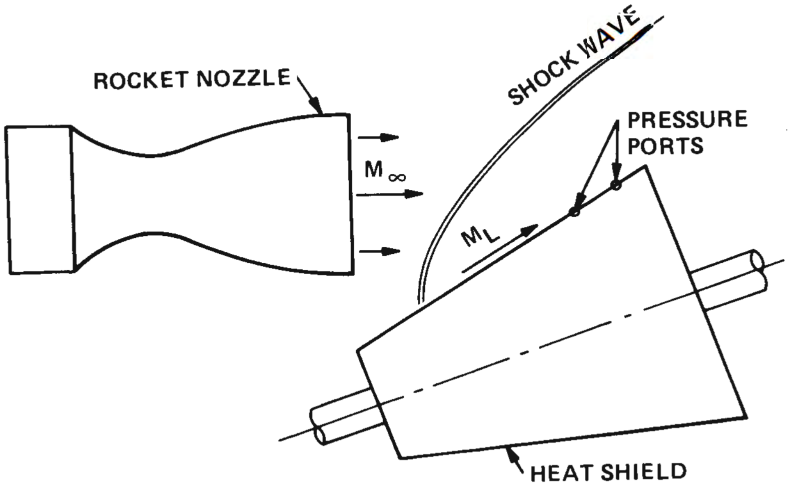
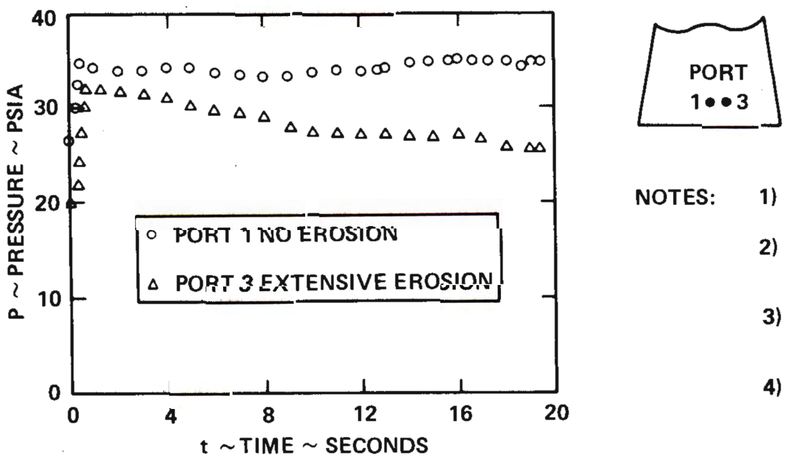


Figure 3. Malta Rocket Test Facility.



NOTES:

1) HEAT SHIELD AT ANGLE OF ATTACK
2) PRESSURE PORTS ON WINDWARD MERIDIAN
3) LOW HELIX ANGLE CARBON PHENOLIC HEAT SHIELD
4) 0.060" HOLE PRESSURE PORT

Figure 4. Pressure Versus Time on Ablating Heat Shield in Malta Rocket Exhaust.

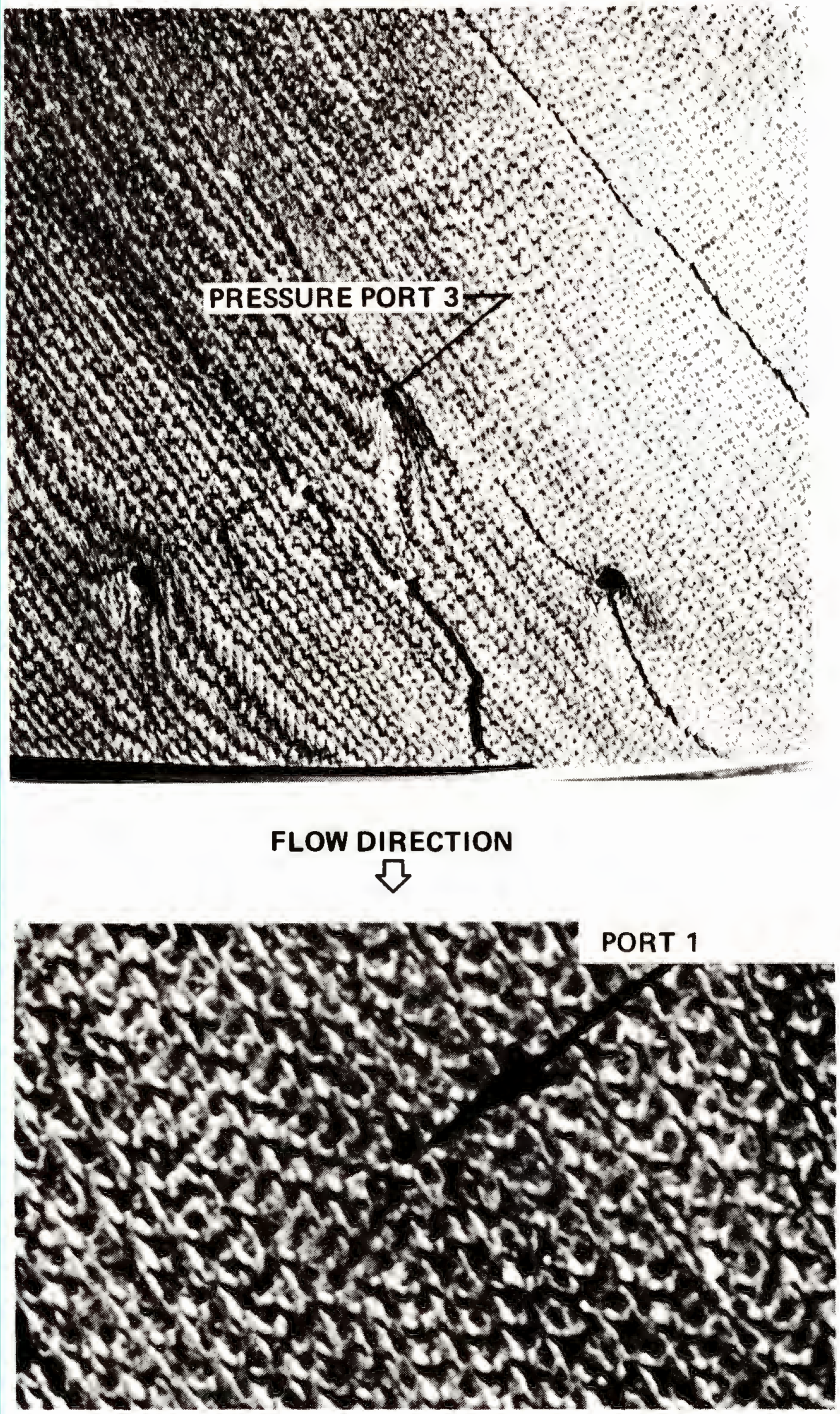


Figure 5. Full Scale CP Heat Shield After 20-Second Malta Rocket Run at Angle of Attack.

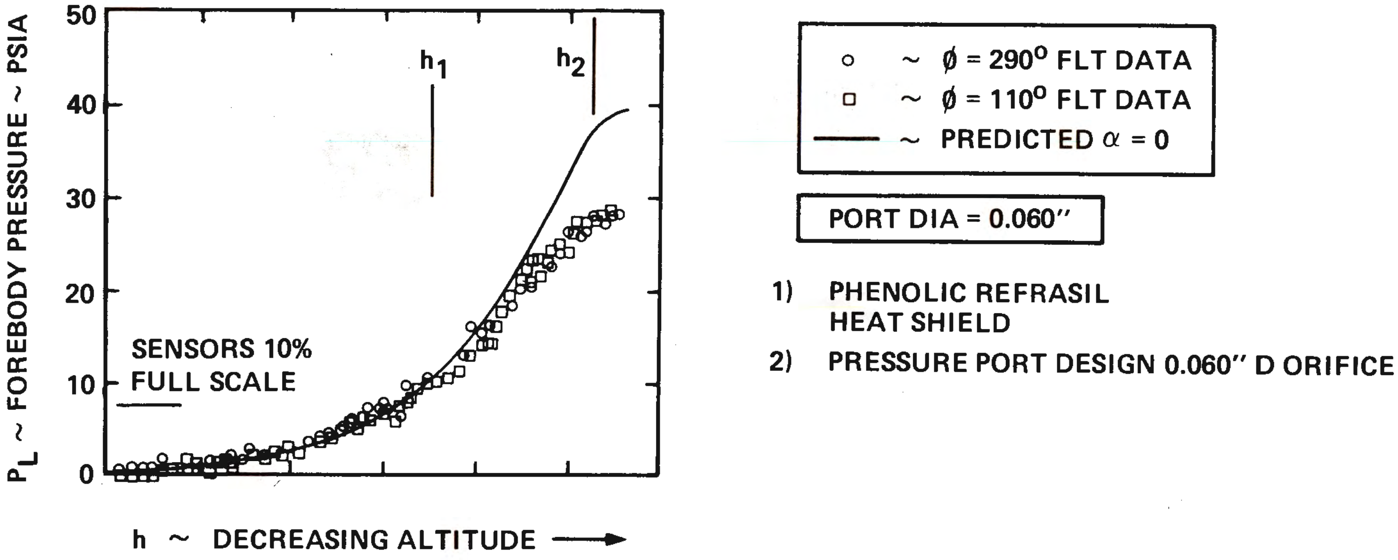


Figure 6. Forebody Flight Test Pressure Data at Aft Station.

lower than predicted by ~20 percent. This particular R/V was recovered, and the heat shield subjected to a detailed examination. The pressure ports were clearly eroded (Fig. 7) thus supporting the hypothesis derived from ground test experiments that erosion effects will produce lower pressures. In fact, the previously presented flight and ground test data for eroded ports correlate well (Fig. 8).

Figure 9 illustrates forebody flight test pressure data in laminar and turbulent flow for an R/V having 0.030 inch diameter pressure ports. The data are in good agreement with predictions indicating negligible pressure port erosion effects.

In summary, the smaller the pressure port orifice in the heat shield the better from a port erosion standpoint. Extremely tiny port diameters are difficult to machine, can clog easily, and can cause time lag effects at high altitudes. It is considered that ~ 0.030 inch diameter port represents a near optimum design for R/V forebody pressure measurements to minimize port erosion effects and not produce a time lag in the measurement.

B. PRESSURE TUBING EFFECTS

Pressure ports are connected to the pressure transducer by tubing. It is obvious that the tubing length should be minimized to minimize time lag corrections to the flight data. Pressure tubing lengths vary anywhere from ~ 3 to 12 inches in current R/V designs and tubing (ID) diameters range from 0.055 to 0.385 inch.

Pressure tubing length and diameter are important when measuring very low pressures ($P < 0.5$ psia) and can introduce significant time lag effects. For pressure > 0.5 psia time lag effects are relatively insensitive to tubing geometry.

Low level flight test pressures ($P < 0.5$ psia) are generally associated with base pressure measurements to determine onset of boundary layer transition. The determination of transition onset from base pressure measurements is a simple techinque (Ref. 2). The rate of change of base pressure d_P/d_t increases rapidly from laminar to turbulent flow, due mainly to the increase in mixing rates in turbulent flow. This manifests itself in a sharp slope change in the raw flight test pressure data.

Ground tests have been conducted (Ref. 3) to empirically verify the required pressure tubing diameter to minimize time lag effects. For these tests, pressure tubing lengths varied from 6 to 12 inches. Tests were conducted on various diameter flight tubing lengths by simulating

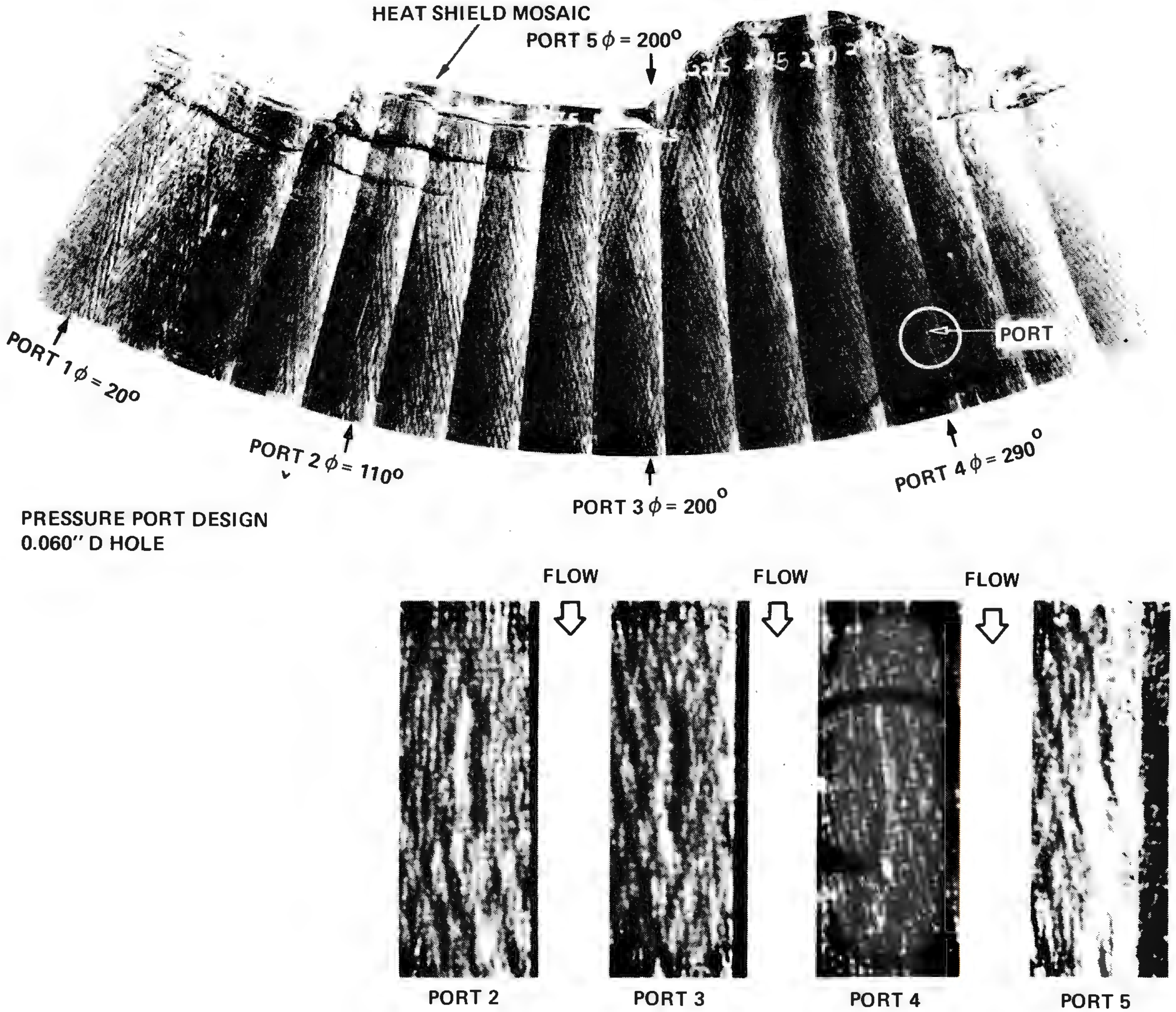


Figure 7. Eroded Pressure Ports From Recovered Heat Shield (Phenolic Refrasil).

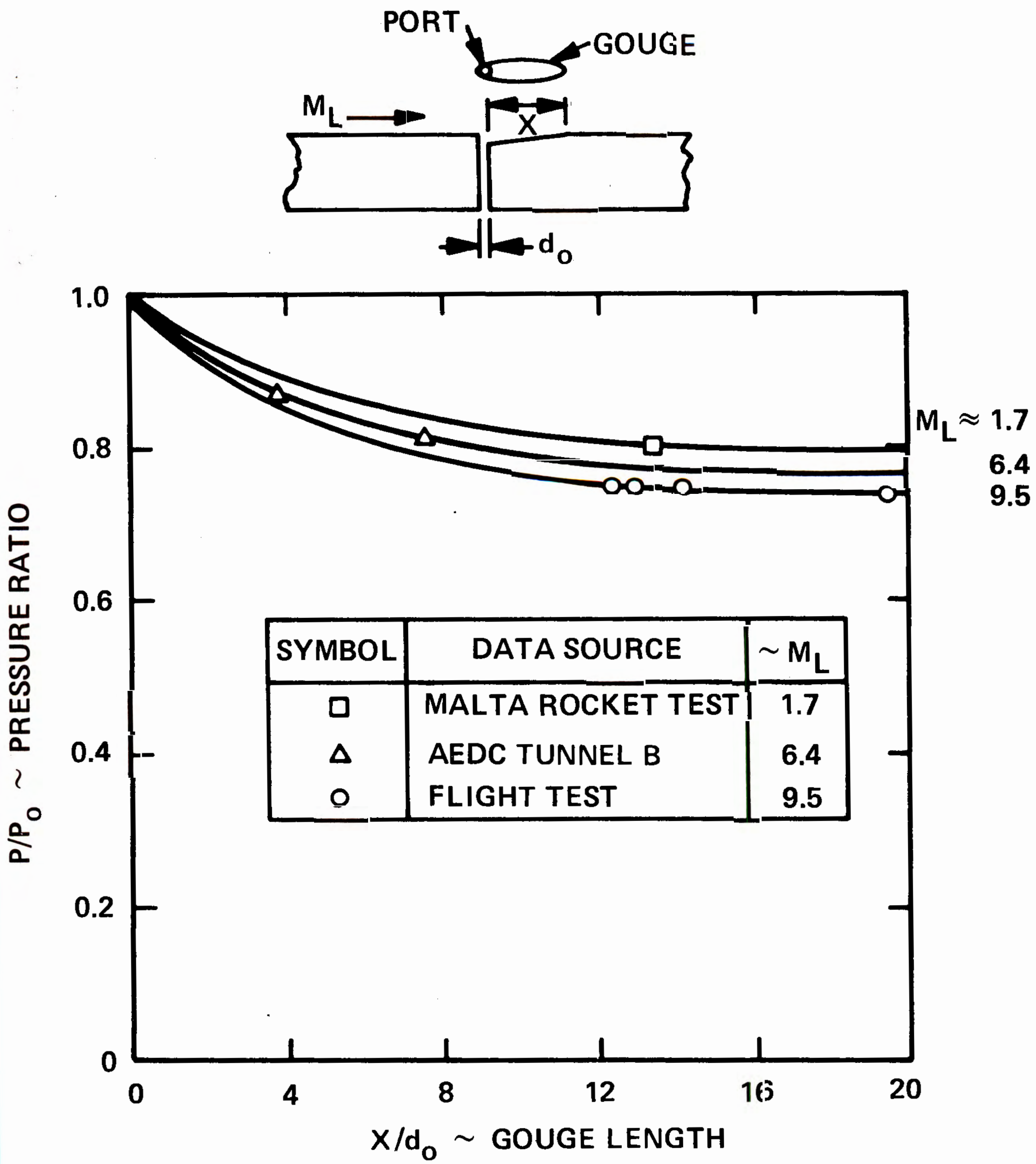


Figure 8. Effect of Gouge Length and Mach Number on Measured Pressure.

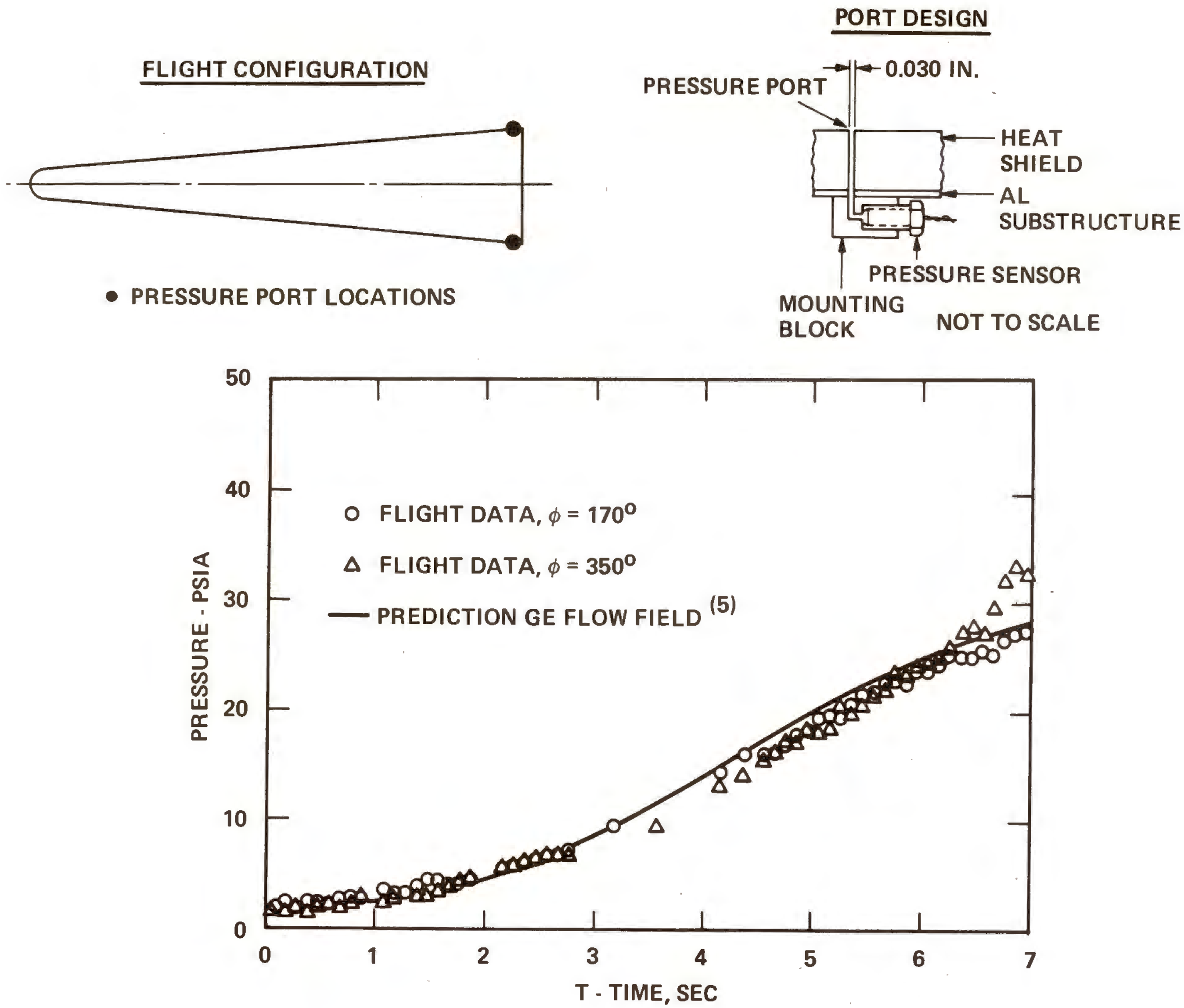


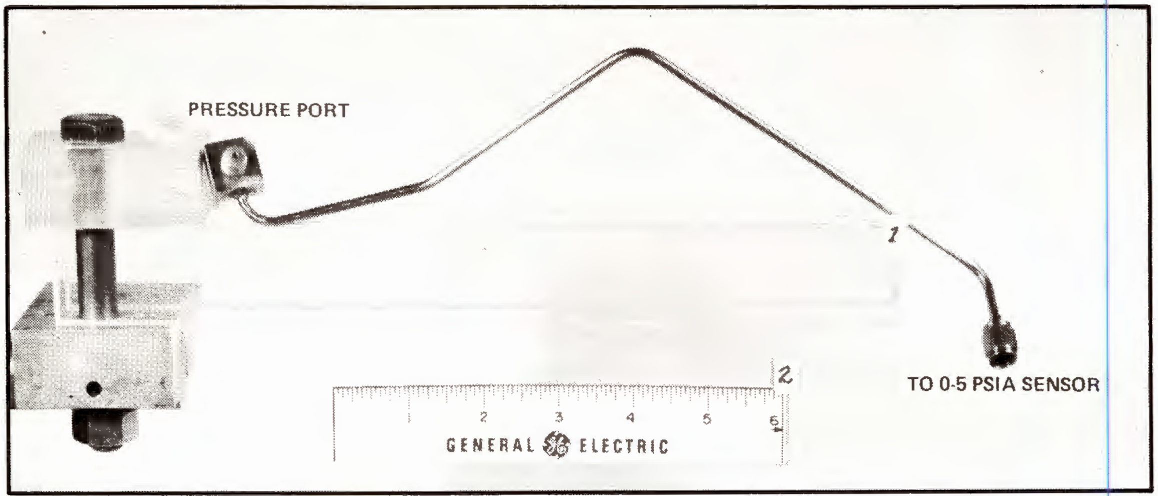
Figure 9. Pressure Sensor/Port Flight Experiment (Laminar and Turbulent Flow Flight Data).

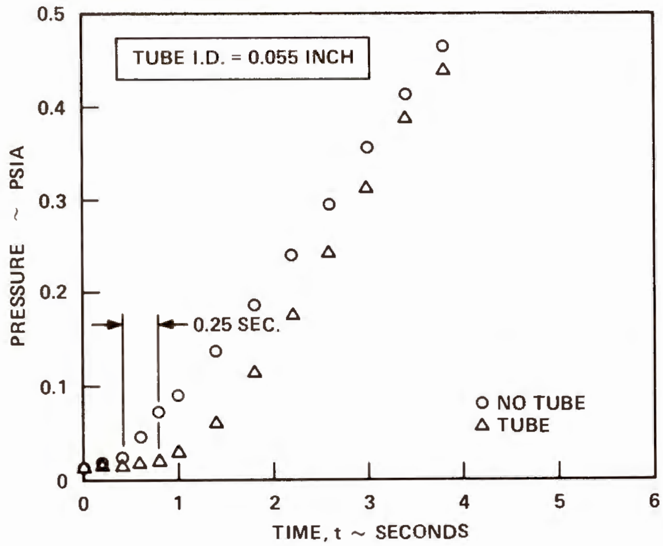
a base pressure time history during boundary layer transition for a typical re-entry trajectory. Tests were conducted by placing two identical low range capacitance transducers in a bell jar. One transducer was utilized as a standard and had no tubing while the other transducer was tested with various tubing lengths and diameters. Typical results on 0.055 inch diameter tubing clearly show that this diameter produces a time lag on the order of 0.25 second, when compared with the standard sensor with no tubing (Fig. 10a). This time lag is acceptable if it is known; is repeatable, and is factored into the flight data analysis. However, a more palatable solution is to increase the tubing diameter to minimize or eliminate time lag effects. The same test was conducted using a tubing diameter of 0.101 inch (Fig. 10b) and illustrates that the time lag has been eliminated.

The main conclusion to be drawn here is that a pressure tubing diameter of at least 0.10 inch ID is required for negligible time lag effects for low range 0 to 0.5 psia base pressure measurements. Tubing diameter requirements to eliminate time lag effects increase as the pressure level to be measured decreases.

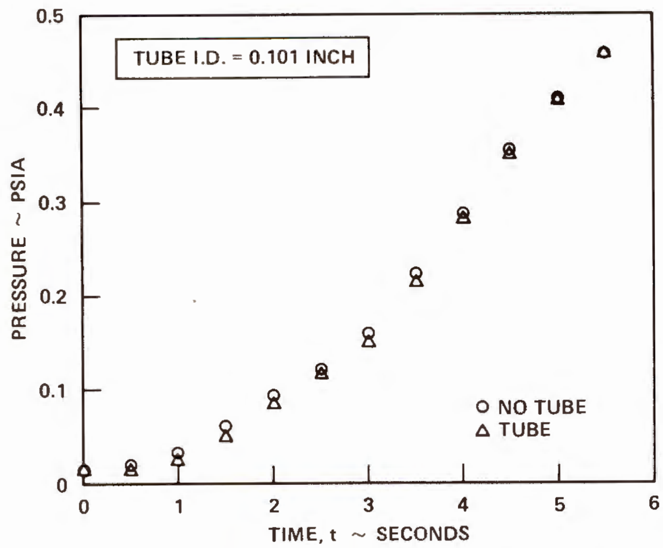
C. PRE-FLIGHT CALIBRATION OF PRESSURE TRANSDUCERS

The general procedure has been established at GE-RESD of calibrating pressure transducers in the field while the re-entry vehicle is undergoing the pre-flight checkout phase (Ref. 4). This is basically because it has been the author's experience that pressure transducers change calibration with time. The sensitivity curve, Volts per psi, is constant but has an ordinate or abscissa shift. This is generally due to reference chamber leakage. Even though pressure sensor vendors have a reported shelf life of ~ 2 or 3 years, it has been found through experience that it is best to check the calibration of all pressure transducers through the R/V telemetry system prior to flight even if the sensor is less than six months old. GE-RESD has utilized a portable field calibration ring (Fig. 11) consisting of two primary standard Wallace and Tiernan gages with overlapping ranges, 0 to 200 mmHg and 0 to 800 mmHg. The calibration is performed by pumping a typical pressure port to a partial vacuum, isolating the pump and observing the leak rate. The "tare" leak rate of the field calibration rig varies from ~ 0.005 to 0.01 mmHg/sec. If the pressure port does not noticeably increase the leak rate above the "tare" reading, the calibration proceeds. A calibration point is obtained by pumping the pressure port to a specified partial vacuum, isolating the pump and holding that pressure until both Wallace and Tiernan gages and the R/V telemetry system





10a



10b

Figure 10. Effect of Tubing Diameter on Pressure/Time Lag

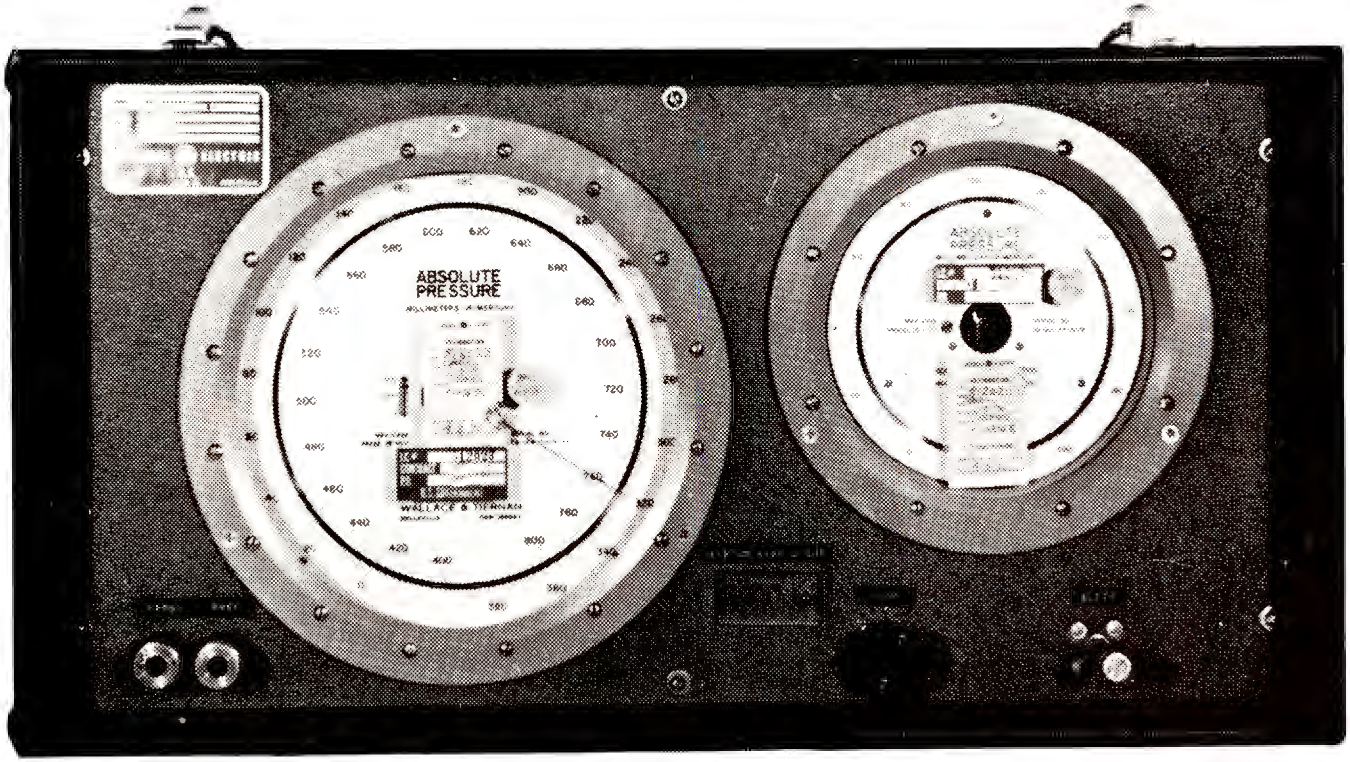


Figure 11. Aerothermodynamics Pressure Sensor Field Calibration Rig.

settle out to a constant value. The outputs are monitored for at least 15 seconds; at the end of that time period, the telemetry system is interrogated and the precise telemetry count recorded along with the pressure indicated by the Wallace and Tiernan gages. The pressure port is then vented up to a higher pressure level and the procedure repeated. Typical data for a "pot" type pressure sensor that has a shifted calibration curve from the original vendor calibration data is shown in Figure 12a. Note that it is perfectly legitimate to fly this sensor as long as the new calibration curve is used to reduce the flight data. Figure 12b shows a calibration curve for a different "pot" sensor that has remained constant and matches the vendor calibration data. Similar pre-flight calibrations have been performed on solid state strain gage sensors (Ref. 5) with similar results (Fig. 13). In summary, pressure transducers should be re-calibrated in the field prior to flight during the pre-flight check out phase and prior to lift off to insure valid flight test data.

D. FLUCTUATING PRESSURE MEASUREMENTS/ACOUSTIC DATA

All of the previous data presented were based on steady state pressure measurement requirements. Fluctuating pressure measurements are sometimes required on re-entry vehicles to make acoustic measurements of the turbulent boundary layer noise level. This section will deal with recent GE-RESD measurements of a high frequency pressure measurement system in conjunction with a telemetry system that had a frequency response of $\sim$ 25 kc. The decision was made to utilize a Kulite solid state strain gage pressure transducer (Ref. 5) to make the measurement based on past shock tunnel and wind tunnel tests which demonstrated that:

a. The sensor has a high enough frequency response to make the fluctuating pressure measurement

b. The sensor can measure both steady state and fluctuating pressures simultaneously

Figure 14 shows a schematic of the dual band pressure measurement system and signal conditioner that was used to make low frequency steady state pressures and high frequency fluctuating pressure data. High frequency pressure measurements require a short, large diameter port to obtain a short rise time. The exact port geometry was a tradeoff between thermal penetration (which favored a long port) and the high frequency response (which favored a short port). One other design constraint was consideration of a protector screen for the transducer. The Kulite transducer has a very fragile diaphragm which can be easily damaged. Accordingly, a protector screen had been designed to make the unit more rugged

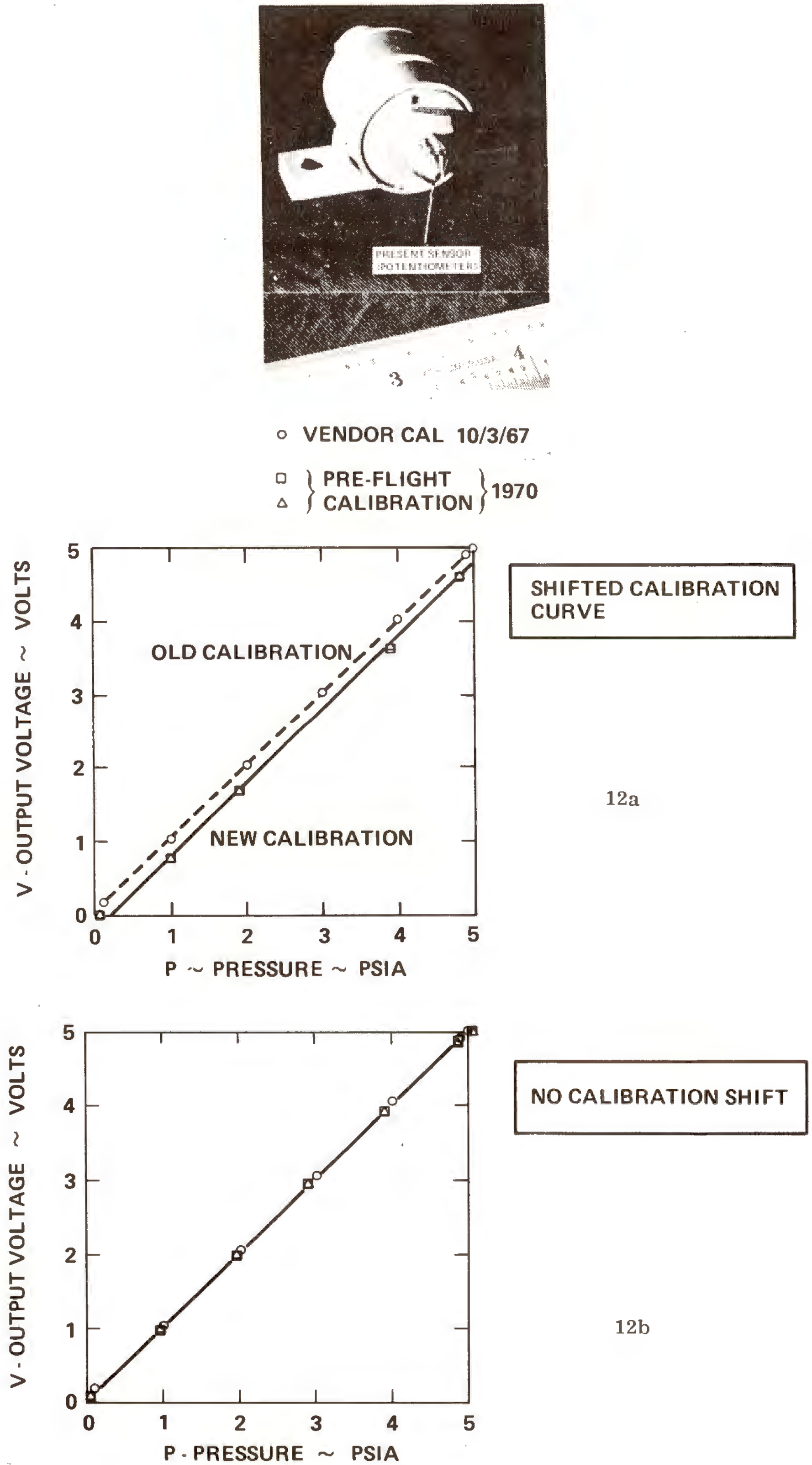


Figure 12. Typical Calibration Curve for Pot Type Pressure Sensors.

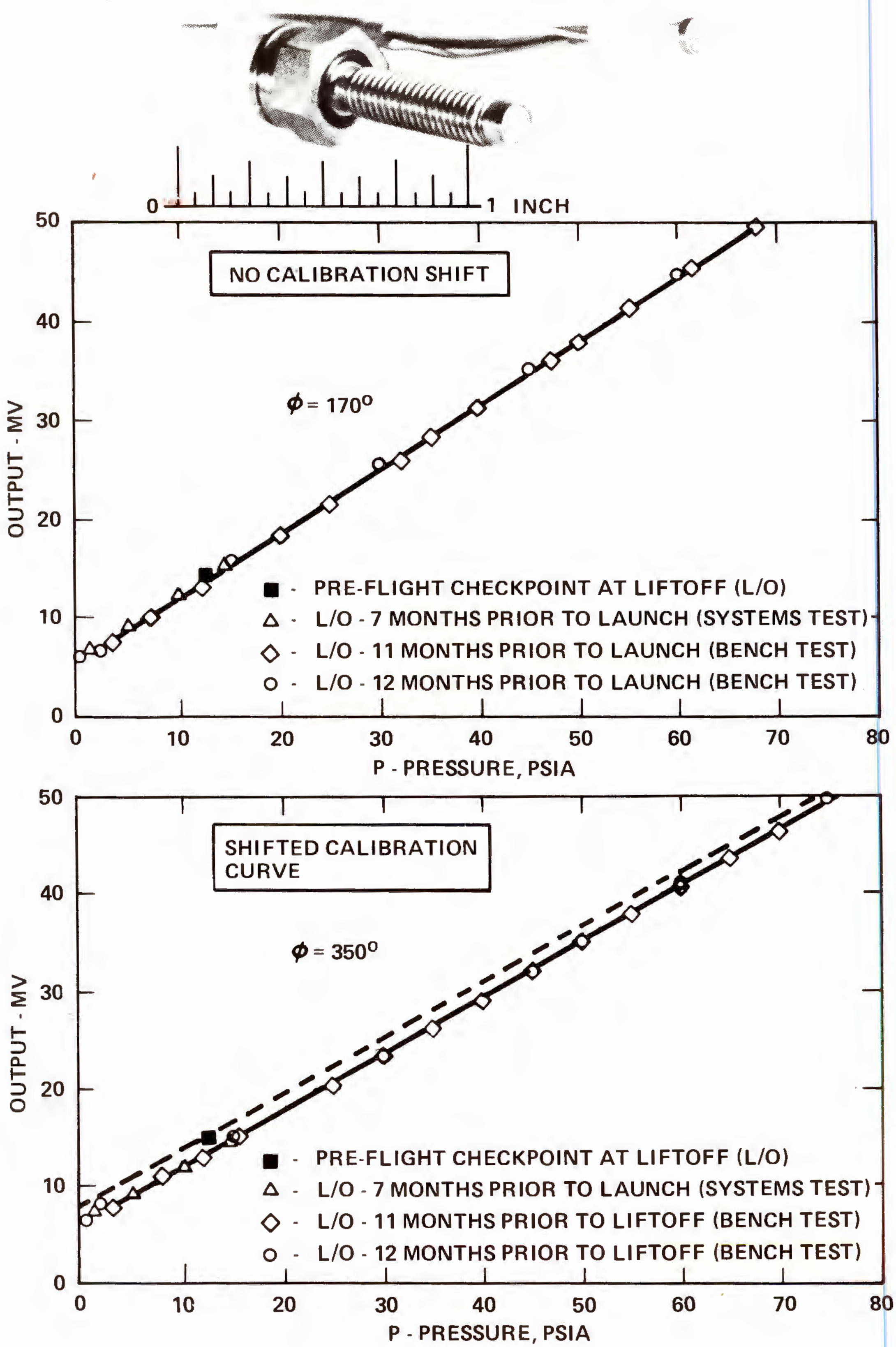


Figure 13. Typical Calibration Curves for Solid State Strain Gage Pressure Sensor.

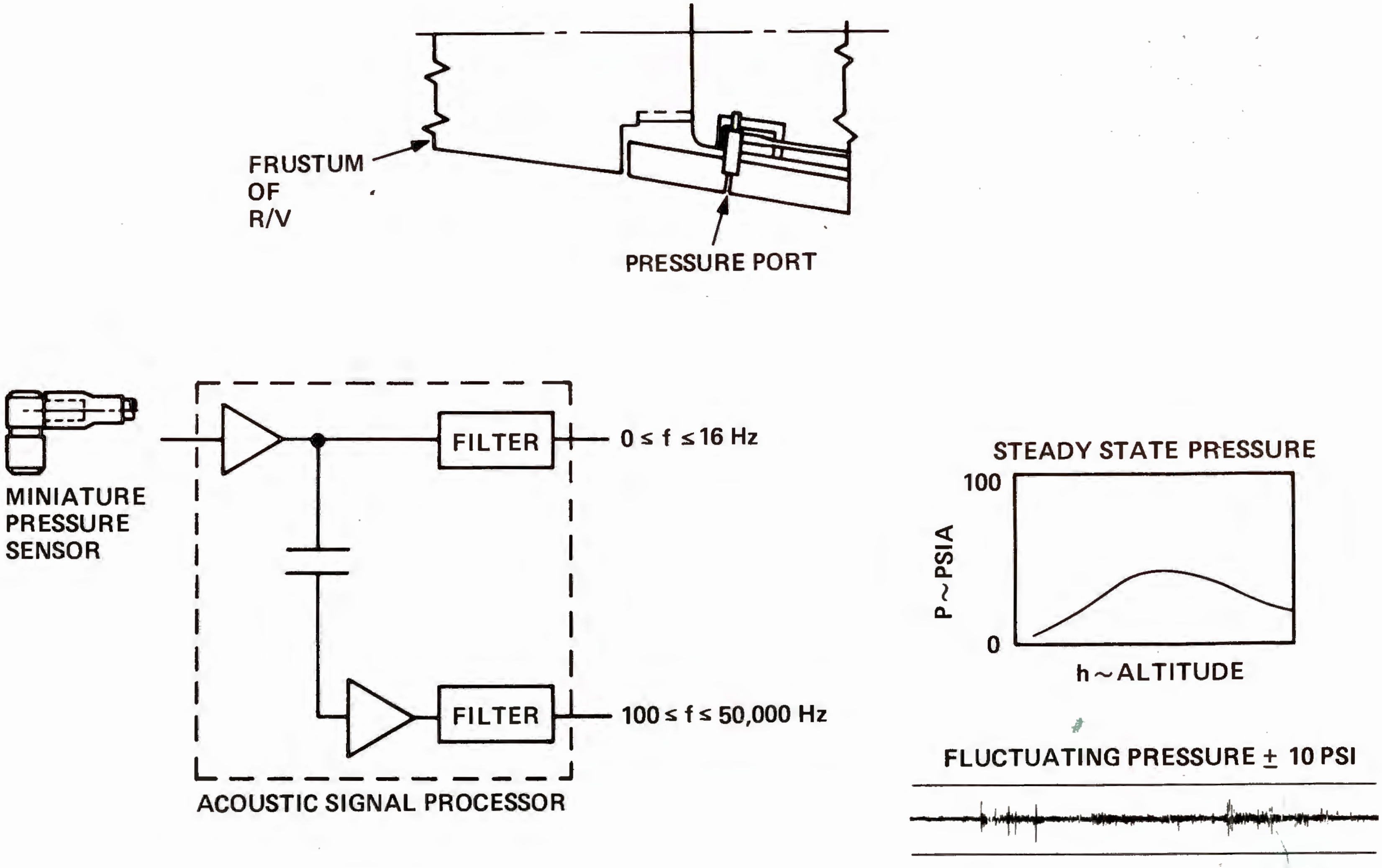


Figure 14. Dual Band Pressure Measurement System.

and to protect the diaphragm from dirt, etc. Previous step function shock tunnel data at very low pressure levels indicated that the screen did not degrade the frequency response of the sensor (Fig. 15). However, subsequent tests on two high range standard Kulite pressure sensors (0 to 100 psia) with and without a standard protector screen showed that the screen seriously degraded the frequency response at the high step function pressure history expected in flight (Fig. 16). In addition, a flight geometry screen was fabricated and tested. In all cases both screens seriously degraded the frequency response of the sensor as shown in Figure 17. The flight sensor was specifically designed to maximize frequency response and was made available in two designs, with and without a protector screen (Fig. 18). The decision was made to eliminate the screen for the flight sensor to maximize the frequency response.

The effect of port length on rise time (frequency response) was evaluated in step function shock tunnel tests (Ref. 6). The frequency response for the pressure measurement system was found to be independent of port passage length (Fig. 19). Therefore, the exact flight port geometry was chosen to make the port diameter as large as possible and port length as short as possible (consistent with thermal constraints) to maximize the frequency response of the pressure port/sensor. The exact flight port geometry and a flight sensor sans protector screen was tested in the shock tunnel and demostrated that the rise time of the system is on the order of 15 usec (Fig. 20). Calculations from this rise time indicate the flight pressure port and sensor combination have a frequency response in excess of 25 kc. For information purposes, the flight sensor mounted flush in the same shock tunnel test is a factor of three faster (~ 80 kc) than the ported configuration (Fig. 21). Based on these tests, it was concluded that the flight pressure sensor port combination had a frequency response greater than 25 kc, the telemetry bandwidth, and an acceptable port design had been demostrated for the flight measurement.

Fluctuating pressure data in the form of a Power Spectral Density (PSD) plot from a typical flight vehicle show broad band characteristics with a definite "roll off" for frequencies in excess of 10 kc (Fig. 22). This indicates that the pressure port is cutting off at frequencies higher than ~ 10 kc. The significance of this is simply that "no flow" ground test results indicated a port design with a 25 kc frequency response while the actual flight data (with flow) indicate the port was good to only ~ 10 kc. This substantiates that every possible technique

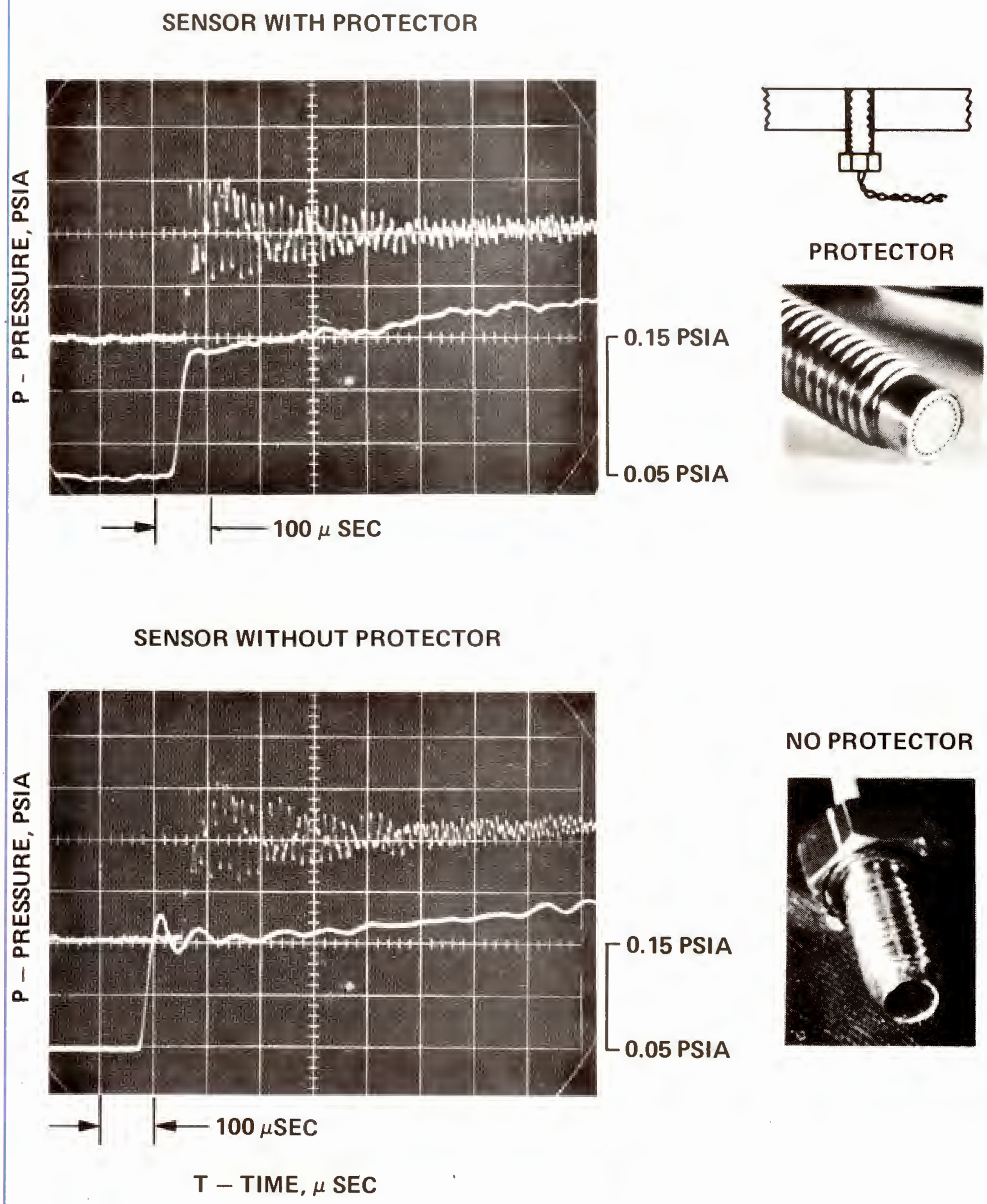


Figure 15. Effect of Protector Screen on Response Time of Flush Mounted Kulite Pressure Sensor.

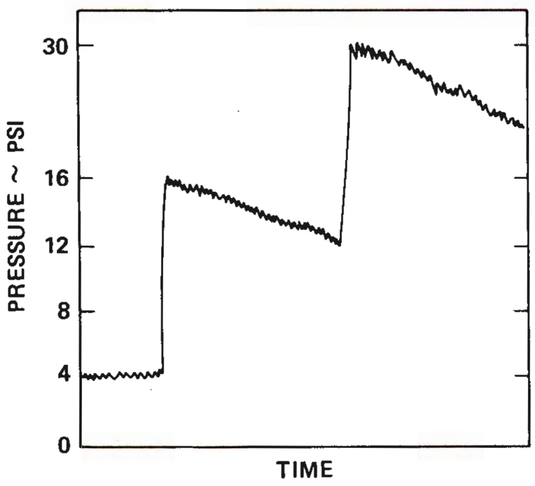


Figure 16. Typical Shock Tunnel Pressure Pulse History.

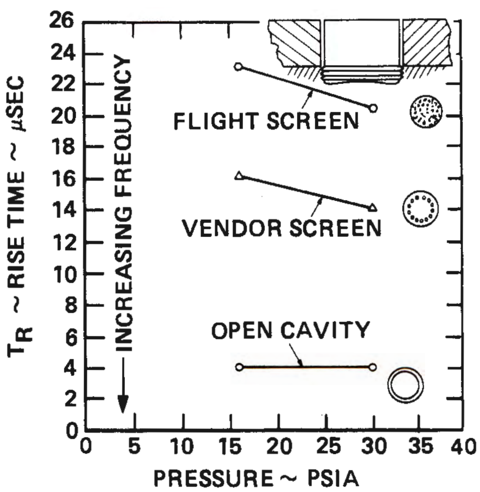


Figure 17. Effect of Protector Screen on Time Response.

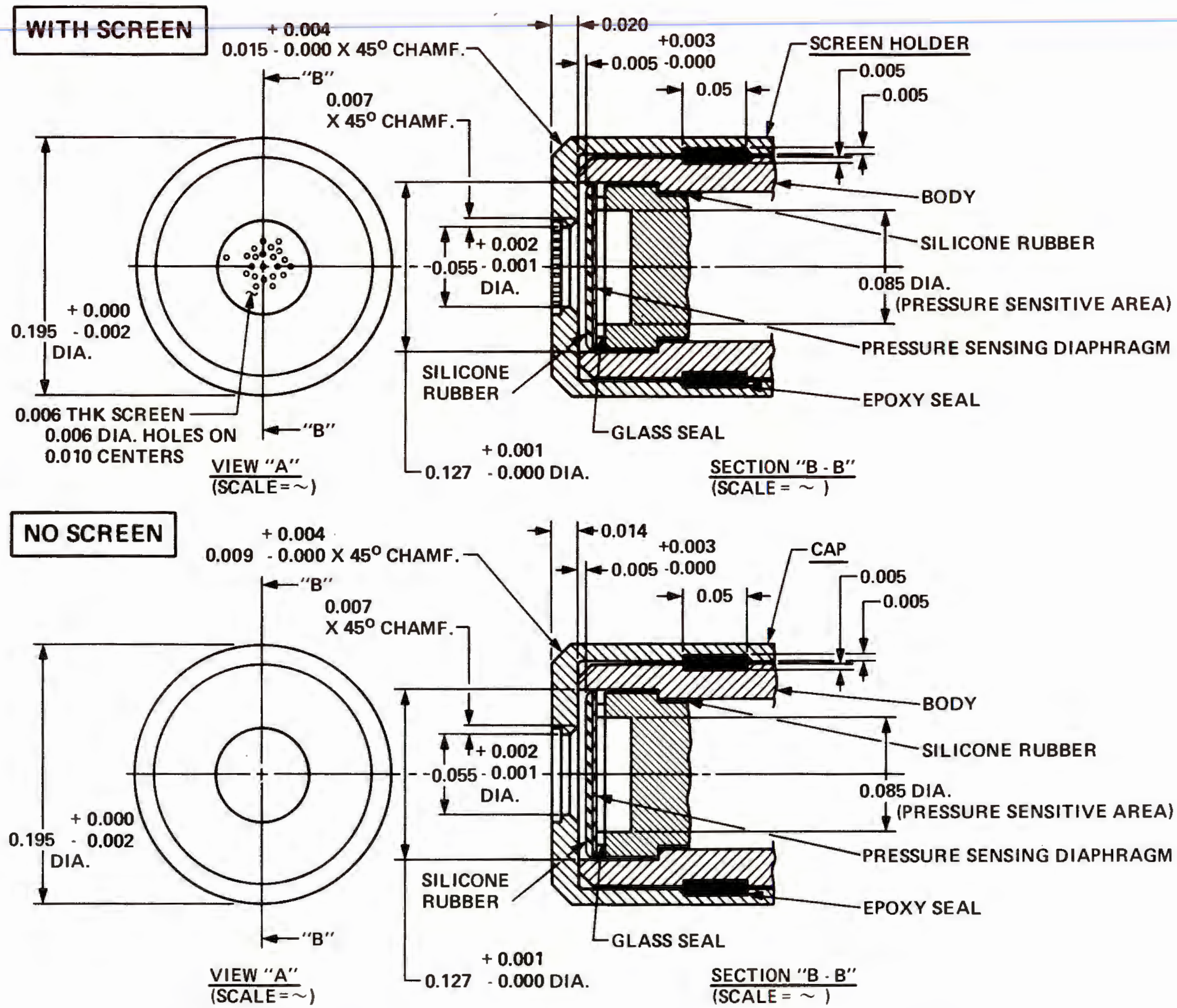


Figure 18. Flight Pressure Sensor for Fluctuating Pressure Measurement.

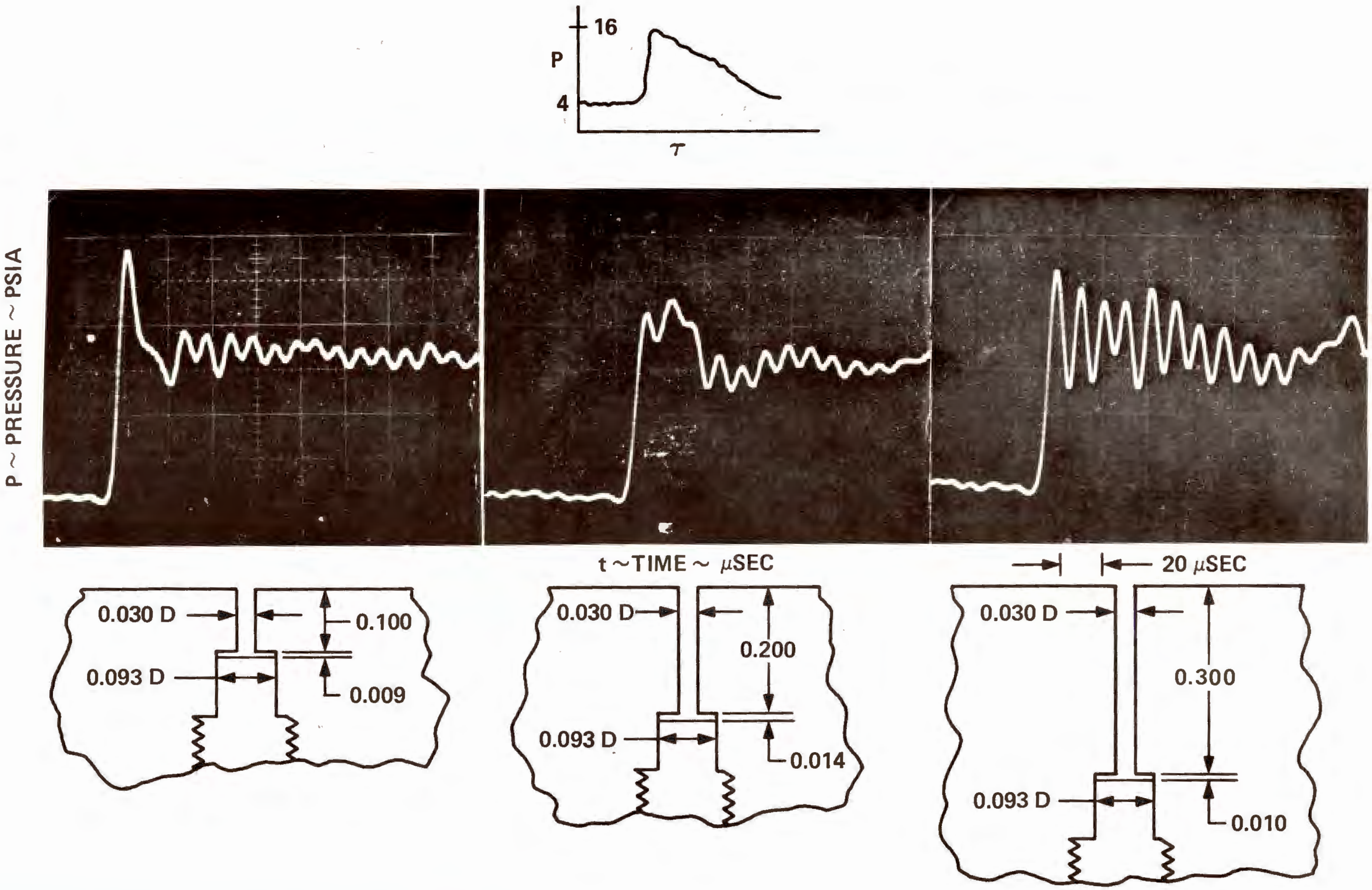
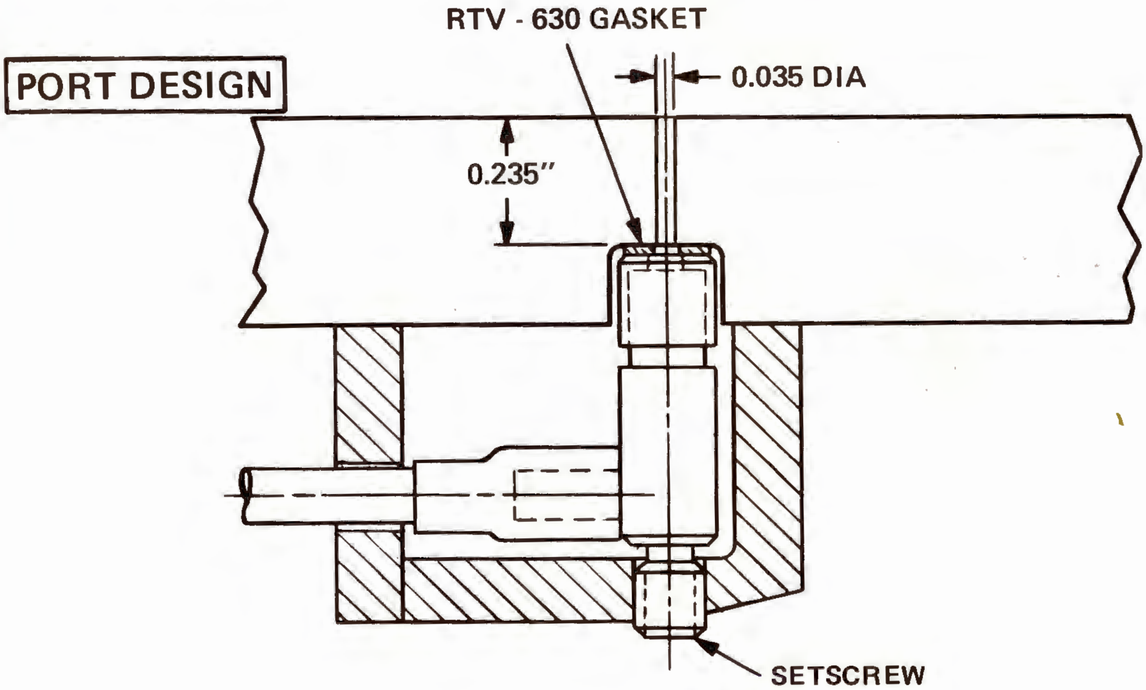


Figure 19. Effect of Port Length on Pressure Response.



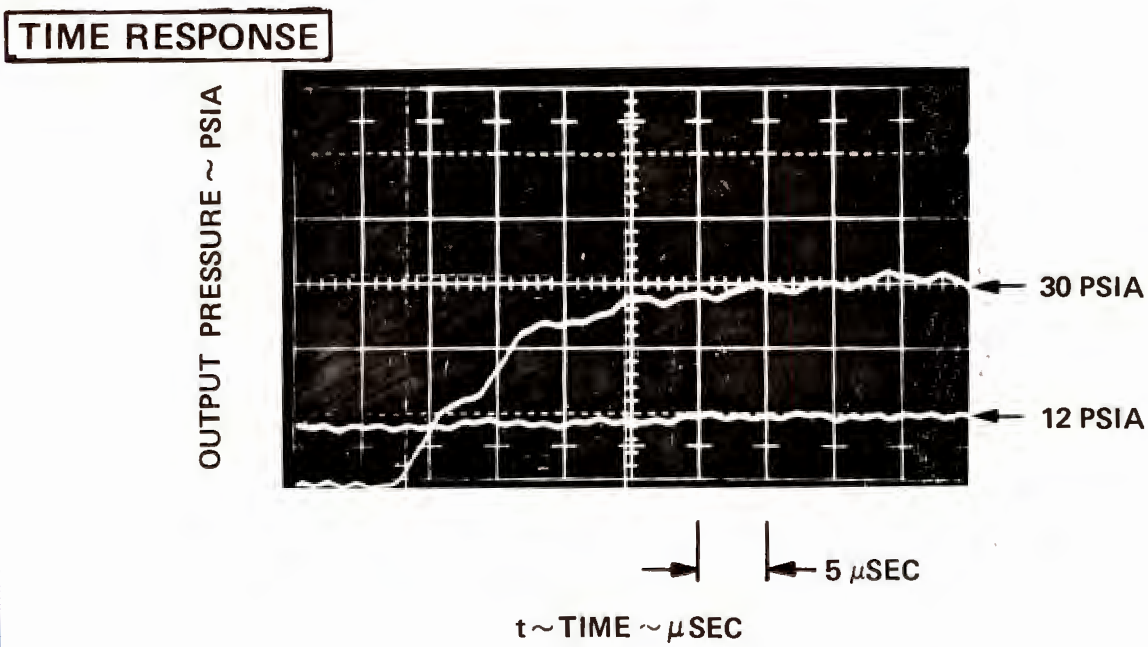


Figure 20. Rise Time Characteristics of MPS Inflight Port Geometry (Shock Tunnel Test).

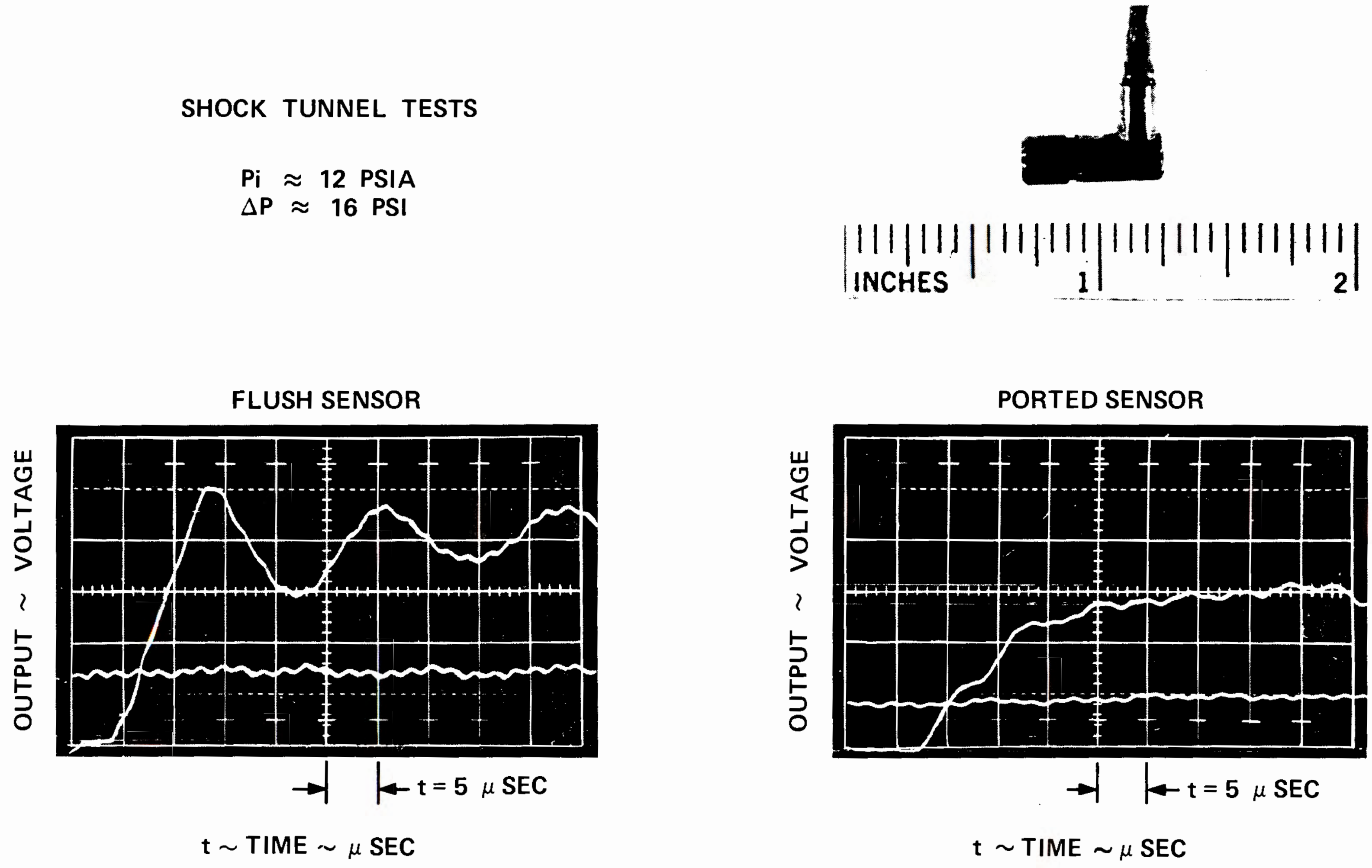
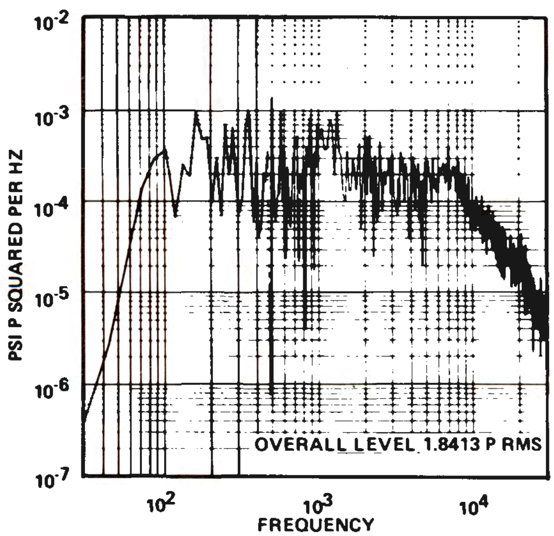


Figure 21. Effect of Flight Port Geometry on Rise Time of MPS.



f)

Figure 22. PSD Plot of Typical Flight Data From Fluctuating Pressure Measurements.

should be utilized in ground tests to maximize the frequency response of the port - even when the ground test results indicate a given port will meet the flight objectives - all additional modifications to the port that will increase the frequency response should be employed; e.g., ports should be as large a diameter as possible and as short as possible. And above all, eliminate protector screens. Finally, it is recommended that the conservative approach be utilized and every attempt made to obtain a port design from ground tests that provide a frequency response a factor of 3 to 4 higher than the flight objectives.

III. CONCLUDING REMARKS

Recent state-of-the-art R/V flight test pressure techniques in use by GE-RESD have been touched upon: pressure port diameter/erosion effects, pressure tubing diameter effects, pre-flight calibrations, and acoustic (fluctuating pressure) measurement techniques. First, it has been found that the larger the pressure port diameter the more likely the port will experience erosion effects and produce erroneous data. Flight test experience indicates that a 0.030-inch diameter port represents the near optimum port diameter to minimize erosion effects. Second, the tubing geometry connecting the pressure port to the transducer is significant and can produce time lags when measuring low pressure levels in flight such as base pressure during transition onset. Ground data have indicated that tubing diameter should be at least 0.10-inch ID to minimize time lag effects. Third, pressure tranducers tend to shift calibration with time due to reference chamber leakage. Accordingly, pre-flight calibrations of all pressure transducers throught the R/V telemetry system during the pre-flight check out phase of the R/V and prior to lift off will insure that valid flight data will be obtained. Fourth, high frequency acoustic (fluctuating pressure) measurements have been made in flight with a wide band telemetry system ($\sim$ 25 kc). Ground test data have indicated that a protector screen on the transducer significantly reduces the frequency response of the system, and it is recommended that protector screens not be utilized. In addition, step function pressure tests in a shock tunnel indicated the pressure port design would have a frequency response in excess of 25 kc when, in fact, the flight data indicated the port design started to "cut off" at approximately $\sim$ 10 kc. It is, therefore, recommended that port designs chosen from ground test data be a factor of $\sim$ 3 to 4 higher than the flight requirements.

REFERENCES

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2. Cassanto, J. M.; "A Method of Determining Onset of Boundary Layer Transition from Flight Test Base Pressure Data," GE-RESD ATFM 67-23, Oct. 1967.

3. Burton, T.; "Unpublished Data," 1973.

4. Cassanto, J. M.; "Flight Test Pressure Measurement and Analysis Techniques for Hypersonic Re-entry Vehicles," Internal GE Document, Oct. 6, 1970.

5. Cassanto, J. M., Rogers, D. A., Droms, C. and Robison, A.; "Use of a Miniature Solid State Pressure Transducer for R/V Flight Test Applications," Paper presented at the ISA 20th International Aerospace Instrumentation Conference, Albuquerque, New Mexico, June 1974. Also see GE-RESD TIS 73SD251, Dec. 1973.

6. Maguire, B. L. and Fehl, C.; "Experimental Investigation of Ported Pressure Sensors," GE-RESD Report to be published.

COLLECTION OF ENVIRONMENTAL DATA FOR THE HARPOON MISSILE PROGRAM IN USS PEGASUS (PHM-1)

Presented To

Inter-Range Instrumentation Group
Eighth Transducer Workshop
Dayton, Ohio
22 - 24 April 1975

by

W. Paulson

and

J. Nuhfer

Naval Ship Weapon System Engineering Station, (NSWSES)
Port Hueneme, California

COLLECTION OF ENVIRONMENTAL DATA FOR THE HARPOON MISSILE PROGRAM IN USS PEGASUS (PHM-1)

W. Paulson & J. Nuhfer

Naval Ship Weapon Systems Engineering Station
Port Hueneme, CA

Abstract

This paper describes an instrumentation suite which measures the following environmental parameters: pressure, vibration, temperature, acoustics, voltage, current, strain and events. It describes a calibration system which enables the operator to calibrate almost 70 channels of information easily, shortly before missile firing, with minimal chance for human error.

It gives special emphasis to the measurement of missile canister deflection during launch using semiconductive strain gages and a calibration technique developed at NSWSES. The advantage of high passing strain information at 0.5 Hz for dynamic measurements is described.

It also describes a NSWSES developed event stacker unit which multiplexes event channels.

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22-24 APRIL 1975

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DAYTON, OHIO

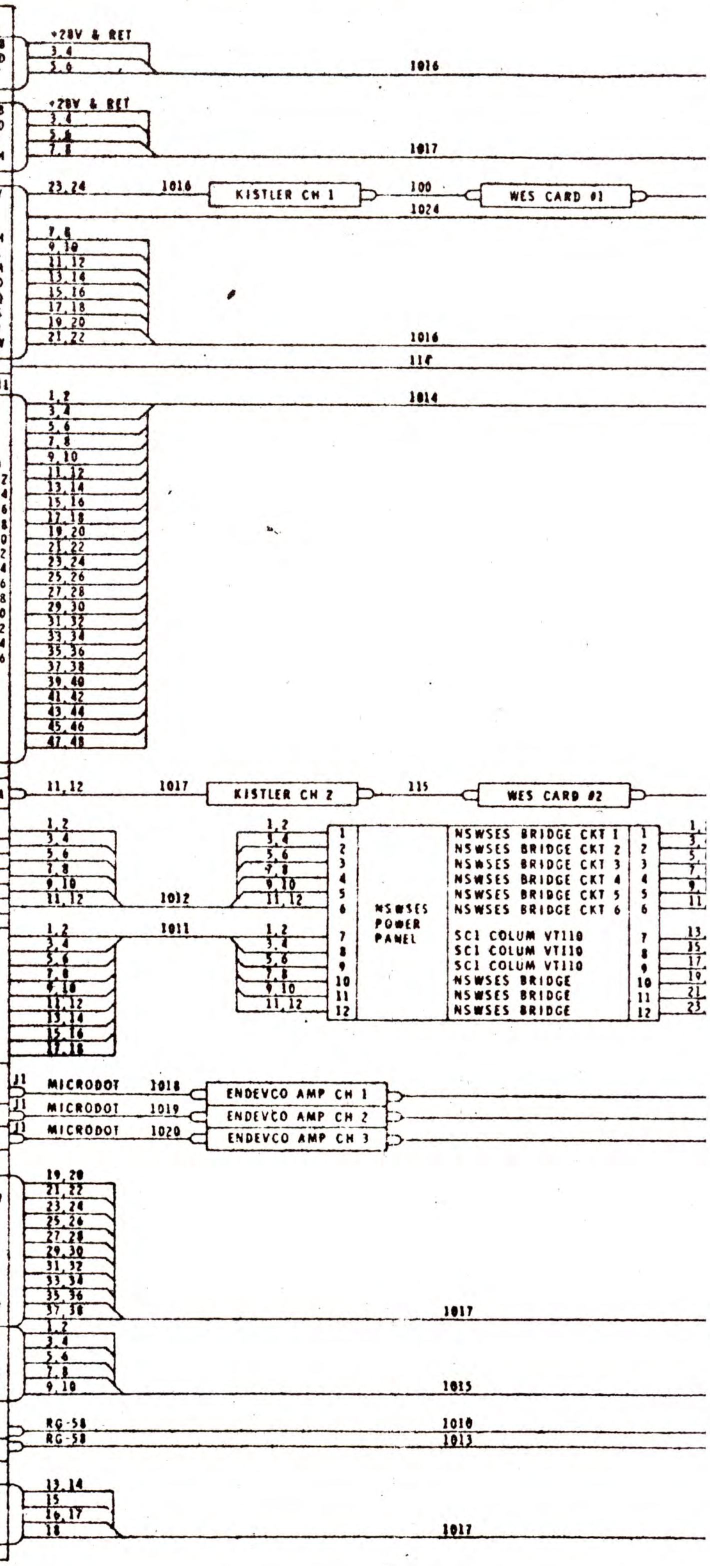
Figure 1

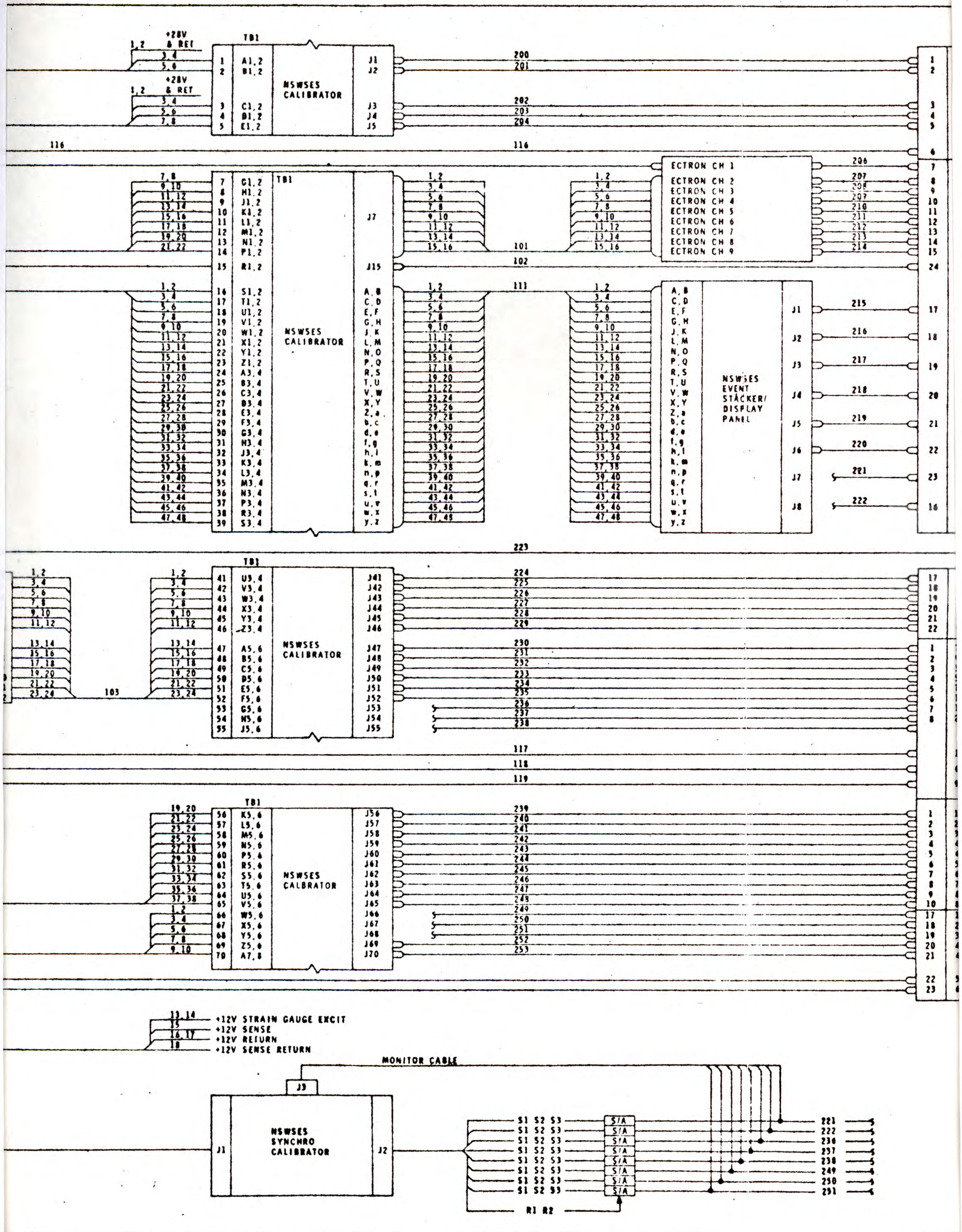
Pegasus Block Diagram

Code 49000

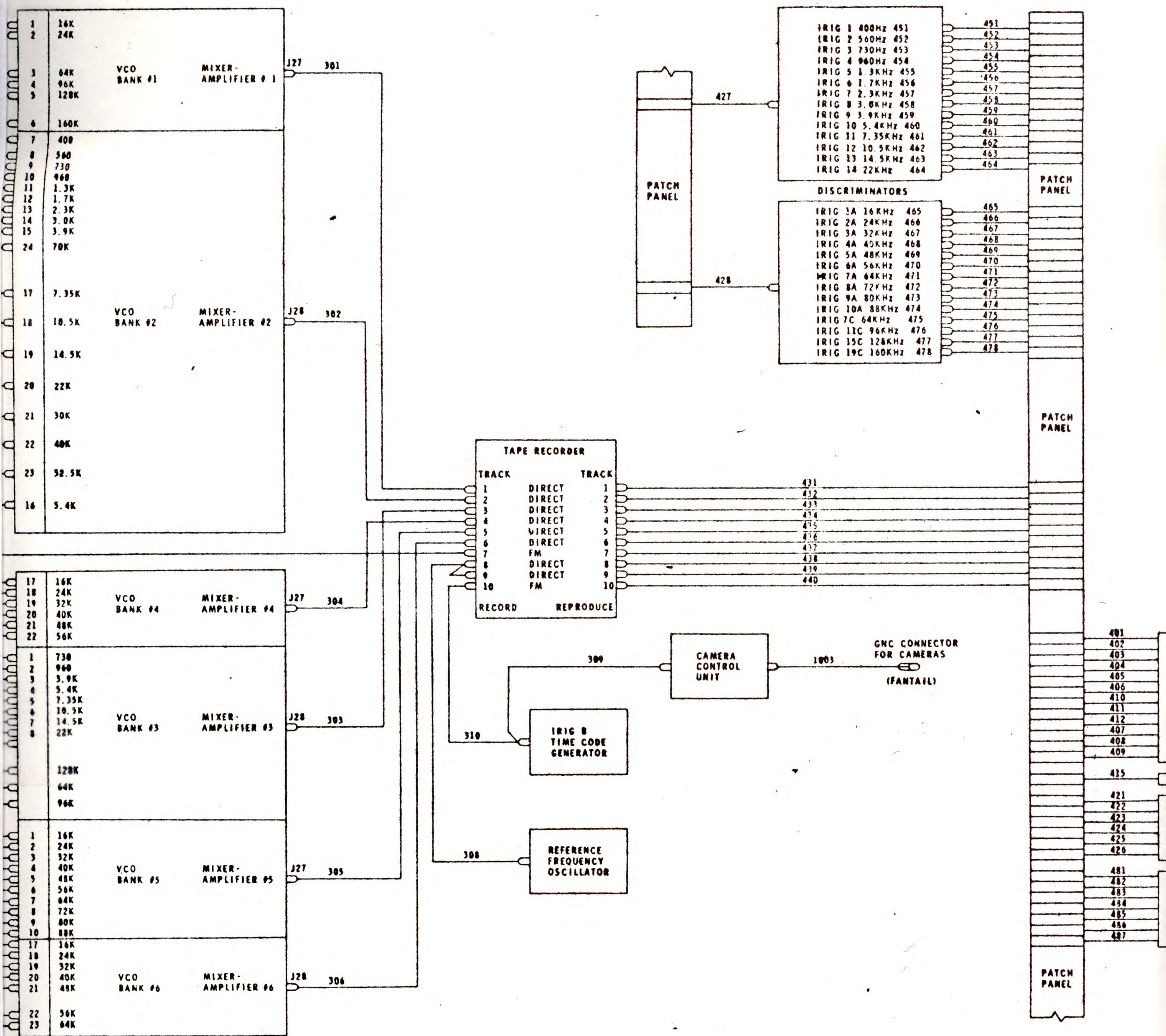
Pages 203 – 204

DESIGNATION	FUNCTION	SENSORS	CONNECTOR / PINS
CDE 10	L PRESS	EDCLIFF H-612	P121 A, B / C, D / E, F
CDE 11	L PRESS	ENCLIFF H-612	
CDE 12	A VIB. LONG	GULTON 10180073	P101 A, B
CDE 13	A VIB. RAD (BOOSTER)	GULTON 10180073	C, D / E, F
CDE 14	A VIB. RAD (MSL)	GULTON 10180073	G, H
CDE 18	L LAN AQ	KISTLER MODEL 202	P121 X, Y
CFE 21	△ TEMP "J"	THERMOCOUPLE TYPE J	Z
CFE 17	L TEMP "J"	THERMOCOUPLE TYPE J	G, H
CFE 15	L TEMP "J"	THERMOCOUPLE TYPE J	J, K
CFE 13	A TEMP "J"	THERMOCOUPLE TYPE J	L, M
CFE 14	L TEMP "J"	THERMOCOUPLE TYPE J	N, O
CFE 18	L TEMP "K"	THERMOCOUPLE TYPE K	P, Q
CFE 19	L TEMP "K"	THERMOCOUPLE TYPE K	R, S
CFE 16	L TEMP "W-5"	THERMOCOUPLE TYPE W-5	T, U
CFE 20	L TEMP "W-5"	THERMOCOUPLE TYPE W-5	V, W
CEH 13	FIRE POWER PRIMARY CUR	EON MODEL 1107 TOROID	
		CON BOX #1 TB1	
CEH 01	H HDP READY	HWCC J16-67, 1	1, 2
CEH 02	H ITL ACCEPT	HWCC J16-2, 64	3, 4
CEH 03	H MSL ENABLE	HWCC J16-3, 64	5, 6
CEH 04	H HFCS READY	HWCC J16-4, 64	7, 8
CEH 05	H BOOSTER ARMED	HWCC J16-21, 64	9, 10
CEH 06	H READY TO FIRE	HWCC J16-7, 64	11, 12
CEH 07	H ITL DELAYED	HWCC J16-67, 8	13, 14
CEH 08	H FIRE ENABLE	HWCC J16-67, 9	15, 16
CEH 09	H BOOSTER SAFE	HWCC J16-22, 64	17, 18
CEH 10	H ENABLE	HWCC J16-13, 64	19, 20
CEH 11	H PORT/STBD SELECT	HWCC J16-19, 63	21, 22
CEH 12	H LAUNCH CELL SELECT	HWCC J16-17, 65	23, 24
SPARE	SPARE	SPARE	25, 26
CEH 14	H HARPOON IN LAUNCH CELL	HWCC J16-44, 82	27, 28
CEH 15	H FIRE SW CLOSED	HWCC J16-10, 64	29, 30
CEH 16	H FUZE SELECT	HWCC J16-23, 82	31, 32
CEH 17	H LAUNCH CELL EMPTY	HWCC J16-28, 82	33, 34
CEH 18	H DUD IN LAUNCH CELL	HWCC J16-36, 82	35, 36
SPARE ↓	SPARE ↓	SPARE ↓ NO CONNECTION	
CDE 19	A LAN AQ	KISTLER MODEL 202	L, M
CPP 01	P ØA △ 1 400 Hz	EON MODEL 1107 TOROID	
CPP 02	P ØB △ 1 400 Hz	EON MODEL 1107 TOROID	
CPP 03	P ØC △ 1 400 Hz	EON MODEL 1107 TOROID	
CPP 04	P ØA HEAT 1 400 Hz	EON MODEL 1107 TOROID	
CPP 05	P ØB HEAT 1 400 Hz	EON MODEL 1107 TOROID	
CPP 06	P ØC HEAT 1 400 Hz	EON MODEL 1107 TOROID	
CPP 07	S ØA-N } MSL VOLTS	SCIENTIFIC COLUMBUS VT110	TB
CPP 08	S ØB-N } MSL VOLTS	SCIENTIFIC COLUMBUS VT110	
CPP 09	S ØC-N } MSL VOLTS	SCIENTIFIC COLUMBUS VT110	
CPP 10	S ØA-1 400 Hz } MSL	EON MODEL 1107 TOROID	
CPP 11	S ØB-1 400 Hz } MSL	EON MODEL 1107 TOROID	
CPP 12	S ØC-1 400 Hz } MSL	EON MODEL 1107 TOROID	
CDE 15	B VIB X	ENDEVCO MODEL 2272	J1
CDE 16	B VIB Y	ENDEVCO MODEL 2272	J1
CDE 17	B VIB Z	ENDEVCO MODEL 2272	J1
CDE 22	L STRAIN C. S. 2. 5	BLH SPB 1-20-35	P101 T, U
CDE 23	L STRAIN C. S. 10. 0	BLH SPB 1-20-35	V, W
CDE 24	L STRAIN C. S. 18. 0	BLH SPB 1-20-35	X, Y
CDE 25	L STRAIN C. S. 22. 0	BLH SPB 1-20-35	Z, a
CDE 26	L STRAIN C. S. 23. 0	BLH SPB 1-20-35	b, c
CDE 27	L STRAIN C. S. 33. 0	BLH SPB 1-20-35	d, e
CDE 28	L STRAIN C. S. 41. 0	BLH SPB 1-20-35	f, g
CDE 29	L STRAIN C. S. 46. 0	BLH SPB 1-20-35	h, j
CDE 30	L STRAIN C. S. 64. 0	BLH SPB 1-20-35	k, m
CDE 31	L STRAIN C. S. 69. 0	BLH SPB 1-20-35	n, p
	DECK STRAIN	BLH SPB 1-20-35	A, B
	DECK STRAIN	BLH SPB 1-20-35	C, D
	DECK STRAIN	BLH SPB 1-20-35	E, F
	DECK STRAIN	BLH SPB 1-20-35	G, H
	DECK STRAIN	BLH SPB 1-20-35	J, K
CDE 21		B & K MODEL 2209	OUTPUT
CDE 20		B & K MODEL 2209	OUTPUT
		+12V STRAIN GAUGE	P101 N, O
		+12V SENSE	P
		+12V RETURN	Q, R
		+12V SENSE RETURN	S





+28V & RET
TB1
NSWSES CALIBRATOR
ECTRON CH 1
ECTRON CH 2
ECTRON CH 3
ECTRON CH 4
ECTRON CH 5
ECTRON CH 6
ECTRON CH 7
ECTRON CH 8
ECTRON CH 9
NSWSES EVENT STACKER/ DISPLAY PANEL
NSWSES CALIBRATOR
NSWSES CALBRATOR
+12V STRAIN GAUGE EXCIT
+12V SENSE
+12V RETURN
+12V SENSE RETURN
MONITOR CABLE
NSWSES SYNCHRO CALIBRATOR
S1 S2 S3
S/A
R1 R2


VCO BANK #1
MIXER-AMPLIFIER # 1
J27
301
16K
24K
64K
96K
128K
160K
VCO BANK #2
MIXER-AMPLIFIER #2
J28
302
400
560
730
960
1.3K
1.7K
2.3K
3.0K
3.9K
70K
7.35K
10.5K
14.5K
22K
30K
40K
52.5K
5.4K
VCO BANK #4
MIXER-AMPLIFIER #4
304
VCO BANK #3
MIXER-AMPLIFIER #3
303
VCO BANK #5
MIXER-AMPLIFIER #5
305
VCO BANK #6
MIXER-AMPLIFIER #6
306
PATCH PANEL
427
428
IRIG 1 400Hz 451
IRIG 2 560Hz 452
IRIG 3 730Hz 453
IRIG 4 960Hz 454
IRIG 5 1.3KHz 455
IRIG 6 1.7KHz 456
IRIG 7 2.3KHz 457
IRIG 8 3.0KHz 458
IRIG 9 3.9KHz 459
IRIG 10 5.4KHz 460
IRIG 11 7.35KHz 461
IRIG 12 10.5KHz 462
IRIG 13 14.5KHz 463
IRIG 14 22KHz 464
DISCRIMINATORS
IRIG 1A 16KHz 465
IRIG 2A 24KHz 466
IRIG 3A 32KHz 467
IRIG 4A 40KHz 468
IRIG 5A 48KHz 469
IRIG 6A 56KHz 470
IRIG 7A 64KHz 471
IRIG 8A 72KHz 472
IRIG 9A 80KHz 473
IRIG 10A 88KHz 474
IRIG 7C 64KHz 475
IRIG 11C 96KHz 476
IRIG 15C 128KHz 477
IRIG 19C 160KHz 478
TAPE RECORDER
TRACK
DIRECT
FM
RECORD
REPRODUCE
431
432
433
434
435
436
437
438
439
440
CAMERA CONTROL UNIT
309
1003
GNC CONNECTOR FOR CAMERAS
(FANTAIL)
IRIG B TIME CODE GENERATOR
310
REFERENCE FREQUENCY OSCILLATOR
308
401
402
403
404
405
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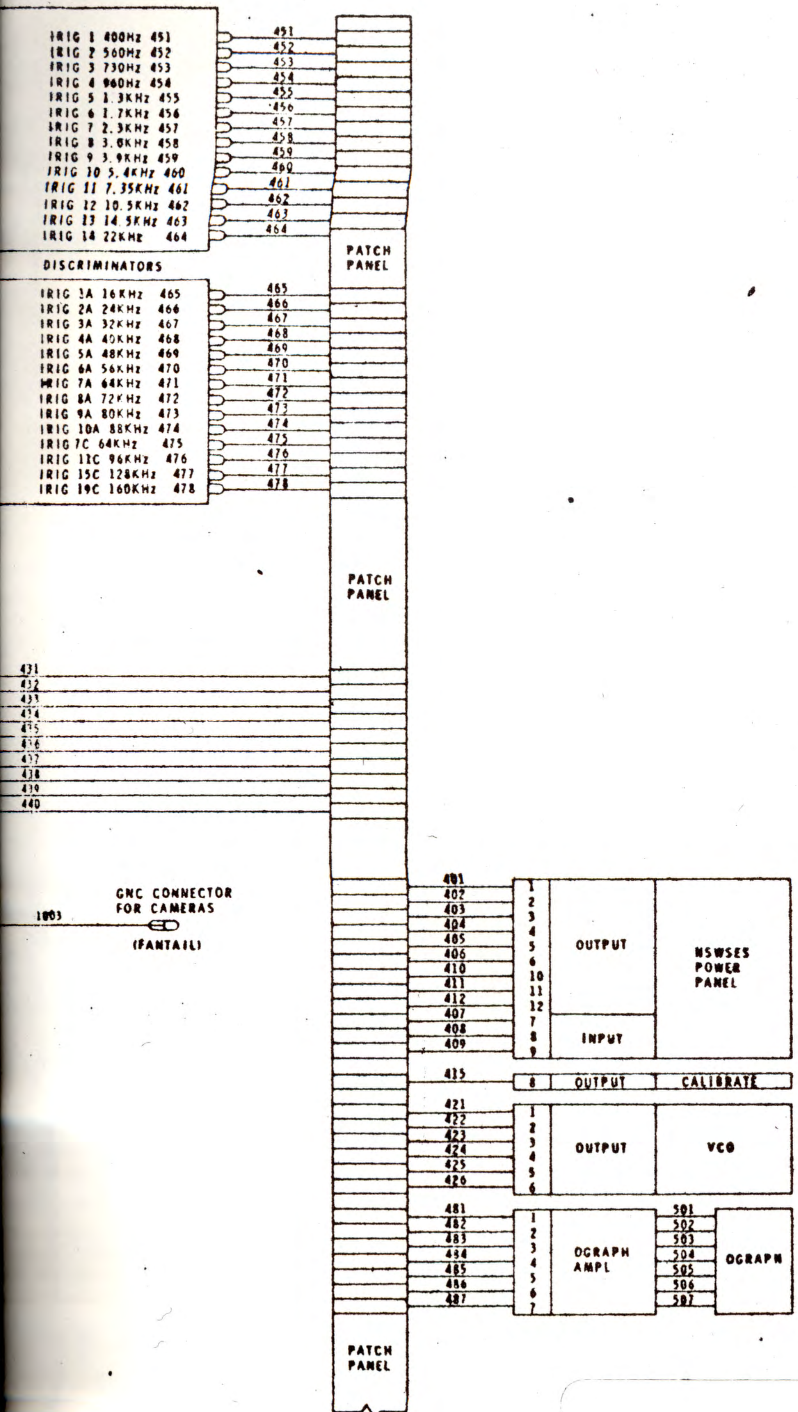

FIGURE 1

PEGASUS BLOCK DIAGRAM

TARTAR SYSTEMS DEPARTMENT CODE 4900		NAVAL SHIP MISSILE SYSTEMS ENGINEERING STATION PORT HUENEME, CALIFORNIA 93043
	NAME / DATE	WIRING DIAGRAM, HARPOON INSTRUMENTATION SYSTEM
DRAWN		
CHECKED		
ENGINEER		
APPROVED: DATE:		SIZE / CODE IDENT NO. 34008 / SKETCH NO. / REV. / SCALE / SHEET OF

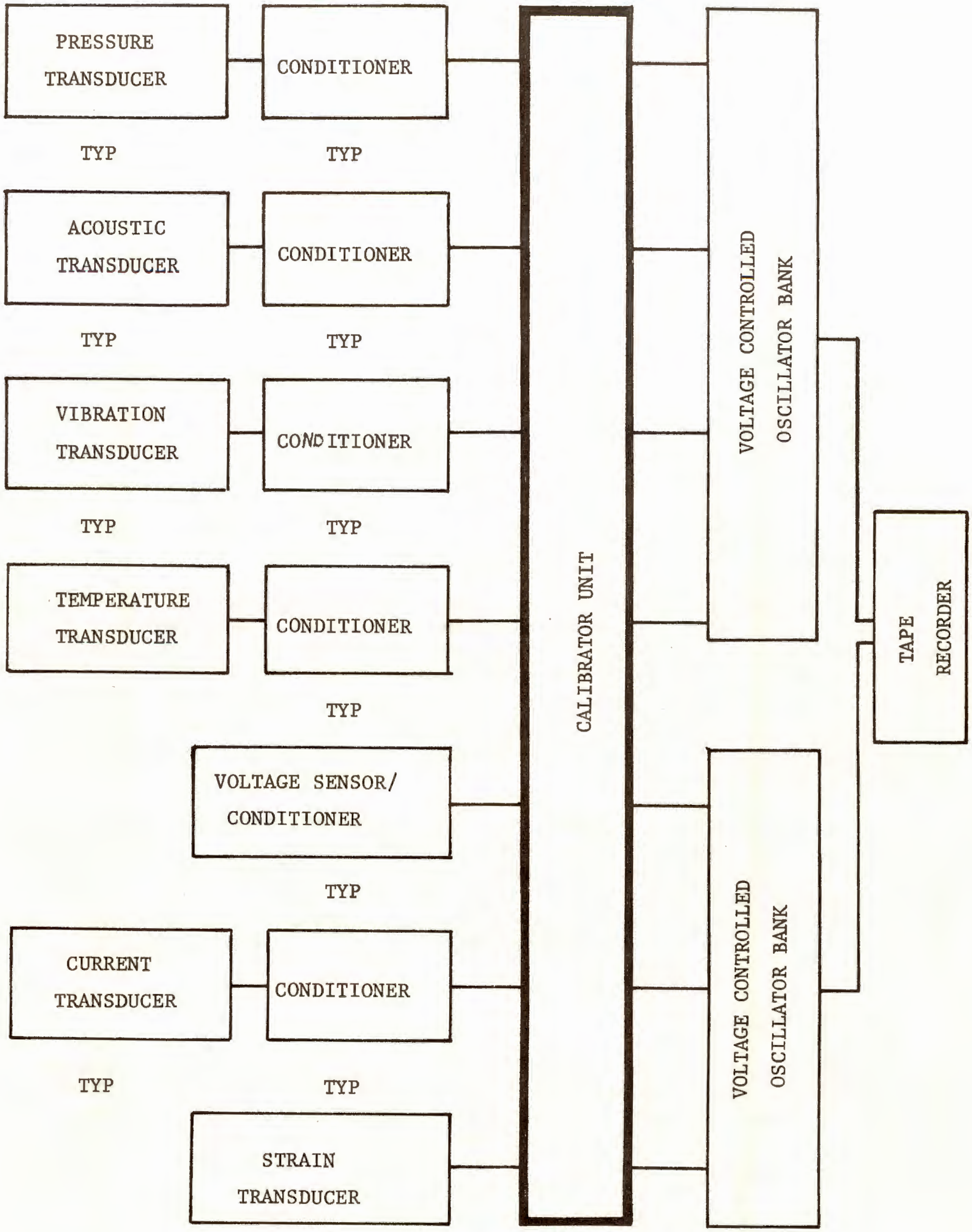

FIGURE 2

CALIBRATOR RELATIONSHIP TO OTHER INSTRUMENTATION ELEMENTS

The calibrator has two principal modes - data and calibrate. The calibrator remains in the "data" mode unless an operator depresses a spring loaded switch which forces the unit to go into the calibrate mode. This prevents the operator from inadvertently leaving the switch in the wrong position during a missile firing. Figure 3 shows one channel of the calibration unit. When the operator depresses the spring loaded calibrate switch, the signal is replaced by one of five internally generated voltages. For the example being used 0 volts represents 0% full scale and 5 volts represents 100% full scale. Voltages representing 25, 50 and 75% full scale are also generated internally.

All voltages, whether developed by a transducer and associated conditioner or by the voltage levels developed within the calibrate box, are passed through an operational amplifier. Operational amplifiers normalize the input signal by offsetting and amplifying so that the full scale output range (regardless of input range) extends between -10V and +10V. This considerably simplifies Voltage Controlled Oscillator (VCO) calibration (VCO calibration is another exercise also performed on the day of the firing, but not discussed here).

An "output select" switch selects one of several normalized outputs to be made conveniently available at the face of the calibrate unit.

The calibrator is located at the "front end" of the system. This eliminates the effects of small errors which might exist in downstream elements. The calibrator amplifier, the VCO, the tape recorder, the discriminators and the data reduction station can all be slightly "out of calibration" without any loss of measurement accuracy. Errors affect the calibrate signal and the data signal in an identical manner, and are thus eliminated. Error cancellation occurs because the signal is being compared with a reference voltage at the "front end" of the system.

The calibrate unit is divided into sections which handle transducers of a given type (temperature, voltage, current, events, vibration). Some channels (temperature and events) are not conditioned by normalizing amplifiers within the calibration unit since normalization for these classes of signals takes place elsewhere. Strain gage channels have a different form (explained later in this paper). The diagram for the complete unit is shown in figure 4. Figures 5 and 6 show photographs of the calibration unit.

3. CANISTER DEFLECTION

The HARPOON missile is usually* housed in and launched from a canister. When normally stowed, the canister is unstressed (see figure 7a). During launch, the missile shoes (supports) extend to the forward part of the canister. The weight of the missile, acting through the shoes, exerts a downward force, depressing the cantilevered portion of the canister (shown greatly exaggerated in figure 7b). This depression would be expected to give the missile a small elevation error when the missile initially leaves the canister.

NSWSES is prepared to measure deflection using strain gages. The canister has been instrumented with 10 pairs of strain gages. The instrumented canister

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**The HARPOON missile may also be launched from ASROC Launchers or Mk 26 Launcher or TARTAR Launcher.*

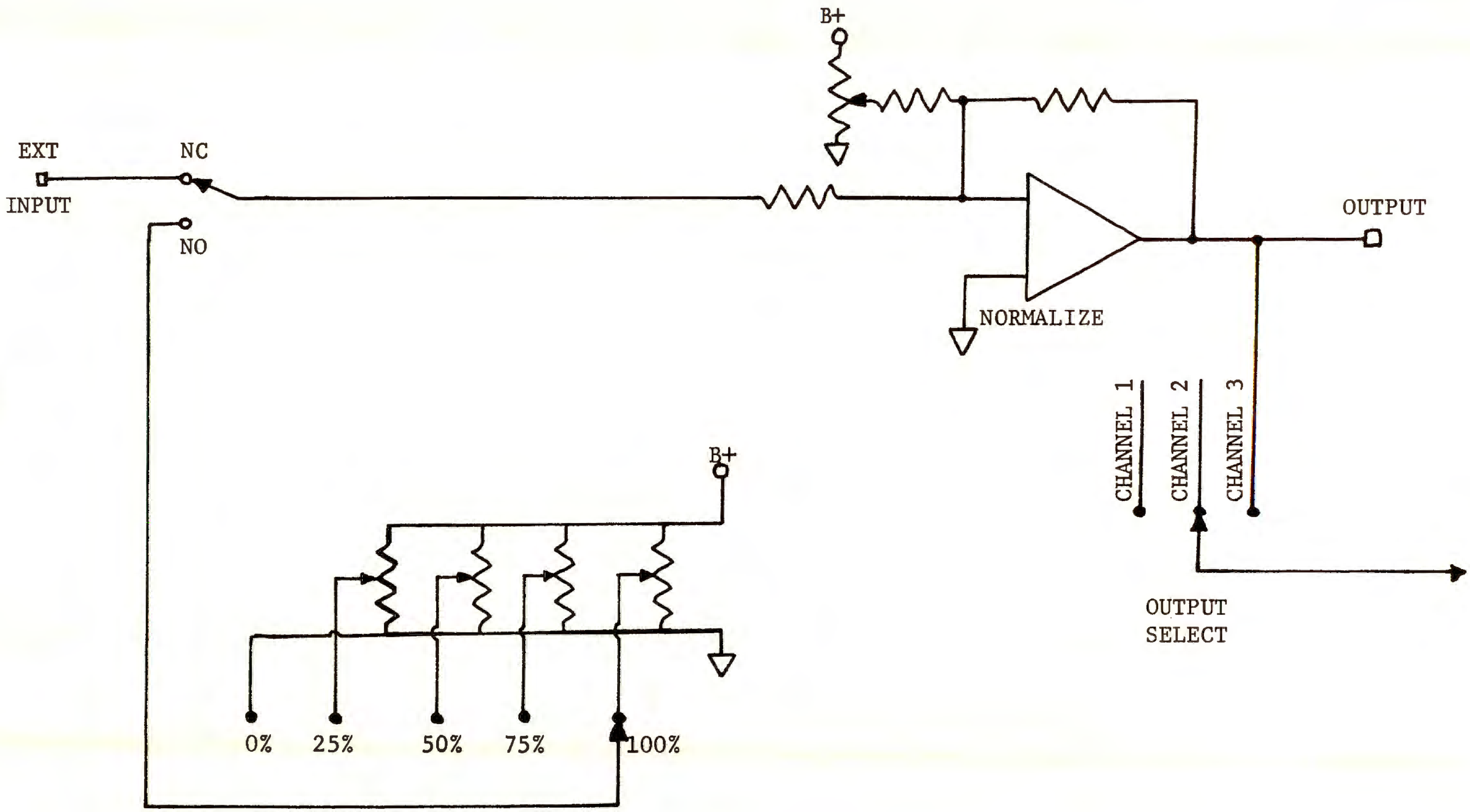

FIGURE 3

CALIBRATION UNIT (ONE CHANNEL)

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Figure 4

Code 49000

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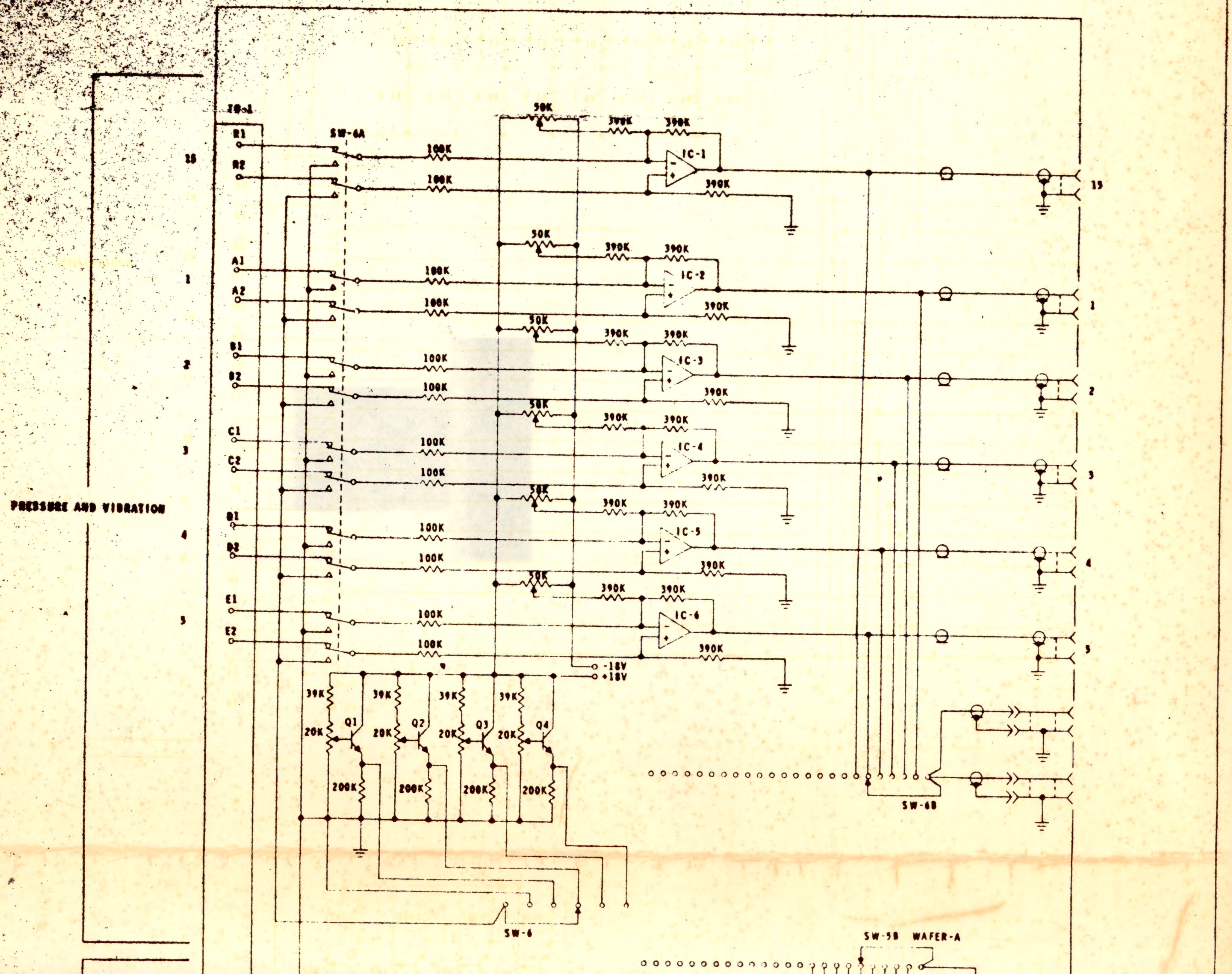
PRESSURE AND VIBRATION
SW-6A
R1
R2
A1
A2
B1
B2
C1
C2
D1
D2
E1
E2
IC-1
IC-2
IC-3
IC-4
IC-5
IC-6
100K
390K
50K
39K
20K
200K
Q1
Q2
Q3
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+18V
SW-6
SW-6B
SW-5B WAFER-A
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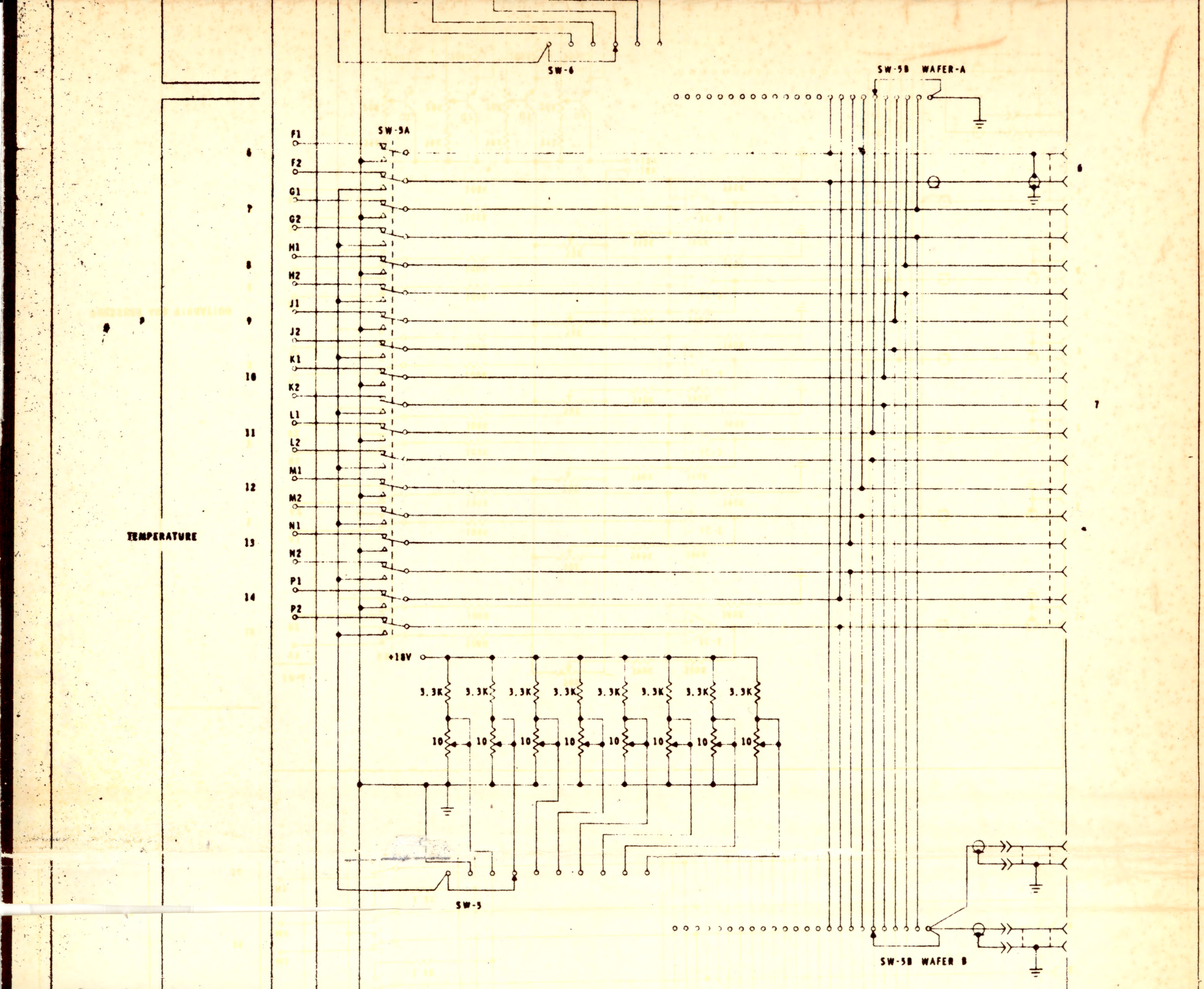
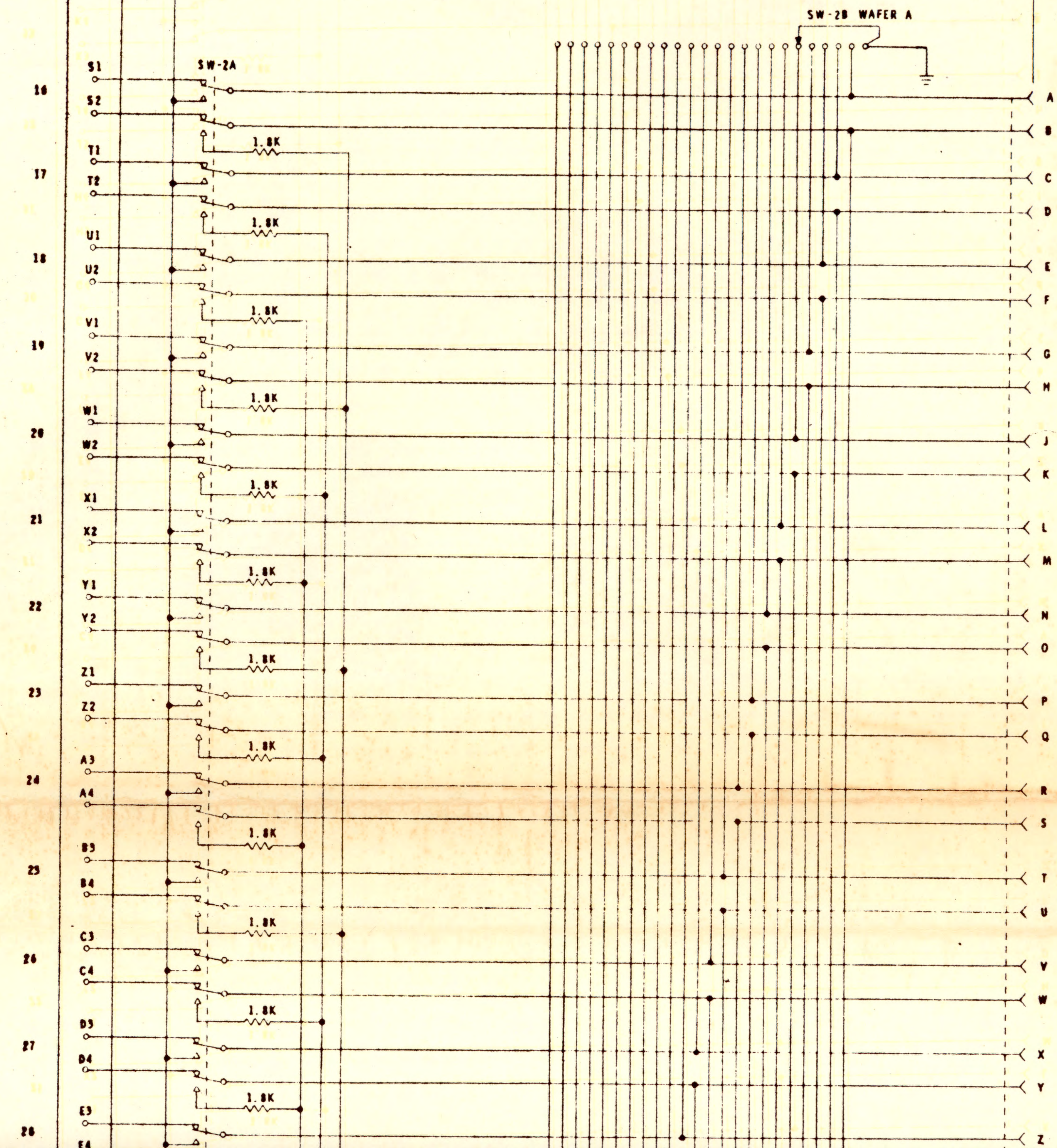
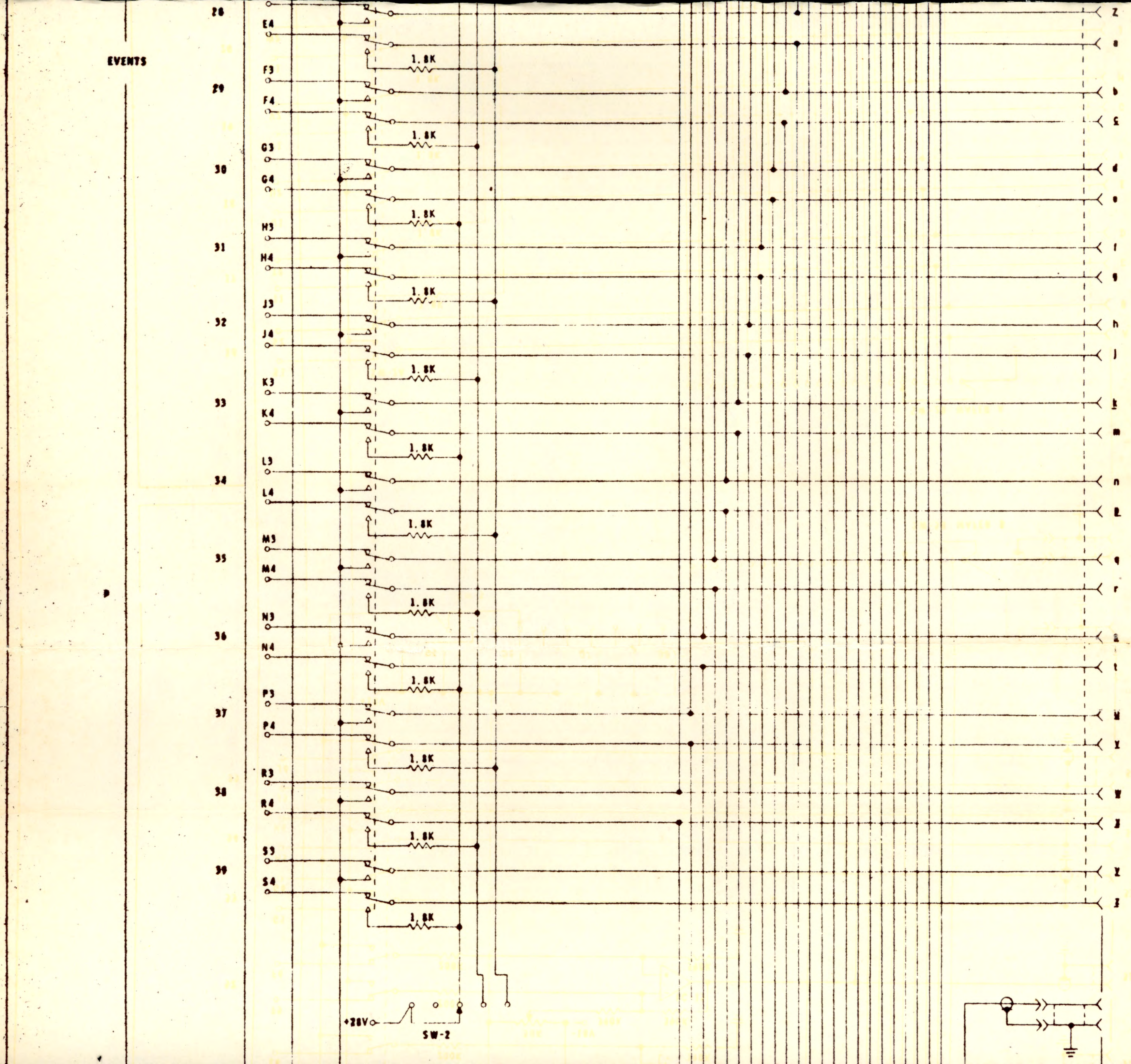
3
4
5



TEMPERATURE
6
7
8
9
10
11
12
13
14
F1
F2
G1
G2
H1
H2
J1
J2
K1
K2
L1
L2
M1
M2
N1
N2
P1
P2
SW-9A
SW-6
SW-9B WAFER-A
SW-9B WAFER B
+18V
3.3K
10
SW-5



SW-2B WAFER A
SW-2A
S1
S2
T1
T2
U1
U2
V1
V2
W1
W2
X1
X2
Y1
Y2
Z1
Z2
A3
A4
B3
B4
C3
C4
D3
D4
E3
16
17
18
19
20
21
22
23
24
25
26
27
28
1.8K
A
B
C
D
E
F
G
H
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z


EVENTS
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E4
F3
29
F4
G3
30
G4
H3
31
H4
J3
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K3
33
K4
L3
34
L4
M3
35
M4
N3
36
N4
P3
37
P4
R3
38
R4
S3
39
S4
1.8K
+28V
SW-2
Z
a
b
c
d
e
f
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v
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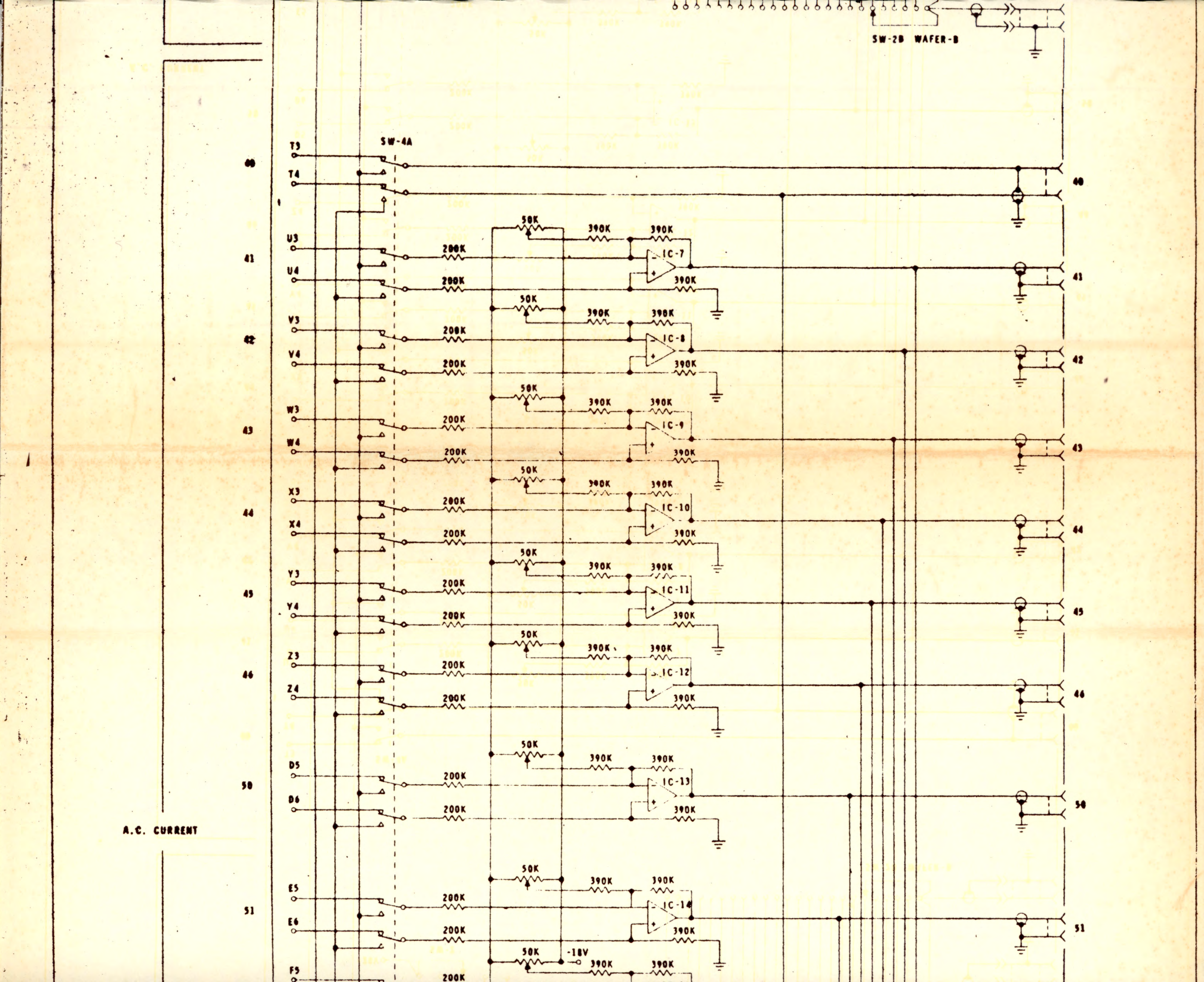
SW-2B WAFER-B
SW-4A
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T4
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U4
V3
V4
W3
W4
X3
X4
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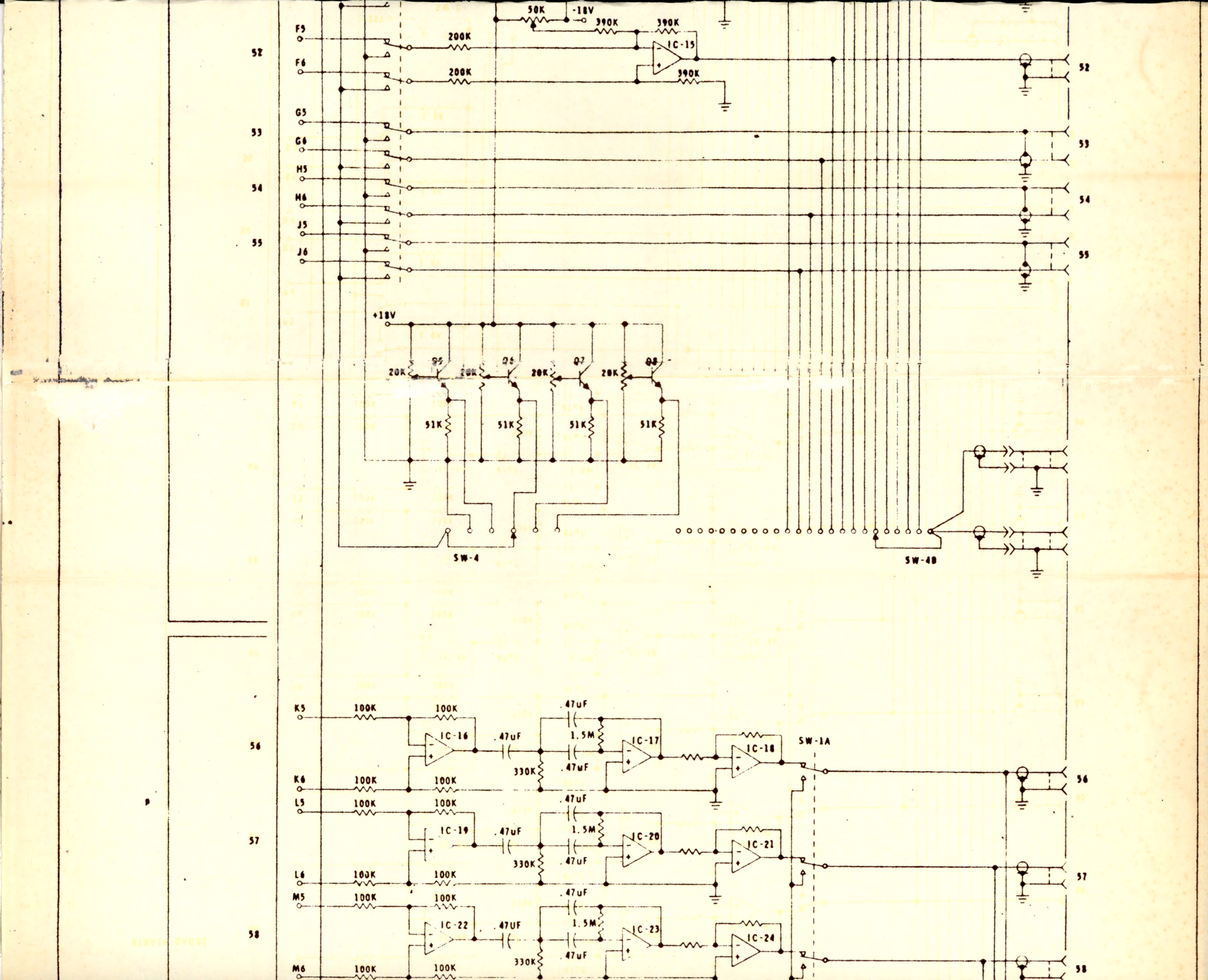
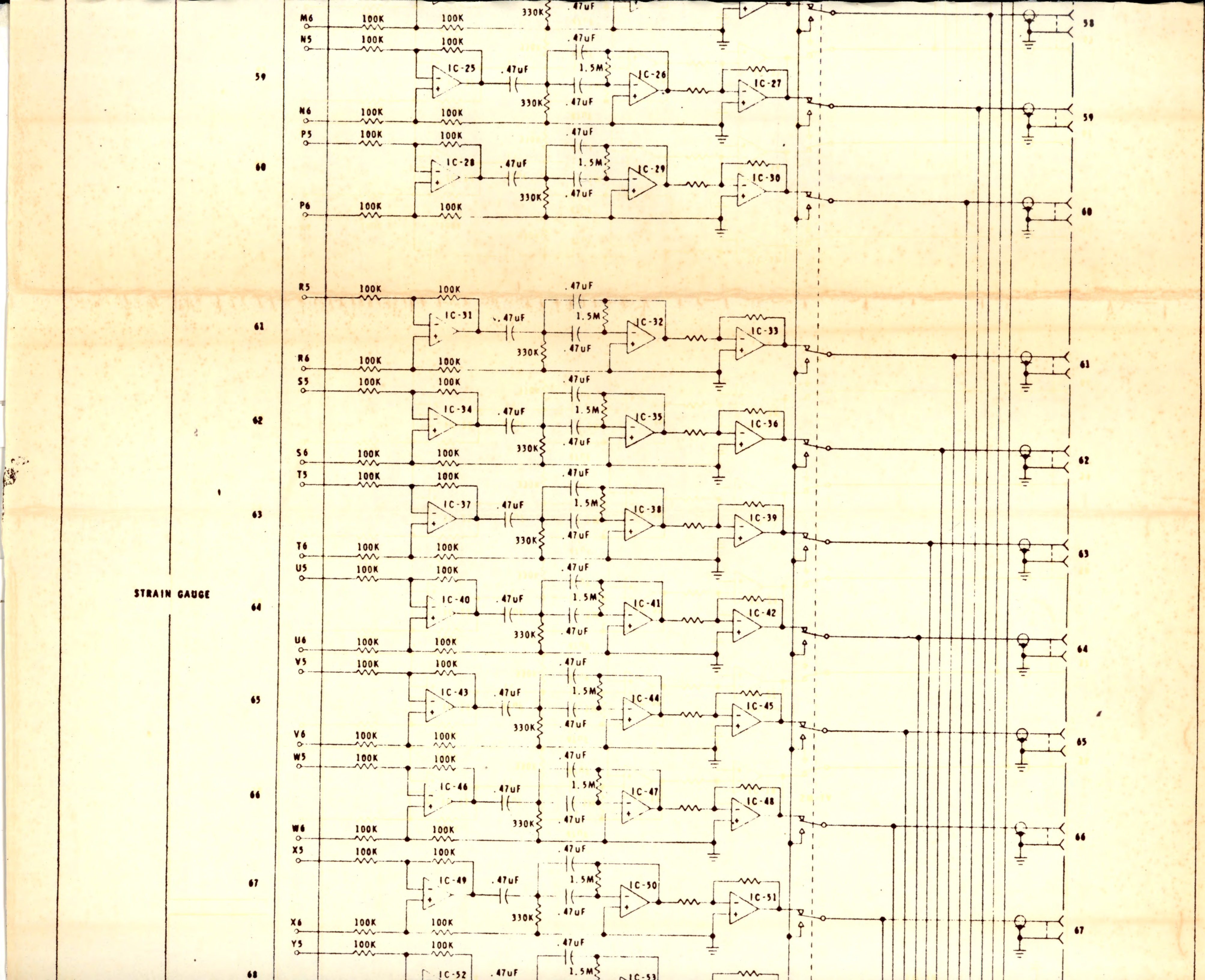
Y4
Z3
Z4
D5
D6
E5
E6
F5
40
41
42
43
44
45
46
50
51
IC-7
IC-8
IC-9
IC-10
IC-11
IC-12
IC-13
IC-14
50K
390K
200K
-18V
A.C. CURRENT



F5
F6
G5
G6
H5
H6
J5
J6
K5
K6
L5
L6
M5
M6
52
53
54
55
56
57
58
50K
-18V
390K
390K
390K
200K
200K
IC-15
+18V
20K
Q5
Q6
Q7
Q8
51K
SW-4
SW-4B
100K
IC-16
IC-17
IC-18
IC-19
IC-20
IC-21
IC-22
IC-23
IC-24
.47uF
1.5M
330K
SW-1A


STRAIN GAUGE
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60
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62
63
64
65
66
67
68
M6
N5
N6
P5
P6
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R6
S5
S6
T5
T6
U5
U6
V5
V6
W5
W6
X5
X6
Y5
100K
330K
.47uF
1.5M
IC-25
IC-26
IC-27
IC-28
IC-29
IC-30
IC-31
IC-32
IC-33
IC-34
IC-35
IC-36
IC-37
IC-38
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IC-41
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IC-52
IC-53
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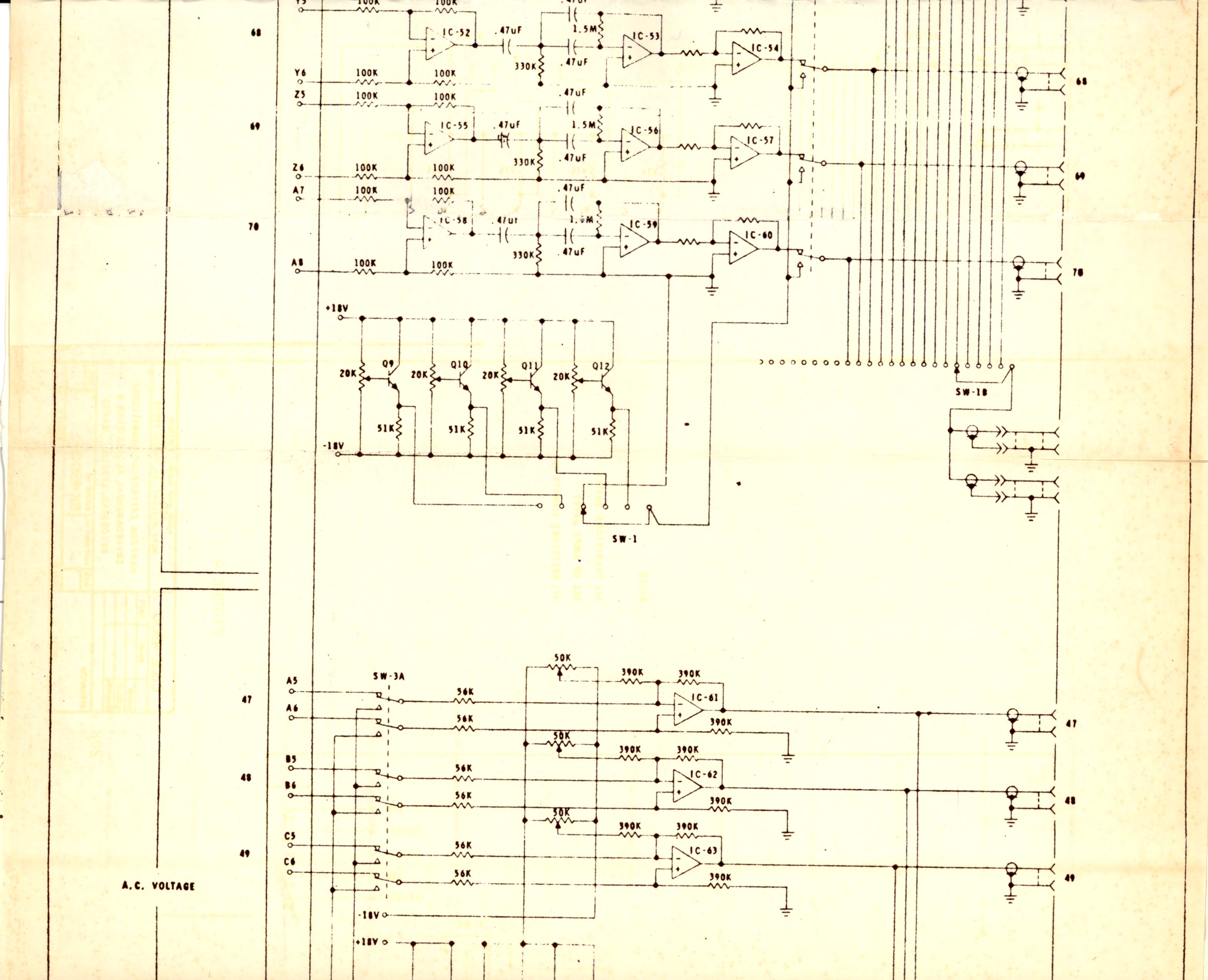

68
69
70
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48
49
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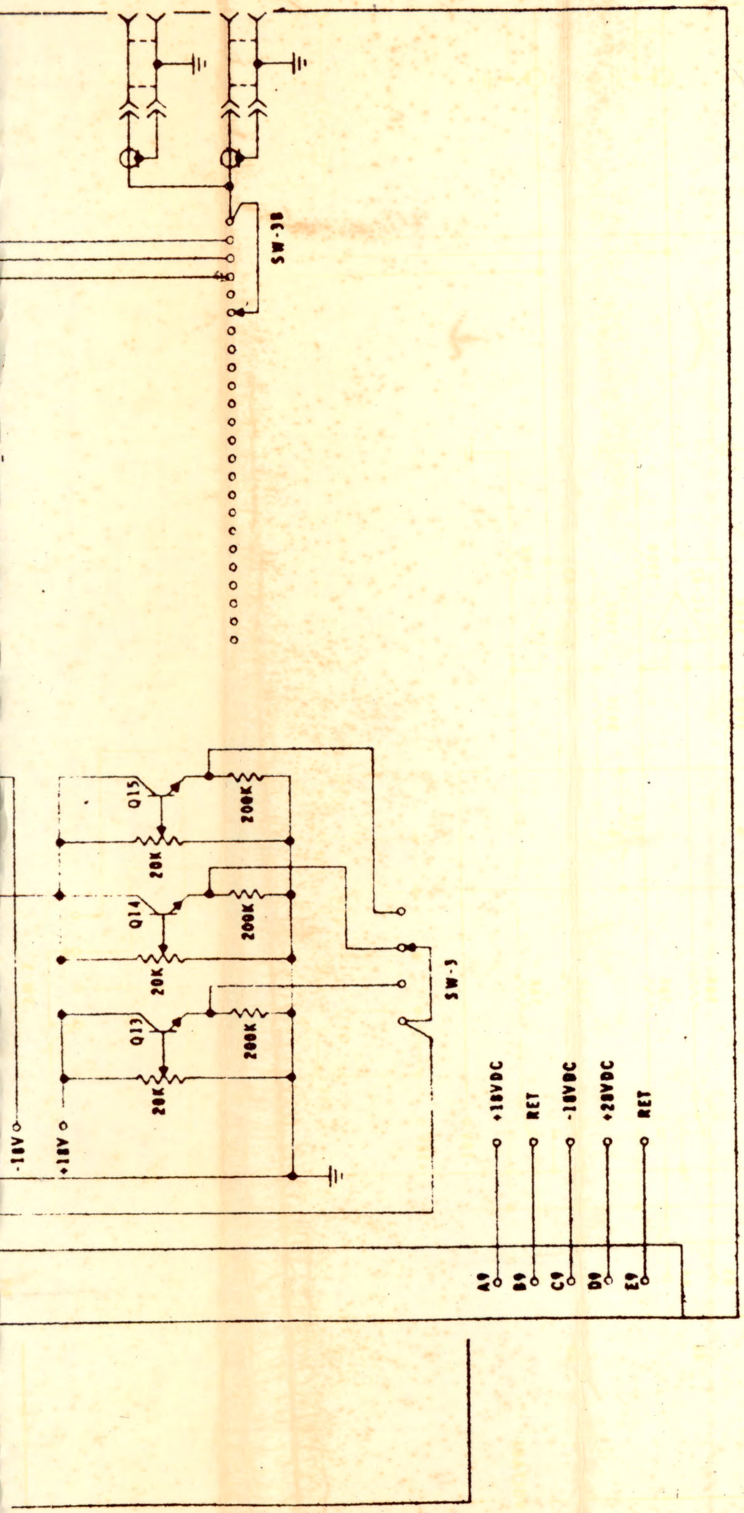
Y6
Z5
Z6
A7
A8
A5
A6
B5
B6
C5
C6
IC-52
IC-53
IC-54
IC-55
IC-56
IC-57
IC-58
IC-59
IC-60
IC-61
IC-62
IC-63
Q9
Q10
Q11
Q12
SW-1
SW-1B
SW-3A
100K
.47uF
1.5M
330K
20K
51K
50K
390K
56K
+18V
-18V
A.C. VOLTAGE



NOTES

ALL TRANSISTORS 2N4123

ALL OP AMPS μA741

ALL RESISTORS 1/4WATT 5%

FIGURE 4

CODE 4900

NAVAL SHIP MISSILE SYSTEMS ENGINEERING STATION PORT HUENEME, CALIFORNIA 93043

HARPOON CALIBRATOR/CONDITIONER ENVIRONMENTAL ACQUISITION & RECORDING SYSTEM (EARS)

	NAME	DATE
DRAWN		
CHECKED		
ENGINEER		

APPROVED:

DATE:

SIZE | CODE IDENT NO. | SKETCH NO. SK 4900- | REV

SCALE | SHEET

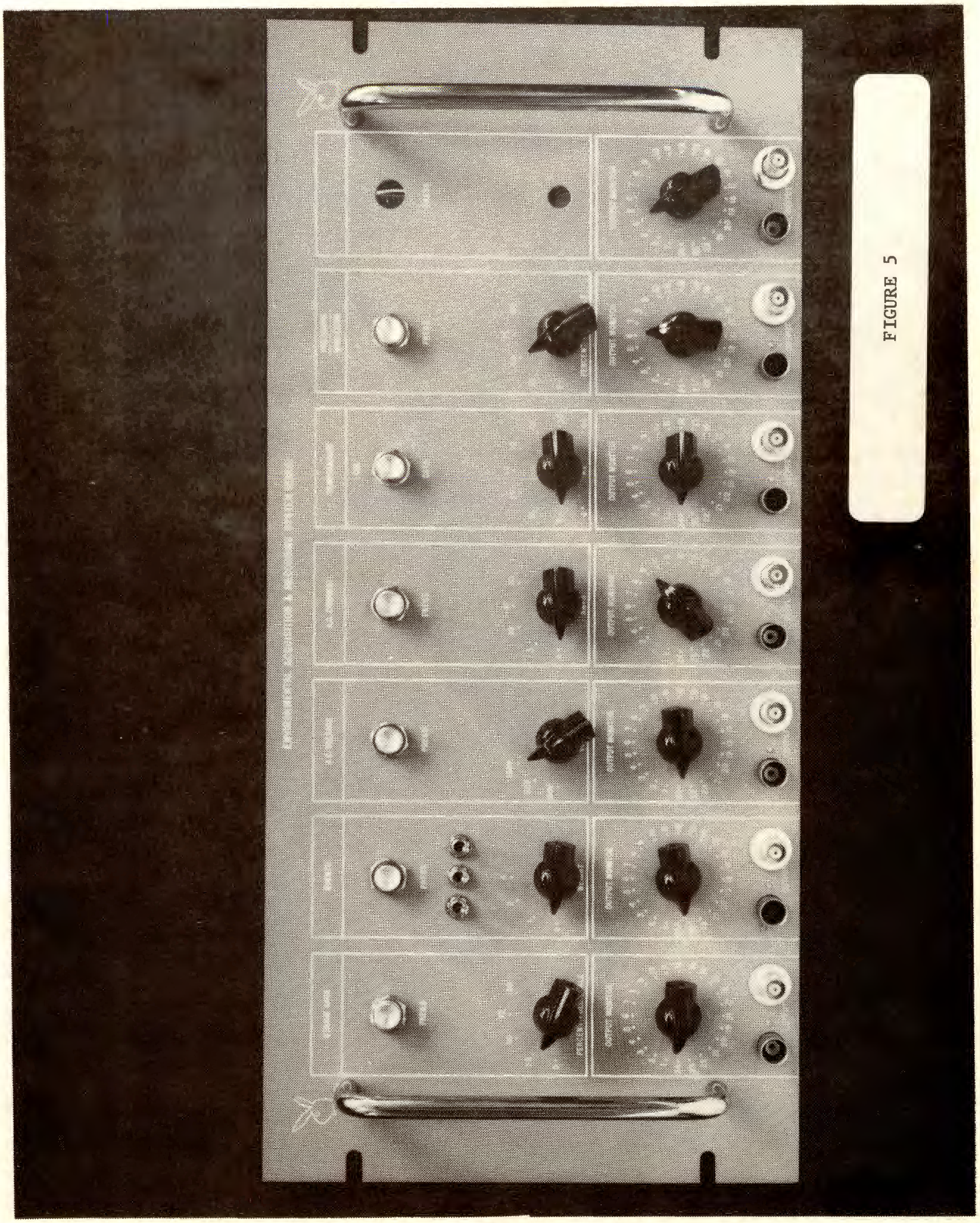


FIGURE 5

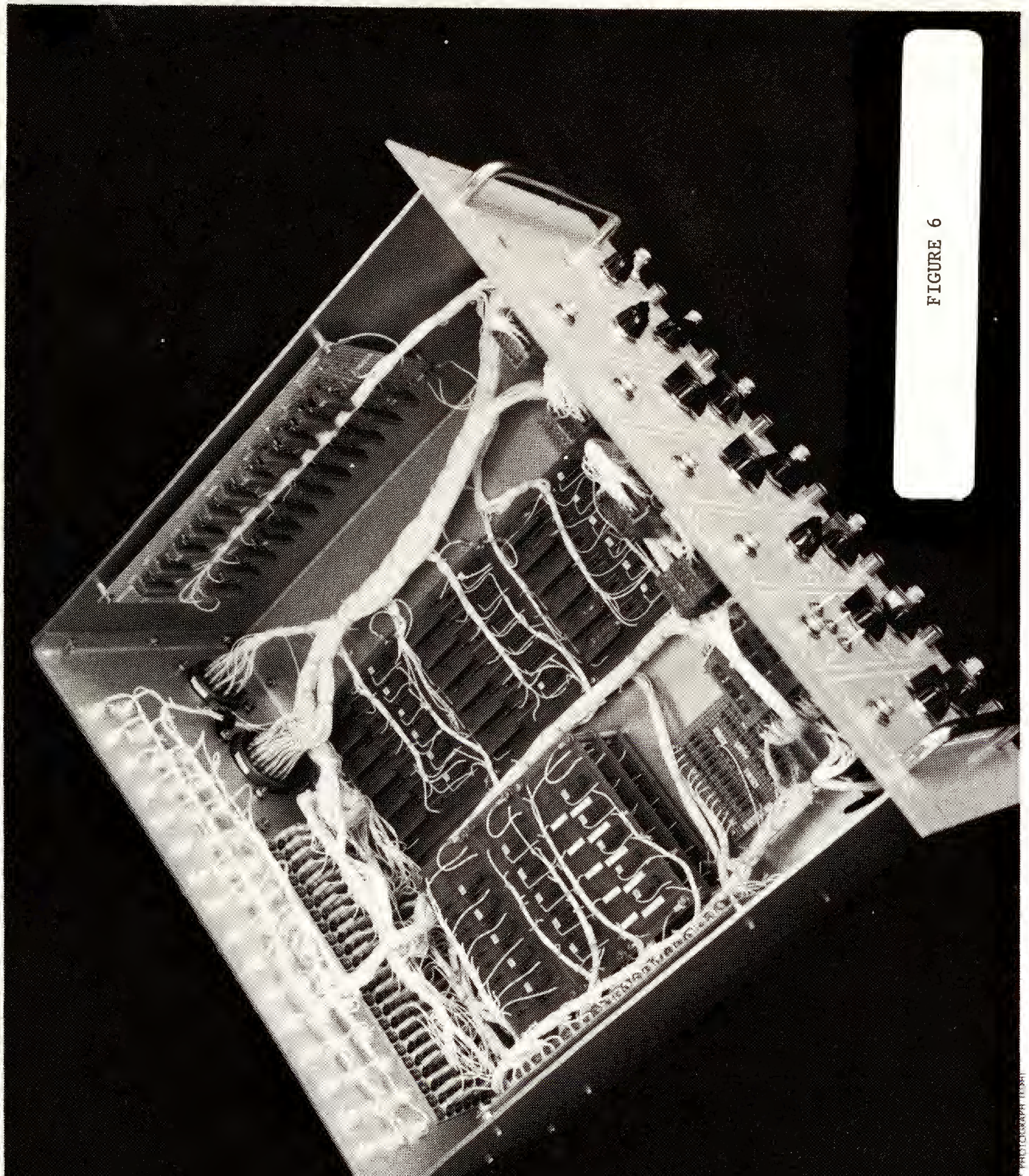
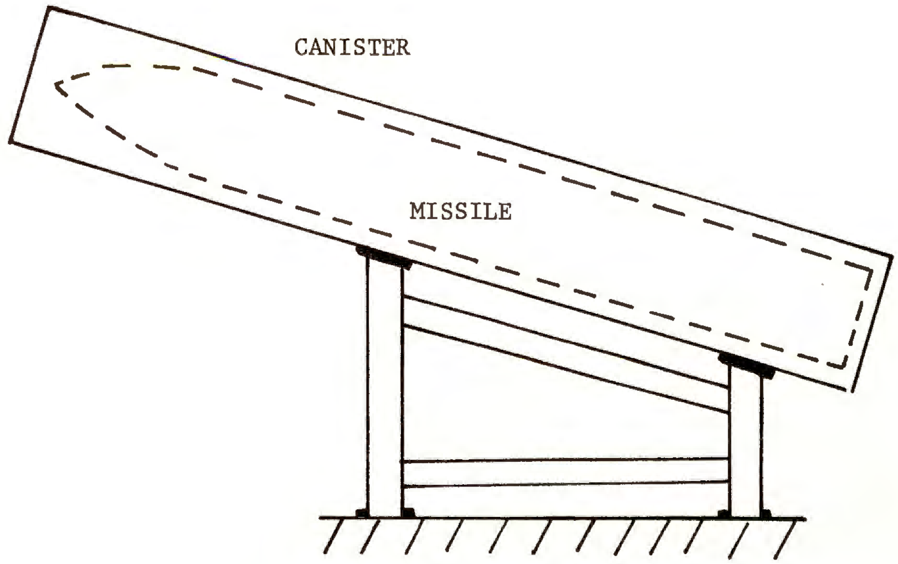


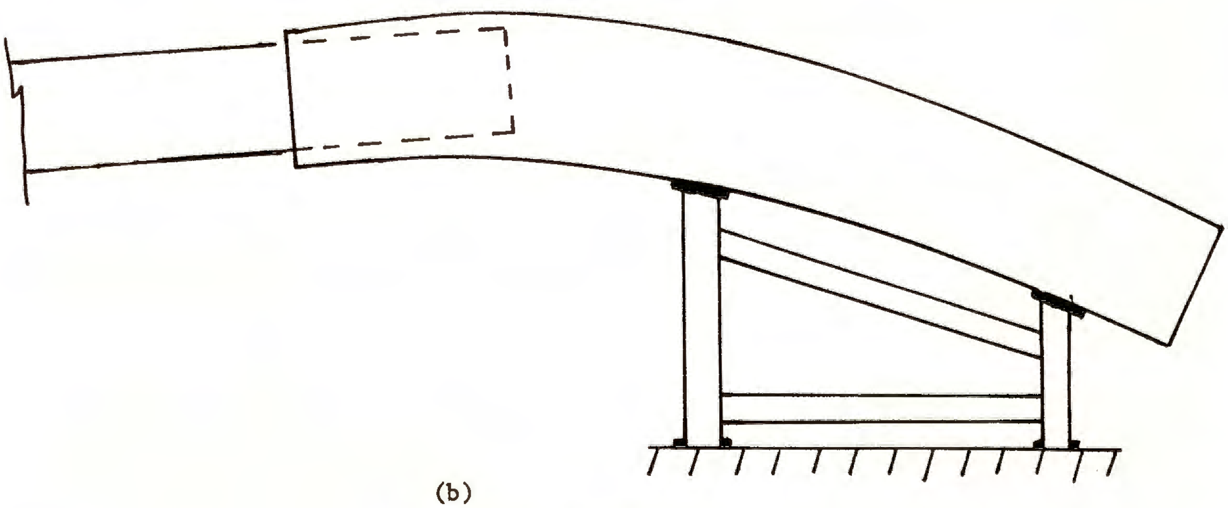
FIGURE 6

OFFICIAL U.S. NAVY PHOTOGRAPH



(a)

UNSTRESSED CANISTER



(b)

STRESSED CANISTER

FIGURE 7

CANISTER DEFLECTION MEASUREMENTS (PICTORIAL) is shown schematically in figure 8 (except that only one pair of strain gages is shown). Figure 8a shows the mechanical setup.

When the canister was in the unstressed state the strain gages (shown in figure 8b) presented equal resistances. The machinist's gage (at the end of the canister) indicated "zero". During calibration 1000 lbs was applied to the canister, causing deflection. The top gage was elongated while the bottom gage was compressed, resulting in an output from the circuit shown in figure 8b. The output was then correlated with canister deflection as measured by the machinists gage (0.066 inch). Calibration involved taking electrical measurements from all ten gage pairs at 0 lbs, 500 lbs and 1000 lbs. The operation was conducted several times and then averaged together. Piezoresistive strain gages were chosen for this exercise because of their high gage factors. These gages are poorly compensated, however, for temperature. Since the phenomenon being examined is transient, a filter was inserted in each data line between the strain gage bridge and its associated amplifier. The two pole Butterworth highpass filter with Fc @ 0.5Hz was selected. Filters were implemented using small, inexpensive IC operational amplifiers. The importance of filtering can be seen in figure 9. Figure 9a shows a highly amplified * strain signal suffering from the effects of temperature change.

In the case being depicted, the dynamic event being measured would be above the useful upper band of the recording device and would not be recorded. Figure 9b shows the signal after high pass filtering. Here the signal is properly recorded.

Everything used in this exercise is linear. By comparing the output of the strain gages during the missile firing to the calibration data, deflection can be inferred. This will enable the data analyst to determine if the small elevation error encountered during launch is attributable to this cause.

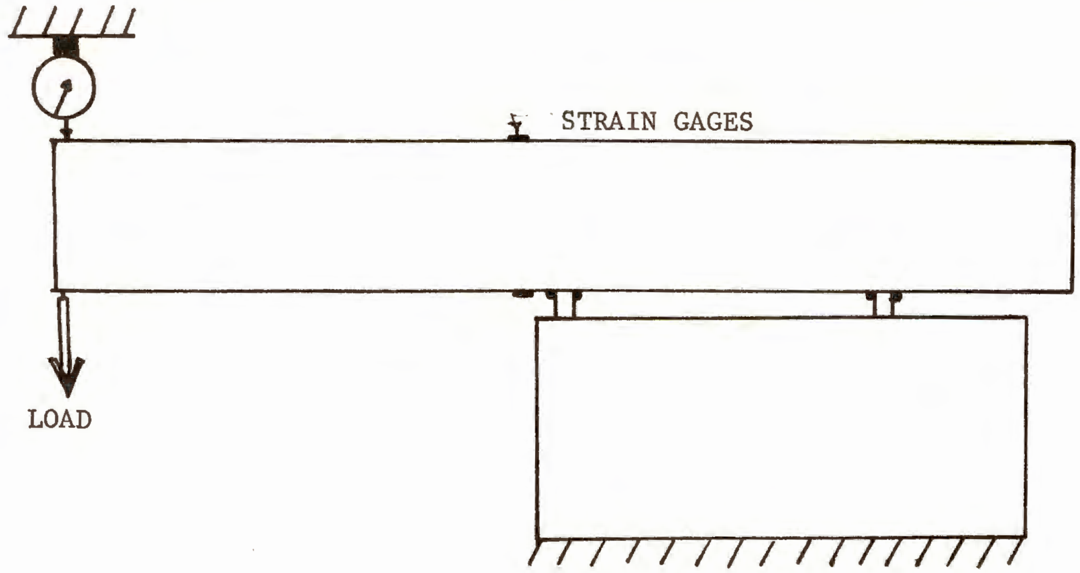
4. EVENT STACKER/DISPLAY PANEL

HARPOON instrumentation in USS PEGASUS (PHM-1) requires a recording system capable of recording 24 event signals. The existing recording system lacked channel capacity for this many event signals. Recording quality of existing channels was, however, high, permitting the recording of octal information. The problem was therefore solved by building binary to octal converters (event stackers). Twenty-four binary signals into the converter are now reduced to 8 octal signals out.

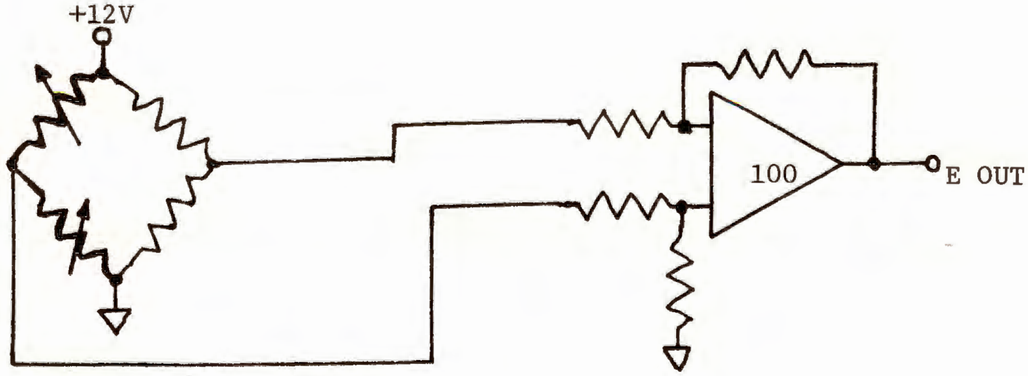
Figure 10 shows how the stacker operates. The heart of the stacker is a low cost IC operational amplifier (op amp) used with precision resistors. Inputs 1 thru 3 are connected to the op amp summing junction through resistors of 100K, 200K and 400K respectively. The effect on the output (assuming equal input levels for all binary channels) is inversely proportional to the input resistors. The inputs are therefor weighted in a 4, 2, 1 (octal) fashion. The three inputs can be subjected to either a "high" or a "low" voltage. The

---

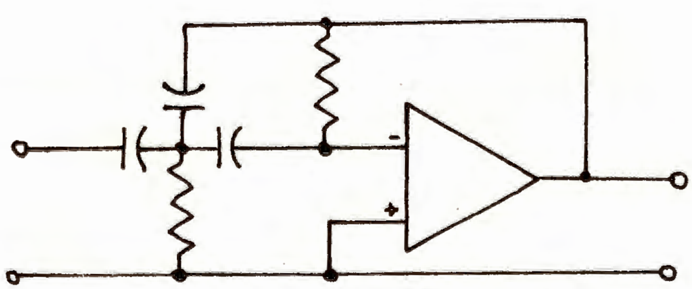
**High amplification is needed to scale a strain signal of a nominal 20μ strain to a voltage level high enough to be properly recorded.*



(a)



(b)

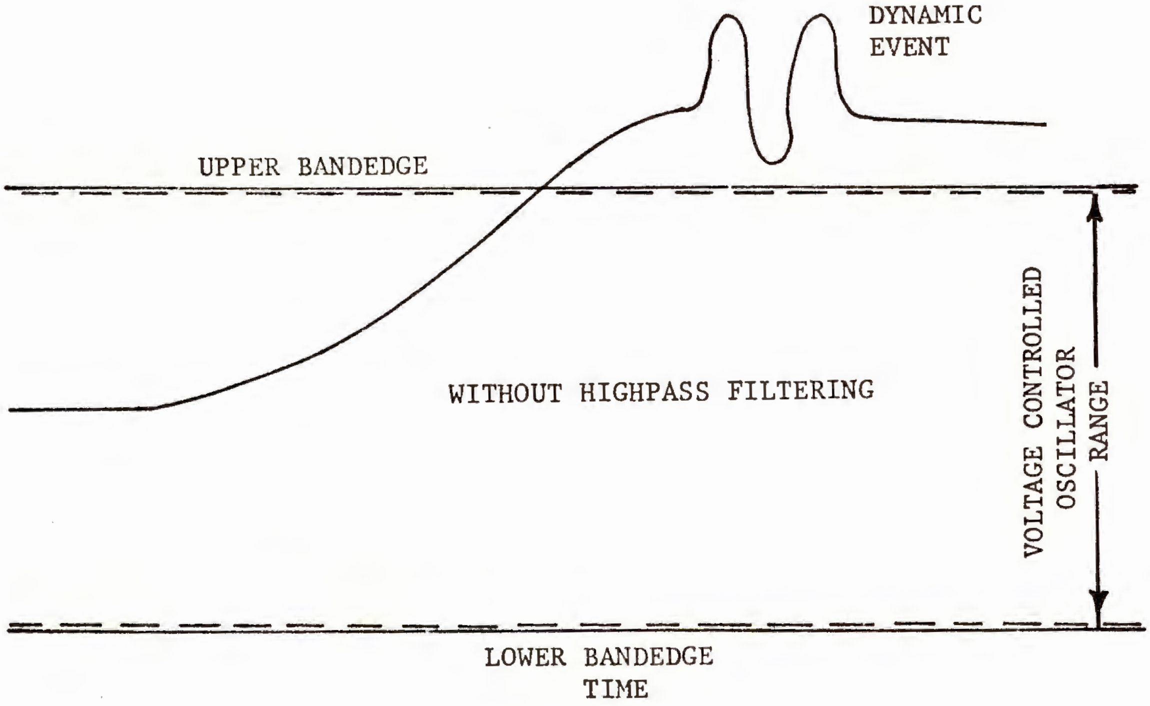


(c)

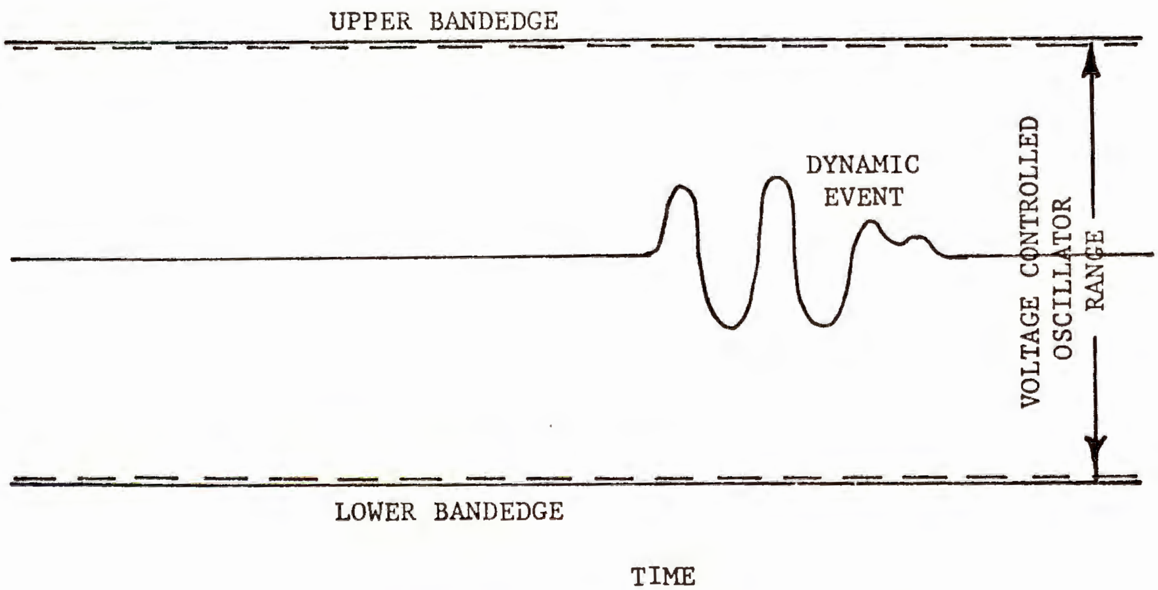
HIGHPASS FILTER (2 POLE BUTTERWORTH)

FIGURE 8

CANISTER DEFLECTION MEASUREMENTS (ELECTRICAL)



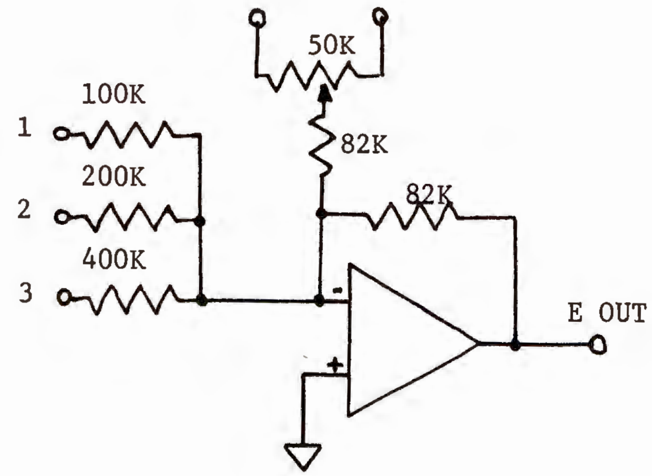
(a)



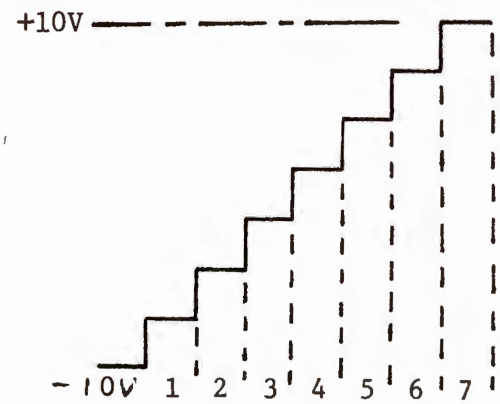
(b) WITH HIGHPASS FILTERING

FIGURE 9

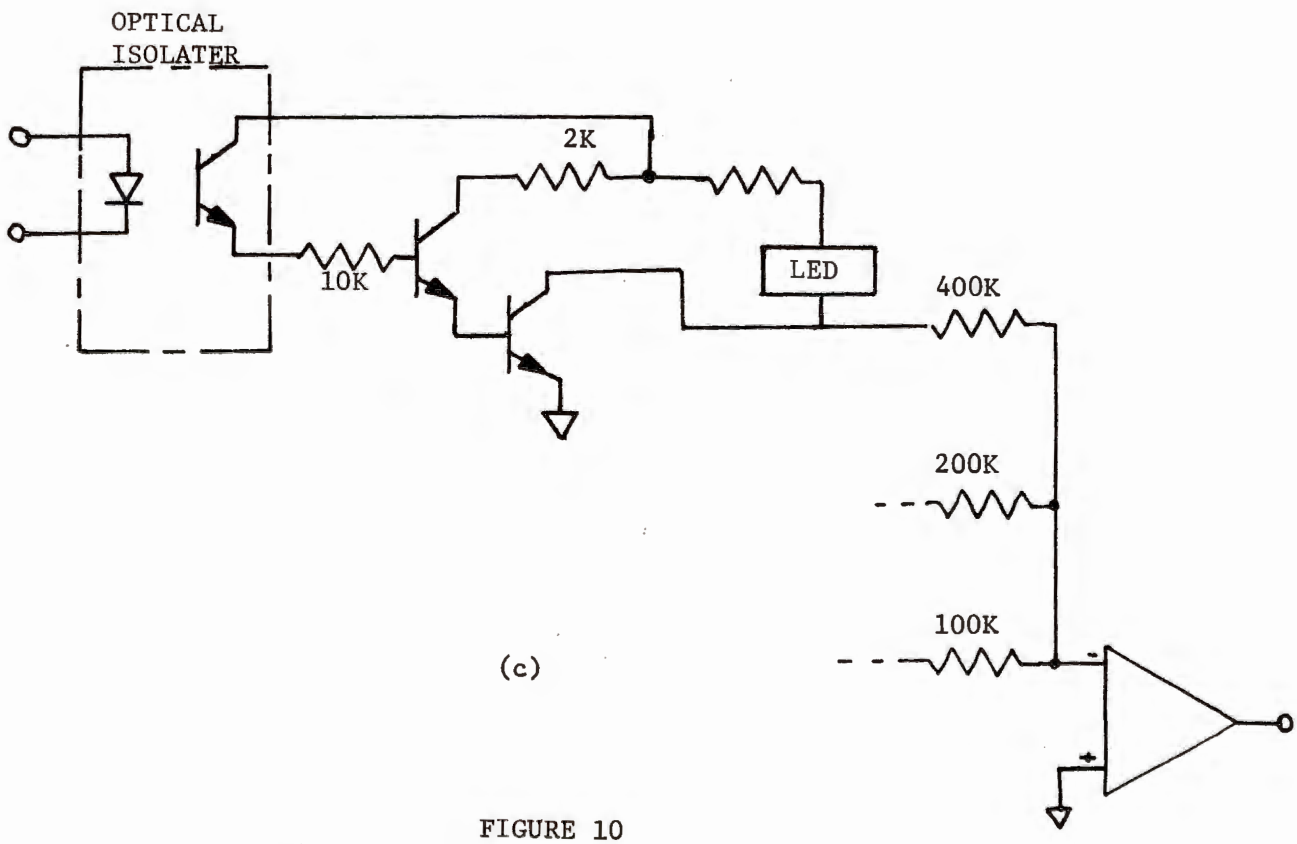
EFFECT OF HIGH PASS FILTERING ON AMPLIFIED STRAIN DATA



(a)



(b)



(c)

FIGURE 10

EVENT STACKERS SIMPLIFIED DIAGRAM

output will vary from a -10V to +10V depending on what levels are presented to the inputs. It is restricted to one of eight possible levels (shown in figure 10b).

Optical isolators are inserted between the event source and the operational amplifiers. They serve two purposes. They protect the equipment under test from even the remote possiblity that an instrumentation problem could feed damaging voltage levels back into the equipment under test. They also remove the instrumentation ground from the signal ground. Several grounds are employed in the equipment under test and therefore isolation is required.

The binary inputs being monitored are current limited sources. The optical isolators receive less than 1 milliamp. They are intended to be used at a nominal 50ma. The output was found to be very small. The small output was fed into a darlington transistor amplifier before being presented to the operational amplifier as a solid, binary signal. Actual implementation of the "stacker" includes light emitting diodes on the front panel to enable the operator to easily verify event status during launch and pre-launch operations.

The complete diagram is shown as figure 11. Stacker photographs are included (figure 12 and 13).

5. TEMPERATURE MEASUREMENT

Eight temperature measurements (some expected to be approximately 3500°F) are required. All temperature measurements are made by thermocouples. The thermocouples dedicated to the measurement of the HARPOON rocket blast temperatures are designed by NSWSES (see figure 14). The thermocouple transducers are made of Tungsten/Rhenium (good to approximately 4200°F). The transducers are surrounded by a ceramic insulator which is in turn surrounded by a stainless steel sheath for support against the rocket blast. The thermocouple junction is exposed for quick response time needed for the electrical output to accurately reflect the very transient nature of the rocket blast.

The thermocouples are electrically connected to their associated amplifiers in a novel manner dictated by the requirement to run only one thermocouple cable to support the eight measurements and to use spare (copper) conductors available in a multi conductor general purpose instrumentation cable (see figure 15 for Block Diagram). The temperature indicated by the thermocouples is the temperature at the active junction less the temperature of the thermocouple/copper junction (the temperature of the connector terminating the general purpose instrumentation cable near the launcher). The active junction of the reference thermocouple is mounted within the same connector which serves as a thermocouple to copper transition for the other thermocouples, and can thereby be assumed to be at the same temperature. The temperature of the active junction can thereby be inferred by adding the indicated temperature to the reference temperature to get true launcher temperature.

Figure 16 describes the data analysis technique for developing true temperature from indicated temperature and reference temperature.

EIGHTH TRANSDUCER WORKSHOP

22-24 APRIL 1975

WRIGHT PATTERSON AFB

DAYTON, OHIO

Figure 11

Event Stacker/Display Panel Harpoon (EARS)

Code 49000

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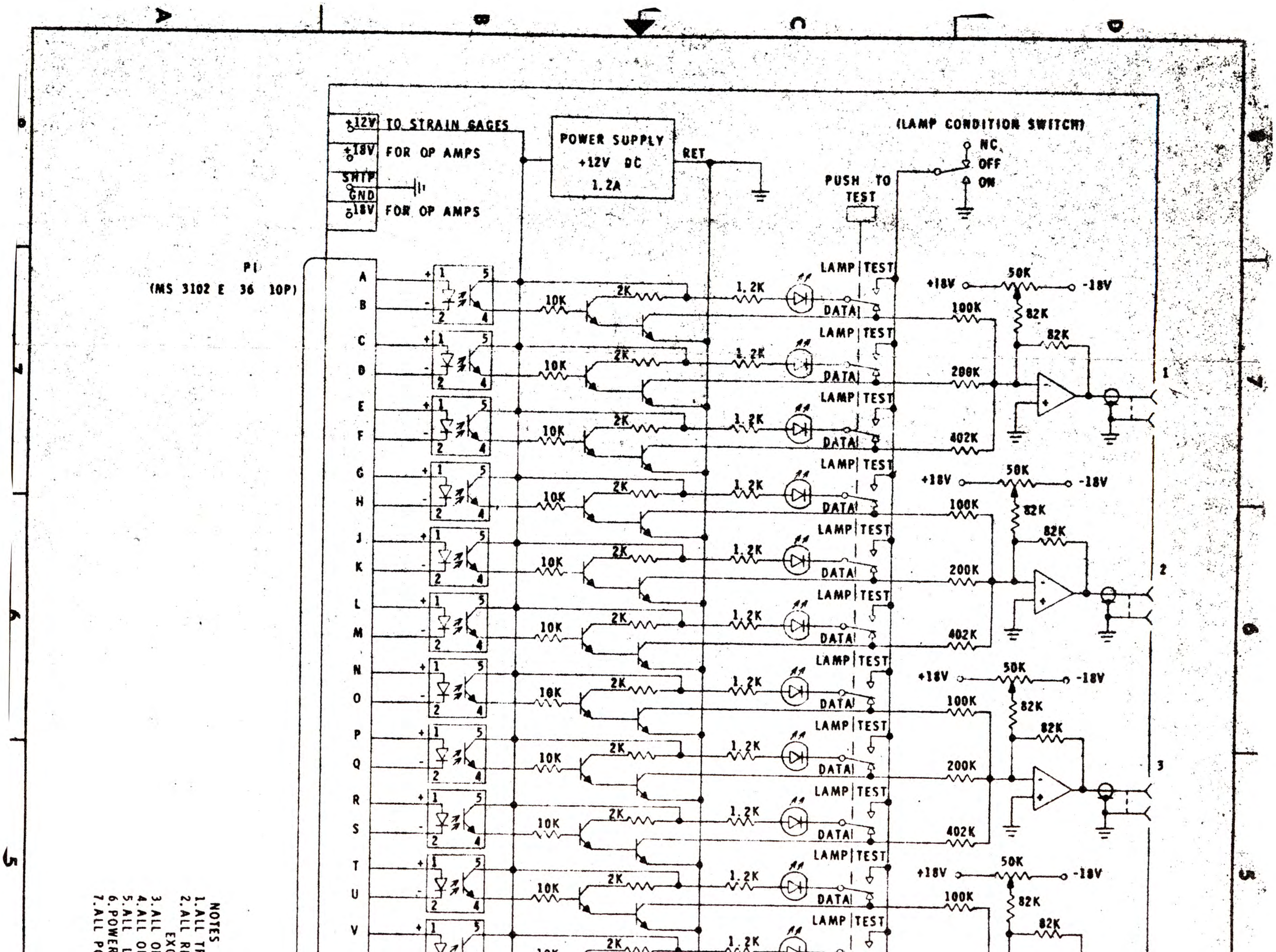


+12V TO STRAIN GAGES
+18V FOR OP AMPS
SHIP GND
-18V FOR OP AMPS
POWER SUPPLY +12V DC 1.2A
RET
(LAMP CONDITION SWITCH)
NC
OFF
ON
PUSH TO TEST
P1
(MS 3102 E 36 10P)
LAMP TEST
DATA
+18V
-18V
50K
82K
100K
200K
402K
10K
2K
1.2K
1
2
3
NOTES

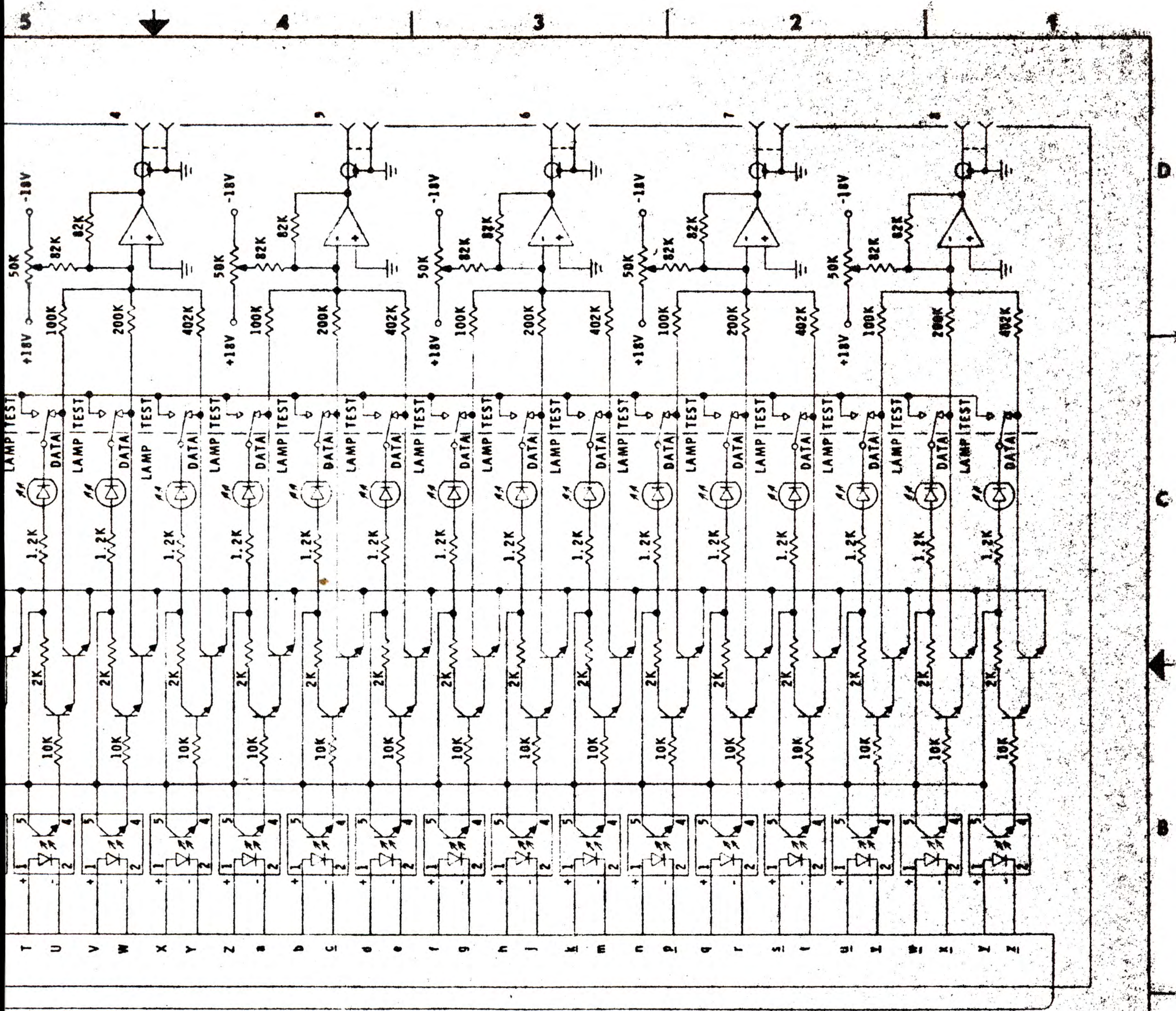


Figure 11

NOTES
1. ALL TRANSISTORS 2N4123
2. ALL RESISTORS 5% 1/4 WATT
EXCEPT 100K, 200K, 402K, WHICH ARE 1% 1/4 WATT
3. ALL OP AMPS MC1741
4. ALL OPTICAL ISOLATORS 4N28
5. ALL LED HP 5082-4850
6. POWER SUPPLY 12V 1.2A ELECTROSTATICS INC.
7. ALL POTENTIOMETERS 1 WATT TRIMPOTS

CODE 4900			NAVAL SHIP MISSILE SYSTEMS ENGINEERING STATION PORT HUENEME, CALIFORNIA 93043
	NAME	DATE	EVENT STACKER/DISPLAY PANEL HARPOON (EARS)
DRAWN			
CHECKED			
ENGINEER			
APPROVED: DATE:	SIZE D	CODE IDENT NO.	SKETCH NO. SK 4900- REV.
	SCALE:		SHEET OF

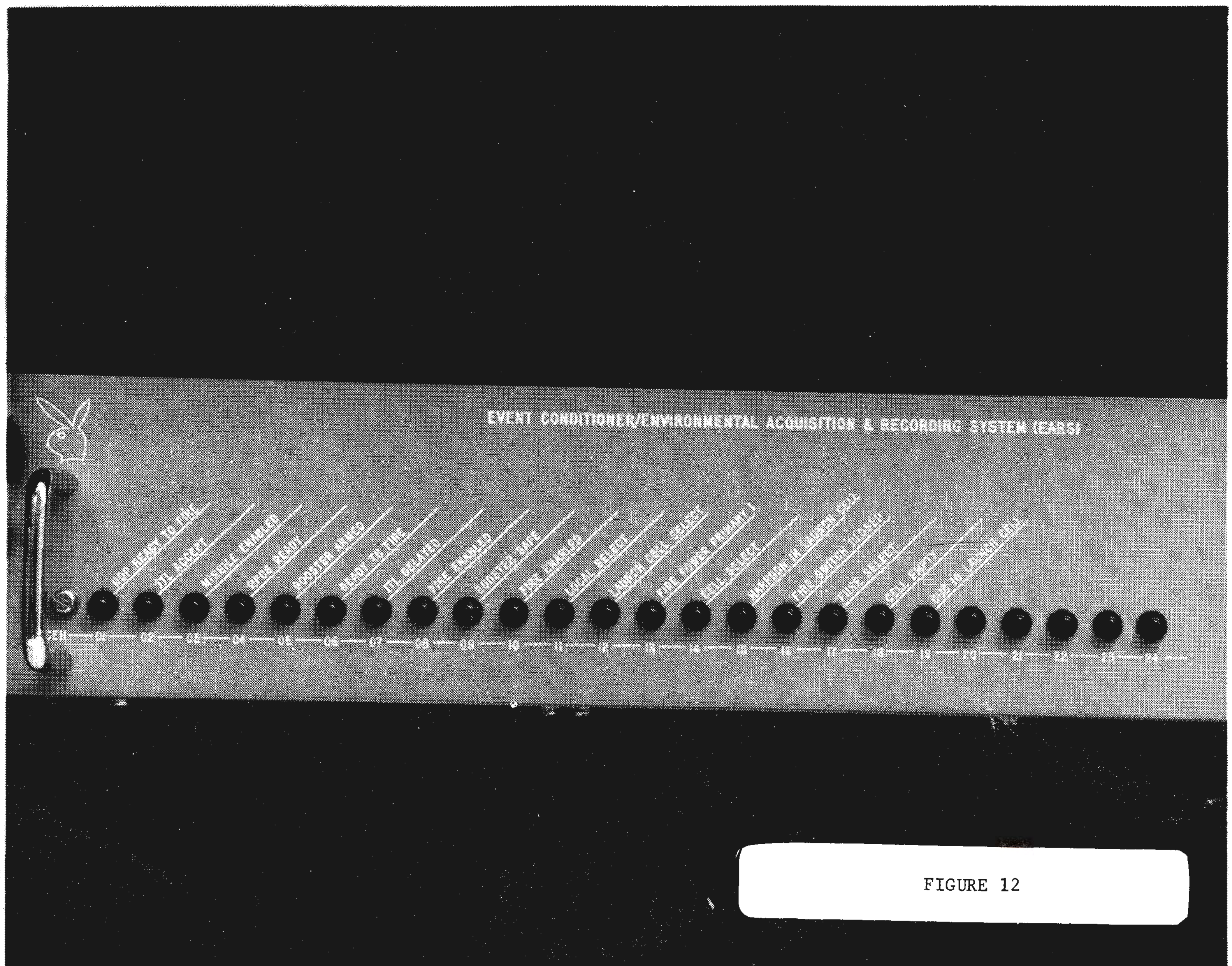


FIGURE 12

OFFICIAL U.S. NAVY PHOTOGRAPH (LDH)
PORT HUENEME, CALIFORNIA

6640-74

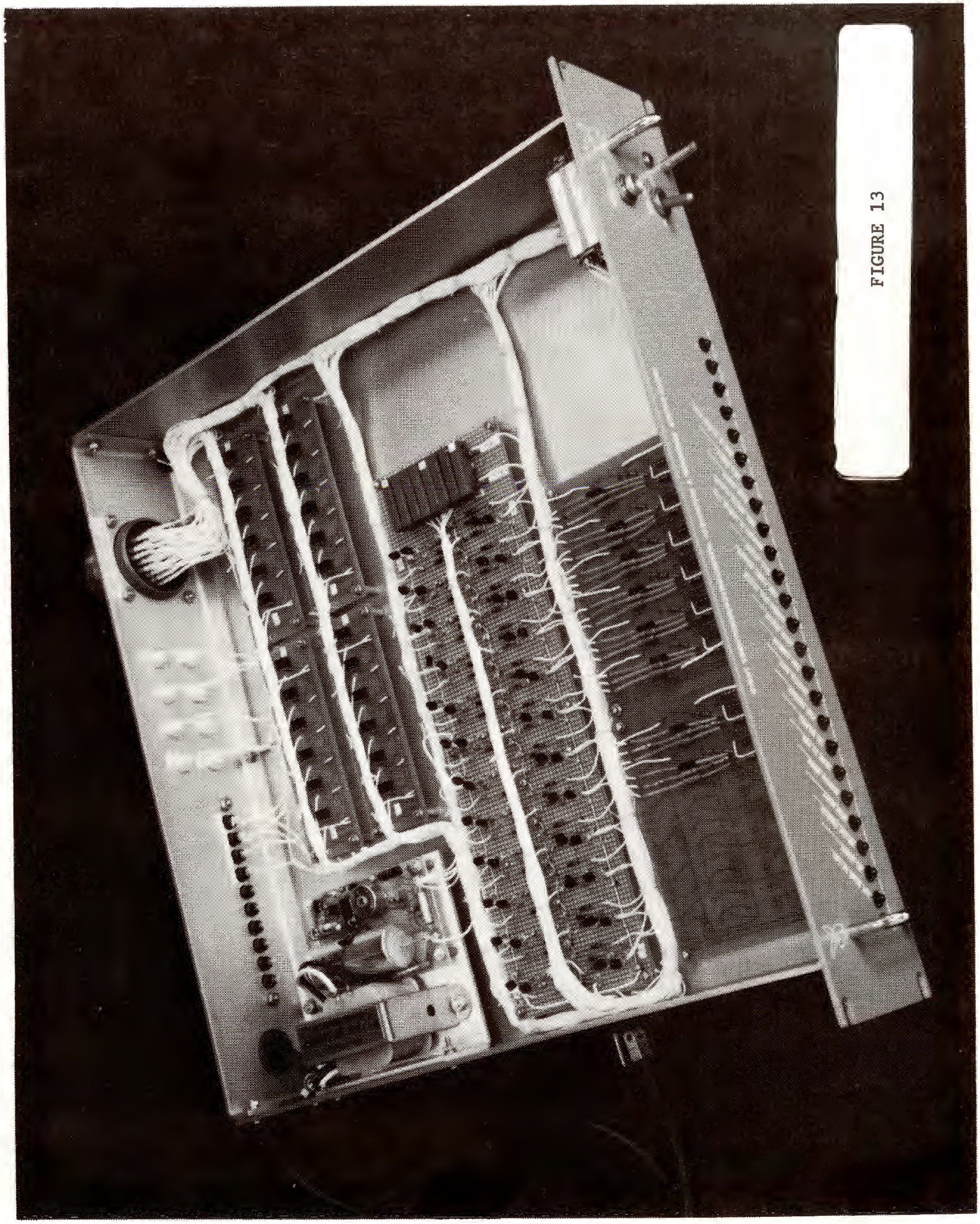


FIGURE 13

FIGURE 14

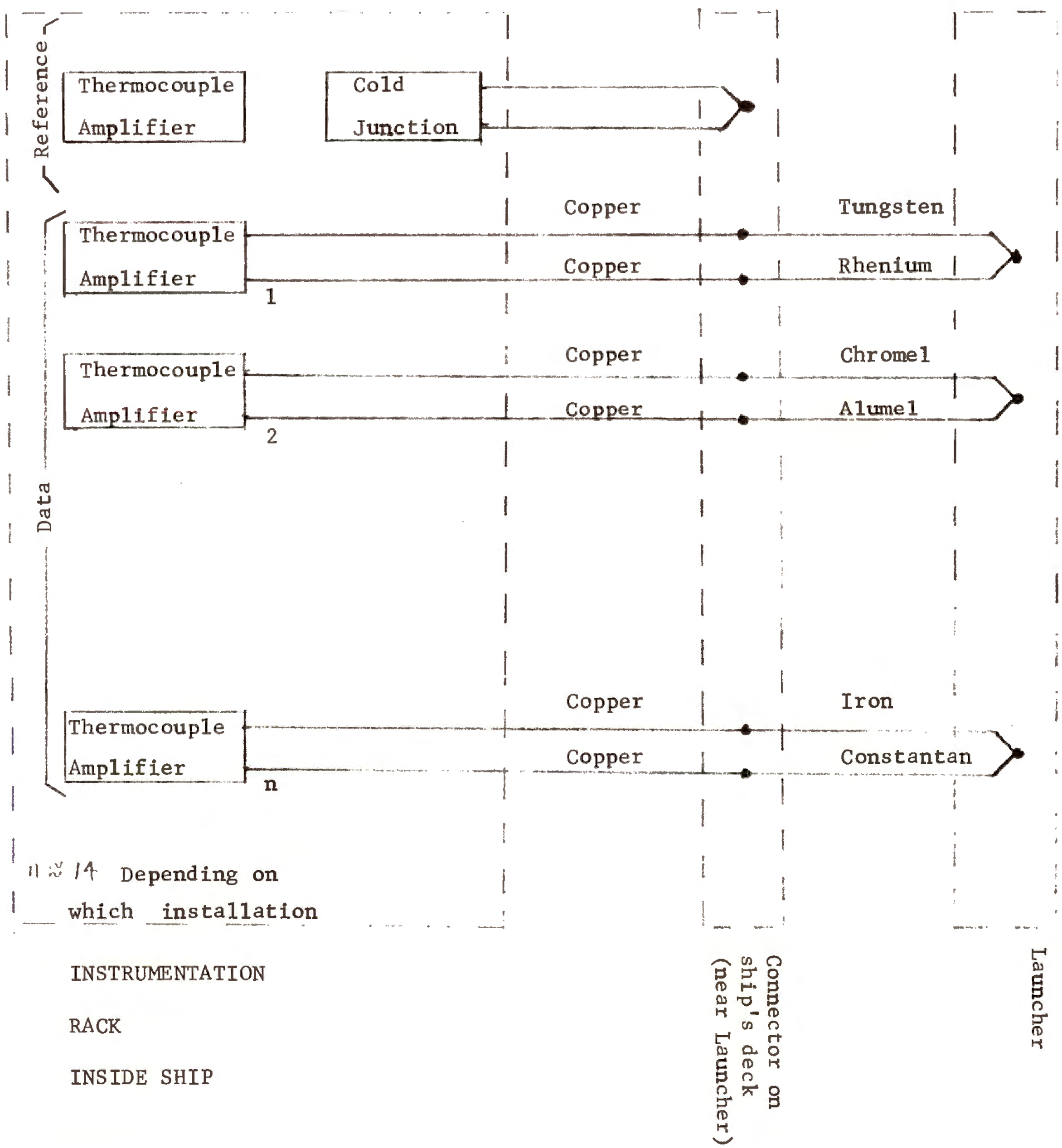


Figure 15 Temperature Measurement Block Diagram.

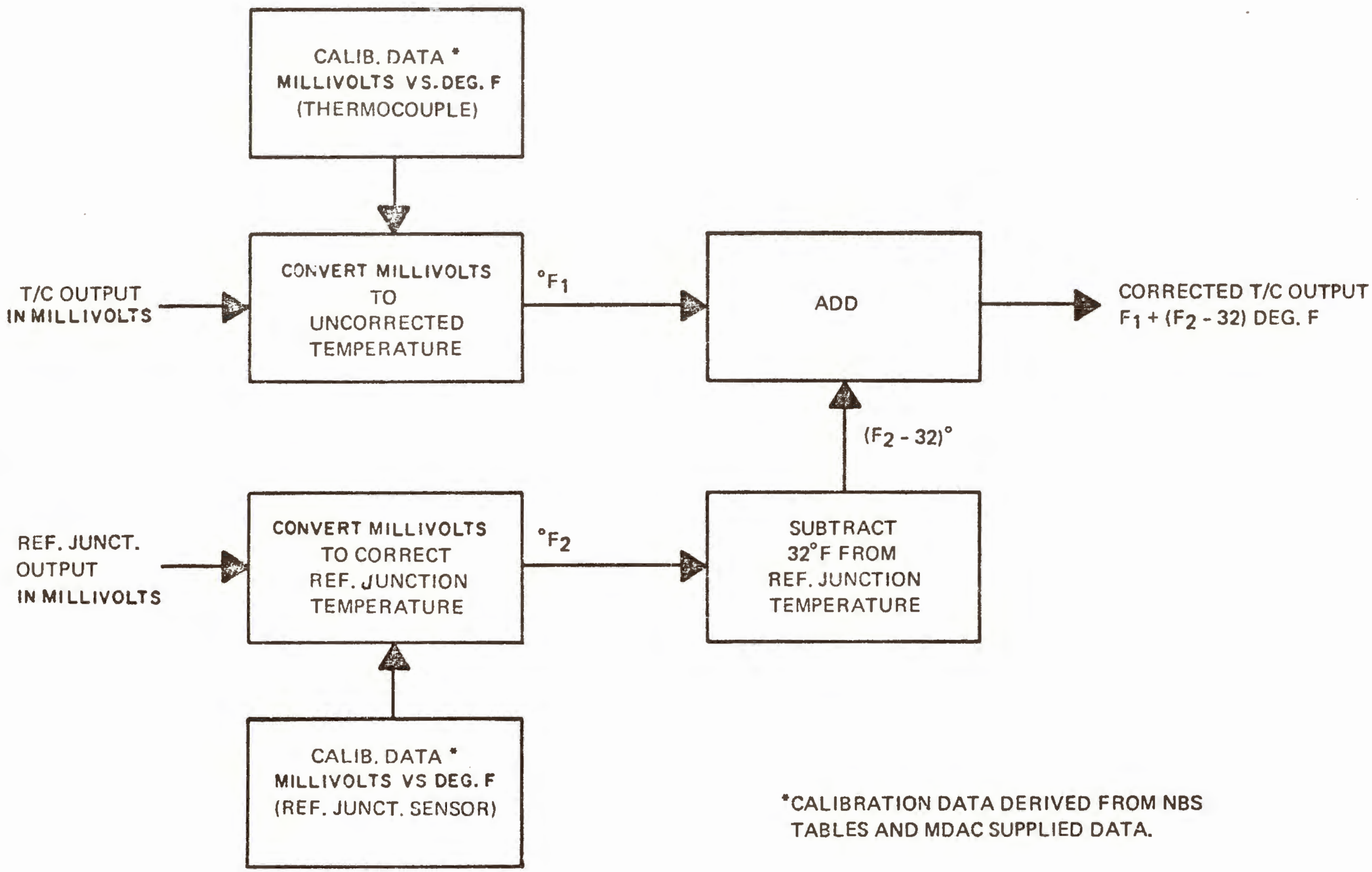
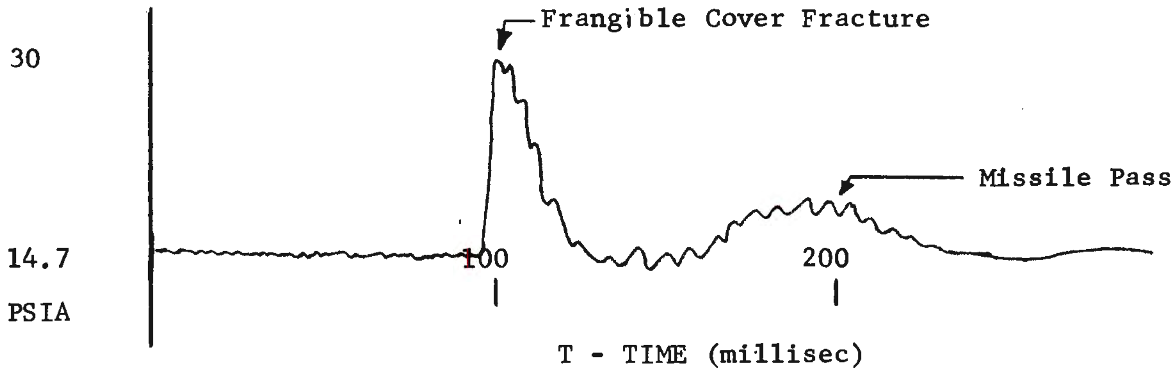


Figure 16 Universal Method Reference Junction Temperature Compensation for All Canister Launcher Thermocouple Measurements.

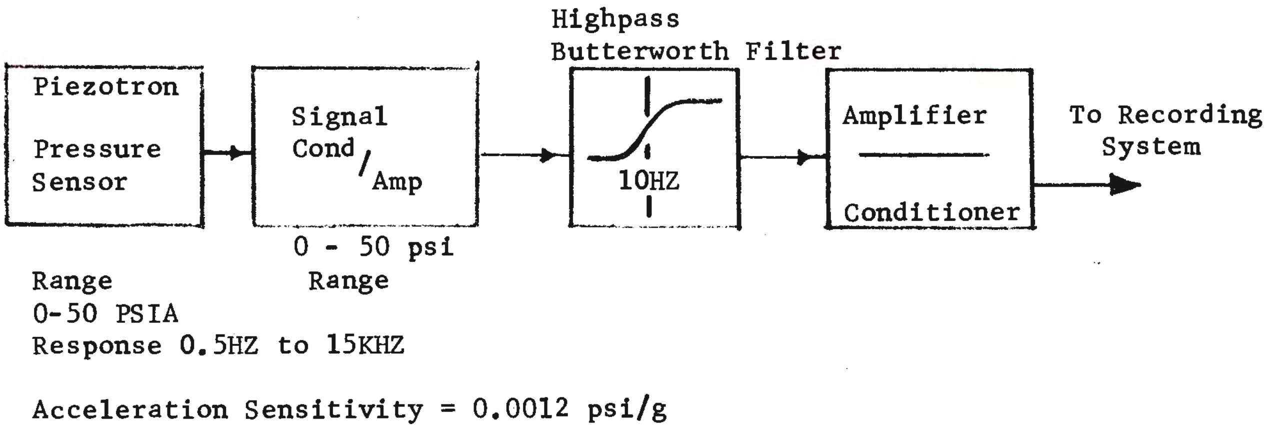
6. ACOUSTIC MEASUREMENT

An extremely unusual acoustic measurement requirement has been presented to NSWSES for determining acoustic sound levels in the firing canister during launch. The complexity of this measurement becomes evident when the physics of the over-pressure condition within the canister is considered as shown in figure 17a. This over-pressure atmosphere would saturate or over-range any conventional acoustic sensor by at least a factor of 10. Therefore, a 60 dB range system has been incorporated (see figure 17b).

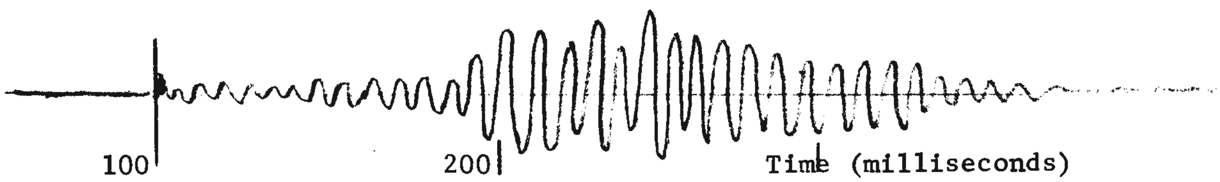
The acoustic system provides the necessary filtering required to separate the acoustical data from the over-pressure, resulting in acoustic data in the frequency range from 10 Hz to 15 kHz (see properly scaled acoustic data in figure 17c). Proper scaling of acoustic data is seen to result in greatly amplifying the high frequency perturbations of the pressure function (acoustic data) while rejecting the gross pressure buildup caused by the rocket blast.



(a) Gross pressure as function of time after launch. (Note low level acoustic data superimposed on pressure data)



(b) Acoustic data conditioning block diagram



(c) Properly conditioned acoustic data

Figure 17 The development of acoustic information from pressure data

SHOCK CALIBRATION OF ACCELEROMETERS

by

Charles Federman, William H. Walston*, and John D. Ramboz
National Bureau of Standards
Washington, D. C.

ABSTRACT

A means to calibrate mechanical shock accelerometers by a comparison method has been developed. Detailed procedures and equipment used to generate mechanical shock pulses, collect data, and analyze the results are discussed. Three piezoelectric accelerometers were subjected to haversine acceleration-time pulses of 50, 500, 900 and 1500 g peak amplitudes and time durations of 8.5, 1.2, 1.0, and 0.7 ms, respectively. Both time- and frequency-domain calibrations were performed. The shock calibrations agreed with sinusoidal calibration values to within a few percent. In addition to the sensitivity calculations which involve the magnitudes of the pulses, phase relationships between the accelerometers are discussed.

The frequency domain analysis utilizes a fast Fourier transform (FFT) algorithm extensively. Certain fundamental problems arise when using the FFT in shock calibration methods. Such problems discussed are sampling rate and pulse shape. A method, previously published by other authors, for the calculation of transform values at pre-selected frequencies is presented along with a Fortran program for its implementation.

INTRODUCTION

Measurement of mechanical shock has led to many problems, one of which is the inability to evaluate and calibrate shock measuring systems in the frequency domain. For instance, the method of measuring the peak response of accelerometers to shock excitation does not allow measurement of the response of the accelerometers as a function of frequency. That is, no attempt is made to determine how the energy of motion is distributed over the frequency range. Instead, only the lumped response integrated over the total energy spectrum is measured. Another calibration method involves the measurement of the output of shock accelerometers to sinusoidal excitation at several discrete frequencies. If the accelerometer is linear with amplitude, its response to a shock can be synthesized from the measurements of its output to sinusoidal motion. Although this approach may result in good accuracy, it is time consuming and subjects the accelerometers to intense, steady-state, sinusoidal motion which may be damaging to the accelerometers.

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Mechanical Engineering Department
University of Maryland

An investigation by the National Bureau of Standards has been made to study and verify the performance of selected shock accelerometers and to develop a general calibration technique. The transfer functions of these standards were determined when used under various conditions of pulse height, pulse width, and overall motion environment. This information is required in order to determine uncertainties in impact measurement. The accelerometers used were piezoelectric types, but others, such as the piezoresistive type, pose no special problems. Two of the accelerometers were of the same manufacturer and model, and of a "single-ended, top-connector" shear design. A third accelerometer was a "piggy-back" comparison standard of the compression design. Charge sensing was used throughout. Shock pulses were generated by a pneumatic shock test machine.

Comparison measurements were made in both the time and frequency domains. For the time domain analyses, comparisons were made by the peak ratio, the area ratio, and instantaneous ratio methods. These methods yielded only a single sensitivity value for each of the accelerometers.

For the frequency domain analysis, the accelerometer's response is transformed from the time domain to the frequency domain through the use of a fast Fourier transform (FFT) algorithm. Ratios of transforms lead to the comparison calibration of one accelerometer in terms of another. The frequency domain analysis yields the solution in complex terms, i.e., amplitude and phase angle. Certain fundamental problems, such as sampling rate and pulse shape, were encountered when using the FFT in shock calibrations. Techniques, including both hardware and software, were implemented for the treatment of these problems. A previously published method [1] for the calculation of transform values at pre-selected frequencies was linked to the FFT program to present the output data in a more manageable and presentable form.

DESCRIPTION OF EQUIPMENT

The laboratory equipment consists of four main items: (1) a mechanical shock generating machine, (2) acceleration measuring transducers, (3) a data transfer system, and (4) a minicomputer for data storage and manipulation. These items provide a means for transient data generation, data collection and reduction, and calibration of test accelerometers.

Mechanical shock pulses are generated in the laboratory with the use of a pneumatically controlled and actuated shock test machine, as shown in figure 1.

[1] *Numerals in brackets refer to references at the end of this paper.*

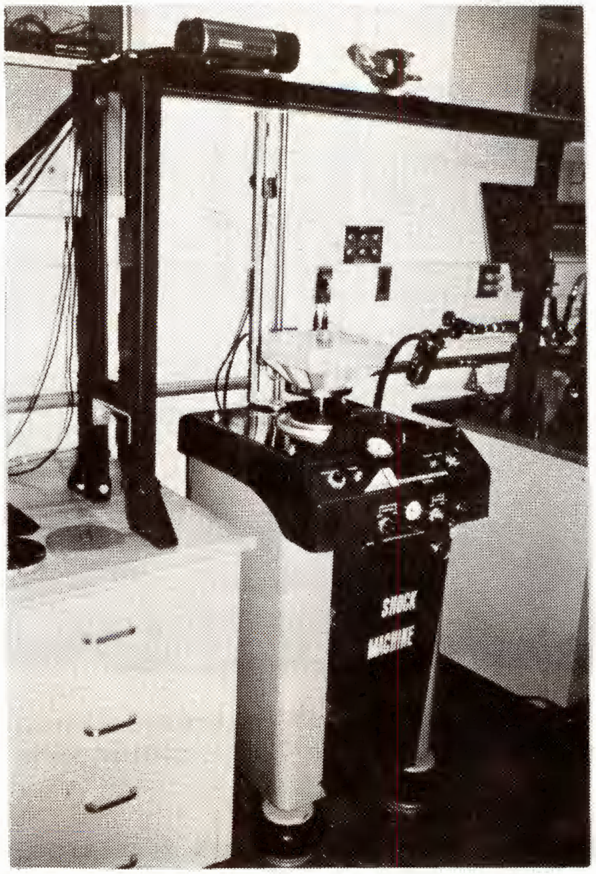

FIGURE 1. Mechanical Shock Generating Machine.

This device can be adjusted to produce those pulse shapes called out in established specifications [2-4], with the capability of producing a variety of shock pulses up to 10,000 g. Shock pulse levels can be set rapidly by a simple adjustment of an air pressure regulator. The principle of operation is to suddenly drive a carriage into a spring element which decelerates the carriage, and then rebounds in the opposite direction. The shock amplitudes, durations and shapes are controlled by the impacting medium, air pressure, and drop height. For all the tests in this paper, only elastomer pads were used. Initial height and air pressure were adjusted to trim the shock pulse to the desired amplitude and duration.

The acceleration measuring transducers included a reference system and two test accelerometers. The reference system consists of a reference accelerometer and a matched solid-state charge amplifier. Because the accelerometer is of the "piggy-back" configuration, other test accelerometers can be flush mounted to its top without the requirement of an additional fixture (see figure 2). This permits calibration by the comparison method, where the electrical outputs of the reference accelerometer and test accelerometer are compared, while both are subjected to the same motion. The accuracy of this method is directly dependent on the accuracy of the calibrated reference. Use of a piezoelectric element in the reference accelerometer permits a flat temperature response and stability with time. This accelerometer-amplifier reference system was calibrated at the National Bureau of Standards. Both reciprocity-based sinusoidal and laser interferometric methods were used.

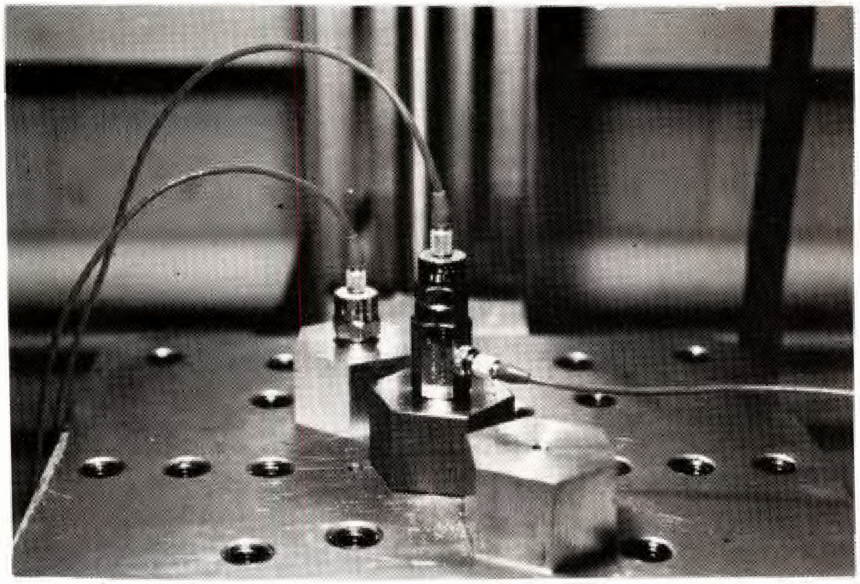

FIGURE 2. "Piggy-Back" Configuration of Reference Standard and Test Accelerometers, with Single Test Accelerometer Mounted Behind.

Two identical, high resonance frequency, shock accelerometers were used as the test accelerometers. Their small size, compact construction, stable operation, and high resonance frequency (approximately 80,000 Hz) makes them useful devices for measuring shock transients. The manufacturer's specifications for the two accelerometers claim a measurement capability of 20,000 g. They are self-generating, shear design, piezoelectric accelerometers.

The analog-to-digital converter and interface control system (ADC-ICS) serves as an interface between the data generation and data collection cycles. Figure 3 shows a block diagram of the equipment used. Data, in the form of analog voltages, are converted and transferred via the ADC-ICS, from the accelerometer systems to a minicomputer. An operator controlled initiation switch, on the front panel of the ADC-ICS, activates the unit and turns on a ready status light. It then waits until it is triggered before the next collection cycle begins. An external oscillator, functioning as a driver, is used to clock the sample-and-hold circuit and the analog-to-digital converter. High-speed and high accuracy are combined, through the use of compact solid-state electronics in the ADC, to convert an analog input signal to an equivalent 14-bit plus sign output digital word. Although this digital word length of 14 bits is available, only 10 bits of the word are normally used for the calculations. A combined parallel-decision/serial-correction technique is used as the method of conversion. Conversion rates of up to 250,000 converisions per second are obtained using this technique. The ICS section provides all the signals required by the ADC to convert the analog input voltage to a digital output. An updated 16-bit address word is generated for each conversion. This address is used to indicate in which memory address the data word is to be stored. During the data collection cycle, two multiplexed channels are outputed to the minicomputer. This puts a restriction on the data in that points from each channel are not time coincident. Thus, a digitization phase error is produced which is corrected for in the final analysis.

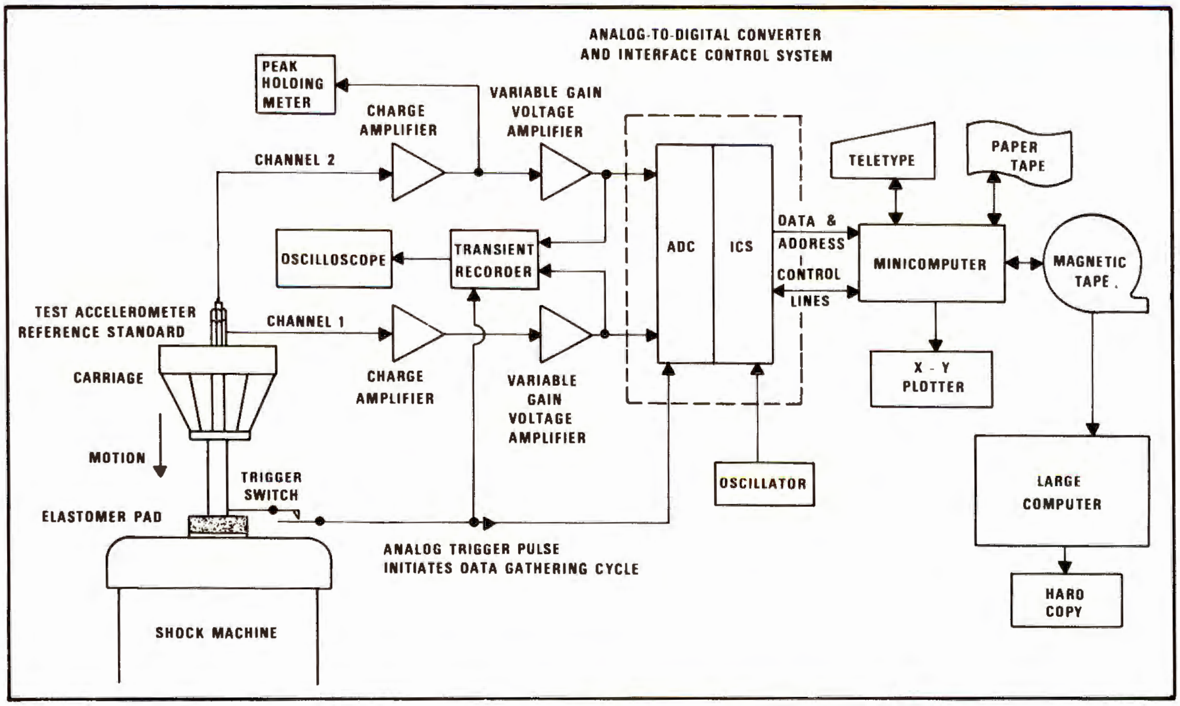

FIGURE 3. Block Diagram of Shock Pulse Data Generation, Retrieval, and Analysis.

A 64 k-byte core memory minicomputer is necessary for the data collection sequence of the calibration process. The memory is directly addressable with the primary instruction word. Sixteen general registers of 16 bits each can be used as index registers or accumulators. Shock data is sent by the ADC-ICS through the direct-memory-access port of the computer. This method insures that all the transient data can be captured and stored in the core memory. After a block of data for a single run is stored in memory, it can be written on either paper or magnetic tape for future transmission to a larger computer for analysis. The analysis may also be done by the minicomputer, but this method can be more time consuming if the minicomputer has only software arithmetic functions.

A transient recorder, shown in figure 3, is used to capture transient data. Because this device is limited by an 8-bit data word and small memory storage, the captured transient information is not used numerically, but is displayed on an oscilloscope to show a visual presentation of the shock pulses. Another device used, the peak-holding meter, gives an approximate acceleration level for each set of data. The readings from this meter are not used in any of the calculations.

SHOCK PULSE CHARACTERISTICS

A perfectly elastic impact onto a linear spring would generate an ideal half-sine acceleration wave shape. However, because of nonlinearities and losses, the pulses generated in the laboratory take on the characteristics of a degraded half-sine and appear similar to a haversine function. Though the description of wave shape is qualitatively called haversine, there are subtle differences in the time domain between a haversine and other similar shapes such as half-sine or Gaussian pulses. Ideally, the accelerometer calibration process should not be critically affected by the wave shape, although there are problems in the analysis for certain wave shapes.

Typical shock pulses shown in figure 4 are from one channel of the two used for test data. These are samples from the 50 g, 500 g, 900 g, and 1500 g peak accelerations.

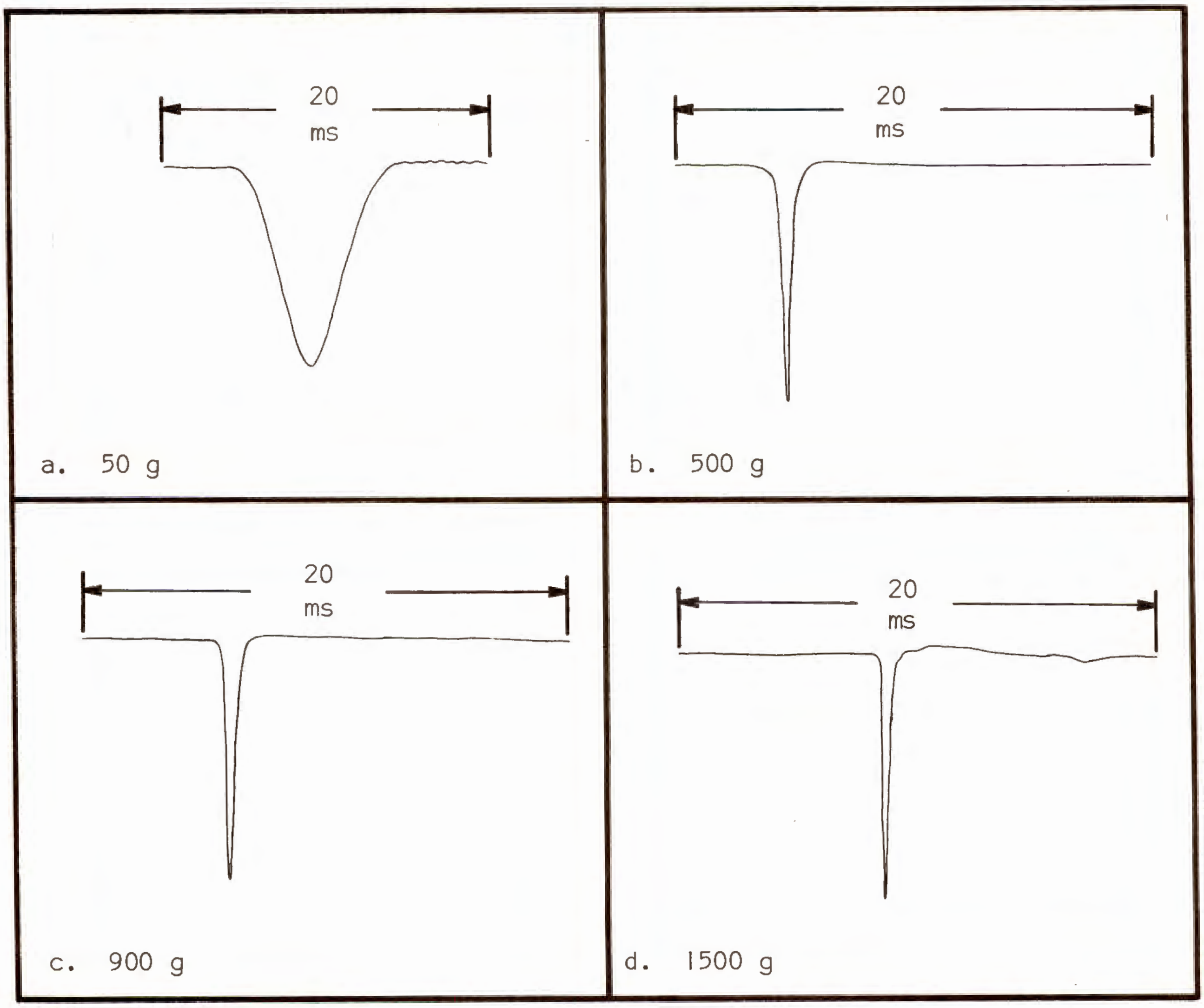

FIGURE 4. Typical Shock Pulses from Accelerometer B.

Three accelerometers were used in these tests. For purposes of this paper, the accelerometers are identified as A, B, and R. Units A and B are nominally identical while unit R is considered as a comparison reference. Laboratory measurements were made by comparing A to R, B to R, and A to B. This gives three basic accelerometer combinations.

TABLE I. ACCELERATION AMPLITUDES AND DURATIONS

Nominal Shock Pulse Parameters	Mean Amplitude	Amplitude Range
50 g, 8.5 ms	52.4 g	49.4-55.8 g
500 g, 1.2 ms	517.5 g	488-560 g
900 g, 1.0 ms	894 g	864-927 g
1500 g, 0.7 ms	1419 g	1346-1524 g

The nominal amplitudes and durations of the pulses are shown in Table I. For any one set of conditions, there were five repeated shock pulses made. In all, there were 60 pulses produced, 15 for each of the four shock conditions, five for each of the accelerometer combinations. The measured amplitudes were within ± 15 percent of the nominal values. Because the calibration results are not a critical function of the shock amplitude, no special care was taken to maintain better control of the amplitude.

TIME DOMAIN COMPARISONS

A popular method for calibration of shock accelerometers is by the peak comparison method [5,6]. This has been even more useful in recent years with the availability of peak-holding meters. For these tests, the time domain data for each channel were printed out as part of the analysis. It is relatively easy to search for the maximum amplitude of the time domain signal for each of the two accelerometers being compared. The ratios of the peak values were calculated for each test of accelerometers A, compared to R and B compared to R. The ratios from the repeated tests for any matching set of parameters were then averaged. This usually consisted of 5 repeated tests. The standard deviation was also calculated.

An instantaneous ratio of two accelerometers can be obtained by reading the magnetic tape into the minicomputer and performing the necessary calculations. Prior to and after the mechanical shock, the ratio is that of two noisy signals. The noise sources include mechanical vibration of the shock machine carriage, accelerometer cable noise, electronic noise from the amplifiers, stray pickup noise and possibly pyroelectric outputs from the accelerometers. In addition to these noises, any dc-offset voltages in the system from unbalanced amplifiers leads to inaccurate ratios. After the impact, over-shoot likewise leads to inaccurate ratios. The only region that the instantaneous ratio becomes reliable is near the peak acceleration. As such, one could merely calculate the peak values.

The general conclusion is that the method does yield a qualitative plot that is sometimes useful, but quantitative data are limited to only the values derived near the peak amplitudes.

It is possible to compare the areas under the acceleration-time pulses. These areas are a measure of the change of velocity of the accelerometers under test. Ideally, the ratio of the velocities should lead to a satisfactory calibration process. In instances where there is minor ringing on the pulses, the area tends to average these effects. However, when there are dc-offsets or over-shoots involved, these can add significantly to the area. Additionally, the process becomes critical as to the time considered before and after the shock pulse because of the integration of offsets and over-shoots. When the areas were computed, large differences were apparent. The general conclusion regarding these tests was that the area ratios are significantly lower than the peak ratios for the same tests and the area ratios have significantly larger standard deviations. Overall, this method cannot be recommended without more effort to refine the process.

FAST FOURIER TRANSFORM ANALYSIS

The Fourier Integral Transform is a mathematical operation which decomposes a time signal, in the form of a data array, into its complex frequency components (amplitude and phase). In order to efficiently analyze a transient shock pulse in the frequency domain, a high speed computational algorithm called the fast Fourier transform (FFT) is utilized in the calculation of the Fourier integral transform of a time signal.

While the mathematical process is not dependent upon any particular input pulse or waveform, one must be concerned with the pulse shape in order to perform accelerometer calibrations. It is necessary to select input pulses which have sufficient frequency content over a wide frequency range. Ideally, the Fourier integral transform of the pulse would saturate the calibration bandwidth. Pulses such as the half-sine and haversine pulses, whose Fourier amplitudes go to zero at certain frequencies, as shown in figures 5a and 5b, lead to difficulties when ratios are taken for the sensitivity calculations. The actual pulses generated in the laboratory were satisfactory in this respect, as shown by a typical plot of a transformed pulse in figure 5c. It is also noted in figure 5c that the pulse contains very little frequency content above 3000 Hz. The frequency range is dependent on the duration of the pulse; generally, as pulse duration shortens, the availability of high frequency content increases. As discussed in the section on sensitivity results, the use of several input pulses, providing overlap at certain frequencies, enables one to calibrate over a wide range.

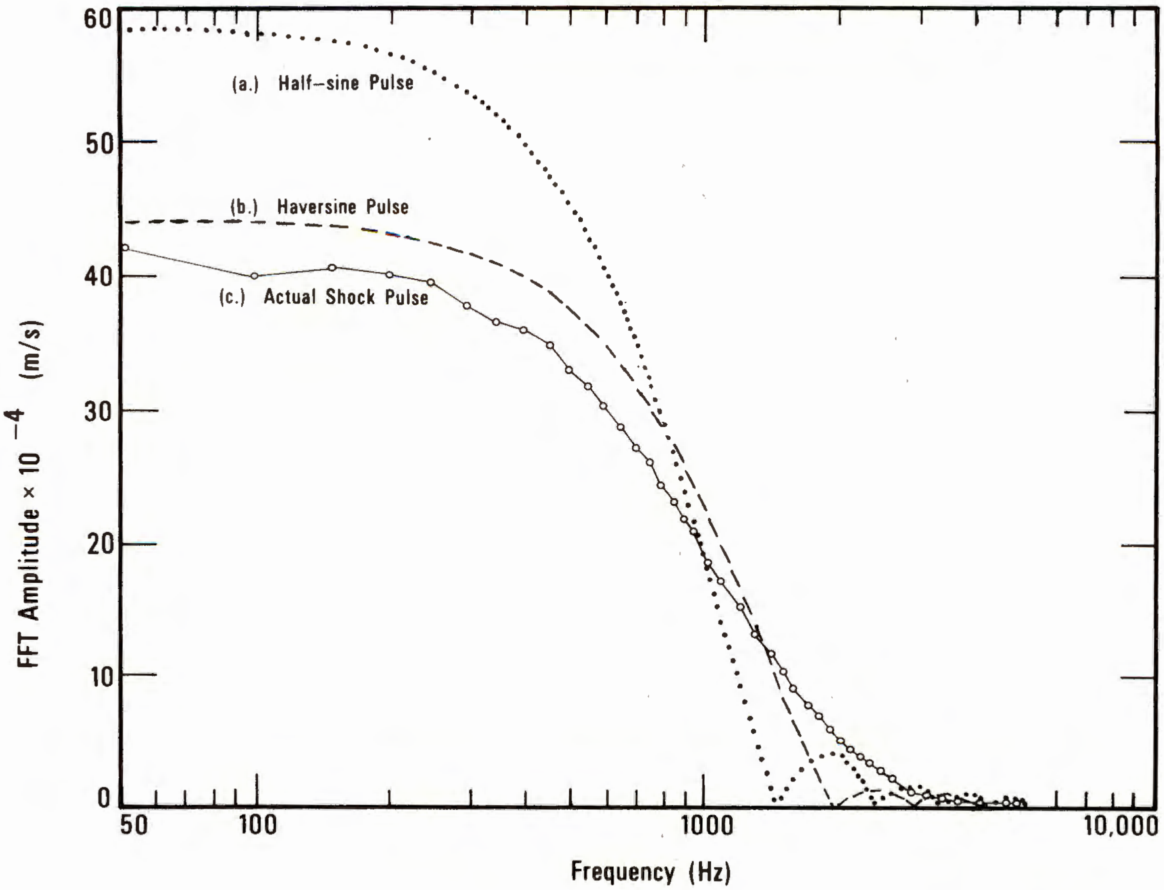

FIGURE 5. Comparison of Three 900 g, 1 ms Shock Pulse FFT Transforms.

Certain difficulties in interpreting the Fourier transform results may arise if the input signal does not begin at a zero level before the pulse initiation and end at zero at pulse completion. During the computation of the Fourier transform, the FFT algorithm treats the pulse as though it is periodic. Thus, if a pulse does not begin and end at zero (or at the same level, since a shift in the zero level could compensate for equal offsets), the periodic signal appears to have discontinuities at the beginning and/or end of each period. It is known that the introduction of small discontinuities makes a significant difference in the Fourier transform computed by the algorithm. Thus, it is desirable to meet the criteria of continuity or to introduce techniques to compensate for the discontinities. Some of the techniques considered are: (1) folding the pulse about a vertical axis at the point where the discontinuity would occur, thus avoiding it and (2) using a tapered window or filter to smooth the pulse to zero at the ends. Investigation of these approaches is continuing.

A version of the Cooley-Tukey fast Fourier transform algorithm is used to analyze the shock pulse data [7]. (See Appendix A.) The program used works on a one-dimensional complex array, and outputs the Fourier real and imaginary frequency components in a similar array. This transform process is accomplished through the use of the NBS UNIVAC 1108 computer. Data from each channel is reduced from 1024 real, time domain measurements to 512 complex frequency components. The frequency range obtainable (Nyquist folding frequency) is a direct function of the sampling rate [8]:

$$\text{Frequency Range} = (1/2)(\text{Sampling Rate}). \qquad (1)$$

Resolution between frequency points is limited not only by the sampling rate, but also by the sample size:

$$\text{Resolution/Line} = (\text{Sample Rate})/(\text{Number of Data Points}). \qquad (2)$$

For example, if one were to use a typical FFT algorithm with the number of sample points being 1024, at a sample rate of 50 kHz:

$$\text{Frequency Range} = (1/2)\ (50\ \text{kHz}) = 25\ \text{kHz, and}$$

$$\text{Resolution/Line} = (50\ \text{kHz})/(1024\ \text{Points}) \approx 48.8\ \text{Hz/Point.}$$

This means that the data taken can be transformed into components out to 25 kHz in steps of approximately 48.8 Hz. The result is a sparseness of data at the low frequencies, where we desire information at smaller frequency intervals, and an overabundance of data at the high frequencies, where we can tolerate information at larger frequency intervals. Also, the frequency points 48.8 Hz, 97.6 Hz, etc. are not necessarily where we want them; for example, in comparison with a sinusoidal calibration.

A technique introduced by Gaberson and Pal [1] allows the determination of complex values of the FFT at any desired frequency. However, it is necessary to first compute the FFT by a standard algorithm and then to calculate the desired values; so computer time is increased. The following expression, developed from Gaberson and Pal's equations, allows the determination of the FFT at preselected frequencies. A Fortran subroutine is presented in Appendix B.

$$F(f) = \left[\frac{\sin 2\pi fT}{\pi T} + i\,\frac{\cos 2\pi fT - 1}{\pi T}\right]\left[\frac{\alpha_o}{2f} + \sum_{n=1}^{M} \frac{\alpha_n f + i\beta_n\left(\frac{n}{T}\right)}{f^2 - \left(\frac{n}{T}\right)^2}\right] \qquad (3)$$

where:

- F = complex Fourier transform
- f = desired frequency
- T = duration of the signal in the time domain
- α_n = real part of the complex FFT
- β_n = imaginary part of the complex FFT
- M = N/2 where N is the total number of intervals in the duration of the signal
- n = frequency index integer

After the time domain data from the test and reference accelerometers have been read from a nine-track magnetic tape, a software FFT program transforms this data from the time to the frequency domain. Immediately after the transformation, this complex data output is converted to amplitude and phase relationships for the two transducers. The amplitude is obtained by taking the square root of the sum of the squares of the real and imaginary parts of each frequency component. For each discrete frequency point, the ratio is taken of the test and reference amplitudes. This ratio is then used as a base for calibration of the test accelerometer by comparison techniques.

Phase information is calculated from the arctangent of the division: imaginary part divided by the real part. Then by using an identity for the conversion from radians to degrees, the phase angle is displayed as a positive or negative number of degrees. To determine the phase relationship between the two accelerometers, the calculated phase angle of the reference accelerometer is subtracted from the calculated test accelerometer phase angle. This result indicates whether the test accelerometer output is leading or lagging the reference accelerometer output.

A phase shift is synthesized into the process by non-coincident sampling of the two accelerometer outputs [9]. As was discussed, the input of the analog-to-digital converter was multiplexed between the two accelerometer inputs. As such, channel 2 is measured at a slightly later time than channel 1. This length of time is equal to the reciprocal of the sampling rate. The uncorrected FFT assumes that coincident time sampling occurred. When coincidence is assumed, it appears that channel 1 lags channel 2. This phase shift is described by

$$\phi_m = \frac{180(\eta - 1)}{N} = 360 \frac{f}{f_s} \qquad (4)$$

where ϕ_m = phase error in degrees due to multiplexing time delay (leading angle as described above)

η = harmonic line number from the FFT algorithm, ($\eta=1$ for f=0 Hz)

N = number of points sampled

f = harmonic frequency

f_s = analog-to-digital sampling frequency

The correction of this synthesized error can be easily made. Because η and N are exact integers, and f_s and f can be measured accurately, ϕ_m can be strictly defined.

SENSITIVITY RESULTS

In the back-to-back configuration, both the test and reference standard accelerometers should experience an identical shock acceleration as a function of time. Letting S_x and S_r represent the unknown and reference sensitivity, respectively, the following relationship can be developed:

$$S_x = \left[E_x(f)/E_r(f)\right] S_r \tag{5}$$

where $E_x(f)$ and $E_r(f)$ are the corresponding Fourier amplitudes at a given frequency.

The sensitivity data for test accelerometer A are plotted graphically in figure 6 to get an overall view of the trends and limitations of the shock calibration process. On this graph, the fitted values for the sinusoidal calibrations are also plotted for reference purposes. The sensitivity data are divided into separate acceleration levels: 50, 500, 900, and 1500 g. For the 50 g curve, the sensitivity tends to drop off much sooner than the other acceleration levels. The drop off is readily seen to begin at approximately 300 Hz. This indicates that there is a lack of high frequency information in the 50 g pulse. The curves of sensitivity for the 500 and 900 g pulses are similar because there is not much difference in their acceleration waveforms. Both follow a smooth exponential curve until they reach the 2000 Hz frequency point, where the curves rise upward. The 1500 g plotted sensitivity follows similar trends in the 500 to 5000 Hz ranges, but at the low frequency end, below 500 Hz, the data become erratic. This inconsistency shows that there was very little or poor low frequency information in the high g pulses.

PHASE COMPONENT RESULTS

Phase relationship data for accelerometer A are plotted in figure 7 to provide an overall view of the phase characteristics. It should be noted that this phase relationship is between the test accelerometer A and the reference standard R. The phase plots are flatter out to higher frequencies than the sensitivity curves. This indicates that the shape and frequency content of the pulse do not affect the phase as much as the accelerometer amplitude versus frequency. The 50 g level pulse is unstable after 300 Hz, but continues within 5 degrees of the other curves, while the others continue in a stable manner out to 2000 Hz.

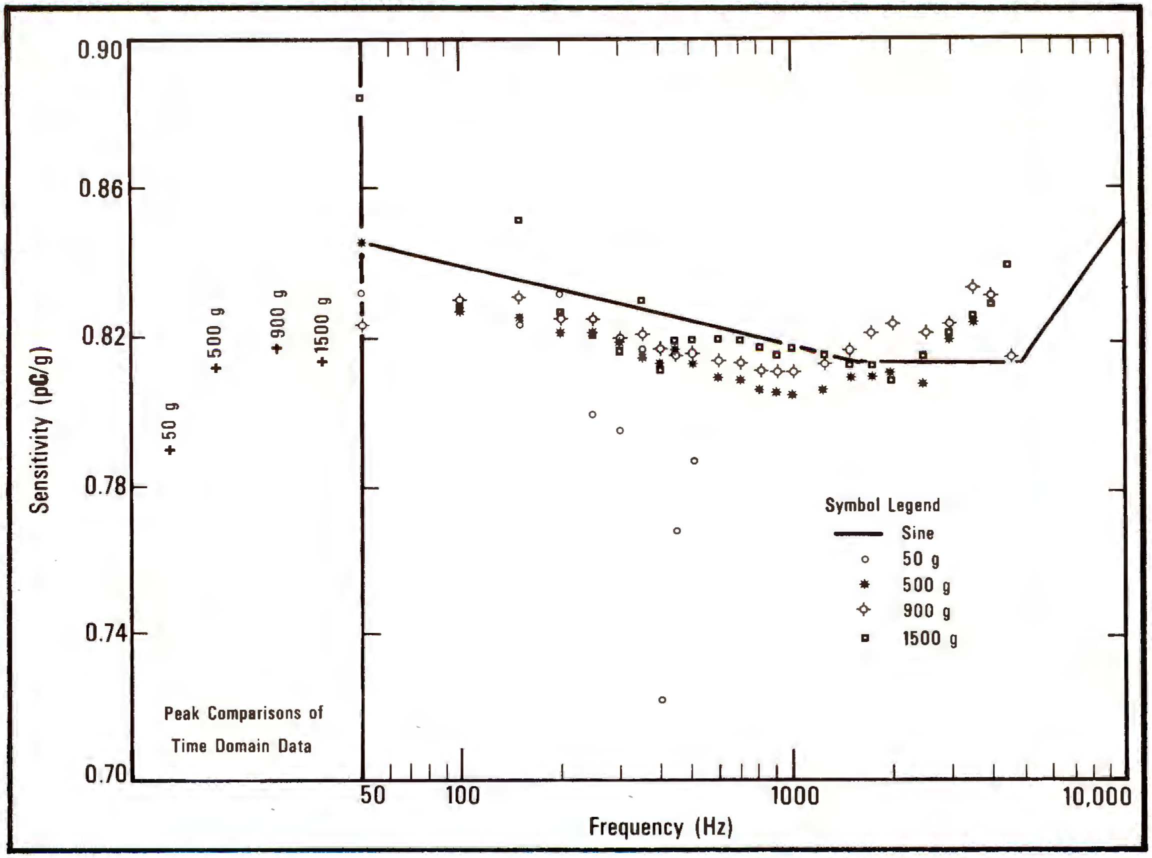

FIGURE 6. Accelerometer A Sensitivity Data.

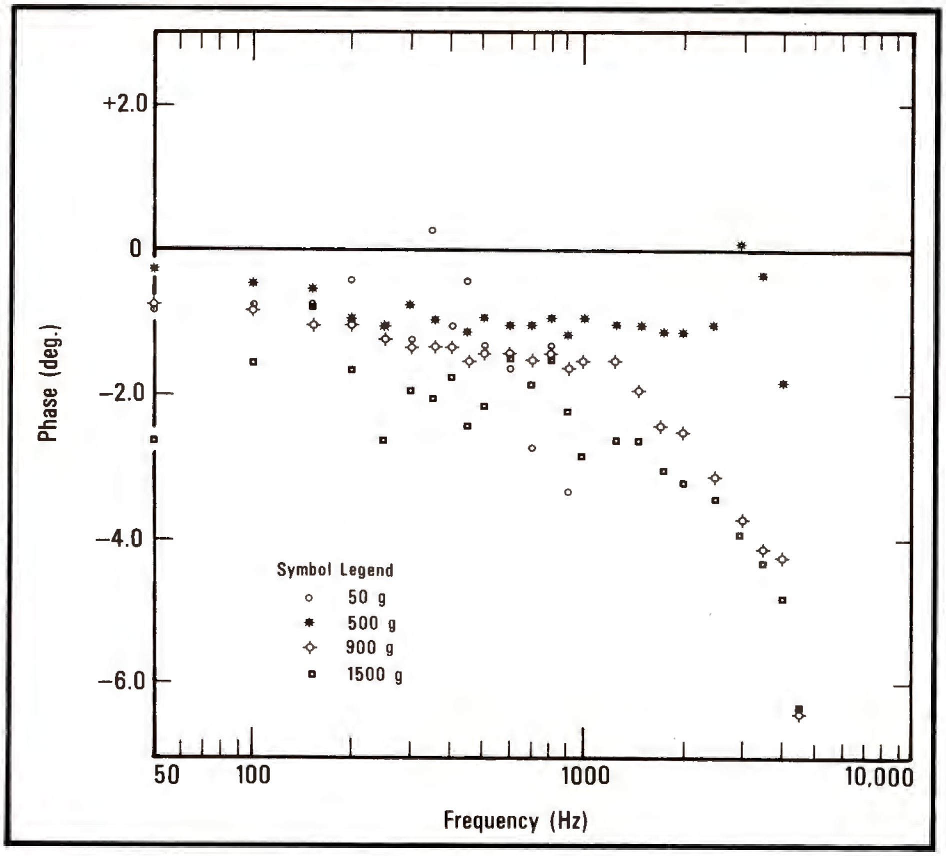

FIGURE 7. Accelerometer A Phase Data.

COMPARISON TO SINUSOIDAL DATA

The curve fitted sinusoidal calibration data, for accelerometer A, are plotted on figure 6a. As seen from this graph, the sensitivities derived from the shock calibrations closely approximate the sinusoidal calibrations. In general, the values from the shock process tend to be lower than the sinusoidal until a point near 2000 Hz is reached. This trend of the shock data shows a constant difference of approximately one percent from the sinusoidal data over the frequency range from 50 to 2000 Hz. Inherent errors in the data processing or the laboratory measurement techniques can cause such errors as described above. The shock and sinusoidal data demonstrate graphically that two independent systems can provide accelerometer sensitivities to within ± 1 percent of each other over long frequency intervals.

COMPARISON TO TIME DOMAIN DATA

There is an important distinction between the shock calibration results in the time domain and the frequency domain. All the calibration methods directly using time domain shock pulse measurements yield a single value of accelerometer sensitivity. For purposes of precision calibration, this is usually inadequate inasmuch as the accelerometer's sensitivity is not a constant value over a frequency range.

A comparison is made between time domain data of shock pulses and frequency domain data derived from these pulses. The time domain data is used to get a peak ratio measurement, and is only one value of sensitivity for each shock pulse. Therefore, it is not a truly valid comparison to the frequency domain data, but should be close to those calculated values. This method of peak comparison in the time domain is widely used as a means for calibrating shock accelerometers, but does not provide any frequency or phase relationships since it only deals with peak amplitudes.

Discrete values of sensitivity, for peak comparison of the time domain data are plotted in figure 6a. Note that the abcissa, for the time domain values, is not labeled in terms of frequency. Good agreement is shown between the two methods. One exception from this correspondence is the time domain sensitivity for the 50 g pulse. In both accelerometers, A and B, this point is almost three percent lower than the other time domain values. At this time, this shift remains unexplained.

CONCLUSIONS

The results obtained from this research demonstrate that a fast, accurate method for shock calibration, by comparison method, is feasible. The Fast Fourier Transform algorithm makes this possible, because of its ability to handle large data blocks, its relative speed in analysis, and its accuracy. Use of a minicomputer, as a data collection device, provides a means to do preliminary processing and to transport the data to a larger computing machine via paper or magnetic tape. Shock calibration in the frequency domain agreed to about one percent of the sinusoidal calibrations on each of the two accelerometers tested. Time domain, peak amplitude ratio calibrations agreed to about five percent of the sinusoidal calibration, depending on what frequency is selected. Frequency domain calibrations become unreliable when the Fourier amplitudes at high frequencies become less than a few percent of the low frequency amplitude.

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APPENDIX A

```
C   COMPUTATION OF TRANSFORM
C
C   SUBROUTINE FFT IS A FAST FOURIER TRANSFORM ALGORITHM WHICH IS
C   UTILIZED IN THE CALCULATION OF THE FOURIER TRANSFORM OF A
C   TIME SIGNAL
C
C   THE FOURIER INTEGRAL TRANSFORM IS A MATHEMATICAL OPERATION WHICH
C   DECOMPOSES A TIME SIGNAL, IN THE FORM OF A DATA ARRAY, INTO ITS
C   COMPLEX FREQUENCY COMPONENTS (AMPLITUDE AND PHASE)
C
C   ARRAY "DATA" MUST BE IN COMPLEX FOR FOR USE IN SUBROUTINE FFT,
C   WHOSE ARRAY LENGTH IS NN=2**K, WHERE L.GE.0
C
C   TRANSFORM VALUES ARE RETURNED IN ARRAY "DATA", REPLACING THE INPUT
C
C   ISIGN=-1 SIGNIFIES A FORWARD FOURIER TRANSFORM
C   ISIGN=+1 SIGNIFIES AN INVERSE FOURIER TRANSFORM
C
C   IF AN ISIGN=-1 TRANSFORM IS FOLLOWED BY AN ISIGN=+1 TRANSFORM (OR AN
C   ISIGN=+1 BY AN ISIGN=-1), THE ORIGINAL DATA REAPPEAR, MULTIPLIED BY
C   NN
C

      SUBROUTINE FFT(DATA,NN,ISIGN)
      DIMENSION DATA(1)
      PI2=1.5707963268
      N=NN*2
      J=1
      DO 55 I=1,N,2
      IF(I-J) 10,20,20
   10 TEMR=DATA(J)
      TEMI=DATA(J+1)
      DATA(J)=DATA(I)
      DATA(J+1)=DATA(I+1)
      DATA(I)=TEMR
      DATA(I+1)=TEMI
   20 M=N/2
   30 IF(J-M) 50,50,40
   40 J=J-M
      M=M/2
      IF(M-2) 50,30,30
   50 J=J+M
   55 CONTINUE
      MMAX=2
   60 IF(MMAX-N) 70,90,90
   70 ISTE=2*MMAX
      DO 80 M=1,MMAX,2
      THET=ISIGN*(M-1)*3.1415927/MMAX
      WR=SIN(THET+PI2)
      WI=SIN(THET)
      DO 80 I=M,N,ISTE
      J=I+MMAX
      TEMR=WR*DATA(J)-WI*DATA(J+1)
      TEMI=WR*DATA(J+1)+WI*DATA(J)
      DATA(J)=DATA(I)-TEMR
      DATA(J+1)=DATA(I+1)-TEMI
      DATA(I)=DATA(I)+TEMR
      DATA(I+1)=DATA(I+1)+TEMI
   80 CONTINUE
      MMAX=ISTE
      GO TO 60
   90 MMAX=N/2
      RETURN
      END
```

APPENDIX B

```
C   COMPUTATION OF INTERMEDIATE TRANSFORM VALUES
C
C   SUBROUTINE GABER CALCULATES THE COMPLEX VALUES OF THE FOURIER
C   TRANSFORM OF A TIME SIGNAL AT PRESELECTED FREQUENCIES, UTILIZING
C   THE PREVIOUSLY CALCULATED VALUES OF THE FFT
C
C   SELECTED FREQUENCIES ARE DETERMINED BY J1, J2, J3, AND J4
C   J1=INITIAL VALUE OF FREQUENCY FOR PRINTOUT
C   J2=FINAL INTERVAL VALUE OF FREQUENCY
C   J3=INCREMENTAL VALUE FOR FREQUENCY INTERVAL FROM J1 TO J2
C   J4=UPPER FREQUENCY LIMIT FOR PRINTOUT
C
C   TINT=TIME INTERVAL OF SHOCK DATA COLLECTION
C
C   K=NN/2
C
C   DATA=COMPLEX FOURIER TRANSFORM VALUES
C
C

      SUBROUTINE GABER(DATA,K,PI,TINT,FREQ,GAB,L)
      COMPLEX DATA(1024),GAB(50),E,C,D,T
      DIMENSION FREQ(50)
      REAL B,BETA
      J1=1
      J2=9*J1
      J3=1
      J4=20000
      L=0
      TINT=TINT/1000.
  310 DO 380 J=J1,J2,J3
      IF(J.GT.J4) GO TO 385
      L=L+1
      FREQ(L)=FLOAT(J)
      TOP=SIN(2.*PI*FREQ(L)*TINT)
      BOT=PI*TINT
      A=TOP/BOT
      TOP2=COS(2.*PI*FREQ(L)*TINT)
      B=(TOP2-1.0)/BOT
      C=CMPLX(A,B)
      D=DATA(1)/(2.*FREQ(L))
      T=CMPLX(0.,0.)
      DO 350 I=2,K
      IF((ABS(FREQ(L)-(I-1)/TINT)).LT.0.1) GO TO 360
      FRQ2=(FREQ(L))**2
      DEN=(FRQ2-((I-1)/TINT)**2)
      TOP1=(REAL(DATA(I))*FREQ(L))
      AIDAT=AIMAG(DATA(I))
      TOP2=AIDAT*((I-1)/TINT)
      ALPHA=TOP1/DEN
      BETA=TOP2/DEN
      E=CMPLX(ALPHA,BETA)
      T=E+T
  350 CONTINUE
      GAB(L)=C*(D+T)
      GO TO 380
  360 GAB(L)=DATA(I)
  380 CONTINUE
      J1=10*J1
      J2=10*J2
      J3=10*J3
      GO TO 310
  385 TINT=TINT*1000.
      RETURN
      END
```

MEASUREMENT SYSTEM CONTROL THROUGH PERIODIC CORRELATION

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Abstract

The periodic correlation of large liquid and gas flow calibration systems using a set of precision flow rate transducers is discussed. The advantages of employing this method of system control over the traditional method of using several transfer standards to verify system accuracy is brought out. Future correlation of systems using computer controlled "intelligent" transducers is also discussed.

MEASUREMENT SYSTEM CONTROL THROUGH PERIODIC CORRELATION

W. P. Callis/Mechanical Engineer
US Air Force Physical Standards Laboratories

The traditional concept of the Air Force Calibration Program is to maintain several echelons of transfer standards for each measurement area. These transfer standards are usually shipped to a centralized location (AGMC) where they are certified with absolute or higher accuracy standards. They are then disseminated to various selected locations and used to calibrate Precision Measurement Equipment (PME). In some cases as high as 140 of these transfer standards are purchased and maintained. The standards are shipped back and forth at prescribed intervals for recertification and reissue. This concept involves large initial costs, resulting damage through shipment of fragile standards, and a degradation of weapons system accuracy due to the number of instrument comparisons involved.

In some cases this concept is not feasible due to the physical size and nature of the standard involved. The Cox 311 Liquid Flow Calibrator shown here, for example, is 15-feet long, 8-feet high and 5-feet wide and weighs 4000 pounds. It is also permanently installed at each location. A similar item is the Cox Gas Flow Nozzle Calibrator shown in this slide. It is possible to control these measurement systems through periodic surveillance of their primary functions by employing very stable transducer elements.

An electromechanical system, such as the Cox 311, can be controlled using a single set of flow transducers which cover the range of the system. The requirements necessary for the transducers are that they be highly repeatable and stable over a reasonable period of time. This has been accomplished in the field of liquid flow measurements for a number of years. The transducer set presently in use consists of four turbine flowmeters which cover a range of 15 to 100,000 pounds per hour of hydrocarbon fluid. These instruments are calibrated at the National Bureau of Standards at selected flow points throughout the range of the system to be tested. The package is then shipped to the bases where the equipment is located. The systems are tested with these transducers according to a specific schedule, or procedure. The data is then sent to a central location (AGMC) where it is statistically analyzed by a computer. The results are forwarded to the users of the system to assist them in defining the errors associated with their particular equipment and/or environment.

This type of measurement analysis has several advantages:

(1) It examines the functional aspects of the total measurement system in a very short time period. The total flow range of the Cox Model 311 calibrator can be analyzed in about 16 manhours.

(2) It defines the errors in specific subsystems. Knowledge concerning the behavior of the system under certain conditions and in response to specific errors will localize the problem area. For the Cox 311 a constant systematic percent of reading error in one direction would indicate an improper beam ratio in the weigh tank system of the calibrator.

(3) It includes all parts of the measurement system including the human operator and the system environment. Changes in ambient temperature surrounding the equipment and effects due to drafts, etc, effect the variance of a given set of readings.

(4) Analysis of system performance can be controlled by a small, central group using statistical techniques which are standardized. In this case all data is returned to AGMC where it is processed for statistical deviation from known parameters by a single computer program.

(5) Test results can be easily disseminated using time-sharing computer techniques communicating to a central location. Remote computer terminals at each base location can be used to transmit the correlation results almost immediately.

(6) Labor, material costs, and shipment damage is reduced. One set of four flowmeters is used for the correlation and shipped from base to base instead of shipping 140 separate standards.

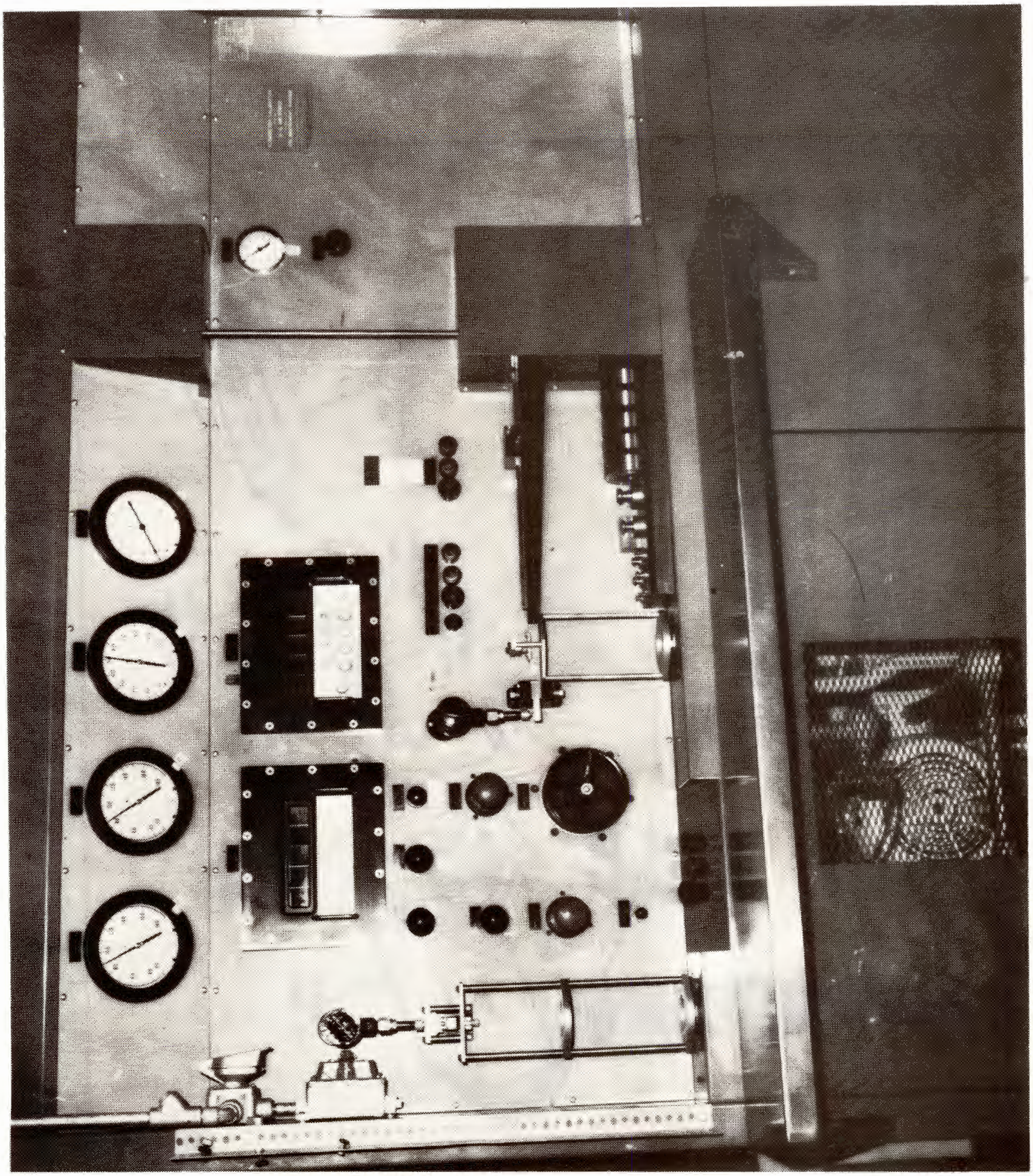
(7) Compilation of the history of a particular measurement system is simplified. The history of the measurements of each calibrator can be stored in a single computer memory and can be compared to other calibrators or to its own past history at will. The reliability and mean time between failures of these systems can be projected very accurately.

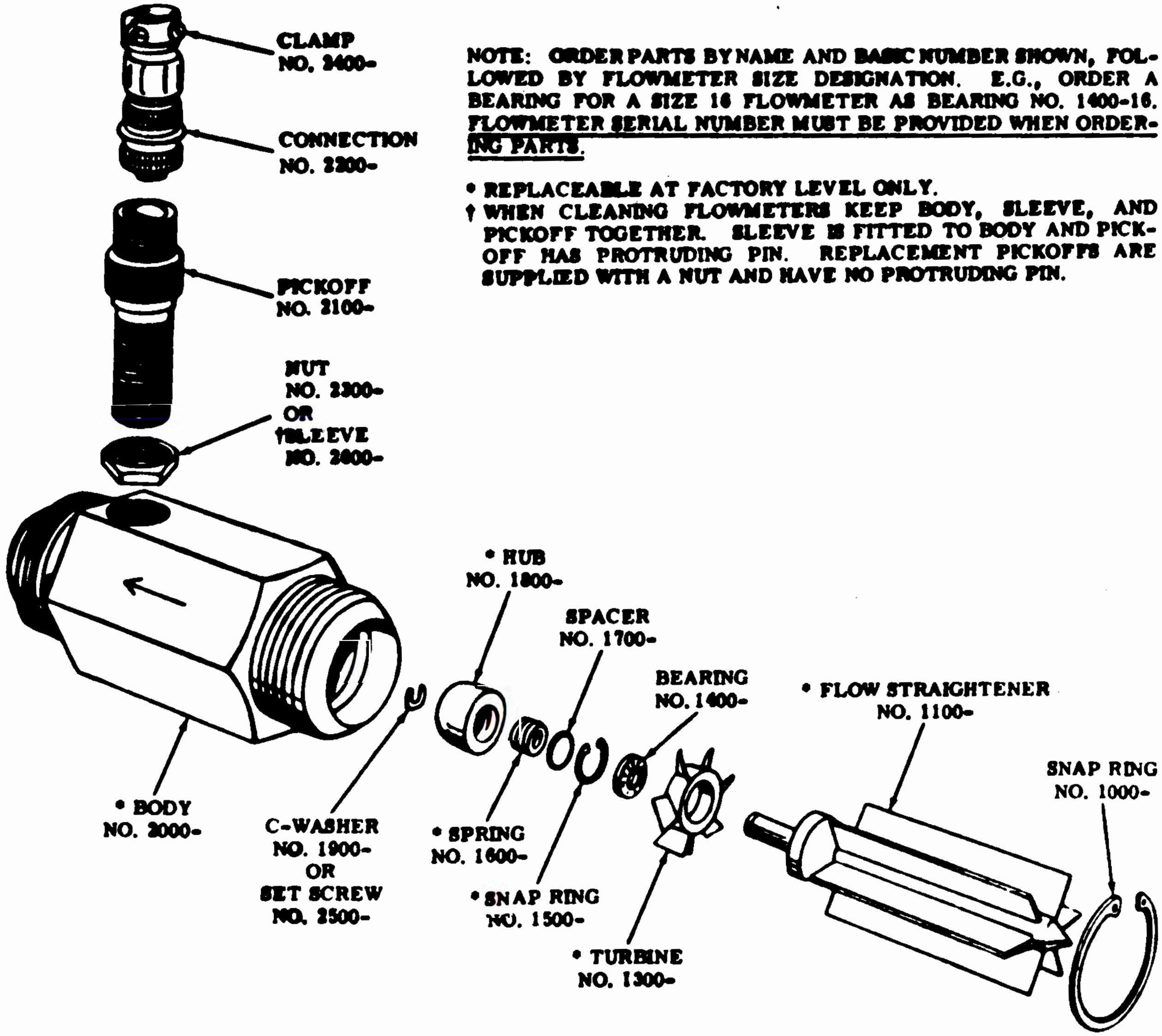
(8) Procedures can be designed to reflect the true precision of routine calibrations performed on a particular system. This method of system correlation is almost identical to the way the calibrators are used during routine flowmeter calibrations. Therefore the real system accuracy, precision, repeatability, and resolution are reflected in the correlation.

(9) Echelons of physical standards are eliminated. The correlation measurements are directly traceable to the National Bureau of Standards since the transducers are calibrated there. This deletes the need for a transfer standard at AGMC (with a corresponding loss of accuracy to the field measurement).

Evaluations are now being performed on several gas flowmeter transducers which may be used to correlate gas flow calibrators. One such instrument is the prototype meter shown here. This meter has an extreme rangeability for a single element (.01 to 1000 cubic feet per minute) and high accuracy (±.5% of the reading). The primary element is a matrix of very small laminar flow channels built into the meter body. The differential pressure across the laminar matrix is measured by a diaphragm manometer. The position of the diaphragm is sensed by a capacitance bridge. The meter is automatically compensated for pressure and temperature changes within the element.

Progress is being made in other measurement areas but intensive research is needed to develop very stable and repeatable transducers in all fields. Solid-state circuitry and integrated electronics are beginning to aid stability in the read-out portion of these elements but more work is needed to develop stable primary elements. It may be possible, at some future time to design transducer systems that are so stable and repeatable that they could be installed on site permanently attached to the measurement system. These transducers would be electrically connected to a computer system in a central laboratory which would receive the data and analyze it automatically. This concept would completely eliminate shipping of physical hardware of any kind thereby eliminating damage and loss of expensive equipment.





NOTE: ORDER PARTS BY NAME AND BASIC NUMBER SHOWN, FOLLOWED BY FLOWMETER SIZE DESIGNATION. E.G., ORDER A BEARING FOR A SIZE 16 FLOWMETER AS BEARING NO. 1400-16. FLOWMETER SERIAL NUMBER MUST BE PROVIDED WHEN ORDERING PARTS.

* REPLACEABLE AT FACTORY LEVEL ONLY.

† WHEN CLEANING FLOWMETERS KEEP BODY, SLEEVE, AND PICKOFF TOGETHER. SLEEVE IS FITTED TO BODY AND PICKOFF HAS PROTRUDING PIN. REPLACEMENT PICKOFFS ARE SUPPLIED WITH A NUT AND HAVE NO PROTRUDING PIN.

US AIR FORCE MEASUREMENT STANDARDS LABORATORY
AEROSPACE GUIDANCE AND METROLOGY CENTER

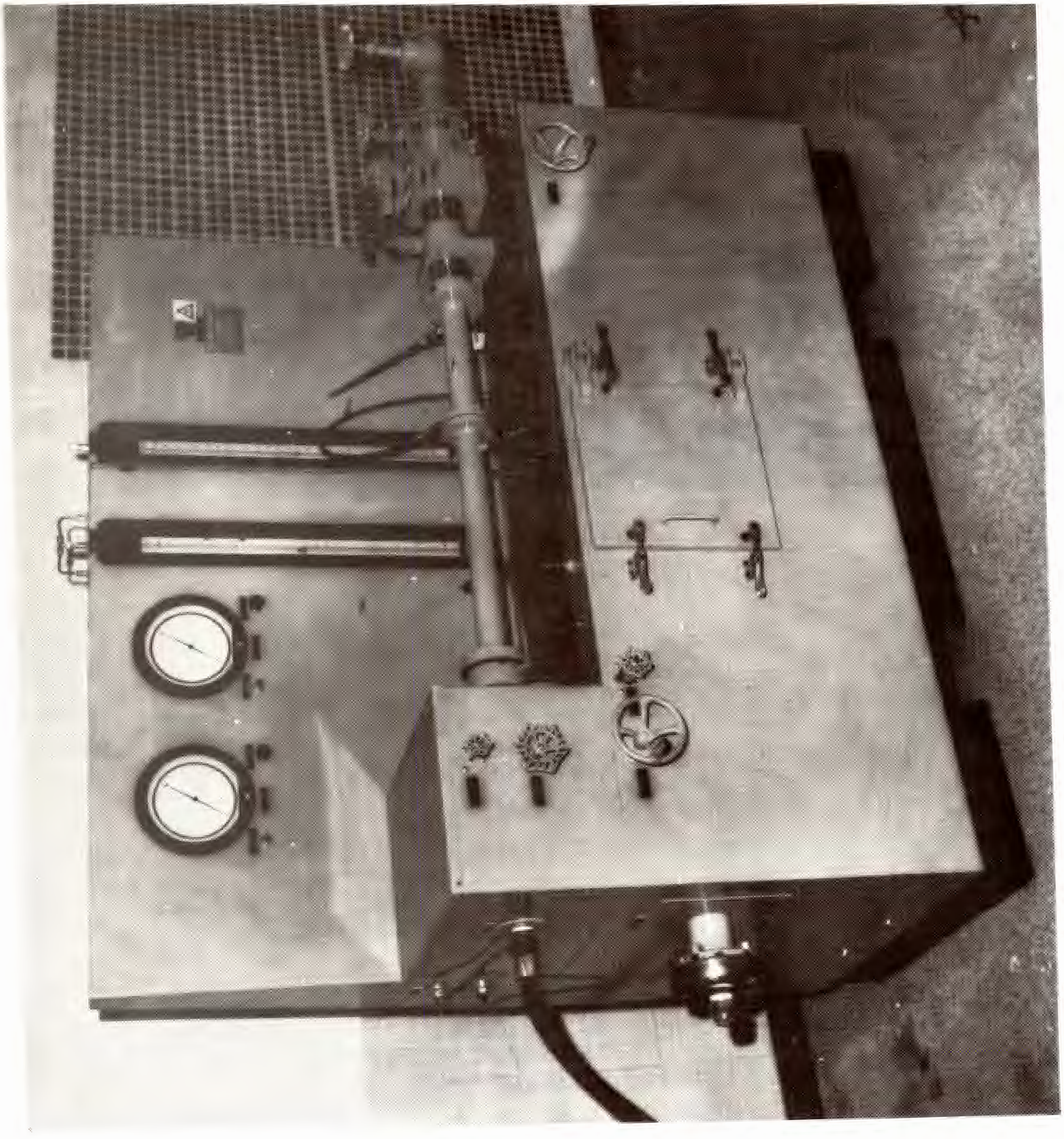
REPORT OF MEASUREMENT
ON
LIQUID FLOW CALIBRATOR
COX INST CO
MODEL 311AHT, S/N 866077-1

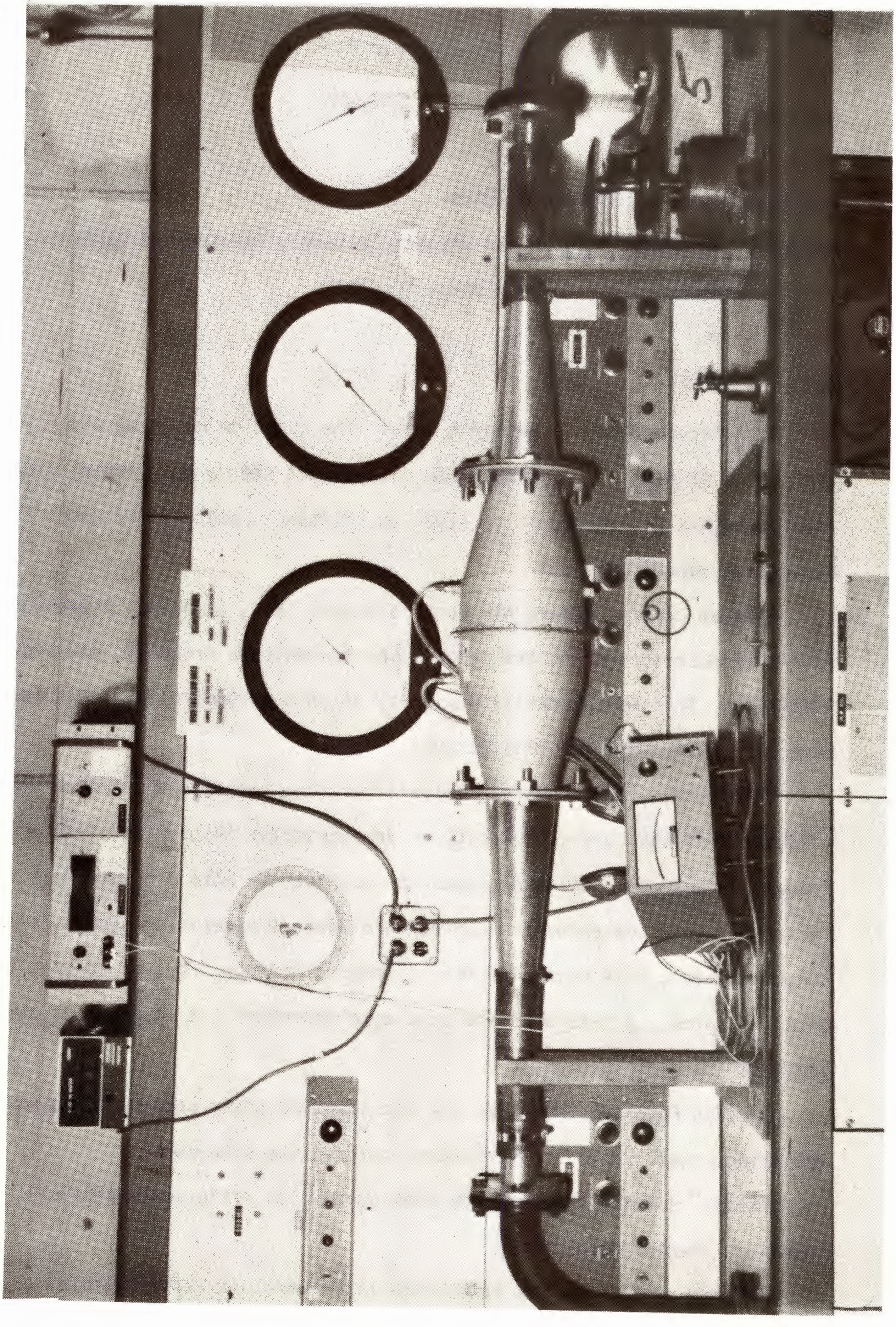
FOR
VANDENBERG AFB CA

THE ATTACHED TABLE SHOWS THE PERCENTAGE DEVIATION FROM THE NATIONAL BUREAU OF STANDARDS READINGS FOR EACH FLOW SETTING, AND FOR THE AVERAGE OF THE FLOW SETTINGS, ON THE SERIAL NO CALIBRATOR ABOVE. THIS TYPE OF CALIBRATOR IS CAPABLE OF PERFORMANCE WITHIN A TOLERANCE BAND OF ±0.5%.

CALIBRATION OF THE INDIVIDUAL PARTS OF THE CALIBRATOR ACCORDING TO THE INSTRUCTIONS GIVEN IN TO 33A6-3-30-1 MUST BE COMPLIED WITH EVERY SIX MONTHS EXCEPT FOR THE ADJUSTMENT OF THE WEIGH PAN BEAM RATIOS WHICH WILL INVALIDATE THIS REPORT.

CALIBRATED BY:	REVIEWED BY:	DATE:
A. C. ANDERSON	W. P. CALLIS	1 Oct 1974
VAFB	LABORATORY ENGINEER	
	MLLME, EXT 7636	





SESSION II

DISCUSSION SUMMARY

Session Chairman: Garland Rollins

Papers: Josephson; Rodgers and Wright; Cassanto; Paulson and Nuhfer; Federman, Walston and Ramboz; Callis

DISCUSSION:

John Carrico, Bendix Research Labs: The gas flow meter on which you are trying to develop standards--how did you get the dynamic range? You indicated that you go from 1 to 1,000 cu. ft/min. Laminar flow doesn't cover that range, does it?

William Callis, Newark Air Force Station: Yes, it does. There were four transducers covering the range. The transducers are 8-in. diameter by 4-ft long. This was a special design by us--not a commercial item. They were especially made for this purpose.

Peter Stein, Arizona State University: The literature includes some evidence that the surface to which an accelerometer is mounted affects the frequency response. Wilcoxon Research and Fuselier both did some work in that area. An accelerometer mounted on different materials such as steel, tungsten, etc., will have different impedance matches. Do you reverse the order in which the reference and test accelerometers are mounted, or how do you take that into account?

Charles Federman, NBS: We use the standard piggy back mounting without reversing order. Both accelerometers observe the same pulse.

Stein: How can they see the same pulse with different mechanical impedance loading conditions?

Federman: I think the difference is so small it is negligible.

Allan Diercks, Endevco: Perhaps I can help here. The model 2270 accelerometer is built upside-down. The reference surface to which the test accelerometer is mounted is the top surface, not the bottom surface. The two reference surfaces of the accelerometers are in close, intimate contact, and the presumption is that they do move together. There is no bending transmitted, or it is insignificant. I want to ask NBS what shock amplitudes and pulse widths can you attain?

Federman: We have a range of 50 g to 5,000 g amplitude and 40 ms to 1/2 ms width.

Diercks: Is NBS planning to offer shock calibration as a service?

Federman: We are right now and have been since November.

Bruce Wilner, Becton Dickinson Labs: Does the FAE program have any end-to-end calibration that establishes transducer integrity?

Larry Sires, Naval Weapons Center: The method of calibration at the two sites is different. At the air drop facility we use a PCB model 101A04 acceleration compensated pressure transducer with built-in electronics and adequate frequency response. The transducer has a 100-sec time constant. We use a dynamic pressure calibrator with a 20-ms rise time feeding a pulse through a large capacitance bank to increase the time constant of the electronics. The only thing different between that and live data is that we do not have 1,000 feet of line that we do in the field. We found negligible difference in calibration levels with and without the long lines. Over a 4-month period of time and a great number of gages, the average deviation was about 2%.

At the static test facility we use a Susquehana model ST4 which does not have built-in electronics, and calibration is another problem solved in a different manner. There we use a calibrator built in-house with a 2-1/2 ms rise time or a portable drop hammer system with electromagnetic bottom valve relief system.

(At this point several people discussed the calibration approach using a drop in pressure from a given level back to ambient. The point was raised that some transducers can be damaged by negative-going pressure pulses. In the case of piezoelectric devices, some charge can bleed off at pressure causing an error that is masked.)

Question for Joseph Dolis, General Electric: In the system you are using the transducer does not see the direct application of the forcing function. There is some kind of transfer function between the 30-mil diameter hole and the transducer due to the length of tube you have. Have you done any kind of computer modeling where one might use any tube restriction or tube length and calculate the response in advance?

Dolis: We have done extensive testing in that region to determine the time lag. Most of the publications were in-house. I think I could send you some documents on the work we have done with time response of the pressure transducer versus different tubing diameter and lengths.

Douglas Marker, Naval Weapons Lab: Question for Callis: You mentioned the fact that your calibration system lent itself to determining whether error sources came from the operator, the system or the environment. Could you give us more information on how that is determined and what percent of errors occur in the different elements?

Callis: Let me explain with an example. A facility at Sacramento, California, wanted to use a fluid that was hazardous because it had a low flash point. The base safety officer required the operation to be performed in a hazard-protected room which was not available. Another fluid was substituted having the same density but a higher flash point. The substitute fluid did not have the same viscosity, which had a definite effect on the turbine flow meter. We were able to show that the use of this substitute fluid caused errors of 9% and more.

William Anderson, Naval Air Test Center: In the FAE program, give us an idea of the characteristic thermal environment, and how did you actually check whether the transducers weren't responding to the temperature environment?

Sires: Actual measurement of the thermal environment is almost impossible. We have no instrumentation capable of measuring thermal response in that time regime. We check our transducers for photosensitivity and thermal transient effects by testing with a flash bulb heat source. Black electrician's tape did as good an insulation job as anything else.

Stein: Question for Larry Rodgers of Eglin Air Force Base: You're not actually measuring store trajectories with that instrumentation, are you?

Rodgers: There is a method developed within our group which can determine the ballistic perturbation put on the bomb. We painted patterns on the bomb and used on-board cameras to photograph the initial bomb departure. Later some Mark 82 dummy bombs had cameras installed in their noses. A grid pattern was established in the target area; the cameras started automatically after discharge from the bomb rack and photographed to about 500 feet from the ground where they are ejected and landed by parachute. We have three kinds of information: the airplane flight parameters, the energy input to the bomb from the rack instrumentation, and ballistic characteristics from the camera records.

Stein: Have you tried triangulation with two cameras?

Rodgers: We tried that and it doesn't work too well. At the time we did our instrumentation we couldn't get two cameras to run synchronously at the high framing rates required by our work. We could get better results with a single camera.

Jonathan Alexander, Eglin Air Force Base, to Sires: In your procedure you mentioned screening transducers using a shock tube. What procedures do you use to determine linearity and sensitivity?

Sires: The shock tube produces a 14-20 psi pulse, and we look at ringing on the transducer as a first screening process. We then go through full system calibration using a slow rise time pulse. We do have one problem I want to warn you about, and that is moisture sensitivity of transducers sealed with epoxy. We solved the problem by leaving them on their power supplies for a week or so to bake out the moisture.

Alexander: Do you plot from points for check of linearity and sensitivity or do any kind of lab calibration?

Sires: We do a six-point dynamic calibration taking the data through a digital system and fitting to a least-squares lines.

Alexander: Something else I missed--what is the system frequency response?

Sires: Gages have 100 kHz frequency response. We are recording them wide band, 20 kHz at 60 in./sec. The recording system acts as a low-pass filter. On the low end, gages are capable of a 100-sec time constant.

John Ramboz, NBS: I would like to elaborate on Stein's question with respect to mechanical impedance. It is important to understand what's going on. The apparent shift in sensitivity when you're mounting an accelerometer on different materials having different mechanical impedances is due to resonance frequency shift. If you operate sufficiently below that resonance frequency, it is essentially insignificant what you mount it on. Now the reference transducer, the piggy-back 2270, has a resonance of about 55 kHz. The test accelerometer resonance is between 60-80 k Hz. We are looking at data between 5 Hz and 10 kHz, so far down on the response curve as to be immaterial.

Second order mass loading effect does occur for some models on the piggy backs. We believe it is due to case bending or top surface bending. A very large loading mass change from 0 to 100 grams affects the response by only a few percent at 10 kHz.

There are a lot of applications measuring significantly higher frequencies, and there are accelerometers with resonances of say 30 kHz. If you try to measure at 10 kHz, that is about 1/3 the resonance frequency, and you are well up on the resonance skirt. There will be a very definite change in sensitivity of the accelerometer when mounted on different materials; for example, steel, tungsten, aluminum, beryllium, ceramics. We typically stay away from the resonance skirt.

One other comment--the maximum calibration levels we use are 5,000 g at 1/2 ms. We can mechanically generate higher amplitudes, but getting enough samples across the pulse in order to do frequency analysis is our problem. There are electronics available, but our funds are limited.

Patrick Walter, Sandia Laboratories: We use piezoelectric accelerometers rated at 100,000 g which of necessity are calibrated only in the dynamic mode. What has been the problem at NBS that you haven't been given the backing you need?

Ramboz: Thank you Pat. I think the basic problem is a funds-limited operation. The Bureau of Standards tends to go with the tide and work on the bigger programs, such as air and water pollution, that are of national interest. The work we do in the vibration section (and other groups in the Bureau as well) is funded by internal money and also by other-agency transferred funds. The vibration area is heavily oriented toward defense, aerospace and aircraft. Remove them, and our vibration community wouldn't have much left. The large developments coming to the Bureau have been spurred by defense and aerospace. In response to Pat's question, "Why can't we do 100,000 g?" there is such a small number of people working in that area that it assumes a very low profile. If that problem is important to you and we have the capability to help you, we will be happy to negotiate some kind of project with your agency.

Walter: We come to meetings and sit around talking about 100's and 1000's of g's, and then the first time you become aware that the Bureau can only give traceability to 10 g, it's like somebody telling you there's no Santa Claus.

Paul Lederer, National Bureau of Standards: I would like to answer Pat's second question, the one he hasn't asked yet. Why don't we have dynamic calibration of pressure transducers? NBS does not have the capability for the same reasons that have just been mentioned. There has been more demand for a longer period of time for dynamic calibration of pressure transducers than there has been for shock calibration of accelerometers. And the answer is the same.

Garland Rollins, NASA Langley, ended the session with an anecdote from his work experience.

SESSION III

TRANSDUCER SIGNAL CONDITIONING

Paul Lederer, Chairman

SAND-75-5269

Miniature Transducer Amplifiers Developed for Telemetry Applications

Frederick Schelby
Sandia Laboratories, Albuquerque, New Mexico

Abstract

A new generation of miniature signal-conditioning amplifiers has been developed for use with piezoelectric and bridge-type transducers in telemetry systems. Both the charge amplifier and the dc amplifier/power supply are less than 1 cubic inch in volume and are further characterized by gains adjustable over a wide range, adjustable output bias, and high-shock survival capability.

Introduction

For many years Sandia Laboratories has been a heavy user of transducers and transducer telemetry amplifiers in a wide variety of projects involving such diverse activities as high-speed sled tests, rocket flights, earth motion studies and many others. In recent years environments have become increasingly severe and the space available for telemetry equipment has become more limited.

In these circumstances it became necessary to obtain improved charge and strain-gage amplifiers to meet current test conditions. In general we wanted to obtain amplifiers that were physically smaller, had higher shock capability, and were more flexible than available units in terms of the options incorporated, such as adjustable output bias and choice of filtering. Our purpose was to stock these amplifiers as off-the-shelf items that could be used for a wide variety of applications.

The major new requirements are listed in Table I for charge amplifiers in comparison with typical specifications for some amplifiers used previously for many of our projects. The same type of comparison is made in Table II for dc amplifier/power supplies. Requirements common to both amplifiers are listed in Table III.

Development

The development phase was handled by writing detailed specifications incorporating the basic requirements of the preceding three tables. Contracts were then placed for evaluation units with several suppliers who were willing to design and build units to our specifications. Development proceeded on an iterative basis; i.e., evaluation units were submitted to Sandia, their properties evaluated and then they were returned to the supplier for any necessary reworking. Close liaison was maintained with the manufacturers at all times and required compromises were incorporated into the specifications when necessary. This procedure worked quite well but was time consuming, requiring about two years from the writing of the original specifications to the final qualification of acceptable amplifiers.

TABLE I. CHARGE AMPLIFIERS

	Old	New
Gain Range	2-20 mV/pC(10:1)	0.3-30 mV/pC(100:1)
Bias	0 or 2.5 volts (fixed)	0 to 5 volts (adjustable)
Shock	100g	20,000g
Volume	2.14 cubic inches	Less than 1 cubic inch

TABLE II. DC AMPLIFIER/POWER SUPPLY

	Old (Type 1)	Old (Type 2)	New
Gain Range	83-500 (6:1)	330 (fixed)	10-330 (33:1)
Bias	0	0	0-4 (adjustable)
Shock	100g	2500g	2500g
Volume	4.5 cubic inches	0.7 cubic inches	Less than 1 cubic inch

TABLE III. COMMON SPECIFICATIONS

Supply Voltage	28 ±4 V dc
Supply Current	50 mA or less
Effect of Polarity Reversal	None
Operating Temperature Range	-40°F to 200°F

Final Charge Amplifier Configuration

Figure 1 shows photographs of the two types of charge amplifiers that were designed and qualified to our specifications. Although the two amplifiers are superficially different in size and shape, they are electrically very nearly identical. Their characteristic properties are shown in Table IV compared to the design goals in the first column. Very few compromises were necessary: the only one of significance being the lowering of the shock requirement to 10,000g. I would like to make several observations about these amplifiers: first, note we have specified a low frequency response between .4 and .8 Hz. This corresponds to a time constant of 200 to 400 milliseconds. These numbers represent something of a compromise since it was desirable for good signal reproduction to get a response as close to dc as possible but at the same time the low frequency response had to be rolled off above dc in order to keep the pyroelectric effects in ceramic transducers from producing output instabilities. Since these thermally-induced variations are relatively slow - on the order of seconds - the response we have chosen offers a reasonable compromise.

The output bias and gain figure are set by soldering the appropriate resistors in a cavity in the amplifier housing. For high shock environments these resistors are normally potted in the cavity. A silicone rubber potting material works very well for this and can be easily removed.

The amplifiers also include an internal filter option. The high frequency response can be rolled off above 4 kHz by making the proper connections. Without the filter the response is flat to 50 kHz or above.

These charge amplifiers are single-ended and the case is isolated from the signal leads but the signal common feeds straight through without isolation.

The flexibility of the design can be illustrated by observing that the 100:1 gain range and high shock capability of these amplifiers permits their use for a great variety of measurements from 10g vibration testing to 10,000g ballistic testing.

Final DC Amplifier/Power Supply Configuration

The three types of dc amplifier/power supplies qualified under this development are shown in Figure 2. Once again, these amplifiers are superficially different in shape but are electrically similar. Their characteristics are listed in Table V in comparison to the detailed design goals. In this case the bias and gain resistors are soldered directly to the appropriate feedthroughs. The high frequency response is flat within ±2% from dc to 4 kHz and thereafter rolls off at a 6 dB/octave rate. There is no other filter option incorporated but different frequency responses can be obtained by special order from the manufacturers. A five-volt chopper-stabilized excitation supply is incorporated in the circuits. The output of the excitation supply is isolated from ground.

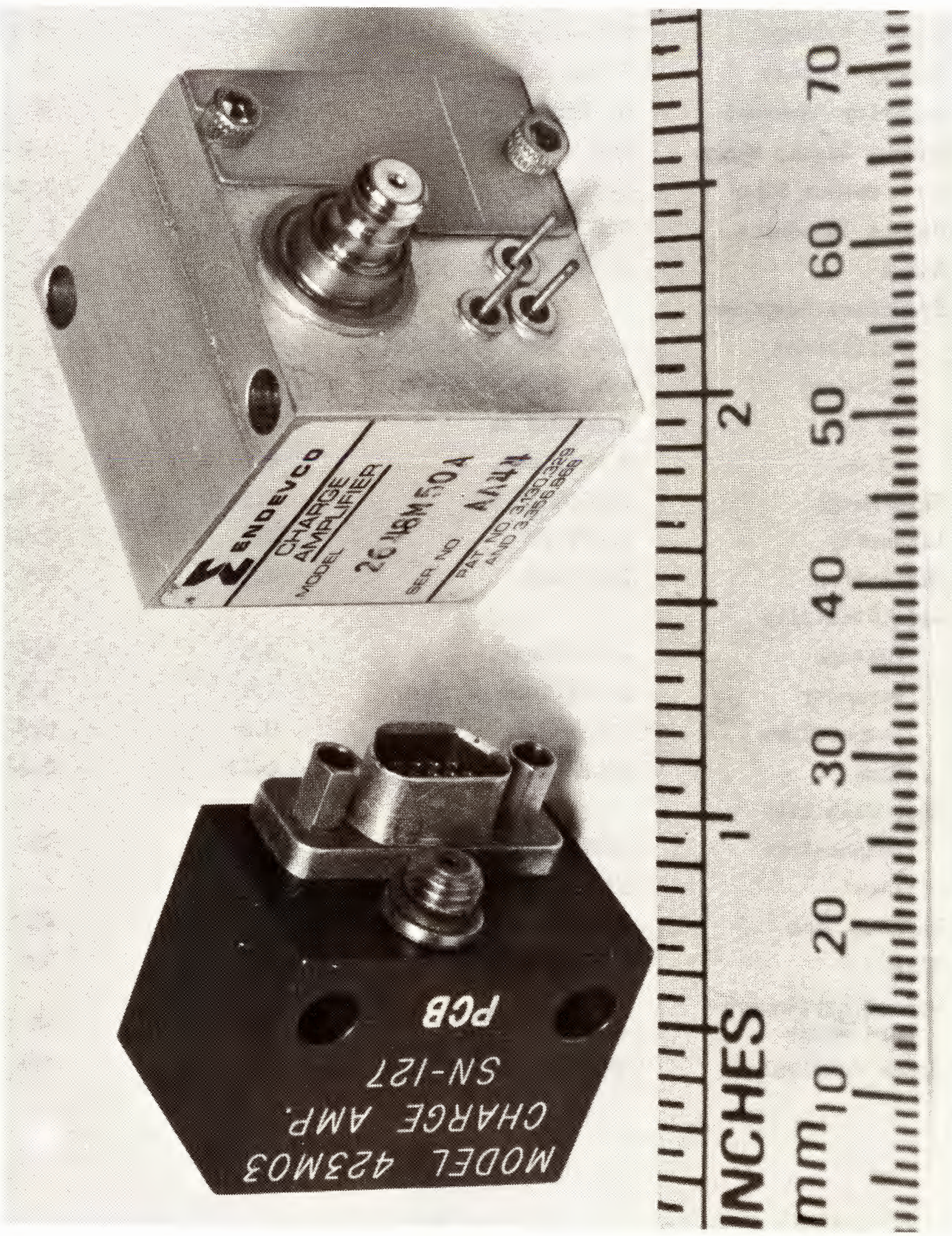

ENDEVCO
CHARGE AMPLIFIER
MODEL 423M03
CHARGE AMP.
SN-127
PCB
INCHES
mm

Figure 1

TABLE IV. CHARACTERISTICS OF CHARGE AMPLIFIERS

Parameter	Specifications	PCB Model 424M03	Endevco Model 2648M50
Supply Voltage	28 ±4 V dc	28 ±4	28 ±4
Supply Current	50 mA max.	16	16
Polarity Reversal	No Effect	OK	OK
Output Signal Range	0-5 V dc	0-5.4	0.2-5.1
dc Output Bias	0-5 V dc	0-5.4	0.2-5.1
Output Impedance	500 ohms, max.	400	1
Noise	10 mV PP max. RTO	10	15
Frequency Response			
Unfiltered	±5%, 3 Hz to 20 kHz	3	2
Filtered	±5%, 3 Hz to 4 kHz	3	2
-3 dB	0.40-0.8 Hz	0.6	0.6
+3 dB	8 kHz, max.	8	12
Gain Range	0.3-30 mV/pC	0.3-30	0.3-30
Linearity	±0.2% FS	0.1	0.02
Distortion	1.5% max.	0.75	0.6
Gain Stability			
Voltage	±0.25% max.	0.1	0.1
Capacity	±0.2%/1000 pF max.	1.7	0.5
Temperature	±1% max.	0.8	0.9
Time	±0.2% max.	0.17	0.42
Bias Stability			
Temperature	±25 mV max.	16	25
Time	±10 mV max.	4	4
Warm-up Time	45 sec. max.	45	45
Size	1 cu. in. max.	0.5	0.9
Operating Temperature Range	-40 to 200°F	OK	OK
Shock Survival	10,000g, 0.5 ms	Yes	Yes

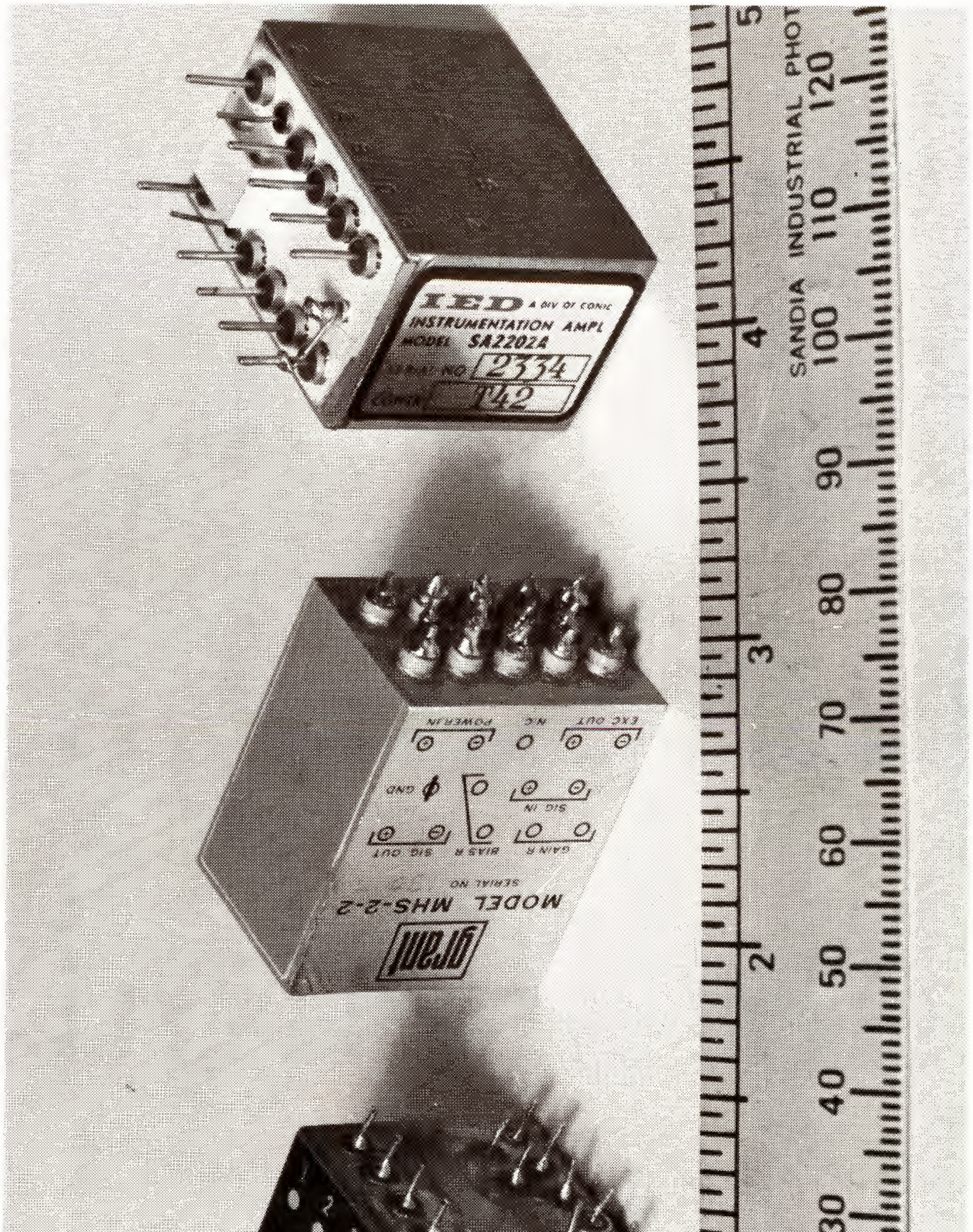

IED A DIV OF CONIC
INSTRUMENTATION AMPL
MODEL SA2202A
SERIAL NO 2334
T42
grant
MODEL MHS-2-2
SERIAL NO
SIG OUT
GND
BIAS R
GAIN R
SIG IN
POWER IN
N.C
EXC OUT
ECTRON CORPORATION
DIFF DC AMPLIFIER
AND BRIDGE SUPPLY
MODEL 314
SER. NO. 4032
NCHES
SANDIA INDUSTRIAL PHOT

Figure 2

TABLE V. CHARACTERISTICS OF DC AMPLIFIER/POWER SUPPLY

Parameters	Specifications	Grant Model MHS 2-2	IED Model SA2202A	Ectron Model 314
Supply Voltage	28 ±4 VDC	28 ±4	28 ±4	28 ±4
Supply Current	50 mA max.	50	26	39
Polarity Reversal	No effect	OK	OK	OK
Excitation Voltage	5.0 ±0.1 V	5.008	5.032	4.998
Excitation Voltage Stability				
Time	±10 mV max.	1	0	1
Temperature	±0.6% max.	0.25	0.25	0.25
Output Signal Range	-0.6 to 5.5 V	-0.7 to 5.8	-0.7 to 5.6	-0.7 to 5.4
Linearity	.075% FS	0.11	0.06	0.08
Gain Range	10 to 330	10 to 330	10 to 330	10 to 330
Frequency Response	±2% to 4 kHz	0.7	3.0	2.6
Bias Range	0-4 V	-0.5 to 5.8	0 to 4.8	0 to 4.6
Thermal Gain Shift	±1.8%	0.8	1.5	0.6
Thermal Bias Shift	±1.2%	0.07	1	1.3
Noise, DC - 20 kHz	30 mV PP max.	10	15	30
Distortion	3%	4	1	0.8
Shock	2500g, 0.5 ms	Yes	Yes	Yes

These are differential-input amplifiers with input-output isolation. Like the charge amplifiers the output is limited so that it swings nominally between 0 and 5 volts in order to prevent cross-talk on adjacent telemetry channels. Negative signal excursions are handled by setting the output bias voltage at the proper value.

The gain range of 10 to 330 is adequate for both metal and semiconductor strain-gage transducers. The bias and gain circuits do not interact with each other in order not to upset the thermal compensation of semiconductor bridges.

<u>Summary</u>

To sum up, this development has resulted in a group of shock-resistant, small, flexible transducer amplifiers designed for telemetry use. The packaging problem in both these amplifiers was severe and its successful solution is a tribute to the suppliers who designed them.

FSchelby:9486:phs

A SYSTEM FOR MEASURING STATIC STRAINS TO 1500°F

Darrell R. Harting
Boeing Aerospace Company
Seattle, Washington

ABSTRACT

A high temperature strain measuring system is described. The system consists of a self-temperature compensated capacitive strain gage and a new type of signal conditioner for use with it. The system is capable of up to ± 5 volts full-scale output at any strain from ± 2500 με to ± 20,000 με.

The strain gage contains a compensating link, which establishes the gage length and provides nominal self-temperature compensation at constant temperature, and a coaxial capacitive half-bridge sensor. A flexural system provides for alignment of the gage parts, attachment to the test specimen, and minimization of bending errors. Miniature thermocouples provide data for use in compensating for thermal errors, including those caused by transient conditions.

The gages, which are pre-calibrated, have the same range, sensitivity, and linearity in tension and compression. The strain sensitivity of the gage changes less than 4% between 70 and 1500°F.

The signal conditioner contains an unusual type of carrier amplifier (3.39 kHz) with a charge-follower input. A ΔC calibration signal source, calibrated capacitive balance, and calibrated variable gain controls are included.

Response of the system to strain and temperature, and to adverse conditions such as bending, torsion, misalignment, shock and vibration are discussed.

INTRODUCTION

Past attempts to measure static strains at temperatures to 1500°F have failed completely or have, at best, been marginally successful. Some of the most important reasons for this history of failure follow:

1. Materials change mechanical properties with temperature.

2. Materials change electrical properties with temperature.

3. The mechanical strains to be measured are usually very small (< 500 $\mu\varepsilon$) compared to thermal expansion strains (around 13,000 $\mu\varepsilon$ for typical structural materials).

Since 1957*, millions of dollars were spent by private industry and the Government to try to overcome these problems in the development of bonded resistance strain gages. When it became apparent that only small further gains could be made in the resistance gage field regardless of expenditures, other concepts were explored, including the thermal-null strain gage[1,2,3] and capacitive strain gages[4,5,6,7].

THE SYSTEM

The problems listed above have been reduced to a manageable level in the capacitive strain measuring system described here. The system consists of a half-bridge capacitive strain gage, an unusual carrier-type signal conditioner, and interconnecting leads. All are important to the success of the overall system; it is necessary to overcome both mechanical and electrical problems which have limited the performance of past high temperature strain measuring devices. Some important considerations in the success of this system are:

- Half-bridge configuration
- Self-temperature compensation
- Transient temperature compensation
- Wide full-scale strain ranges (± 2500 to ± 20,000 $\mu\varepsilon$)
- Excellent resolution (< 1 $\mu\varepsilon$)
- High linearity in both tension and compression (non-linearity less than 0.5% to ± 3000 $\mu\varepsilon$; 2.0% to ± 20,000 $\mu\varepsilon$)

**Symposium on "Elevated Temperature Strain Gages," sponsored by the Aeronautical Structures Laboratory, Naval Air Material Center, Philadelphia, Pennsylvania, 4-5 December 1957.*

- Stable zero and sensitivity
- Low force (80 grams at 20,000 $\mu\varepsilon$)
- Cable-length insensitivity

THE STRAIN GAGE

A cross-sectional mechanical schematic of the strain gage is shown in Figure 1. Major elements of the gage are:

1) A compensating rod, usually made of the same material as the test specimen. This rod establishes the gage length of the gage, and provides nominal self-temperature compensation for thermal expansion strains.

2) A pair of cylindrical excitation plates, mounted on, but electrically insulated from, the compensating rod.

3) A sensing ring, coaxial with and surrounding the excitation plates.

4) Attachment ribbons for fastening the gage to the test specimen.

5) Flexures which maintain coaxial alignment of the excitation plates and the sensing ring.

Self-temperature compensation of a strain gage is desirable even when temperature changes encountered in service are small. When the operating temperature varies from room temperature to 1500°F, it is essential. In the case of materials such as Rene' 41 and Inconel X750, the average temperature coefficient of expansion at 1500°F is about 9 $\mu\varepsilon$/°F; in other words, the strain due to thermal expansion from 70 to 1500°F is nearly 13,000 $\mu\varepsilon$ - while the maximum mechanical strain produced by structural loading is likely to be in the 500 $\mu\varepsilon$ range! Making the compensating rod of a material having known thermal expansion characteristics (preferably the same as those of the test specimen) can reduce the thermal output of the gage to a relatively small value (usually less than 300 $\mu\varepsilon$) between room temperature and 1500°F.

The coaxial, half-bridge arrangement of the capacitive elements results in superior linearity and cancellation of unwanted effects. In the capacitor configuration used in the gage, the gap between the excitation and sensing rings stays constant. Changes in capacitance result because more or less area of the sensing ring overlaps the respective excitation rings. Area-changing capacitors generate a linear response to relative motion, while gap-changers are inherently non-linear, generating a hyperbolic response. A further advantage of the coaxial configuration is the potential for measuring strains of either sign and unlimited magnitude at a constant sensitivity.

The half-bridge configuration nominally cancels nearly all of the deleterious effects of temperature and temperature change in addition to compensating for edge effects where the capacitive elements overlap. Changes in resistance and capacitance with respect to ground in the gage and lead wire systems, for example, occur in a balanced fashion.

Use of an air dielectric (or other material whose dielectric constant is relatively invariant with temperature) is an important feature of the gage. The use of an air dielectric results in an extremely small change in sensitivity with temperature (about 4% between room temperature and 1500°F). Gages which utilize materials having high dielectric constants to increase the gage capacitance, on the other hand, suffer changes as large as 70%[4] over this range due to changes in the mechanical and electrical properties of the dielectric material.

Figure 2 shows the gage configuration in more detail. The alignment frame is used to maintain the proper relationships between parts of the gage until it is installed. The alignment filaments are severed and the frame is removed after the gage is welded in place.

Electrical connections to the gage are made via the terminal strip. In addition to connections for the capacitive elements, provisions are included to bring out 3 thermocouple wires. A differential thermocouple measures the difference in temperature between the compensating rod and a platinum button welded to the specimen surface; its signal is used to compensate for the differences in temperature between the rod and the specimen. These differences nearly always exist, and are caused by differences in thermal mass under transient temperature conditions and by drafts or uneven heating or cooling under steady-state conditions. Multiplying the difference in temperature by the temperature coefficient of the rod yields a direct correction to the indicated strain. A total-temperature thermocouple in the button measures the specimen temperature for use in other corrections.

Although Platinel II thermocouples are used in the gage, chromel-alumel external lead wires are satisfactory, and are usually used to reduce cost.

Another feature of the gage partly illustrated by Figure 2 is its ability to measure strain at the surface of the specimen, rather than at the elevation of the capacitive sensor when bending is present[8]. Note that the attachment ribbons are not welded over the 0.15 inch length near the gage supports, allowing them to act as torsional flexures. Acting in conjunction with the flexures which maintain sensor concentricity, these flexures hold the compensating rod parallel to the specimen surface and minimize the magnification of bending strains.

Even though the gage is aligned during manufacture, it is possible to knock it out of alignment accidentally. Fortunately, the signal conditioner can be used to measure the total capacitance between the excitation plates and the sensing ring, so that alignment can always be checked simply even if the gage itself is inaccessible. The effect of misalignment on gage sensitivity is shown in Figure 3.

THE SIGNAL CONDITIONER

The signal conditioning system consists of a custom-built mode card (Figure 4) and a commercial signal conditioner (Figures 5 and 6). Operation of the signal conditioner is analogous to that of a carrier system built for use with resistive strain gages, with the functions of the resistive and capacitive balance controls interchanged.

Calibrated controls for the capacitive balance and for the gain permit tracking and/or pre-setting gage and system characteristics. The calibrated balance dial can be used to operate in a nulling mode to measure gage output or, with an adapter cable, to measure total capacitance between the excitation and sensing rings. Since a change in the total capacitance of the gage affects the gage sensitivity in a known fashion, the signal conditioner can be used to check gage sensitivity at any time, even without direct access to the gage.

The mode card contains no inductors. A combination of resistances, capacitances, and active elements produces a 3.39 kHz, 7 V rms carrier which is connected to the excitation plates of the gage by a shielded twisted-pair cable. The signal from the sensing ring is connected to a charge-amplifier input stage on the mode card by means of a coaxial cable. The carrier signal is demodulated in a unique fashion[9], utilizing a 4-quadrant multiplier.

The use of a low carrier frequency, separate excitation and signal cables, and a half-bridge gage largely eliminates problems with cross-talk, noise, stray capacitances, and cable motion. The charge-amplifier input eliminates the effect of signal lead-to-shield capacitance, making the system insensitive to cable length. The demodulator contains no switching elements, so is capable of producing an output which is an extremely linear function of the input, even around and through the zero-signal level.

Full-scale output of the signal conditioner is 5 volts; the minimum strain in the gage to produce this output is 2500 $\mu\varepsilon$. The gain controls can be used to adjust the full-scale strain to any desired value over a wide range (110/1). Note that a 5 volt full-scale output is seldom required in laboratory applications. The signal-to-noise ratio in the system is such that a 1 volt full-scale output signal (500 $\mu\varepsilon$) is not noticeably degraded.

SYSTEM EVALUATION

Although a small amount of evaluation data is available on the performance of capacitive strain gages[4,6,10,11,12], at room and elevated temperature, most of the work done to date does not include information on the response of the strain gages to extraneous influences such as bending, torsion, misalignment, shock, vibration, or long-term drift.

A summary of the results of evaluation tests on the system described in this paper follows; details of the tests and test results appear in Reference 13.

1. Mechanical strain at temperature

   Less than 4% change in sensitivity from 70 to 1500°F.

2. Thermal Output

   Proportional to the mismatch in thermal expansions between the compensating rod and the specimen; usually less than 300 με from 70 to 1500°F.

3. Drift

   Less than 0.04 με/hour average (2340 hour test at 1100°F)

4. Bending

   The use of bending-compensation flexures reduced the bending error from 515% to 11% on a 0.188 inch thick specimen[8].

5. Torsion

   The theoretical output of the gage when subjected to pure shear is 2.3 με indicated output/1000 με of applied shear strain. The response of individual gages will be higher, due to manufacturing and installation tolerances. A single gage responded with approximately 60 με indicated/1000 με of applied shear strain.

6. Shock and Vibration

   Three-axis shock and vibration tests produced the following results:

   1. Lowest natural frequency - 370 Hz

   2. Maximum indicated strain at 3.0 G rms random, from 5 - 2000 Hz, was 225 με rms.

   3. Maximum indicated strain from a 10 G pulse was 40 με.

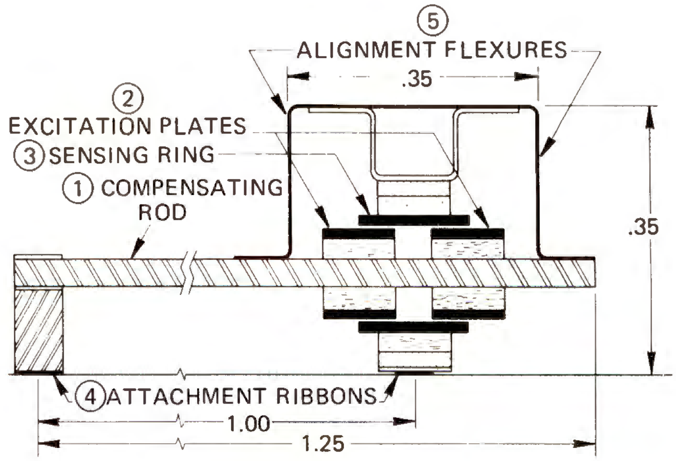


Figure 1. Capacitive Strain Gage — Cross Section View

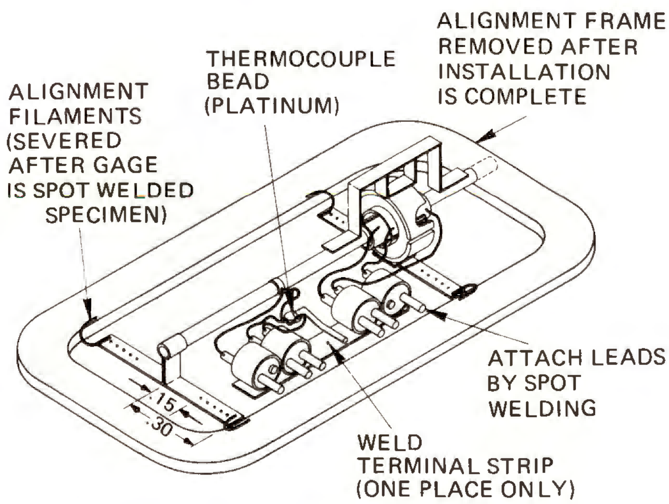


Figure 2. Capacitive Strain Gage in Alignment Frame

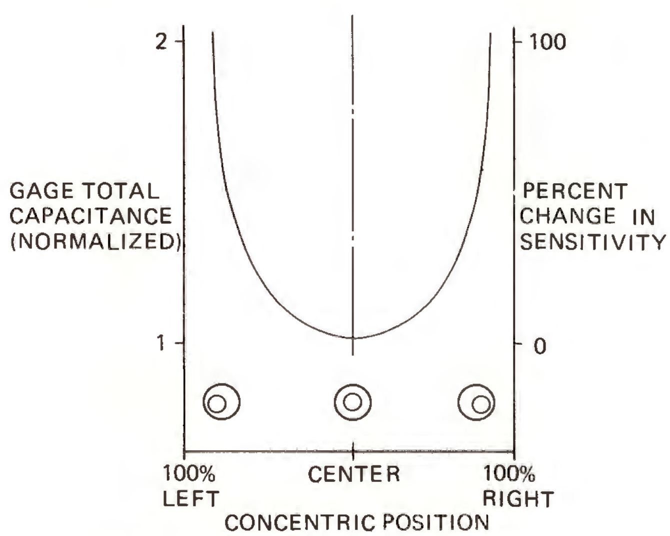


Figure 3. Gage Sensitivity vs Plate Concentricity

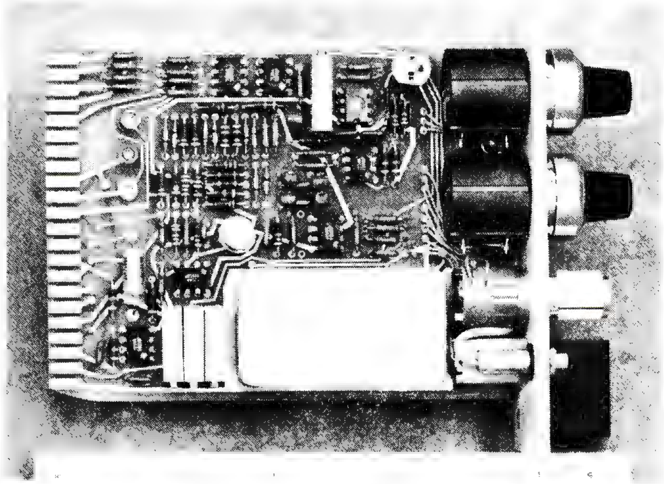


Figure 4. *Signal Conditioning Mode Card Component Side*

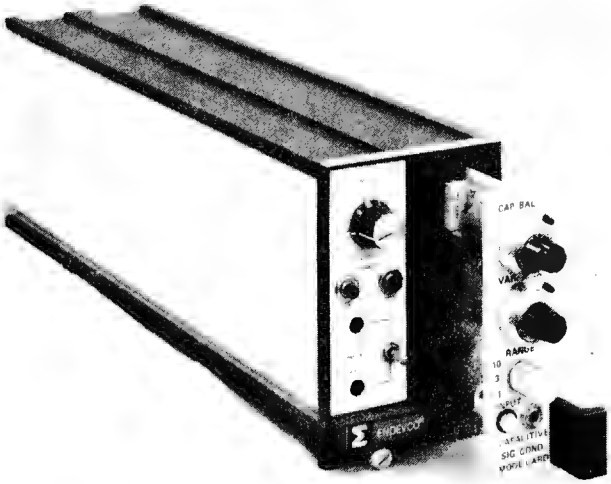


Figure 5. Signal Conditioners: Commercial Signal Conditioning Module and Custom-Built Mode Card

Figure 6. Signal Conditioners Commercial Signal Conditioning Module and Custom Built Mode Card

The gage survived the above environments, plus a 1.0 G sine-wave sweep with no damage.

CONCLUSION

The evaluation data presented here show that the high temperature strain measuring system is useful for measuring long-term static strains at temperatures to 1500°F during laboratory and field tests. Additionally, the errors produced by extraneous conditions such as the presence of bending, shear, small misalignments, shock, vibration, and thermal transients are either nominal or can be compensated for.

ACKNOWLEDGEMENT

Thanks are due to the following people who developed the system described and who ran most of the tests which produced the data for this paper: Richard L. Egger, Everett J. Nelson, Paul J. Powers and Charles F. Sikorra.

Egger, Nelson and Sikorra were awarded the Pacific Northwest Section of the American Institute of Aeronautics and Astronautics Technical Award for outstanding contibutions to the field of aeronautics and astronautics for development of the 1500°F strain measuring system.

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TELEMETRY INSTRUMENTATION FOR ACCELERATION TRACK TEST SYSTEM

Murray Rosenbluth, Picatinny Arsenal, Dover, NJ

ABSTRACT

A prescribed acceleration-time profile composed of a short (100 ms) pulse and a long (1000 ms) pulse was simulated by constraining a test vehicle to move along a track composed of helices and straight sections. The test vehicle contained a multipole switch, whose contacts were actuated at different acceleration levels. Acceleration profile waveshape and switch closure information was transmitted to a telemetry receiving station from the mostly inclosed track (total length 110 ft.) by means of a magnetic field coupler. Problems encountered during the design of the magnetic field coupler and telemetry system are discussed. An analog simulation of a noise problem encountered during the testing phase is also described. The results of the simulation are used to aid in the solution of the problem.

The introductory section describes the initial concepts and design selection. The second section covers the acceleration track mechanics. The third section includes a discussion of design concepts of the telemetry instrumentation. The fourth section covers a noise anomaly encountered during field tests of the system and an analog simulation to solve the problem. The final section describes capabilities and limitations of the system. The text includes eleven figures.

Introduction

The need for instrumentation required for transmission of telemetry data from a mostly enclosed track carrying a test vehicle arose from the requirement of subjugating a multipole acceleration actuated switch to the acceleration profile shown in Figure 1. The switch is used in a missile to sense acceleration thresholds. In addition, there was a requirement for verification of switch closures. The track shown schematically in Figure 2 is composed of three straight sections and two helical sections. Initial investigation indicated that coupling of data from the track with an optical or microwave frequencies carrier or at baseband frequencies was impractical because of the partially enclosed nature of the track. However, coupling of the data at IRIG subcarrier frequencies proved to be feasible.

The Acceleration Track

To obtain the acceleration-time profile (Figure 1), the system was designed to transport the test component at a constant velocity along the track. The track has helical curves of appropriate radii and path length. As the multipole switch, located in the test vehicle, travels along the straight portion of the track, it experiences no acceleration in the lateral, vertical, or horizontal directions. However, as it travels through the curved portions of the track it experiences a radial (horizontal) acceleration. The magnitude of this acceleration is given approximately by

$$A_r = V_t^2/R = W^2R$$

where V_t = velocity in helix
R = helix radius
W = angular velocity

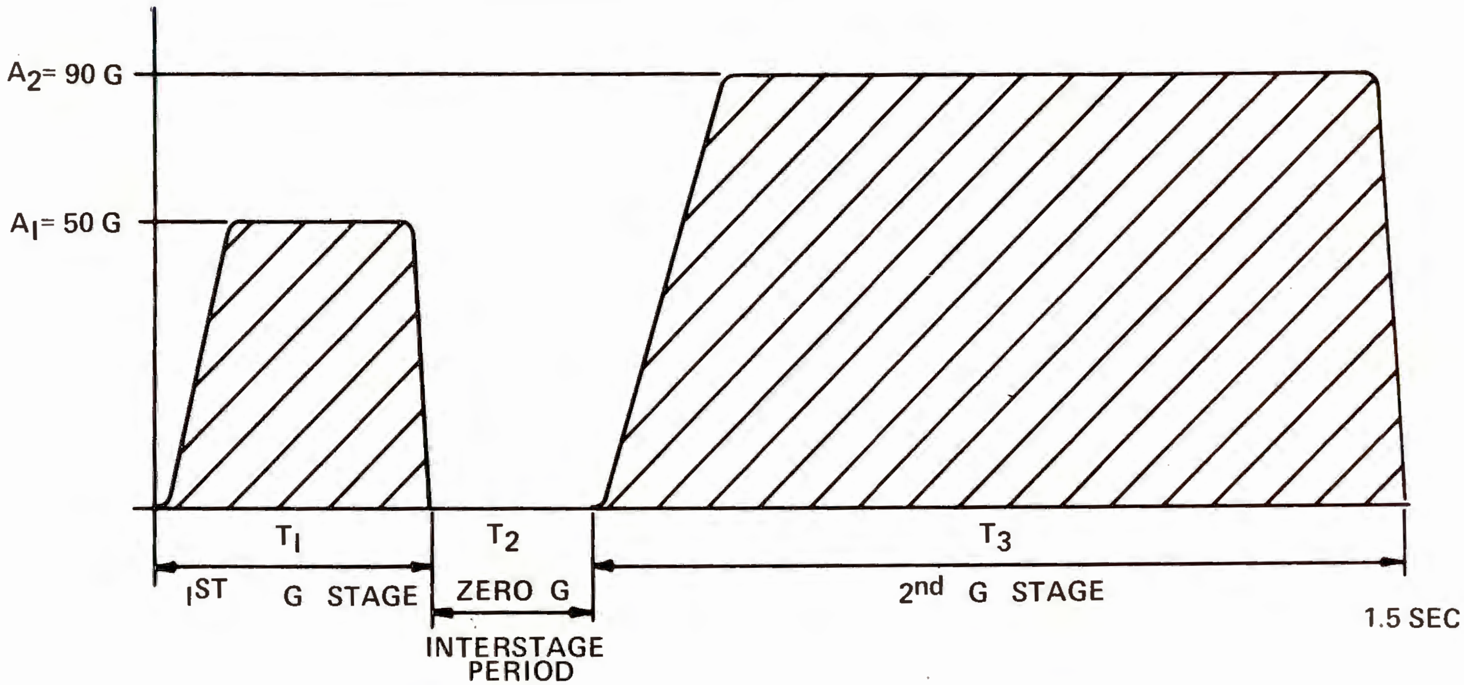


FIGURE 1

TYPICAL ACCELERATION/TIME PROFILE TO BE SIMULATED

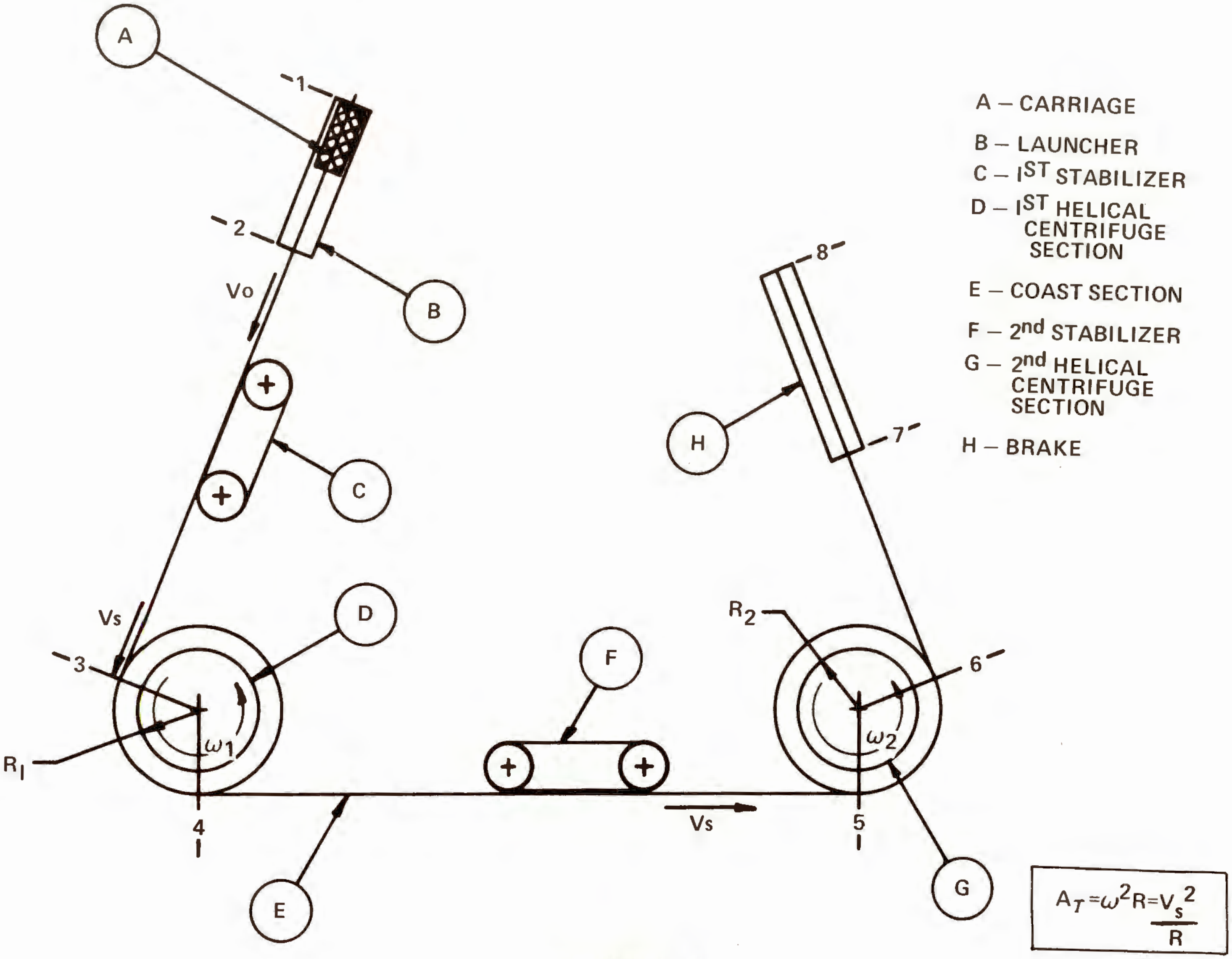


FIGURE 2

TRACK ACCELERATOR SCHEMATIC

The track and mechanical drive are integrally connected. Thus, the test vehicle is forced to travel along the track at a constant velocity V_t. As the test vehicle enters the helix drum, a rotating inner drum frictionally engages the test vehicle, maintaining the constant tangential velocity V_t inside the drum. The vehicle then travels around the helix the number of revolutions necessary for the required acceleration time profile. The launcher is a pneumatic type; a frictional deceleration system is used to slow down the vehicle when it leaves the second helix. Figures 3 and 4 show the test vehicle and the electronic components, boards, test switch and accelerometer.

Telemetry Instrumentation

The problem consisted of measuring the acceleration profile that the multipole acceleration actuated switch undergoes during its traversal through the track and correlating switch closures with particular levels of the acceleration profile. The test vehicle in which the switch is located moves on a track, which is at times partially, and at times fully, enclosed; track crossections are shown in Figure 5. IRIG subcarrier frequencies are used as carrier frequencies (40, 52.5, 93 kHz) for the data. Magnetic field coupling is used as the link between transmitter and receiver. The transmitter-receiver block diagram is shown in Figure 6. The transmitter consists of three channels with each channel having a 1000 Hz data bandwidth. Channels A and B are functionally identical. Closure data from three switches is amplitude multiplexed in the signal conditioner, and

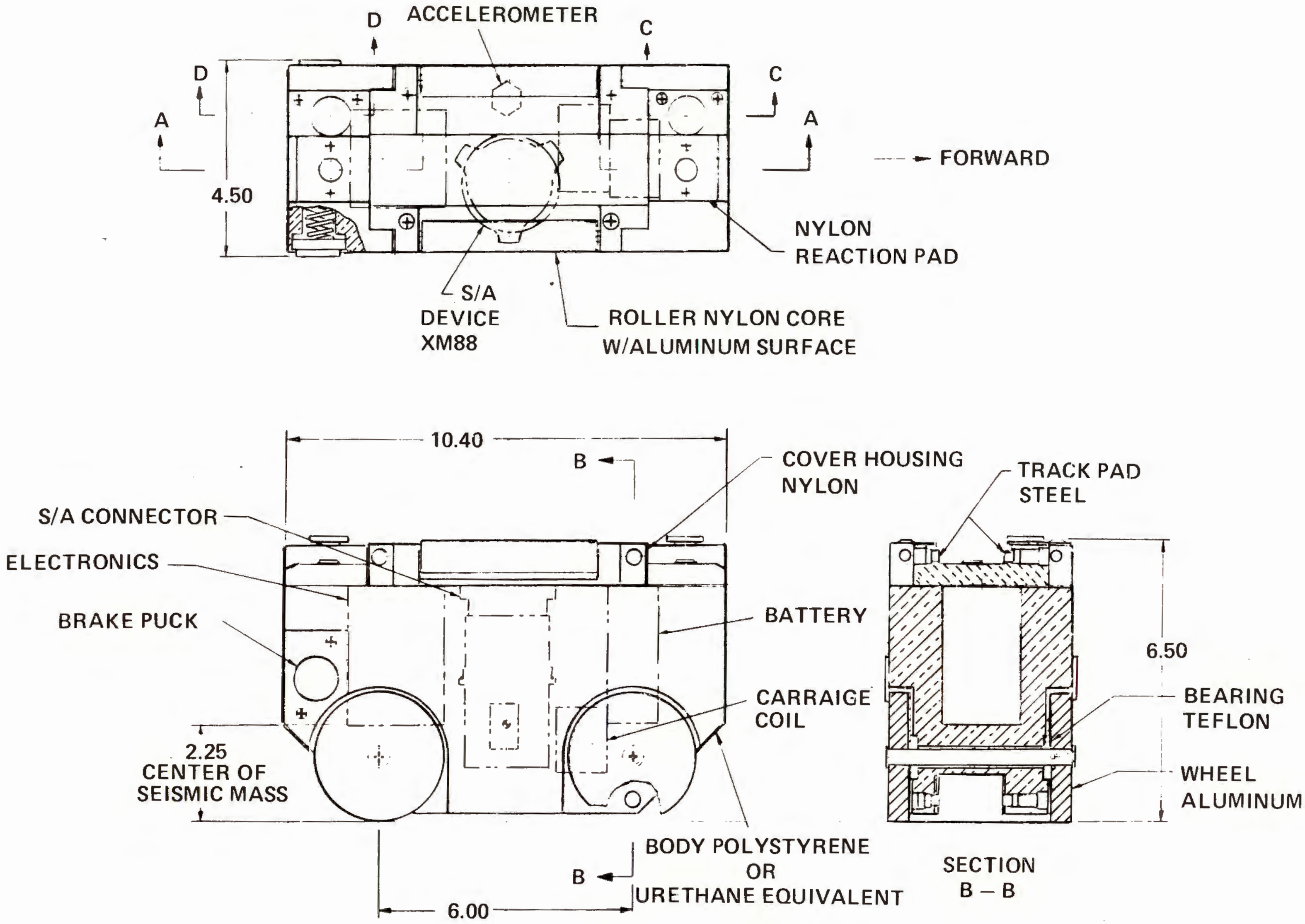


FIGURE 3

COMPONENTS IN CARRIAGE

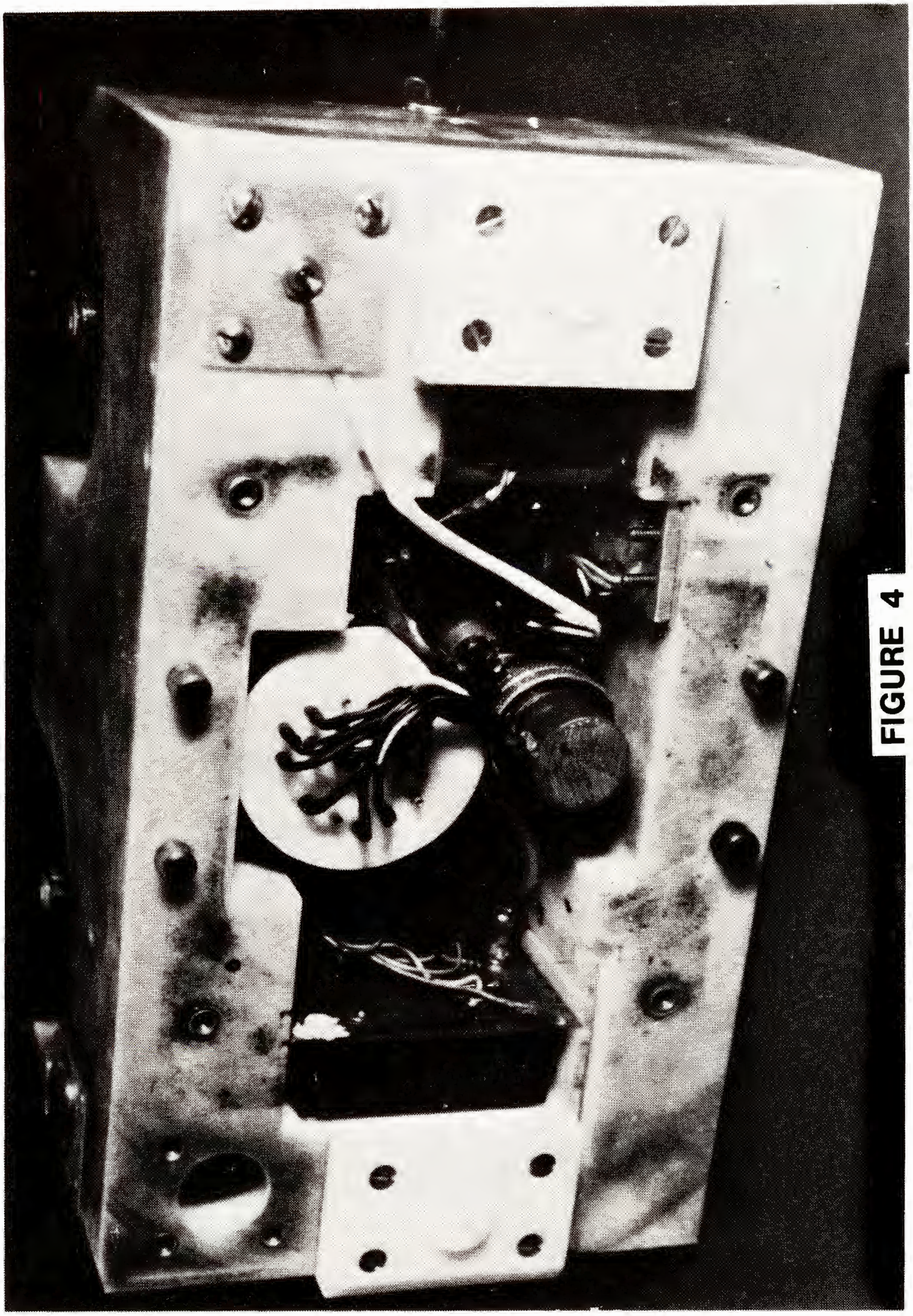


FIGURE 4
COMPONENTS IN CARRIAGE

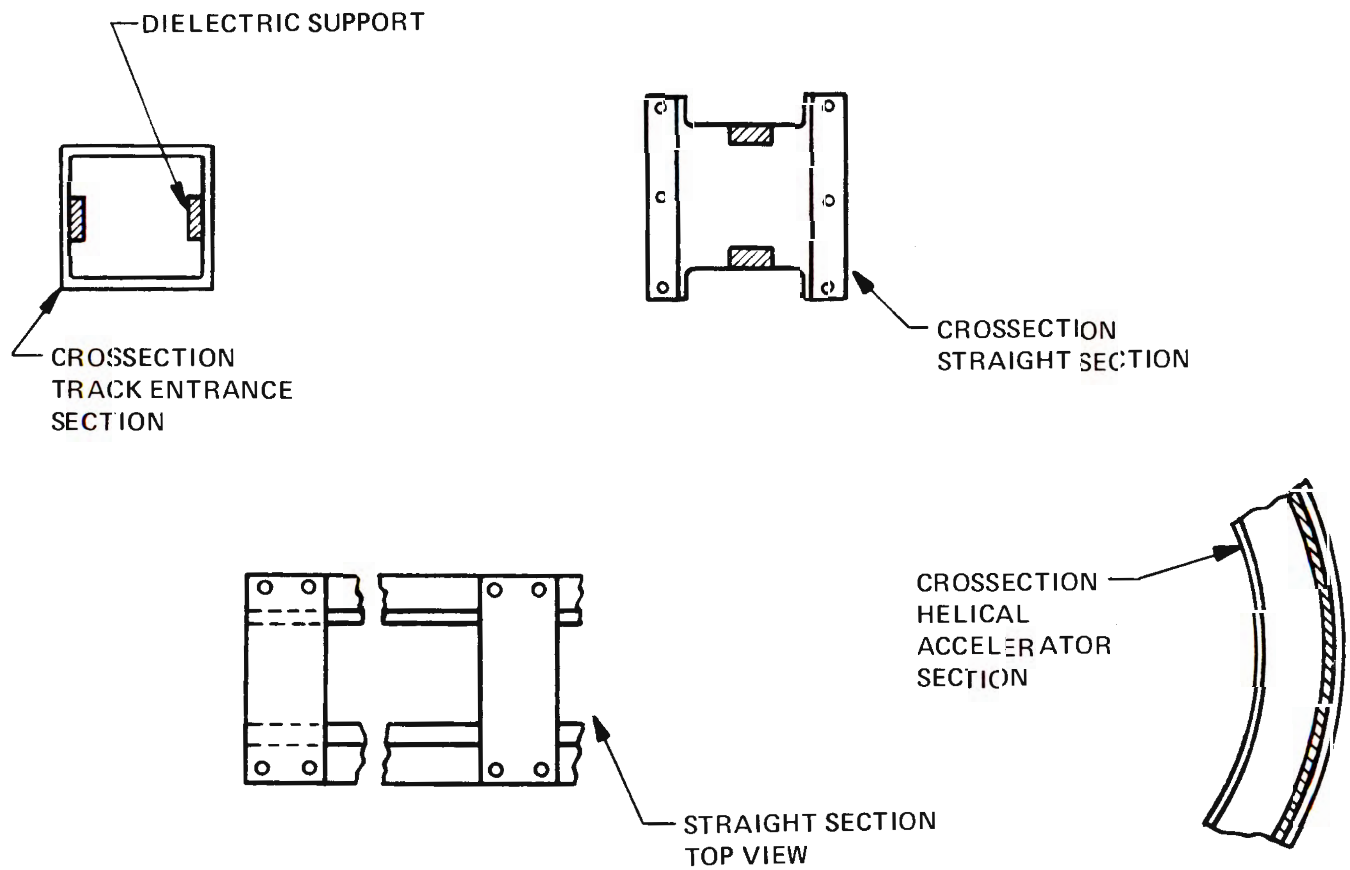


FIGURE 5

TRACK CROSS-SECTIONS

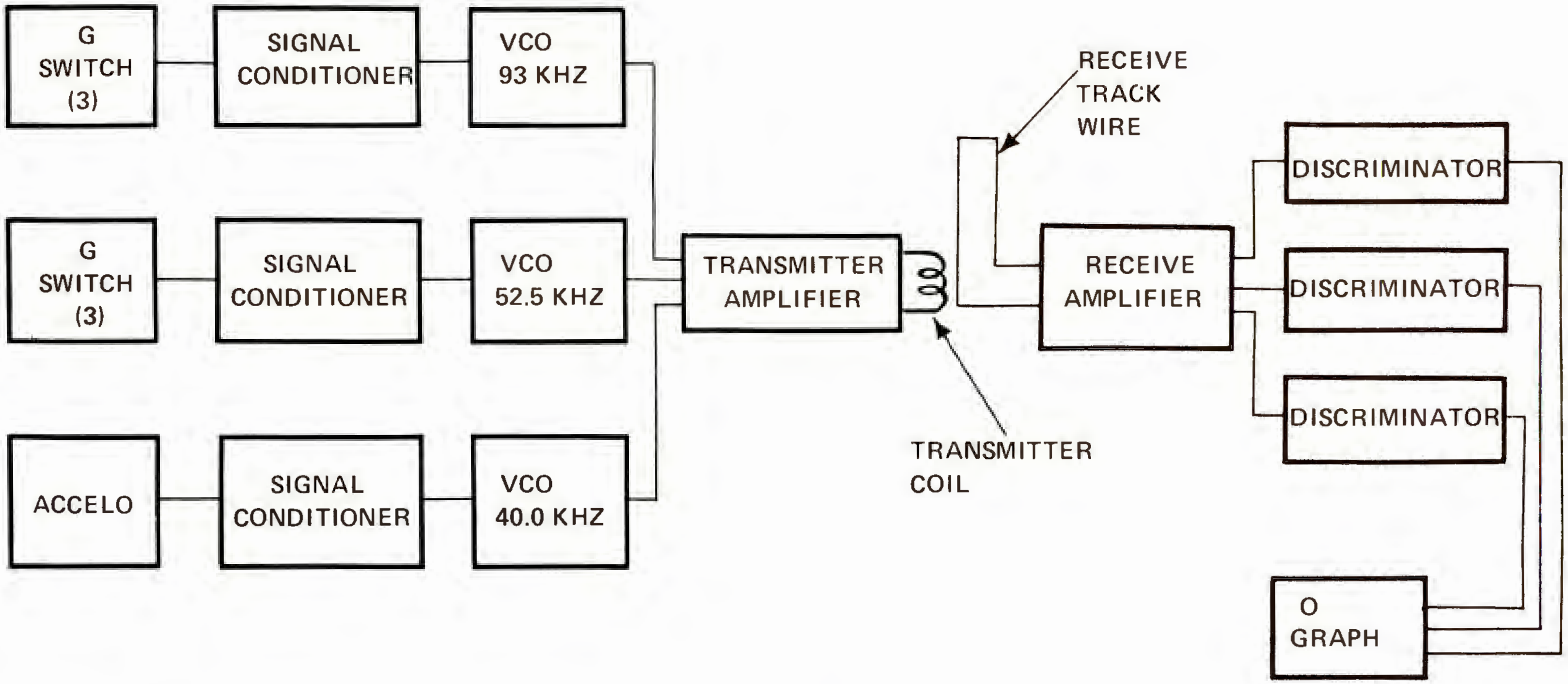


FIGURE 6

TRANSMITTER RECEIVER BLOCK DIAGRAM

subsequently deviates the VCO frequency output in proportion to the amplitude input. In Channel C, the output of a piezoresistive accelerometer is signal conditioned and subsequently deviates the VCO output frequency in proportion to the accelerometer input. The VCO outputs are added and subsequently fed into a voltage amplifier chain. The output of the last voltage amplifier is fed into a hemi-torroid coil which is loosely coupled to the track ribbon wire coil. The signal enters a differential receiver where extraneous noise signals are canceled but required signals are transmitted. The output of the receiver is inputed into three discriminators, where the information is removed from the carrier, and recorded in a permanent paper or tape recorder. The location of the transmitter coil in the carriage is seen from Figure 4. The location of the bonded ribbon cable along the track is on a dielectric support as seen in the track cross section shown in Figure 7. Two ribbons of wires can be seen in the track cross section. The track length is about 110 feet. The design of the transmitter and receiver coils presented problems of very low coupling factor available due to lack of space and losses. Raising the receive and transmit coupling coils about an inch from the track bottom lowered required magnetic field intensity for efficient transmission, and consequently the number of windings of each coil required. The track in Figure 5 is shown to have three different cross sections. The inductance of the receive coil had to be obtained experimentally, since only cross sections B and C had formulas given in the literature. The equivalent of

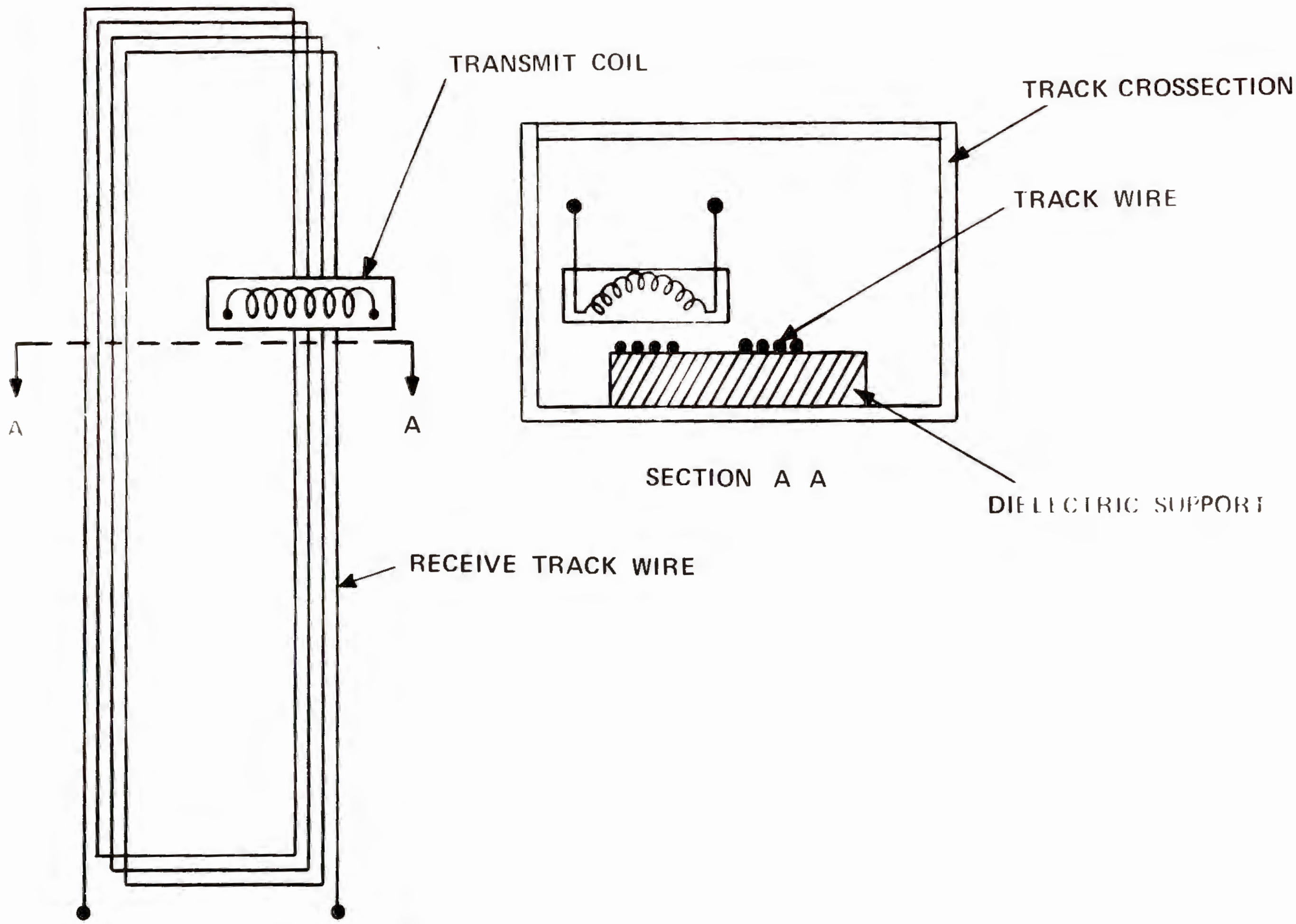


FIGURE 7

MAGNETIC FIELD COUPLER CONFIGURATION

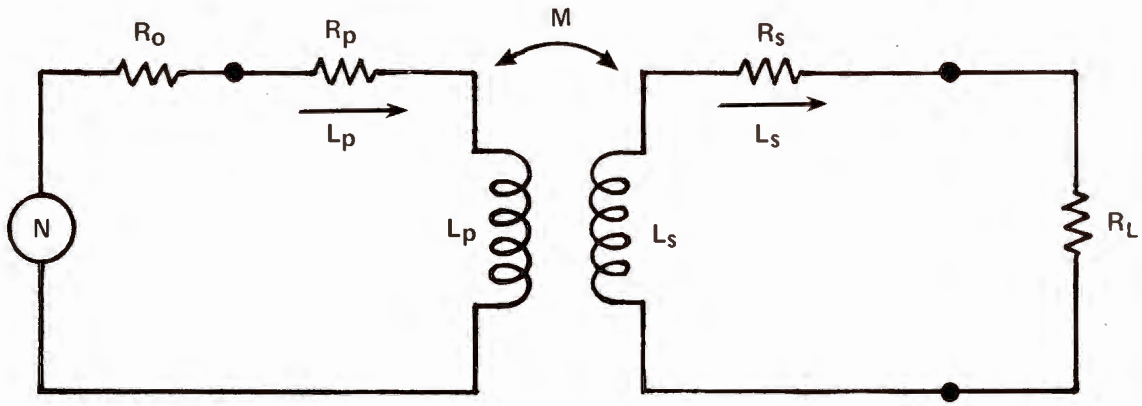
the magnetic field coupler is given in Figure 8. The receive coil is wound so as to cause the magnetic field due to current in each wire of the ribbon to be additive, which happens when a solenoid type coil is flattened. The transmit coil was wound on a dust type hemitorroidal shape core. The acceleration track test system and telemetry are shown in Figure 10.

Testing of Instrumentation

A typical acceleration profile run is presented in Figure 9. After approximately one hundred tests the accelerometer output deteriorated markedly. (See Figure 11). The average acceleration value became negative in each helix which is a physical impossibility. The questions occurring were whether (a) there is an electrical noise problem, (b) an electrical distortion problem, (c) a mechanical vibration problem appearing as electrical noise. The accelerometer problems were examined following logical procedures.*

It was determined after extensive investigation that the problem was not electrical but rather random vibrations were superimposed on the pulse of acceleration due to deterioration of the wheels. The random signals (because of their large magnitude) were being clipped in the system causing the average value of the accelerometer output to become negative. This was verified by a simulation, where a noise source was superimposed on a voltage level equivalent to 80G and inputted into the signal conditioner in Figure 6.

**Stein, P. K.; A Unified Approach to Handling of Noise Problems in Measuring Systems; Flight Test Instrumentation, Advisory Group Research and Development, NATO 9/72, pp 5-1 to 5-11.*



L_p = 1MH

R_o = 1Ω

R_p = 1Ω

f = 93KHZ

$|i_p|$ = 13MA

P_L = .2μμWATTS

$|e_L|$ = 60 MILLIVOLTS

L_s = 500 μH

R_s = 100 Ω

R_L = 20 KΩ

$$L_s \approx \eta^2 \frac{\mu}{\pi} \ln \frac{2\omega}{\pi D \sqrt{A}}$$

$$A = \frac{1}{\sin^2 \frac{\pi D}{W}} + \frac{1}{\sinh^2 \frac{2\pi h}{W}}$$

D = DISTANCE BETWEEN A (+, –) SET OF WIRES

n = NUMBER OF WIRES

W = CENTER TO WALL DISTANCE

h = HEIGHT ABOVE GROUNDPLANE

FIGURE 8

EQUIVALENT CIRCUIT OF MAGNETIC FIELD COUPLER

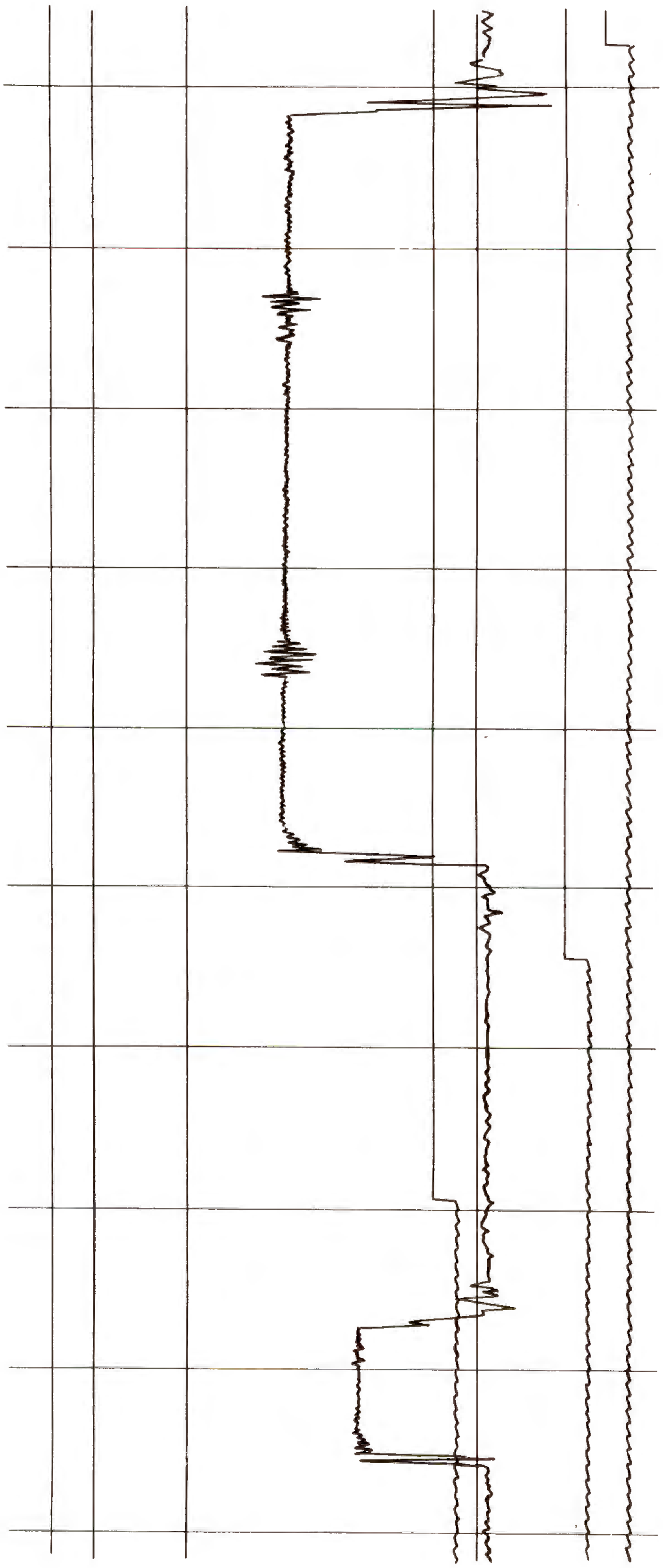


FIGURE 9

MEASURED ACCELERATION PROFILE

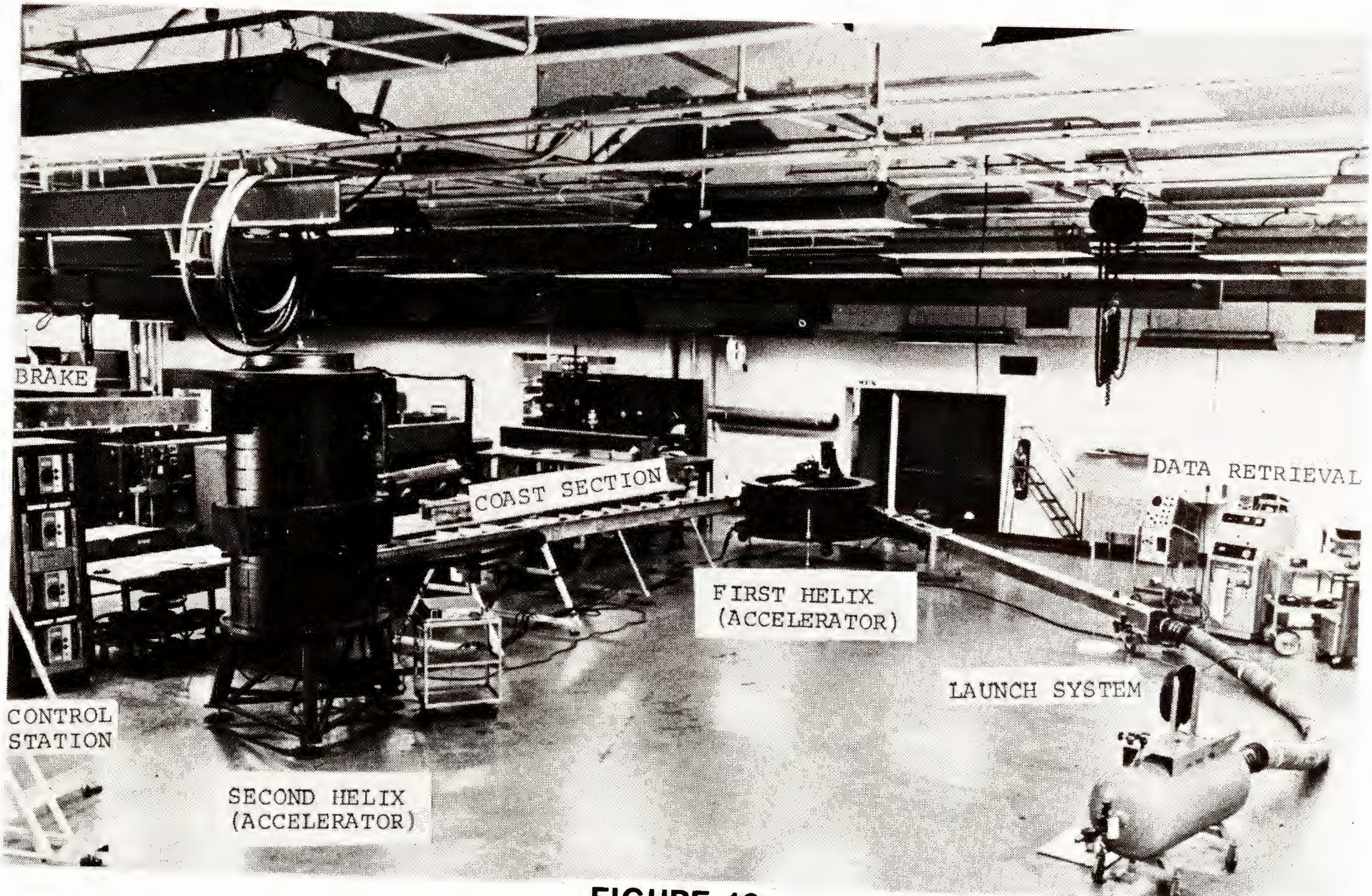


FIGURE 10

ACCELERATION TRACK TEST SYSTEM

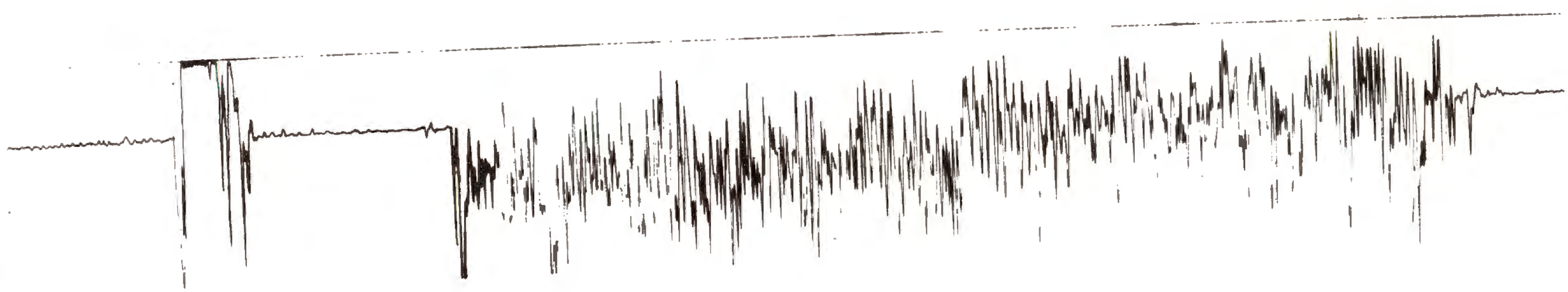


FIGURE 11
NOISE ANOMALY IN ACCELERATION PROFILE

A negative average value could be observed as the output of the system. As the noise power was reduced the average value became positive. It was deduced that the distorted data was due to operation in the nonlinear region of the telemetry system. This, however, was not the case during the initial 100 runs of the test vehicle down the track.

Finally, the gain of the accelerometer amplifier was reduced from 20 to 4 and the distortion problem cleared up. The mechanical vibration problem was subsequently corrected.

AN INSTRUMENTATION SYSTEM FOR MAKING MEASUREMENTS IN A HIGH EXPLOSIVE ENVIRONMENT

J. J. Morrison

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Abstract

Engineering measurements of acceleration, strain and velocity were needed in a feasibility study for HSM --hard structure munition--a conventional two-state weapon. Its first stage is a shaped charge that blows a pilot hole in the concrete and aids the penetration of the second stage main charge.

Static test firings of a shaped charge attached to a fully instrumented main charge case have been conducted at our high explosive test facility.

The fast-burning shape charge provides an electrically noisy environment.

The instrumentation system was designed with the philosophy that the generated electric field was grounded due to interaction in the earth's magnetic field. With the generated noise field grounded, the instrumentation system must be electrically isolated from ground to minimize common mode voltage and input-to-output voltage stress imposed on the amplifier.

Isolation transformers with a primary-to-secondary capacity of 0.0005 pf are used for ac power.

The total instrumentation system is enclosed in a shield driven by the noise source. The driven shield effectively reduces the system capacity to ground.

All control lines are coupled through optical isolators.

Three channels of acceleration, thirty-six strain gages and three velocity transducers were conditioned, amplified and recorded on magnetic tape.

Voltage measurements made from the driven shield to ground while high explosive was burning indicated 40 volts peak to peak.

AN INSTRUMENTATION SYSTEM FOR MAKING MEASUREMENTS IN A HIGH EXPLOSIVE ENVIRONMENT

BY

J. J. MORRISON

INTRODUCTION

Engineering measurements of acceleration, strain, and velocity were needed in a feasibility study for HSM (Hard Structure Munition), a conventional two-stage weapon. Its first charge (FC) is a shaped charge that blows a pilot hole in the concrete and aids the penetration of the second-stage main charge (FT).

Static test firings of a shaped charge attached to a fully instrumented main charge case have been conducted at our HE test facility.

The fast burning shape charge provides an electrically noisy environment.

On some previous tests, strain and acceleration data were masked at zero time or FC ignition.

The instrumentation system was designed with the philosophy that the generated electric field was grounded due to interaction in the earth's magnetic field. With the generated noise field grounded, the instrumentation system must be electrically isolated from ground to minimize common mode voltage and input-to-output voltage stress imposed on the amplifier.

Computer calculations indicated strain levels from 20,000 to 80,000 $\mu\Sigma$ and acceleration to 150,000 g. Data bandwidth was calculated to be from dc to 100 kHz.

DESCRIPTION

This describes a driving shield system where the transducer and its instrumentation are not isolated from the noise source, but just the opposite is done.

Strain gage transducers are very closely coupled to the part they are measuring, the pieso-electric accelerometers have the case as signal common. These conditions of the transducers do not allow isolation from the noise source. If we can electrically drive the transducer completion networks, the instrumentation cables, and the instrumentation system by the same noise pulse, then the noise pulse cannot appear as a signal. This also means that the transducer and its instrumentation system must have no capacity, or as little as feasible, to earthground, or any other potential.

Any capacity to ground will allow noise currents to flow, and these will be dropped across some resistance to appear as a signal. By placing a shield around the total instrumentation system and driving the shield with the same noise source, one finds the effective capacity from the instrumentation to ground approaches zero. The instrumentation ac power must also be isolated and driven by the noise source.

The transducers were 36 channels of 120-ohm, single active strain gages, located at various locations on the FT ·case, 3 channels of 100 K g accelerometers with an integral charge converter, and 3 channels of permanent magnetic velocity transducers.

Mini-noise-treated Twinax was used between all transducers and their completion networks.

The strain gages were provided with a 3-arm individually shielded and isolated completion network. Ferromagnetic beads located in the completion networks acted as inductive loads to the strain gages to minimize high frequency-induced transients.

The piezoelectric accelerometers with their integral charge to current converters were located on the aft end of the FT case. Battery powered current-to-voltage converters and line drivers were individually shielded and isolated. The line drivers provide variable attenuation to the accelerometer signal and provide a very low output impedance--1 ohm or less.

The velocity transducers are permanent magnetic type, and their output is attenuated approximately 750 to 1. The attenuator output is balanced to the input and has an output impedance of 100 ohms. The attenuator cases are again individually shielded and isolated.

If the transducer signal exceeds 1 volt, it is attenuated down to provide a lower impedance to the instrumentation amplifier.

All completion networks are located within 6 to 10 feet of their transducer.

The FT case is tied to the bunker system ground plane with a number 6 stranded, bare copper wire. This is to load the electromagnetic pulse being generated by the burning HE. The ground wire also drives the bunker ground plane toward the potential being generated.

The instrumentation cables for each channel are twisted, shielded pair or pairs. The shield for each channel is driven from the signal low side at the transducer completion network.

All of the individual cables per channel are then enclosed in a metallic zipper tube with a 5/8-inch braid. The braid is electrically bonded to the zipper tube at the completion network end of the zipper tube.

Some additional electrical shielding is required around the transducer completion networks. The completion networks are electrically isolated by individually wrapping them in a pressure-sensitive tape, then bundling them all together with tape.

The bundled transducer completion networks are then wrapped with an aluminum tape, and the 5/8-inch braid is then spiral-wrapped around the aluminum tape.

The 5/8-inch braid is then electrically connected to the common ground (EMP Signal) point for the FT.

A size No. 00 welding cable is also electricallv connected to the FT at the ground (EMP signal) point for the FT. The welding cable is connected to an isolated aluminum plate located under the instrumentation system--more about this later.

When the shape charge detonates, shrapnel and flame will destroy any exposed cables, so all of the cables are buried in trenches. First, the bare copper is laid in the trench. A piece of zipper tube (laid out flat) is placed on top of the copper. The zipper tube is electrically connected to the common ground (EMP signal) point. This acts as a second shield for the No. 00 welding cable and the zipper tube that shields the instrumentation cables. The No.00 welding cable and zipper tube around the instrumentation cables are laid on the flat zipper tube and then covered with pea gravel.

The instrumentation cables and the zipper tube are 150 feet in length. The cables were buried for approximately 100 feet, to a point where they pass through 6-in diameter, 10-ft. long metallic conduits into the firing bunker.

The No. 6 bare copper is electrically connected to the bunker ground plane in a wire-way trench at the base fo the wall (where the feed-through conduits terminate). The bunker ground plane is a No. 00 bare copper.

The zipper tube shielding the instrumentation cables and the No. 00 welding cable are mechanically supported but electrically isolated from an overhead wire-way.

The distance from the termination of the feed-through conduits to the instrumentation system was approximately 35 feet.

The instrumentation system is isolated from ground by a driven shield, optically-coupled timing signals and ac power isolation transformers with a primary-to-secondary capacity of 0.005 pf.

The isolation and driven shield plate for the instrumentation system consisted fo two 3/4-inch by 4 X 8-feet sheets of plywood laid on the floor. On top of this is placed a sheet of 0.030-inch aluminum with the No. 00 welding cable electrically attached in the center of its length, but at one edge. The aluminum is covered with two more sheets of plywood. This produces a driven shield stack that is approximately 1-1/2 inch thick and 4 X 16 feet.

This instrumentation system was located on the driven shield. The isolation transformers, whose outer case is power ground, are located just off the driven shield.

Timing signals from the firing bunker were electrically isolated by a trigger and pulse stretcher chassis, which uses a fiber optics bundle for isolation and data transmissions.

The instrumentation system consisted of five separate insturment racks. The racks were electrically bonded together as two systems, with each system being electrically connected to the 5/8-inch braid from the zipper tube that shielded the instrumentation cables for that system. The instrumentation system was composed of two separate systems electrically isolated from each other because some of the differential amplifiers did not have an isolated input shield, and one of the magnetic tape recorders was single-ended.

One instrumentation system consisted of 20 channels of strain gage conditioners and power supplies, 28 differential amplifiers, IRIG B time code generator, a 32 track differential input FM tape recorder, 3 dual-channel oscilloscopes with differential preamps and Polaroid camera for a quick look at some discrete data channels. The oscilloscopes also offered a data band wider than the 40 K Hz bandwidth of the FM tape.

The second instrumentation system consisted of 12 channels of strain gage conditioning and power supplies and 14 differential amplifiers whose input shields are referenced to the amplifier output. A 14-channel single ended FM tape deck with a 40 kHz bandwidth.

Two oscilloscopes that were not isolated or located on the driven shield plane were used to record the EMP generated by the shape charge detonation. One oscilloscope monitored the EMP magnitude on the 5/8-inch braid from the instrumentation cable zipper tube. The second oscilloscope monitored the EMP magnitude on the driven shield for the instrumentation system. Both oscilloscopes were used with X10 input probes to minimize currents being drawn from the driven shields.

PERFORMANCE

If the system should perform as expected, using the driven-shield concept, there should be a minimum of EMP noise recorded on the data channels.

A series of dry runs were made to evaluate the instrumentation system's ability to reject transient noise generated in the firing bunker complex. For example, cameras, running at a framing speed of 10,000 frames per second, and a capacitor discharge unit that detonates the shape charge were used. The instrumentation system typically rejects all bunker-generated noise pulses and any ac power cross talk or ground loops.

To evaluate the instrumentation system's capacility to reject the EMP generated by the burning shape charge, two of the strain gage bridge excitation channels were turned down to approximately zero volts. The strain gages would not record strain, but they did record the noise coupled into the system.

At zero time, or detonation of the shape charge, no one is allowed to touch the instrumentation system, as they would provide a current path to the bunker ground plane.

Data recorded from the accelerometers shows a negative offset of approximately 5 to 7 percent of full scale (150,000 g) at zero time. The time constant with which the zero offset discharged toward the base line indicated the noise pulse was coupled directly into the charge-to-current converted in the accelerometer. The acceleration data arrived from 40 to 400 microseconds after shape charge ignition. The acceleration data agreed quite closely with computer code calculation in amplitude and frequency.

Noise on the acceleration channels between ignition and data arrival was usually 40 db below full-scale calibration.

The data recorded on the strain gage channels indicated a precursor at zero time caused by the discharge of the CDU firing set, with a return to zero and a noise level of 40 dB below full-scale calibration, 20 to 80 thousand microstrain. Strain data arrived at the gages 150 to 400 microseconds after ignition, depending upon their location and distance from the shock pulse generated by the shape charge. The recorded strain signals agreed quite closely with computer code calculation in both amplitude and frequency.

The strain gage noise check channels did record the precusor, but no other noise during data time.

The data recorded on the velocity transducers did not correlate well with computer calculation, due to mechanical failure of their fixtures.

The noise level was 40 dB below the full-scale calibration of 250 ft/sec.

The data recorded on the oscilloscopes agreed both in amplitude and frequency. Acceleration, strain and velocity were recorded. The data did show more noise because of the oscilloscope's wider bandwidth. The oscilloscope preamps were used with a differential input to prevent degrading the input of the tape recorder on those channels.

The EMP signal recorded on the driven shields and had an amplitude of 40 to 80 volts peak-to-peak and a bandwidth of 40 kHz to 2 MHz.

SUMMARY

Four tests, as described here, have been performed using this instrumentation system. The distance the test part has been above the surface of the firing table (earth ground) has varied from 10 feet to 2 feet.

The EMP signal has increased in amplitude the closer the test part is to the firing table (earth ground). As the amplitude of the EMP increases, the signal-to-noise ratio of the recorded data decreases.

In most cases the data channels have been noise-free before data arrival.

The same instrumentation system has also been used on three sled tests where a massive target moving approximately 1000 miles per hour impacted the target.

No HE was exploded, but there was some electrostatic voltage expected between the test part and the massive target.

Recorded data was excellent with no apparent noise at impact or slightly before impact.

In all of the tests described the cable lengths were short 150 feet, and the data bandwidth maximum was 100 kHz, but with appropriate cable selection and detail to the shielding, longer cable lengths and wider bandwidths should be attainable with the same signal-to-noise ratio.

LAWRENCE LIVERMORE LABORATORY · UNIVERSITY OF CALIFORNIA

ENGINEERING NOTE

SUBJECT H.S.M. INSTRUMENTATION 310

NAME J. J. MORRISON

DATE 8-8-74

PAGE

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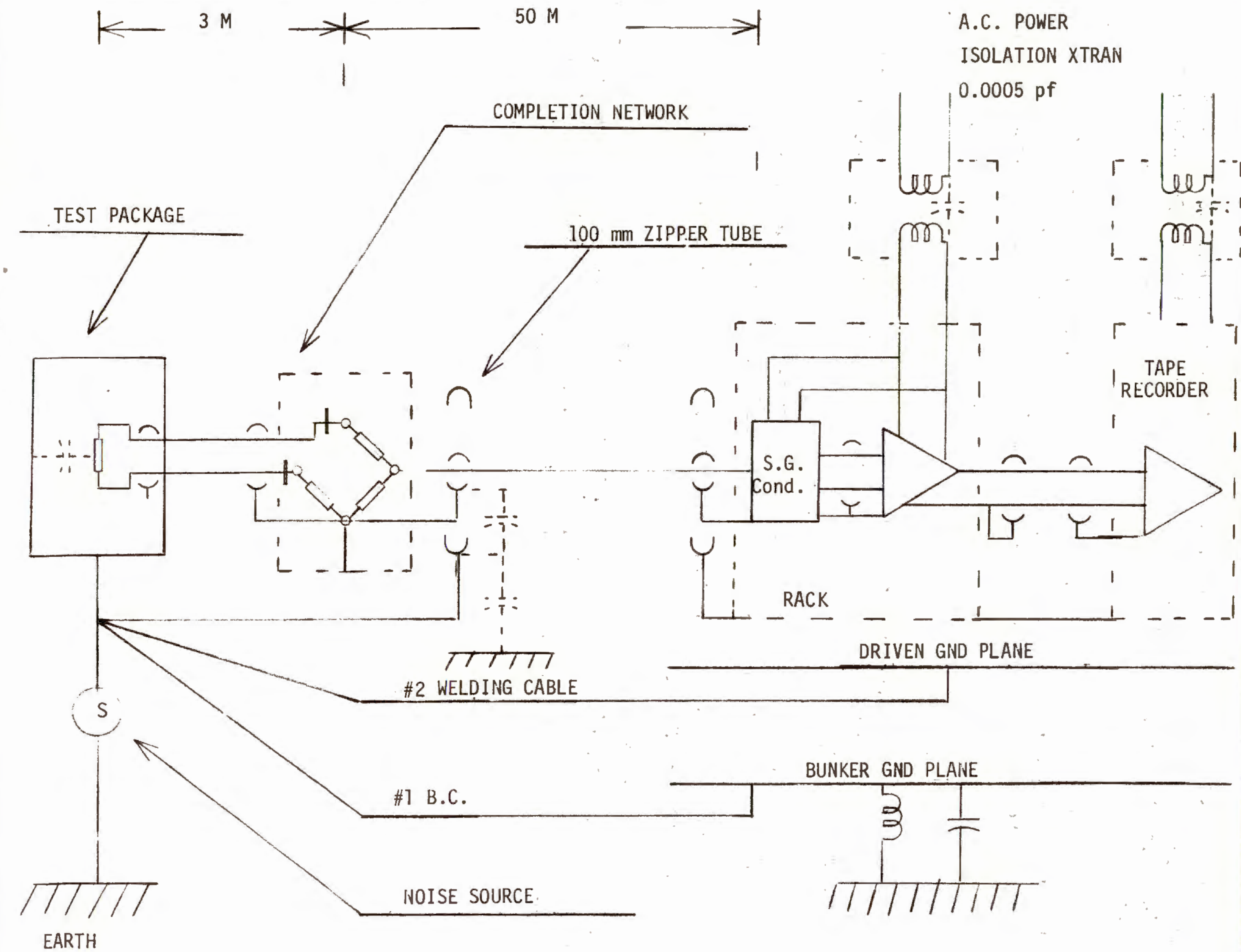

UCRL-51719

HSM, A MEASUREMENTS ENGINEERING CHALLENGE

LAWRENCE LIVERMORE LABORATORY
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WILLIAM SHAY

NOTE: This is a condensed version of the above report

ABSTRACT

After one failure and a partial success at instrumenting the aft warhead case of a hard structure munition (HSM) weapon, we were able to develop instrumentation to record dynamic data in a hostile environment. The environments in which we recorded were the detonation of 100 lb of explosive and the impacting of 15,000 lb of concrete on the instrumented aft warhead case. The case was instrumented primarily with strain gages and accelerometers. Maximum strains were generally less than 10,000 μin./in.; accelerations were generally 100,000 g. An isolated recording system was developed that was immune to external noise sources; transducers were evaluated at anticipated maximum values.

INTRODUCTION

This report is primarily intended for measurements engineers who face the age-old problem of recording transducer outputs in the presence of noise sources - electrical or mechanical.

After one failure and a partial success, we believed it a real challenge to develop a way to record in a hostile environment. This report will concentrate on the instrumentation problems, both transducer and recording, which were encountered in instrumenting the hard structure munition (HSM) weapon, the means used to solve these problems and the results, the actual data traces. The sections of the report follow chronologically the stages of the testing program.

We hope the results of this report can be of value to measurements engineers.

DESCRIPTION OF WEAPON

The HSM is a two-stage high-explosive Air Force weapon. It is designed primarily to defeat reinforced concrete structures. The weapon consists of three separate sections: the forward section, which contains guidance equipment; the center section, which contains the warhead; and the aft section, which contains the propulsion system (see Fig. 1). The Laboratory is concerned only with the center section, or warhead, which is further divided into two sections: a forward warhead and an aft warhead. The combined warhead is approximately 5 ft long and 1.5 ft in diameter, and weighs about 1800 lb. The complete weapon is 15 ft long and 1.5 ft in diameter, and weighs 2500 lb.

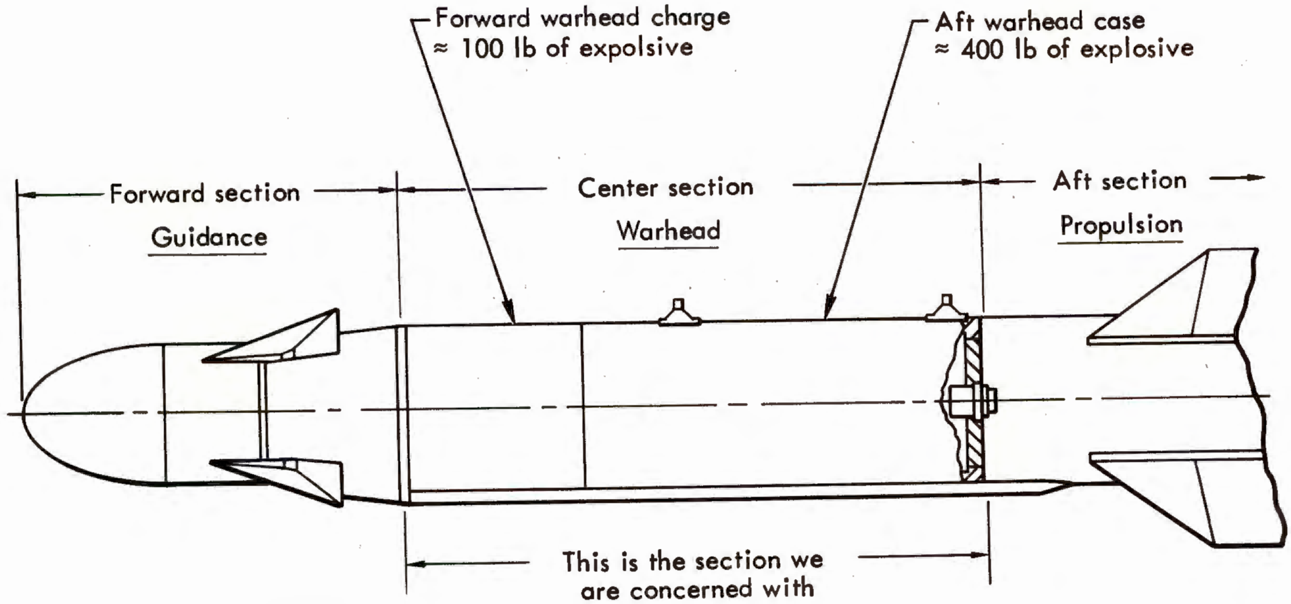

Fig. 1. Hard structure munition (HSM) weapon.

The forward warhead is a shaped charge containing high explosive (approximately 100 lb); the aft warhead contains approximately 400 lb of high explosive. The weapon is launched from an aircraft and guided into a target. When the weapon contacts the target, the forward warhead detonates immediately, causing a cratering of the target. The aft warhead then continues through the blast of the forward warhead and impacts the target in the center of the crater created by the forward war head. After a specified time delay, the aft warhead detonates, virtually destroying the target.

When the forward warhead detonates, it imparts a large shock to the aft warhead. This shock is of a magnitude high enough to sometimes initiate a premature low-order detonation of the aft warhead. This premature detonation in past testing of the HSM has rendered the aft warhead inoperative. It was because of the premature low-order detonations that the Laboratory became involved. The personnel familiar with high explosives were asked to recommend an explosive that would not be as shock-sensitive as that being used.

The impacting of the aft warhead case on the concrete also produced a shock to the aft case. It was decided to investigate these two stress inputs by instrumenting the aft warhead case.

THE FIRST TWO AFT WARHEAD STATIC TESTS

Two static tests (known as STAT tests) were planned at the Explosives Test Site operated by the Laboratory. The tests consisted of instrumenting the aft warhead case, detonating the forward warhead, and measuring the strain, acceleration, etc., on the aft case.

Two aft warhead cases were instrumented both inside and outside, with 12 strain gages, 4 accelerometers, a velocity transducer, and 2 Manganin gages. Both warhead cases contained explosive. Figure 2 shows the location of the transducers for STAT 1 and STAT 2.

Instrumenting the aft warhead case had never been attempted; therefore, nothing was known about the environment in which the transducers would have to survive. Expected magnitudes for strain gages and accelerations were not adequately known, because the output from the forward warhead was unknown. We, therefore, had the challenge to measure something that had never been measured.

STAT 1 (This test was the failure as no data was recorded. Details omitted in this condensed version.)

STAT 2 Figure 3 shows the warhead at the Explosives Test Site prior to the test. The warhead is about 8 ft from the ground.

We used less oscilloscopes than STAT 1, only 30, but added two 14-channel Ampex CP-100 tape recorders. The reduction in oscilloscopes was in part because

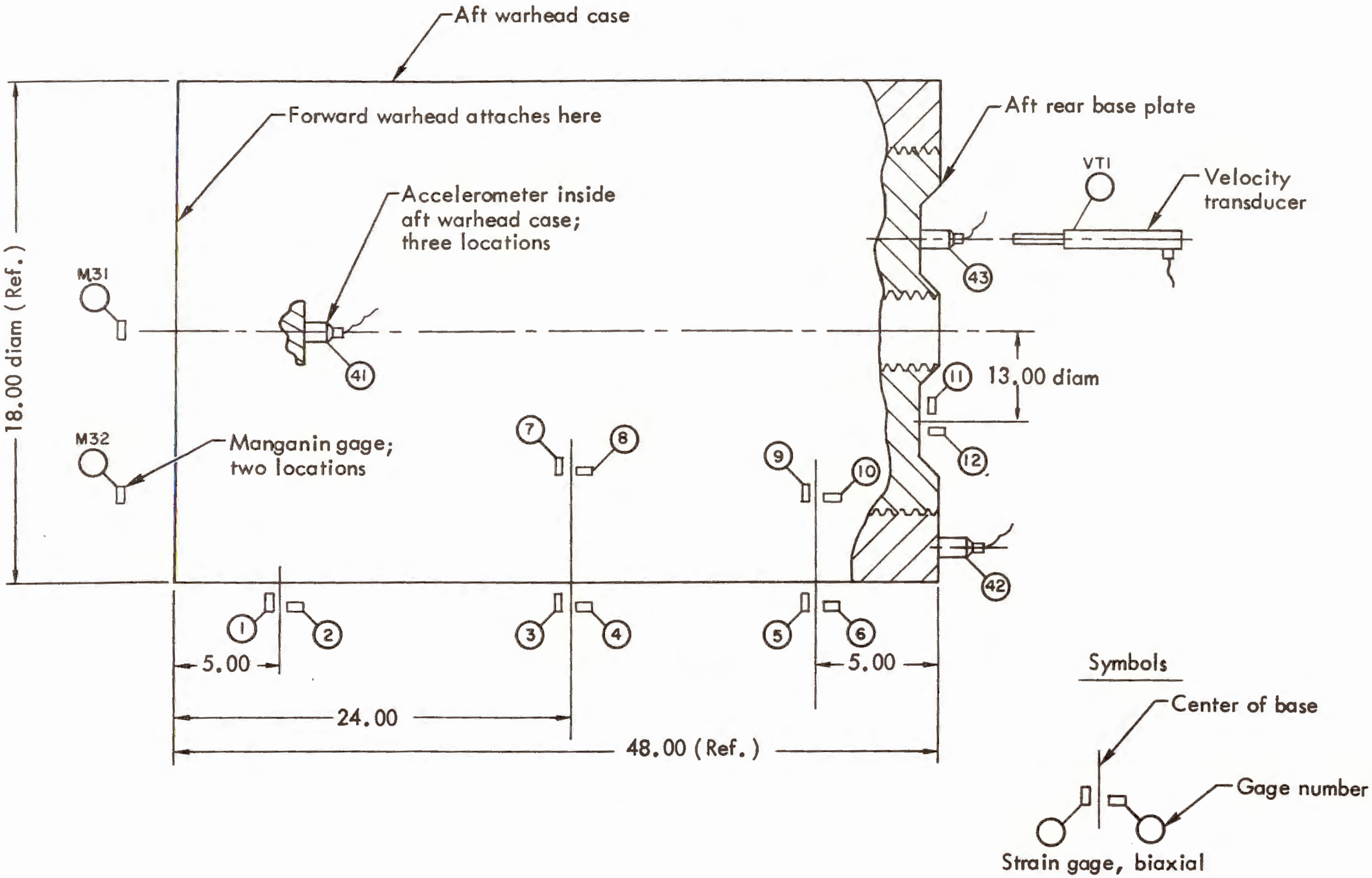

Fig. 2. Transducer locations for STAT 1 and STAT 2.

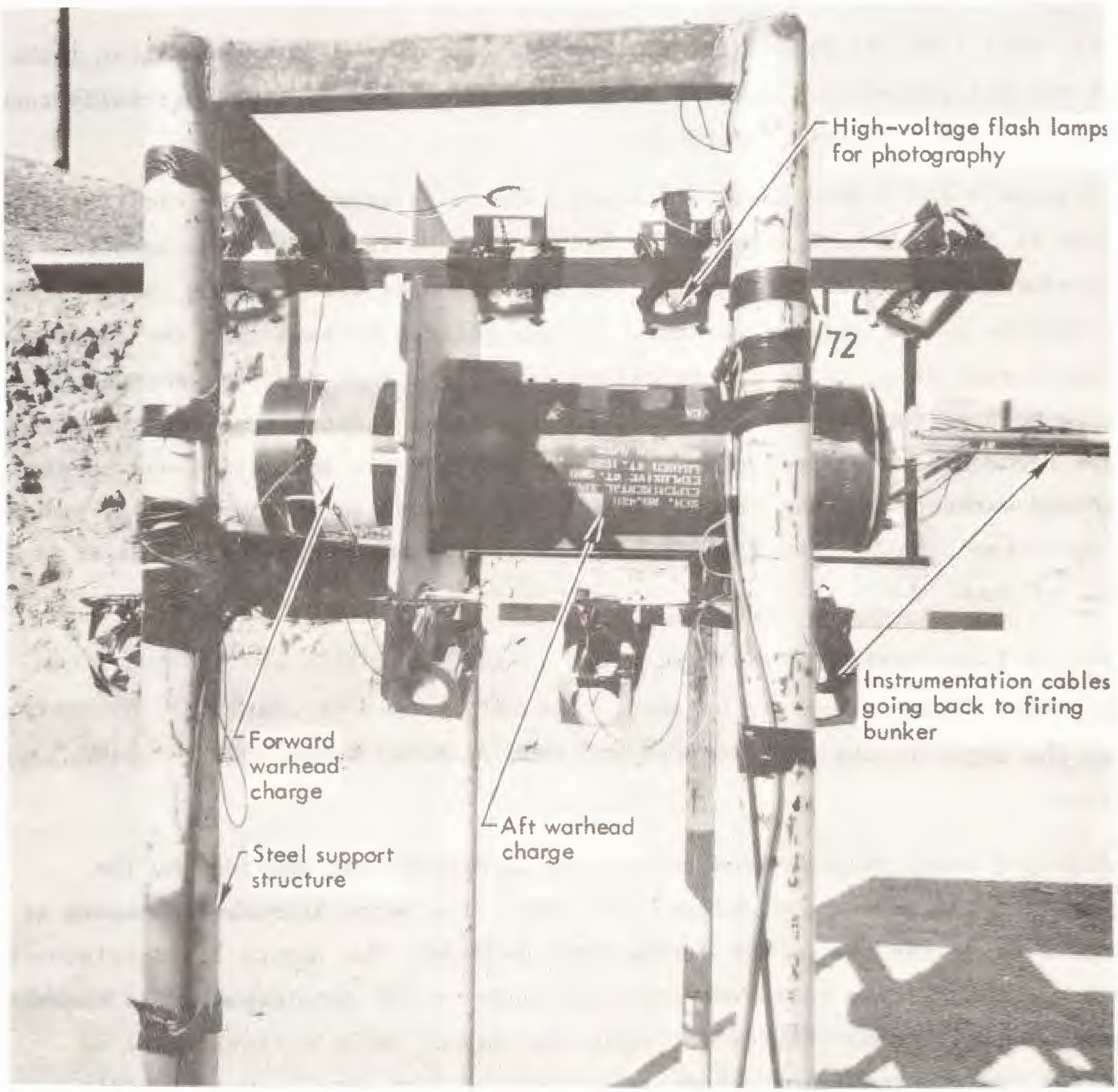

Fig. 3. STAT 2 at Explosives Test Site prior to test.

some arrival times were deduced from STAT 1, and also because we wanted a lower frequency response recorder. Using the frequency-modulation (FM) record electronics, we were able to obtain a frequency response to 20 kHz with the Ampex recorders.

For STAT 2 we did ground the aft warhead case to the instrumentation racks (STAT 1 was not grounded). Because of the grounding this test was partially successful, and some data were recorded.

Figures 4 and 5 show four of the strain gage records from the oscilloscope and three of the same gage recorded by the Ampex tape recorder. The locations of the transducers are shown in Fig. 2. The oscilloscopes were delayed 160μsec from the detonation of the forward warhead. It can clearly be seen that the records do not contain much data, if it can be called data. The tape recorder shows more of the noise because the tape is not delayed. Two large disturbances can be seen on the tape recorder: the first disturbance is probably the detonation and burning of the forward warhead, and the second disturbance (occurring at 150 μsec) is probably the high-voltage (5 kV) flashlamps turning on. This noise deprived us of at least 100 μsec of data.

If one looks carefully at Figs. 4 and 5, the similarity of the data from the two types of recorders can be seen. The data should be identical, however, because the input to the oscilloscope and tape recorder comes from the same amplifier.

Figure 6 shows records from two of the accelerometers recorded by the oscilloscope; the traces are delayed 170 μsec. The large disturbance occurs at the same time as the one on the strain gage records. The record for Accelerometer 42 does not look like a valid reading; the cable or the accelerometer is breaking up periodically. Accelerometer 43, after the noise, looks a little more as predicted; whether the record gives valid acceleration data is questionable.

From this test two things were learned: we could record some data if the instrumentation problem was approached correctly, and the explosive used in the aft warhead was indeed shock-sensitive.

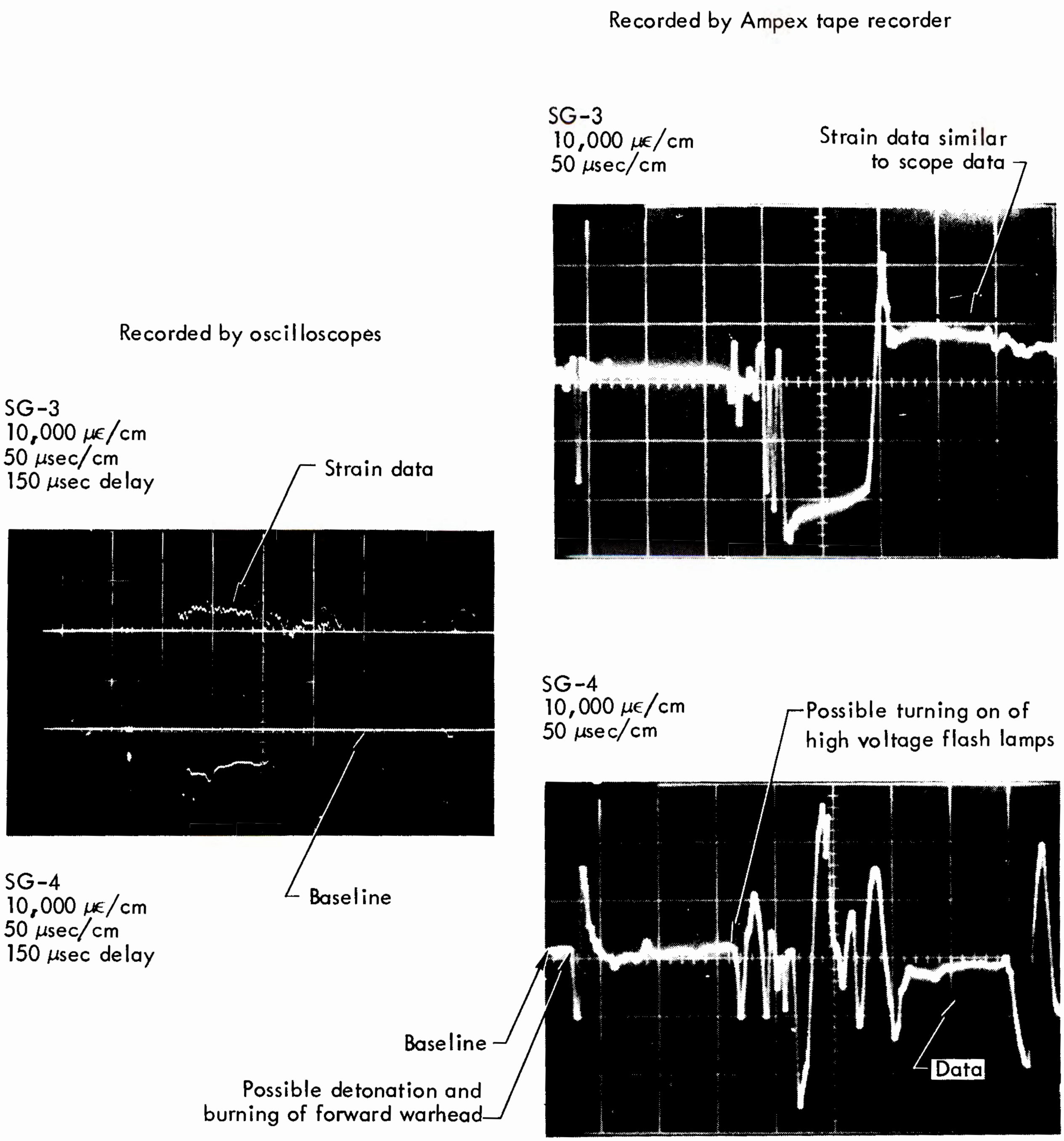

Fig. 4. STAT 2 strain gage records for aft warhead case.

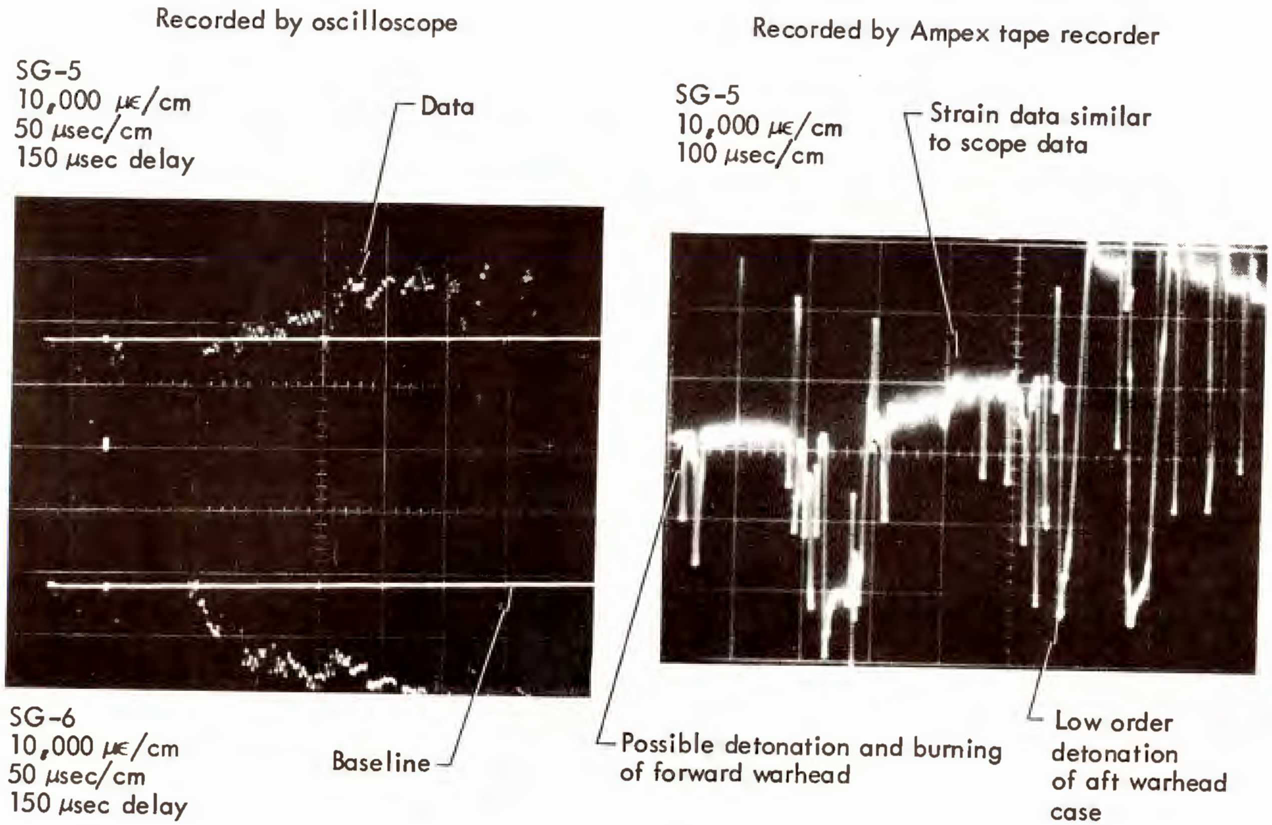

Fig. 5. STAT 2 strain gage records for aft rear base plate.

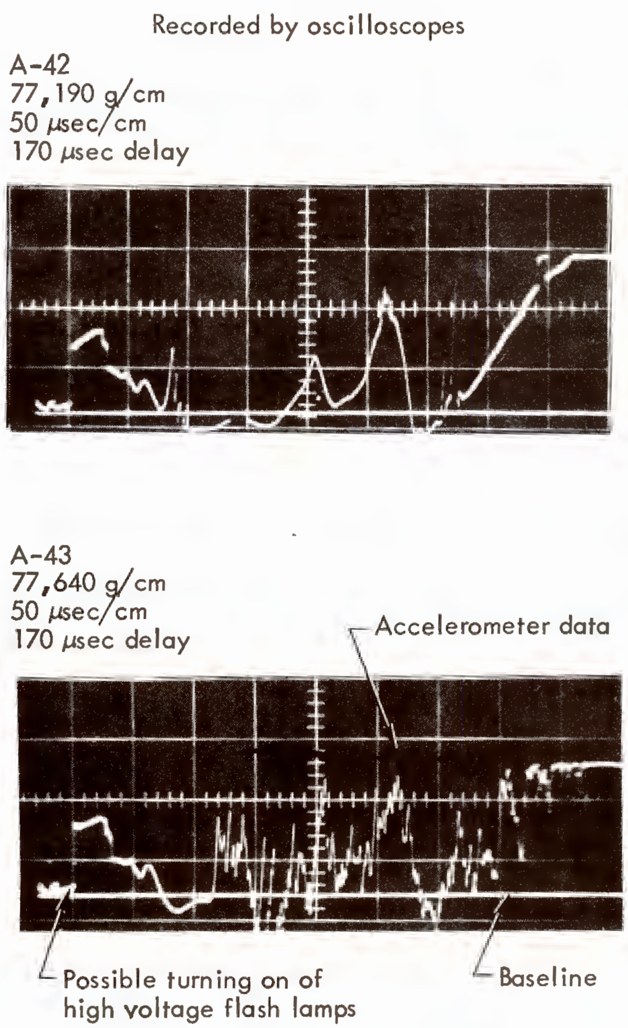

Fig. 6. STAT 2 accelerometer records for aft warhead case.

The following are the two most probable reasons the data were noisy: (1) the aft warhead case was at an electrical potential different from that of the recording equipment, and (2) numerous sources for ground loops existed within the firing bunker.

The forward warhead creates a large ionization cloud that surrounds the aft warhead. This effect can produce a large difference in potential. The oscilloscopes in the firing bunker are not isolated from the circuit that detonates the explosive and provides the high voltage for the flash lamps.

The greater part of the data to be recorded is in the millivolts-to-a-few-volts range. Ground loops and differences in potential between the warhead case and firing bunker can easily affect these voltages. The signal conditioners, amplifiers, and accelerometer power supplies for the transducers were designed for the instrumentation used, but they were not isolated from the firing bunker. This exposure would make them susceptible to ground loops in the firing bunker.

The way to record data under the conditions we have seen and described above would be to isolate somehow the recording system from the firing bunker and all the possible sources of noise. With the completion of these two tests, a period of time elapsed before the next series of tests were scheduled to begin. During this time we evaluated the transducers and developed a way to isolate the recording system.

While the selection and evaluation of the transducers is important, it will be omitted in this condensed version, and only the recording system described.

RECORDING SYSTEM

Figure 7 is a block diagram of the recording systems used for all the STAT tests. The two recording systems received ac power through high-quality isolation transformers. They were manufactured by CEA (Model CEA 35 with a coupling capacitance of 0.0005 pF).

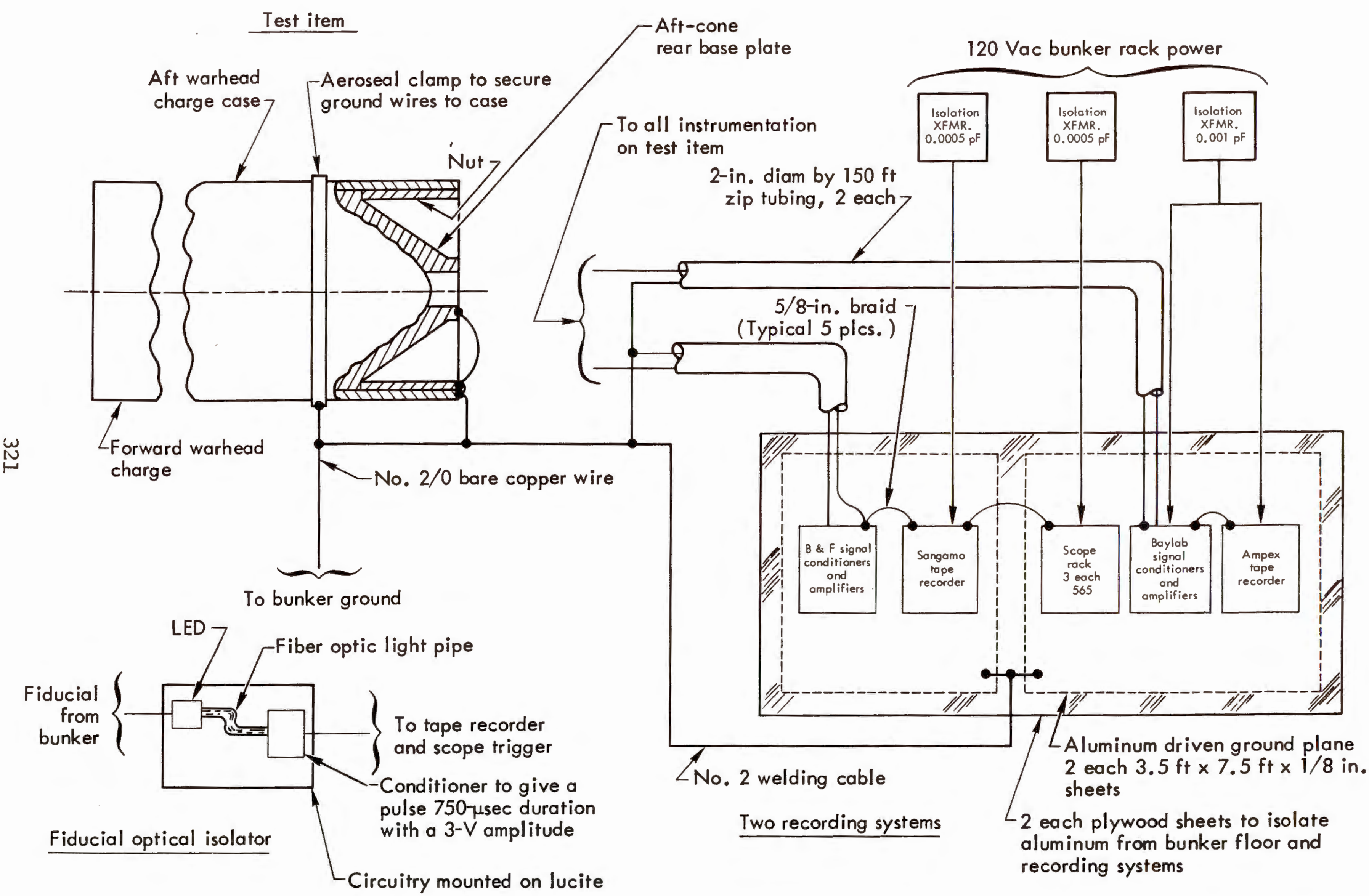

Fig. 7. Block diagram of isolated recording systems used for all STAT tests.

We enclosed the instrumentation cables from the two recording systems to the aft warhead case in an electrostatic shielding. This shielding is known as ZIP tubing (see Fig. 7).

To prevent a loss of data if one system failed, we wired each system to record data from transducers located on one-half of the aft warhead case. These two systems were isolated from each other. The accelerometers were always recorded on the Sangamo system because of its high-frequency response.

We placed both of the systems over an aluminum ground plane the dimensions of which were 15 ft by 3 ft by 1/8 in. We placed the ground plane between two sheets of plywood to isolate it from the floor and the two recording systems.

A large wire connecting the aft warhead case to the ground point at the firing bunker established the ground for the system. Another large wire, connecting the ground plane and the aft warhead case, provided the following function: when the forward warhead detonated and ionized the air, the aft warhead immediately reached an electrical potential different from that of the firing bunker. The wire caused the recording system to be "driven" to the same potential as the aft warhead. When the two were at the same potential, no noise existed to affect the recording.

To provide a "quick-look" at six selected data channels immediately after each test, we used three dual-beam Tektronix oscilloscopes (Model 565) with differential amplifiers (Model 26A3). The scopes were necessary because playing back the data took about one day, and the project staff was anxious to get some test results. The scopes were also isolated, as shown in Fig. 7. We used manually operated camera shutters so as not to introduce electrical noise.

We provided a timing marker, or fiducial marker, on the tape recorder systems to correlate time. The fiducial marker occurred at the time of detonation of the forward warhead. Because this marker was supplied from the bunker firing system, a way to isolate it was needed.

For this purpose, we designed and built a battery-operated optical isolator. When the forward warhead was detonated, a signal from the bunker triggered a light-emitting diode (LED), the output of which was transmitted through fiber optics to a circuit that provided a conditioned fiducial marker with a duration of about 750 μsec at a magnitude of 3.0 V. Ordinarily this signal from the firing bunker was only a few hundred nanoseconds in duration and could not be put on the tape recorders unless it was conditioned. This conditioned marker could now be put on the two tape recorders as well as trigger the three "quick-look" oscilloscopes.

IRIG time code was also placed on each tape recorder to aid in reducing the data. Voice was recorded on the Sangamo tape recorder as an aid in reducing the data.

The strain gages were handled differently from those on STAT 1 and STAT 2. Instead of a three-wire system, we completed the strain gage bridge as close to the aft warhead as possible, and four wires were brought back to the recording systems (the circuitry is shown in Fig. 8). The four wires permitted a better capacitive balanced line than a three-wire system. The completion resistors (Vishay resistors) were installed in a box that acted as the shielding. Two ferrite beads were placed on the leads from the active strain gage. The beads acted like an inductor and attenuated any high-frequency transient pulses.

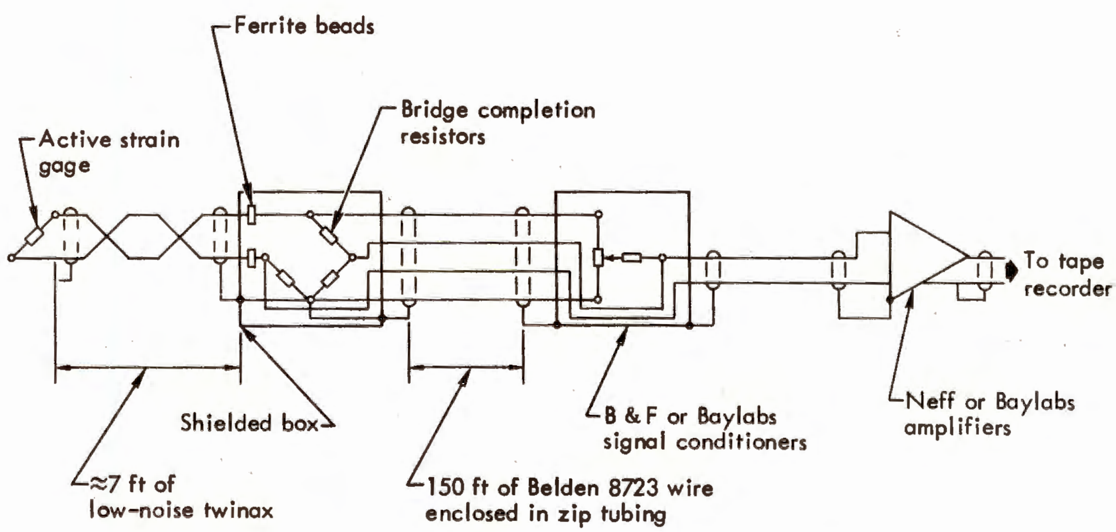

Fig. 8. Strain gage circuitry for STAT tests.

The wire from the active strain gage to the completion box was low-noise twinax manufactured by Microdot Co. The low-noise cable reduced spurious electrical signals caused by the motion of the aft warhead case.

We insulated each strain gage completion box to isolate and to prevent ground loops from occurring between strain channels. We used a shunt calibration for the strain gages. Because a tape recorder was used for the strain gages, the amplifier gain was adjusted to provide a 1.0V output at full scale. This output gave us a 40% safety margin, as the tape recorders can safely accept a 1.4-V input.

The accelerometers also were handled differently from those in STAT 1 and STAT 2. The units were piezoelectric manufactured by Pcb, Inc., and had a built-in charge amplifier. We used a battery power supply to provide the constant current for the charge amplifier. A special line driver was built and connected to the output of the power supply. This circuitry was installed in a box to act as shielding (see Fig. 9 for the circuitry).

The line driver had an amplifier built in to isolate the accelerometer from the recording system and to "drive" a cable longer than that driven by the battery power supply. The amplifier had a gain of unity. The output of the accelerometer at full scale is nominally 3 V, which had to be attenuated to 1.0 V for the tape recorder. This attenuator was also built into the box. A separate power supply and line driver are required for each accelerometer, because the sensitivity of each accelerometer is different. Low-noise twinax cable is used from the accelerometer to the power supply. The output of the line driver was twinax cable.

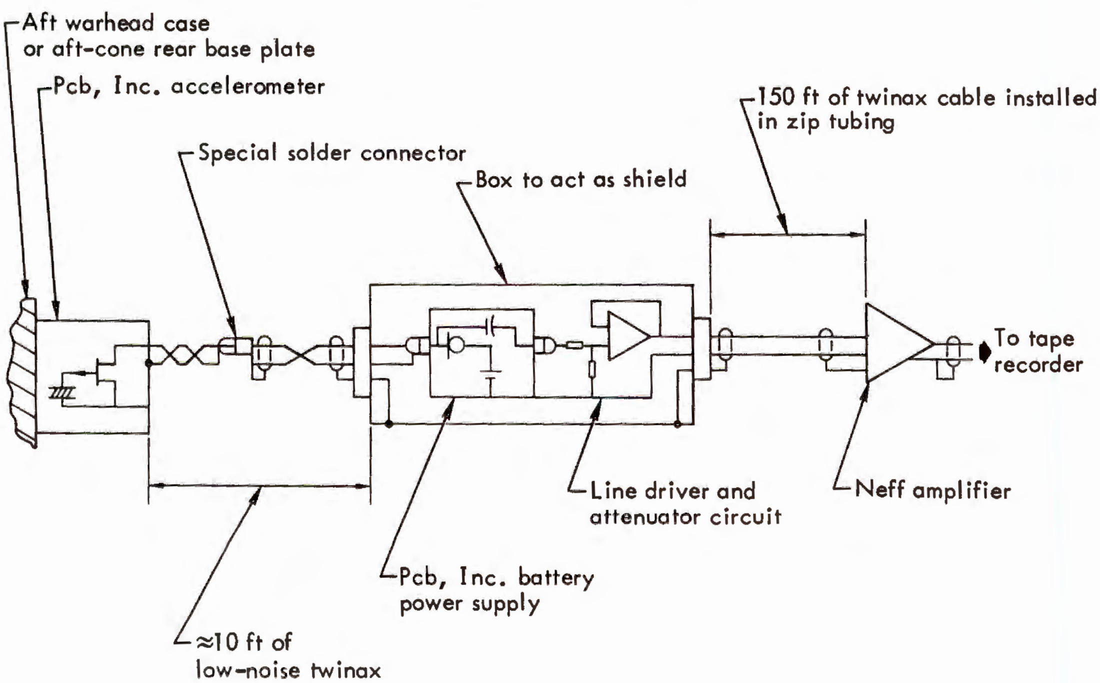

Fig. 9. Piezoelectric accelerometer circuitry for STAT tests.

We also used a piezoresistive accelerometer manufactured by Endevco (Fig. 10 shows the circuitry). This accelerometer has an internal Wheatstone bridge circuit (see Fig. 10), and must be attenuated to provide 1.0 V for the tape recorder; this is done by adjusting the excitation voltage.

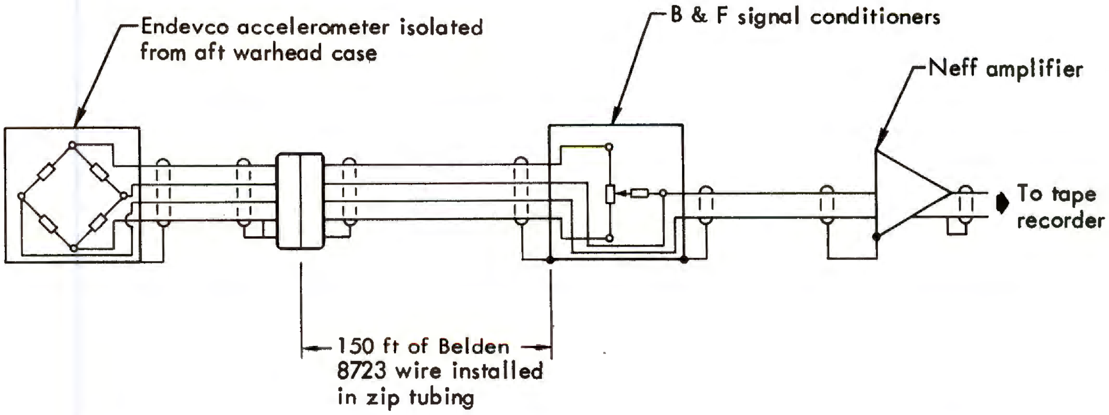

Fig. 10. Piezoresistive accelerometer circuitry for STAT tests.

The velocity transducer required only an attenuator to give the 1.0-V output for the tape recorder. The attenuator is necessary because the output of the transducer is about 750 V at the expected velocity. Figure 11 shows the circuitry.

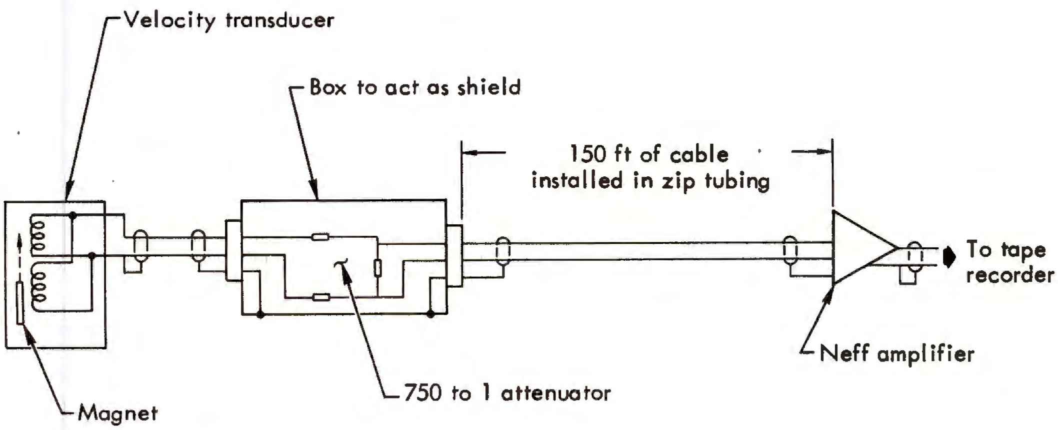

Fig. 11. Velocity transducer circuitry for STAT tests.

Before any of the subsequent STAT tests were performed, we conducted several dry runs in the firing bunker to verify that there would be no noise on the data channels. The dry runs were intended to duplicate the firing sequence of each test except, of course, the detonation of the forward warhead. The dry runs (all the instrumentation powered) consisted of the firing of the bridge wire,* and the firing of a bridge wire with the flashlamps operating and all the cameras running. If we observed any noise during the dry runs, we identified the source and corrected it before the actual test.

As a further precaution against the introduction of ground loops into the systems, because of body capacitance, no one touched any of the recording systems before the detonation of the forward charge. The systems were turned on about 1 min before the detonation, and calibrations were put on the tapes. The systems were turned off after the test.

SUBSEQUENT AFT WARHEAD STATIC TESTS

There were four more tests conducted in this series, STAT 3, STAT 4, STAT 5, and STAT 6. For this condensed version only, the results for one of the tests will be shown.

STAT 4

Figure 12 shows four of the strain gage data traces recorded by the two recording systems for the aft warhead case. The lower trace on the photographs is the fiducial marker. The sudden step in the marker has a special significance; it corresponds to the detonation of the forward warhead. As can be seen in the figure, the baselines of the gages are noise-free before and after the step in the marker. The fiducial marker is breaking up on the Ampex data trace but this breakup has no affect on the data.

Figure 13 shows four data traces from the strain gages on the aft cone recorded by the two systems. Again, no noise is seen on the data when the fiducial marker stop occurs.

Figure 14 shows the data traces of the accelerometers.

Figure 15 shows data traces of the velocity transducers.

We think this data represents a considerable improvement over the data from STAT 2.

**A bridge wire initiates the detonation of the forward warhead.*

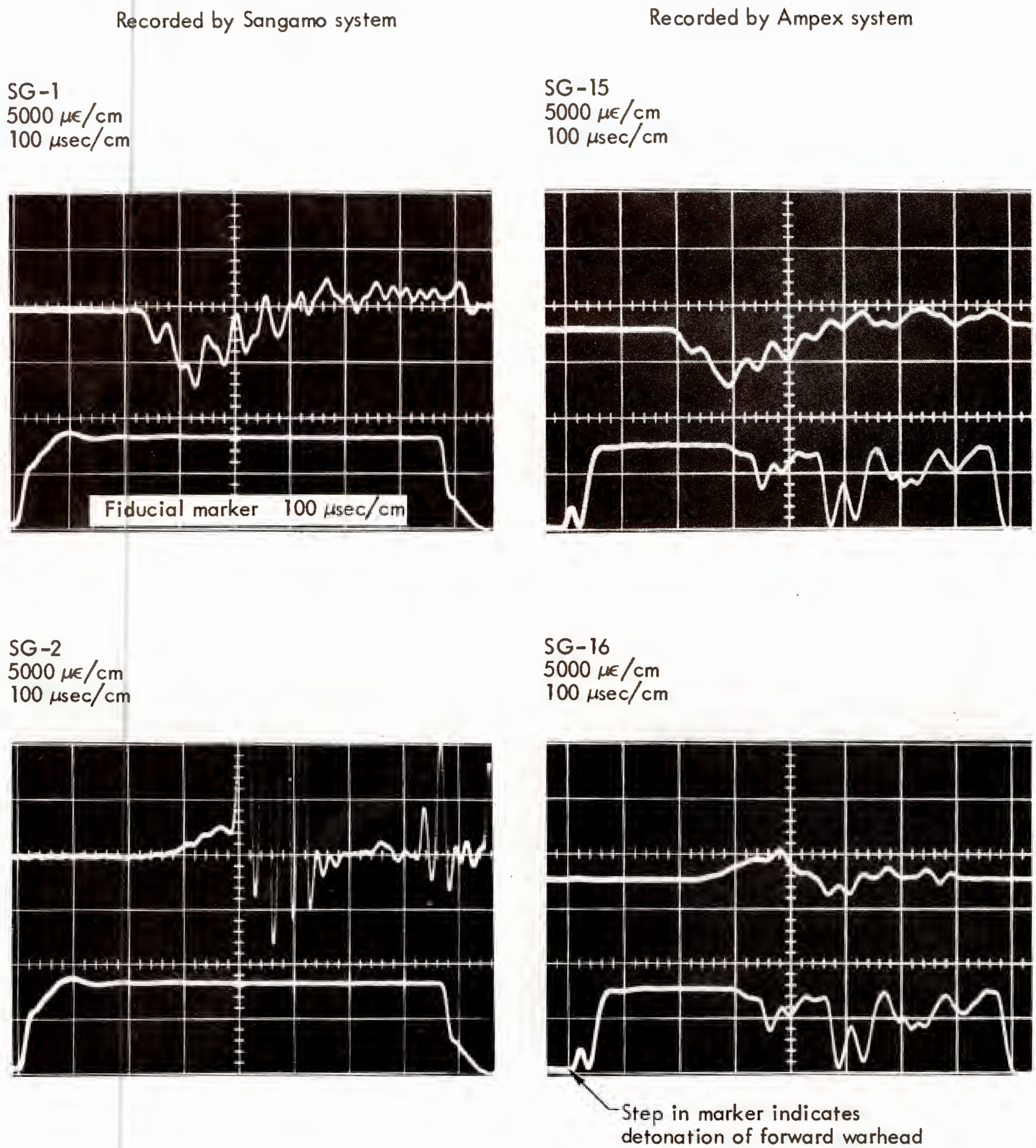

Fig. 12. STAT 4 strain gage data traces for aft warhead case.

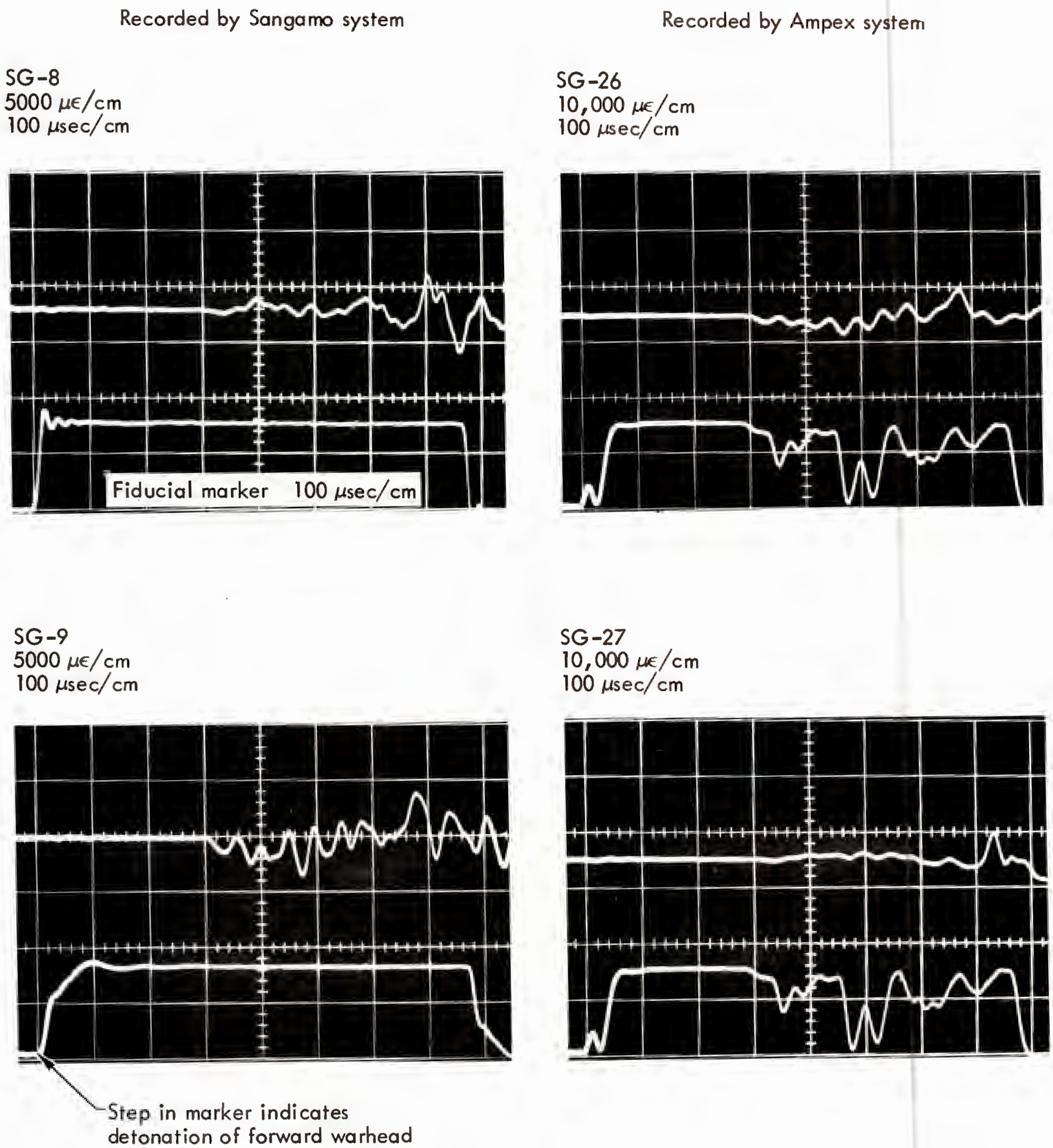

Fig. 13. STAT 4 strain gage data traces for aft-cone rear base plate.

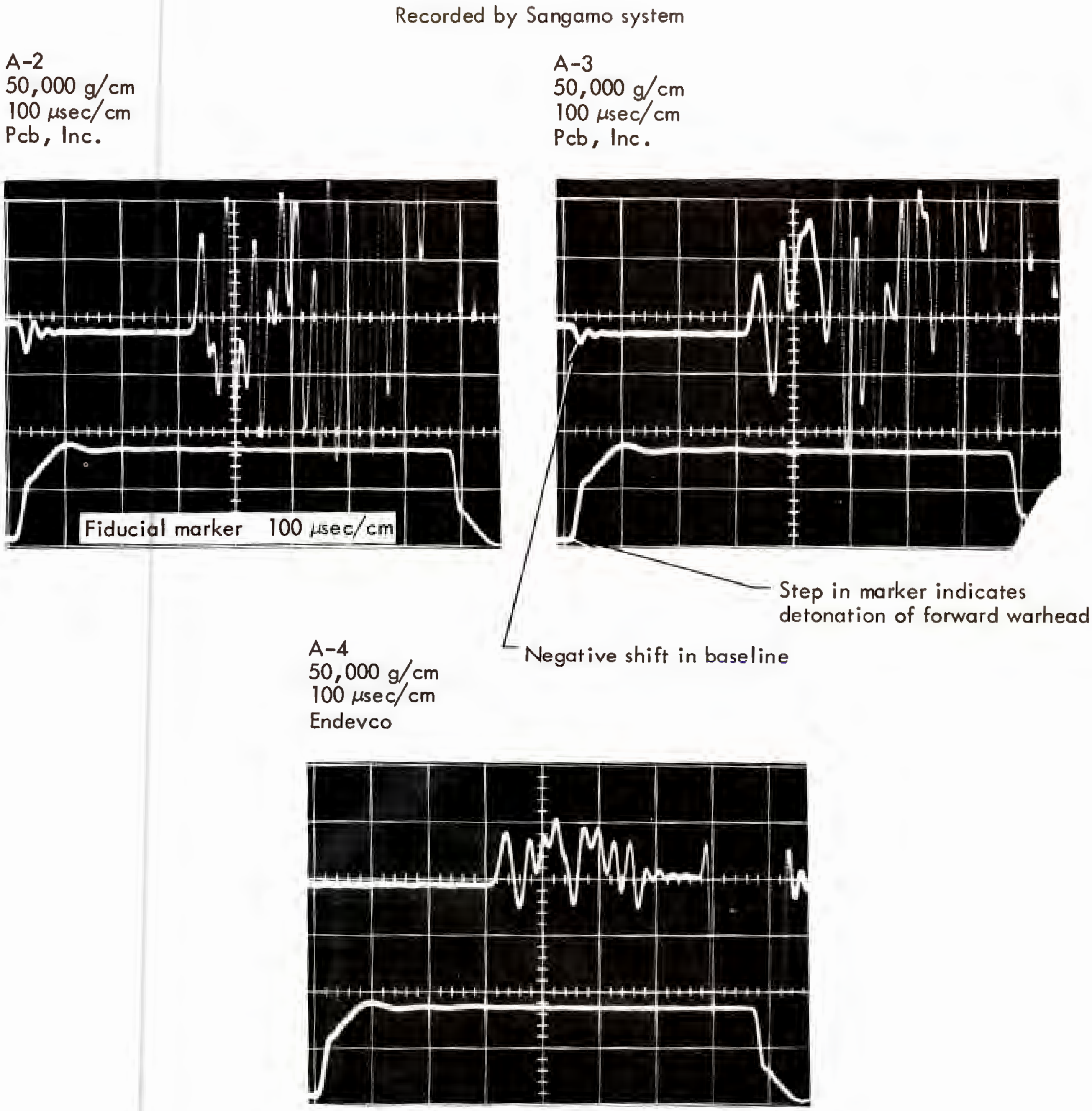

Fig. 14. STAT 4 accelerometer data traces.

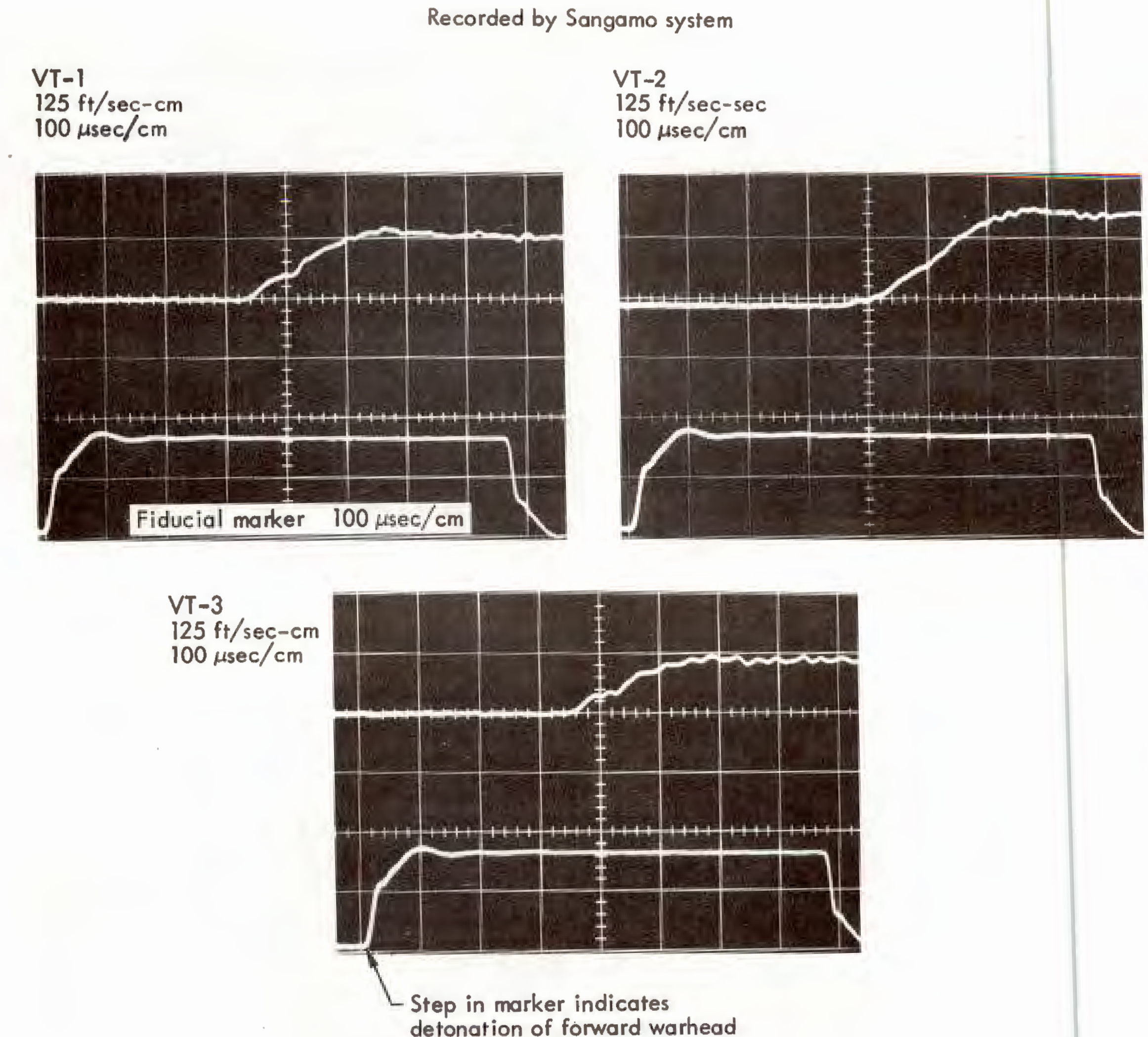

Fig. 15. STAT 4 velocity transducer data traces.

Because our recording system was completely isolated from the firing bunker, it would be very interesting to measure the voltage developed between the aft warhead case and the bunker, if there was anything to measure. Fig. 16 is the measurements. These oscilloscopes within the firing bunker were used, one was connected to the ground plane, one to the braid of the Sangamo system and the other to the braid of the Ampex system. The three oscilloscopes were triggered 6 μsec before the forward warhead was detonated. The time delay would let us see the baseline before anything happened. As can be seen, the voltages developed between the bunker and our isolated recorded system are quite large, but our system rejects the voltage.

This concludes the condensed discussion of the STAT tests and brings us to the second series of tests.

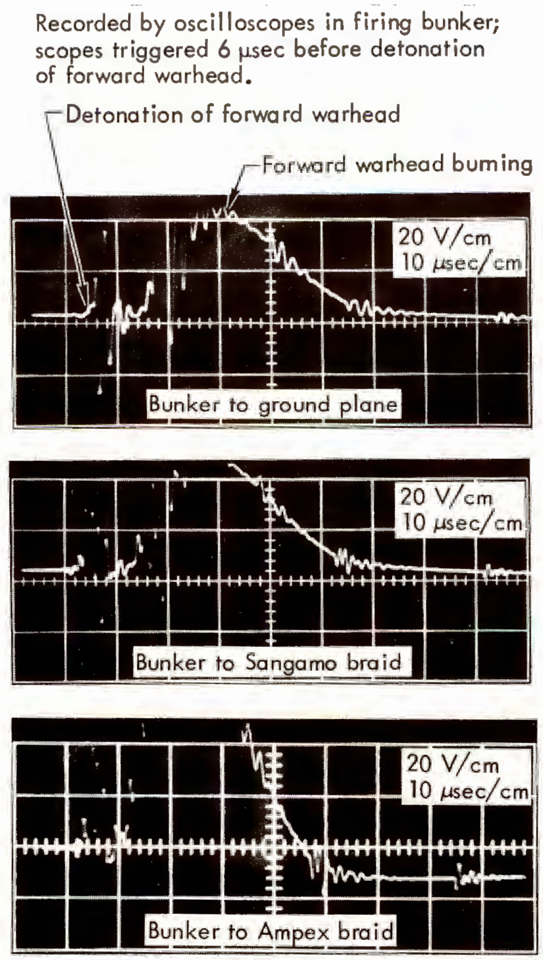

Fig. 16. STAT 6 voltage measurements.

AFT WARHEAD CASE IMPACTING TESTS

As noted in the introduction, the aft warhead receives two shock inputs. We are ready to investigate with instrumentation the second input, which is the impact of the aft warhead case on a concrete target. Since a velocity of approximately 1000 mph of the HSM weapon in flight is a typical velocity, a facility to obtain this velocity was needed. The Laboratory had no way to produce this type of velocity with the weight of the warhead. Therefore, the tests took place at the 5000-ft sled track at Sandia Laboratories, Albuquerque, New Mexico.

It is virtually impossible to instrument the aft warhead case, to accelerate the case trailing instrumentation cables down a sled track, to impact a target, and to record data. Therefore, a "turnaround" test was conducted; the concrete target was shot down the track to impact the instrumented aft warhead case.

There was no high-explosive forward warhead used with these tests. Instead of impacting concrete partially broken up by the forward warhead, the aft warhead case would be impacting virgin concrete, constituting somewhat of an overtest.

The absence of the forward charge meant that there would be no ionization to contend with, but another source of noise was present. This source was the static electricity being stored on the concrete block as it moved down the sled track at the fast velocity. The static electricity could discharge at the impact of the concrete target on the aft warhead, and affect the data recording. A way to discharge the static electricity before impact was sought. Three layers of poultry mesh (chicken wire) 4 in. apart were placed in front of the aft warhead case. The mesh was connected to a ground point at the end of the sled track. It was hoped that the concrete impacting the mesh would discharge any static electricity before impacting the aft warhead case.

Figure 17 shows the isolated recording system used for all SLED tests. Note the similarity in the system to the recording system for the STAT test. The circuitry for the strain gages and the accelerometers was the same as that shown in Figs. 8 and 9. Only one recording system was necessary because the number of data channels was less than for the STAT tests. The Sangamo system was used.

The recording system was placed on the aluminum ground plane. The cables from the recording system to the aft warhead case were enclosed in zip tubing. There was no "quick-look" oscilloscope for these tests.

There were three sled tests conducted at the sled track. The first two tests involved one-third scale models of the aft warhead case, and the third test, a full-size warhead case identical to STAT 5. All the warhead cases were filled with a mock explosive, and were instrumented with strain gages, both inside and outside, and with accelerometers. The same brands of transducers were used for these tests as were used in the static tests.

The aft warhead cases were wrapped with 1/4-in. of fiberglass to reduce the damage from the concrete. The concrete targets for SLED 1 and SLED 3 were shaped like a right circular cylinder to give a normal impact with the warhead cases. The concrete target for SLED 2 was a truncated cylinder with the impact face inclined 45° to its axis, simulating an impact off-normal to measure bending moments of the aft warhead case.

Of the three SLED tests conducted, only SLED 3 will be shown in this condensed version.

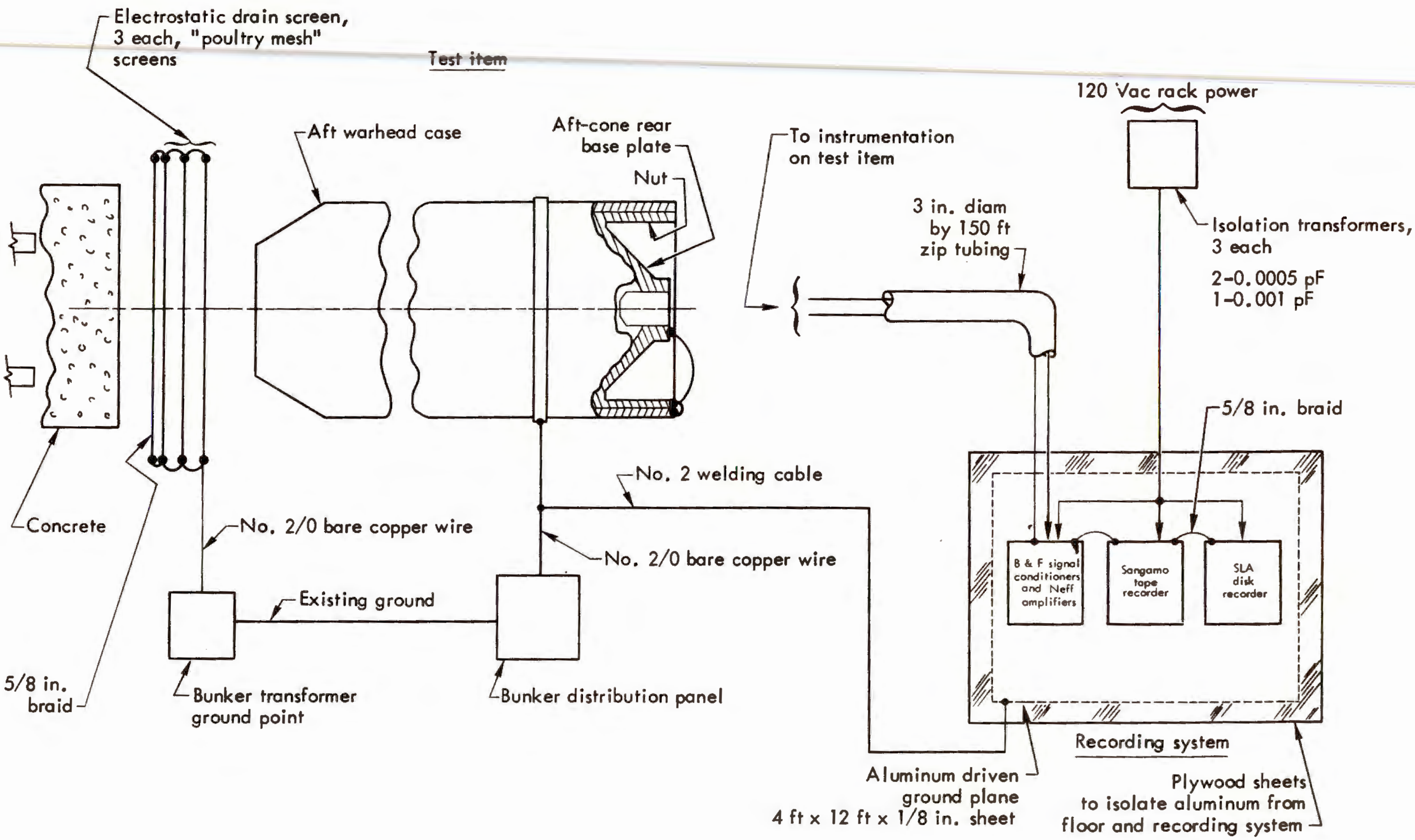

Fig. 17. Block diagram of isolated recording system used for all sled tests.

The concrete target for 1 and SLED 3 before the test is shown in Fig. 18. The target was 5.5 ft in diameter and 4 ft long with a weight of about 15,000 lb. The concrete target was accelerated on the track by 21 solid-fueled rocket motors. A first stage consisting of 9 rocket motors started the concrete target moving and at a predetermined location on the track the remaining 12 rocket motors ignited, accelerating the target to impact.

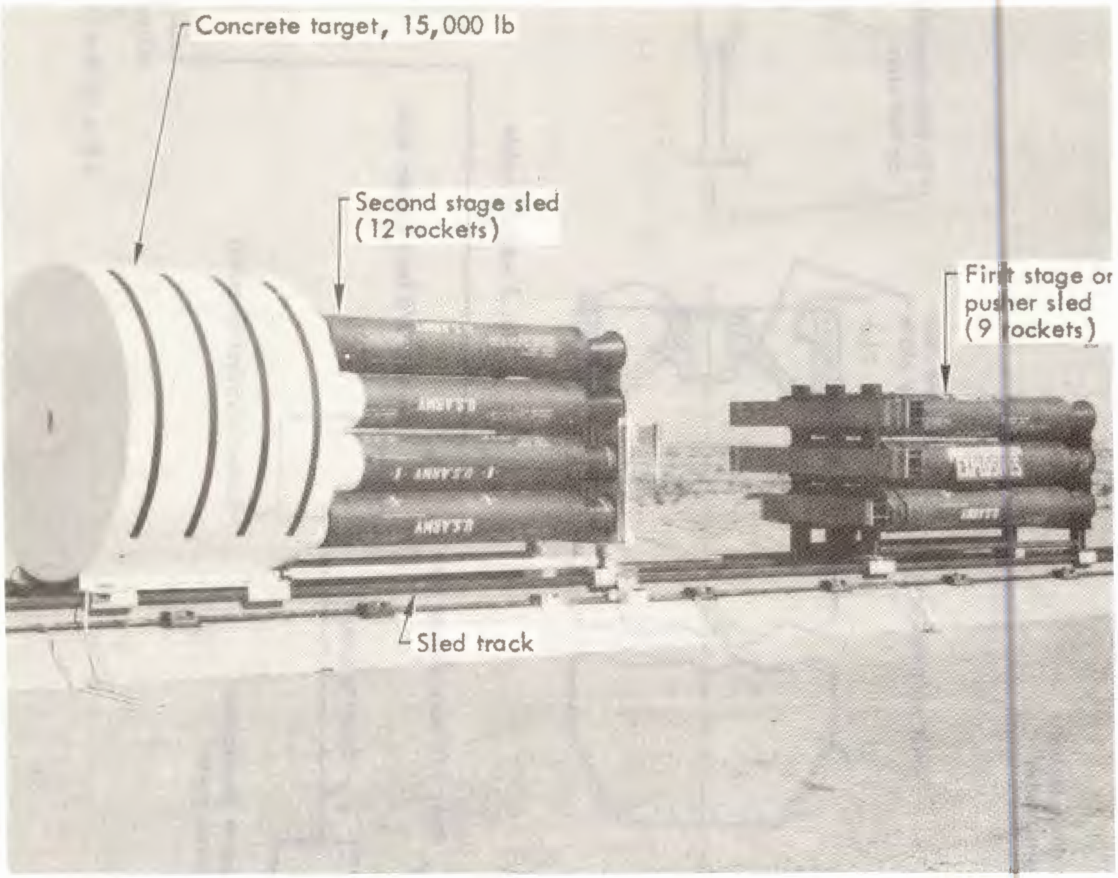

Fig. 18. SLED 1 and SLED 3 concrete target at Sandia Laboratories, Albuquerque, before test (photo: courtesy of Sandia Laboratories).

Figure 19 shows the aft warhead at the end of the sled track before impact. The poultry mesh can be seen.

Figure 20 shows the locations of the transducers.

Figure 21 shows data traces from four of the strain gages on the aft warhead case.

Figure 22 shows data traces from four of the strain gages on the aft-cone rear base plate. Note that the baselines are noise free. Figure 23 shows the data traces from the strain gages on the nut.

Figure 24 shows the accelerometer data trace.

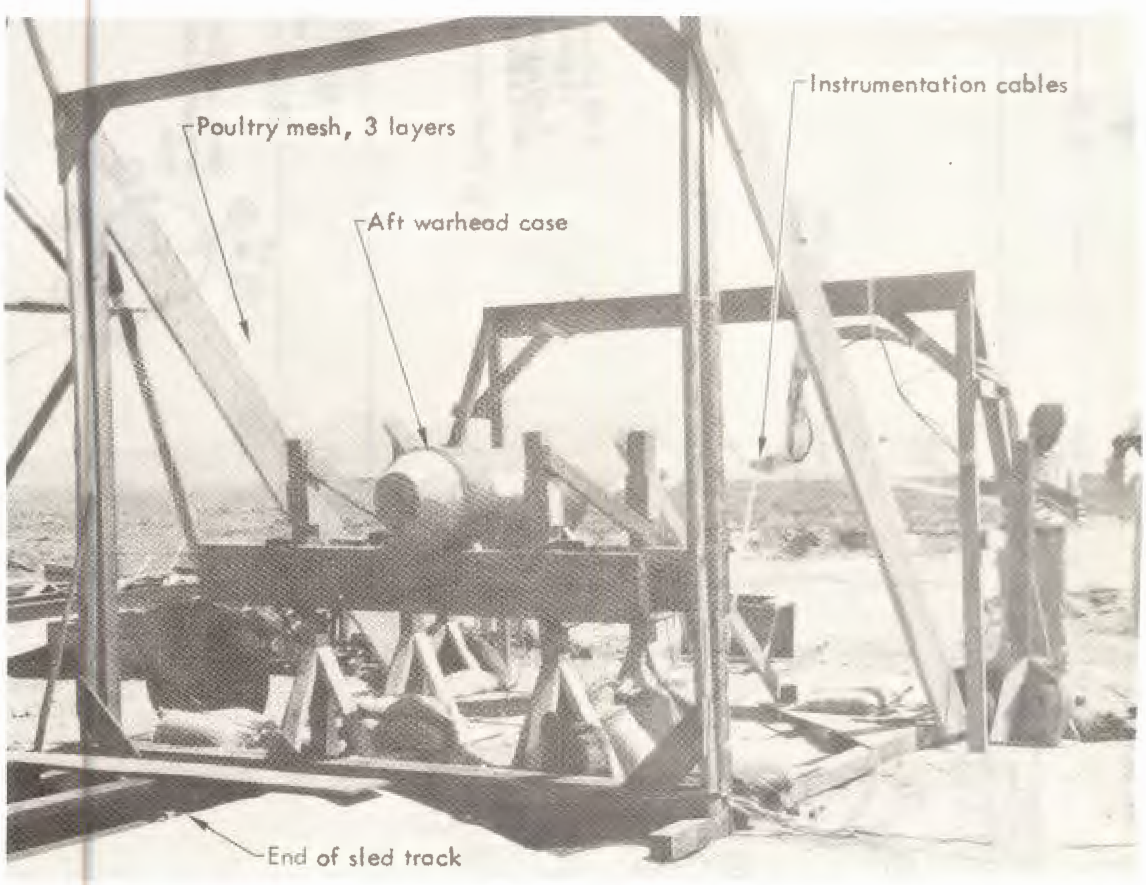

Fig. 19. SLED 3 aft warhead case at end of sled track prior to impact (photo: courtesy of Sandia Laboratories).

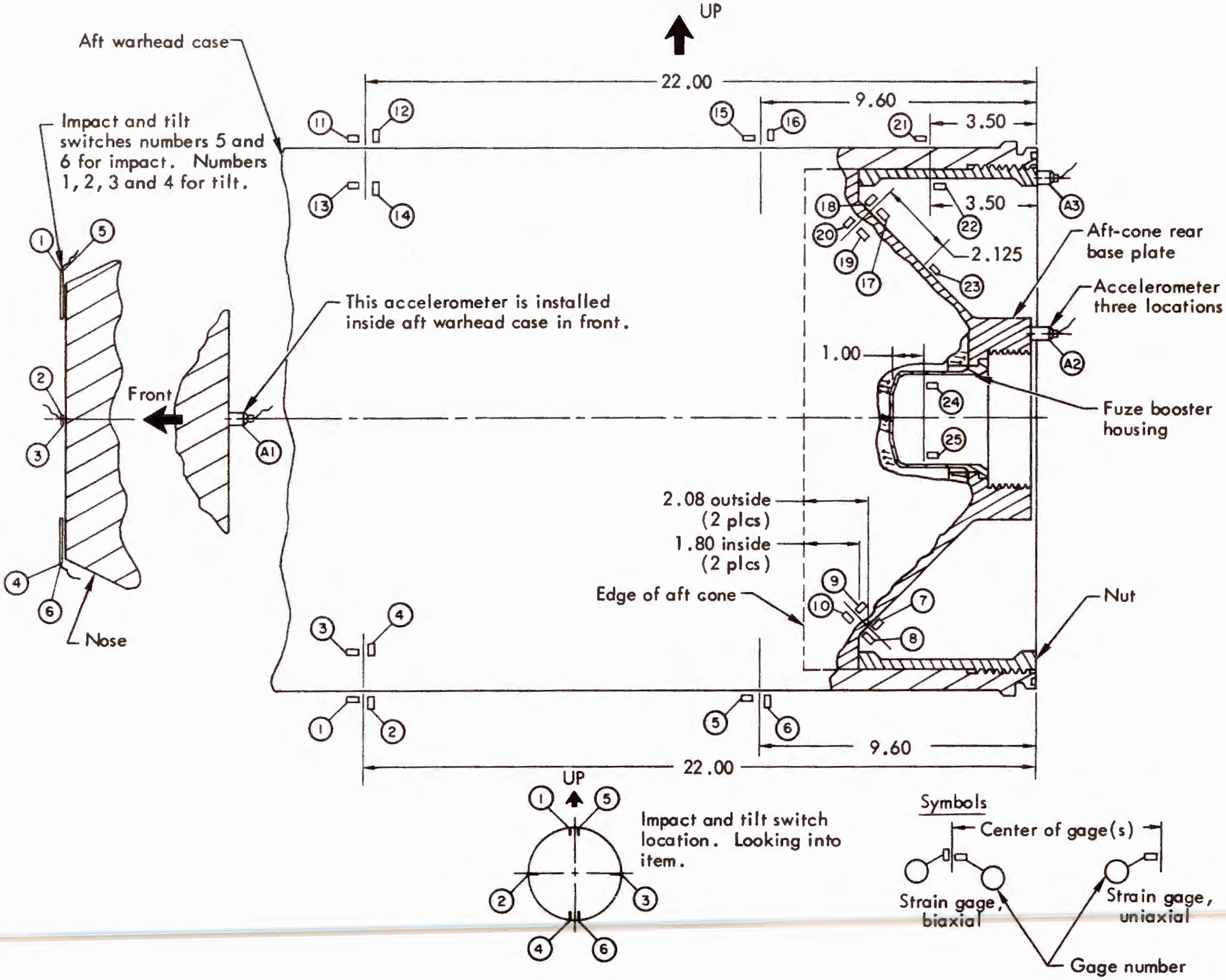

Fig. 20. Transducer locations for SLED 3.

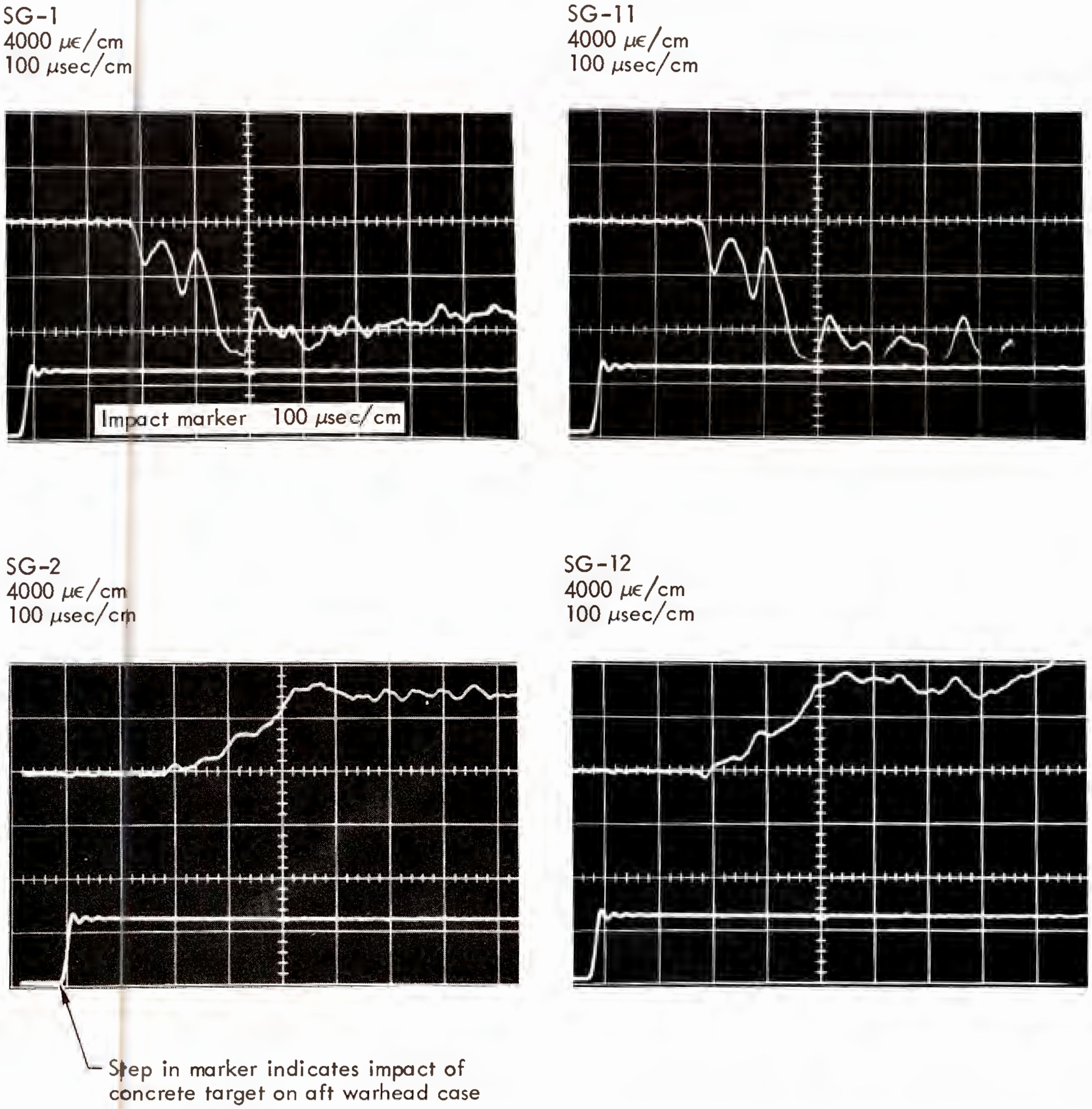

Fig. 21. SLED 3 strain gage data traces for aft warhead case.

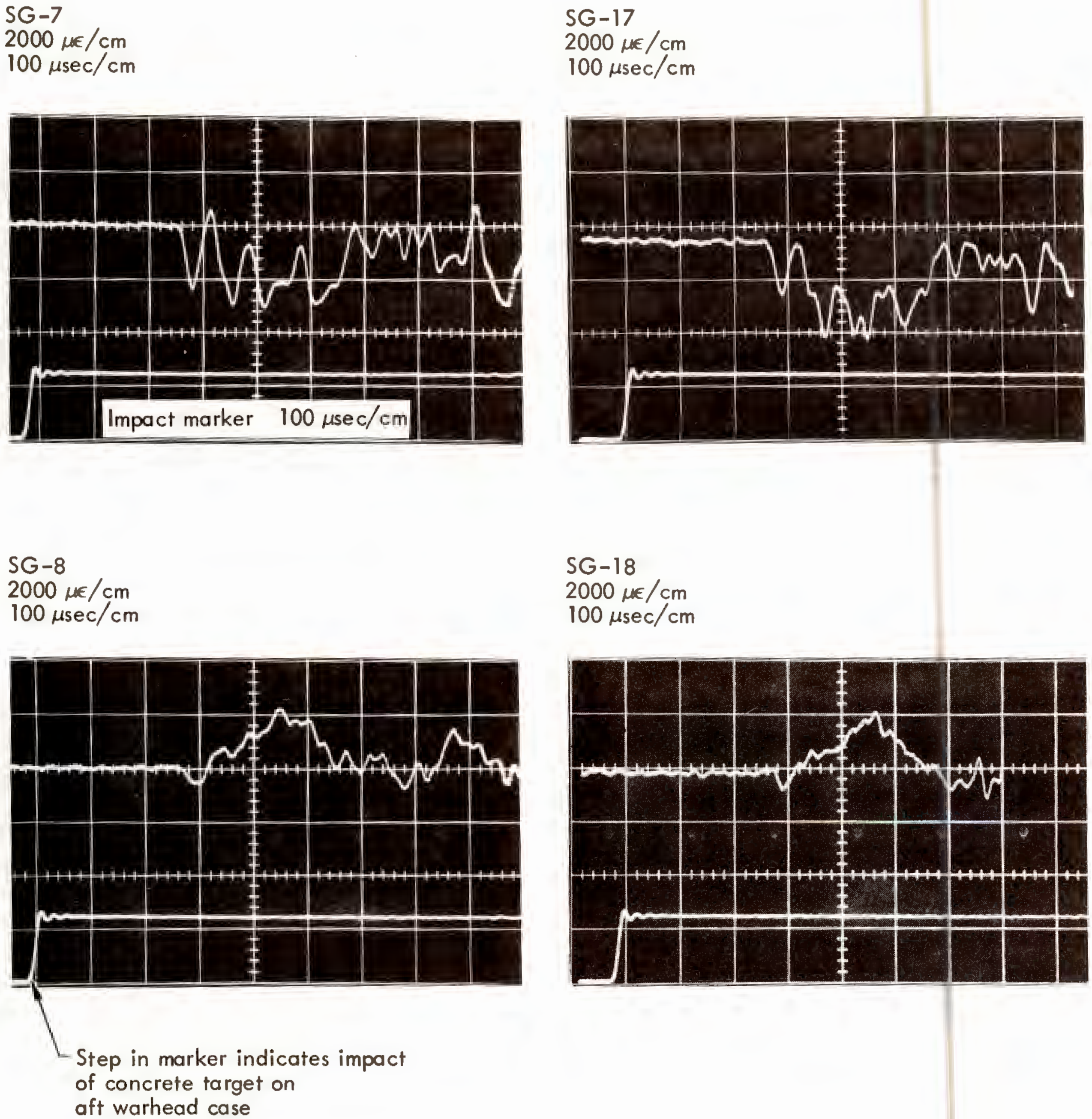

Fig. 22. SLED 3 strain gage data traces for aft-cone rear base plate.

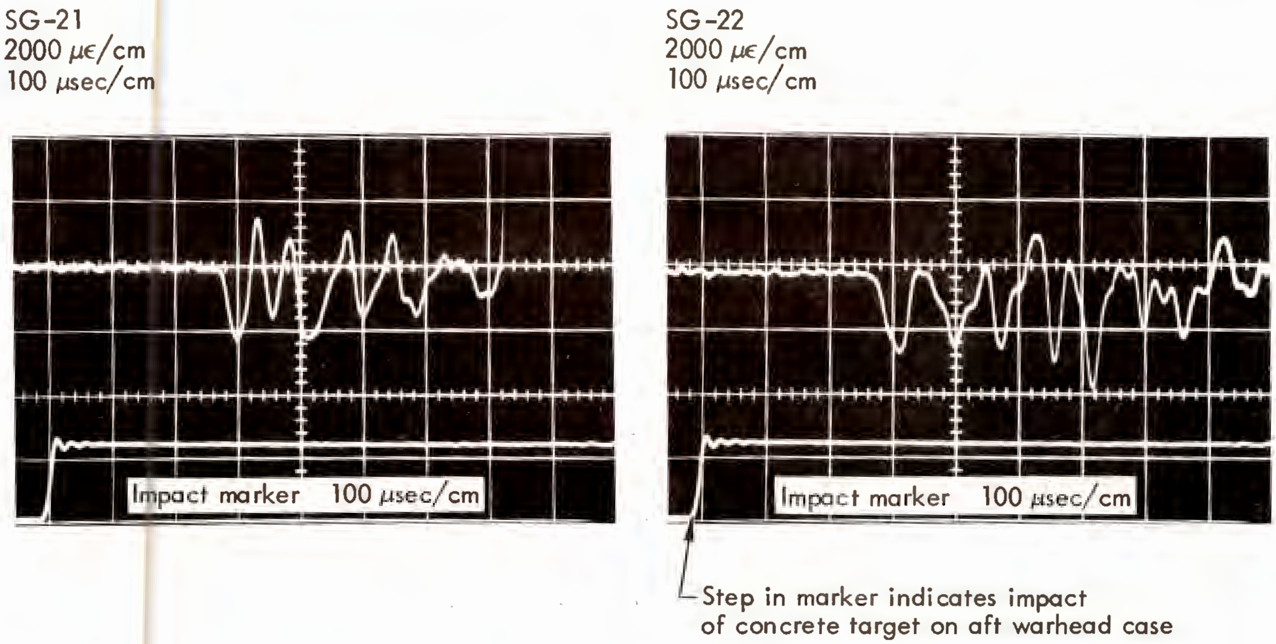

Fig. 23. SLED 3 strain gage data traces for aft warhead case and nut.

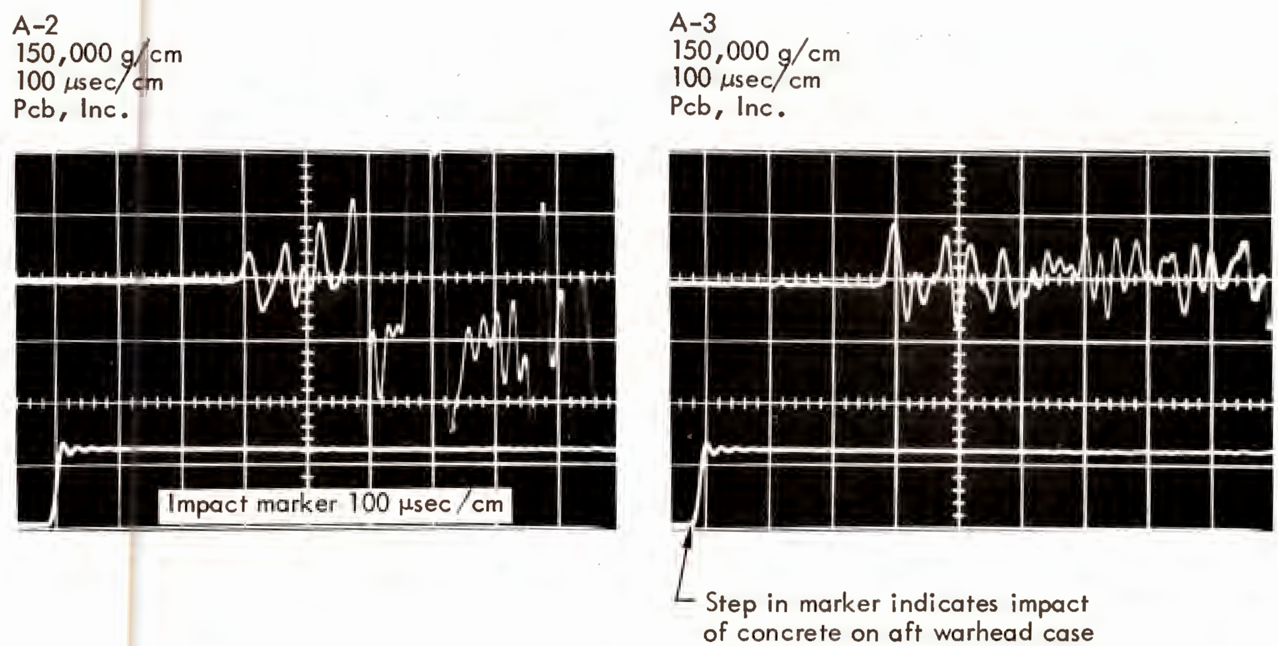

Fig. 24. SLED 3 accelerometer data traces.

CONCLUSIONS

While there are several conclusions we can report, these three are the ones we are presenting here:

1. Data can be recorded in another type of hostile environment encountered by measurements engineers. We were able to record data when 100 lb of explosive detonated and when 15,000 lb of concrete impacted a warhead, each recording for the first time - to the knowledge of the author.

2. Transducers can be used with a recording system to "instrument" yet another hostile environment. After a failure and a partial success, we were able to develop an isolated recording system that was generally immune to external noise sources and to evaluate transducers that were capable of recording dynamic data in the hostile environment we faced. Despite the fact that there were difficulties with the transducers on each test, more channels were recorded than failed.

3. Measurements engineers are often the last to be called into the planning conference relative to a test program. In the case of the HSM project, however, we were included in the planning and budget before the start of the STAT 3 test. The project personnel realized that, if valid data were to be obtained, time and money must be expended. We conclude that it is to the advantage of all concerned to bring in measurements engineers in the planning stages of a project.

To accomplish what has been accomplished has indeed been a challenge, a challenge that has met with success, something that is not always the experience of the measurements engineer.

SSS-R-75-2597

A PARTICLE VELOCITY GAUGE FOR GROUND MOTION STUDIES

By

Philip L. Coleman

Systems, Science and Software

A PARTICLE VELOCITY GAUGE FOR GROUND MOTION STUDIES

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Abstract

The S^3 particle velocity gauge consists of an accelerometer coupled with shock-hardened electronics that accurately integrate the accelerometer signal for periods up to about one second. The low-impedance output has a full-scale range of over ±10 volts and a linear frequency response extending to at least 10 kHz. By a suitable choice of accelerometer, the instrument can handle a very wide range of peak velocities. The unit also includes an externally-commanded calibrator that serves to check out the entire accelerometer-electronics-cable-recorder system. The protective canister can withstand stresses to 3 kbar and has a mean density of 2 grams per cm^3. In recent field tests, samples of the gauge performed properly in shock levels exceeding 5×10^4 g's, measuring peak velocities in excess of 100 meters per second.

A PARTICLE VELOCITY GAUGE FOR GROUND MOTION STUDIES

Introduction

Over the last two years, S^3 has developed a rugged particle velocity gauge for use in ground motion studies. The gauge is basically an accelerometer plus a real-time analog integrator mounted in a shock-hardened package. This configuration can use either piezoresistive or quartz accelerometers, and it offers the advantage of transmitting the lower frequency, lower dynamic range and more easily predicted velocity signal over the long cable usually required for field applications. Major features of the unit are shown in Table 1.

Figure 1 shows a block diagram of the electronics. By a suitable choice of accelerometer, first stage gain and integrator time constant, a wide range of peak velocities and accelerations can be accommodated. Two commands are available. One of these, the "RESET" function, discharges the integrating capacitor just before the expected pulse arrival time. The other command injects a square "calibrate" signal at the electronic input (Fig. 2). The resulting linear ramp at the integrator output provides a check on the piezoresistive accelerometer continuity, accelerometer power supply, and electronic gains, including that of the recorder. The commands are coded as pulses on the supply line; for a pulse to be accepted as a command by the gauge, the product of its amplitude and width must exceed 40 volt-milliseconds. This requirement helps to discriminate against noise-generated commands.

The circuitry makes use of void-free components mounted on printed circuit boards and vacuum-potted in EPON 815 epoxy. A steel canister around the accelerometer and electronics provides protection against stresses to 3 kilobars.

TA TABLE I. $\tilde{S}^3$ VELOCITY GAUGE CHARACTERISTICS

TYPE: Accelerometer plus analog integrator mounted in a shock-hardened canister

ACCELEROMETER: Piezoresistive or Quartz

FREQUENCY RESPONS: ∿2HZ to > 50 kHz

OUTPUT: Z<100Ω, ± 12 V. peak, ± 10 mA peak

POTTING (by mass): 60% EPON 815, 30% VERSAMID 140, 10% TYPE U HARDENER

POWER REQUIREMENTS: ± 20 V. @ : 50 mA. (piezoresistive); 30 mA. (quartz)

RESPONSE: Acceleration Output, Volts/g = $S_B K_1$

Velocity Output, Volts/Meter/Sec = $S_B K_1 / 9.8\ R_1 C_1$

where: S_B = accelerometer sensitivity in volts/g,

K_1 = gain of input amplifier (see Figure 1),

$R_1 C_1$ = integrator time constant.

CALIBRATE LEVELS: Acceleration Output, Volts = $V_B K_1 / (4\frac{R_6}{R_y} + 2)$

Velocity Output, Volts/Sec = $V_B K_1 / R_1 C_1\ (4\frac{R_6}{R_y} + 2)$

where: V_B = Piezoresistive bridge power, nominally 10 Volts

R_6 = Calibrate resistor,

R_y = Fixed element of accelerometer bridge.

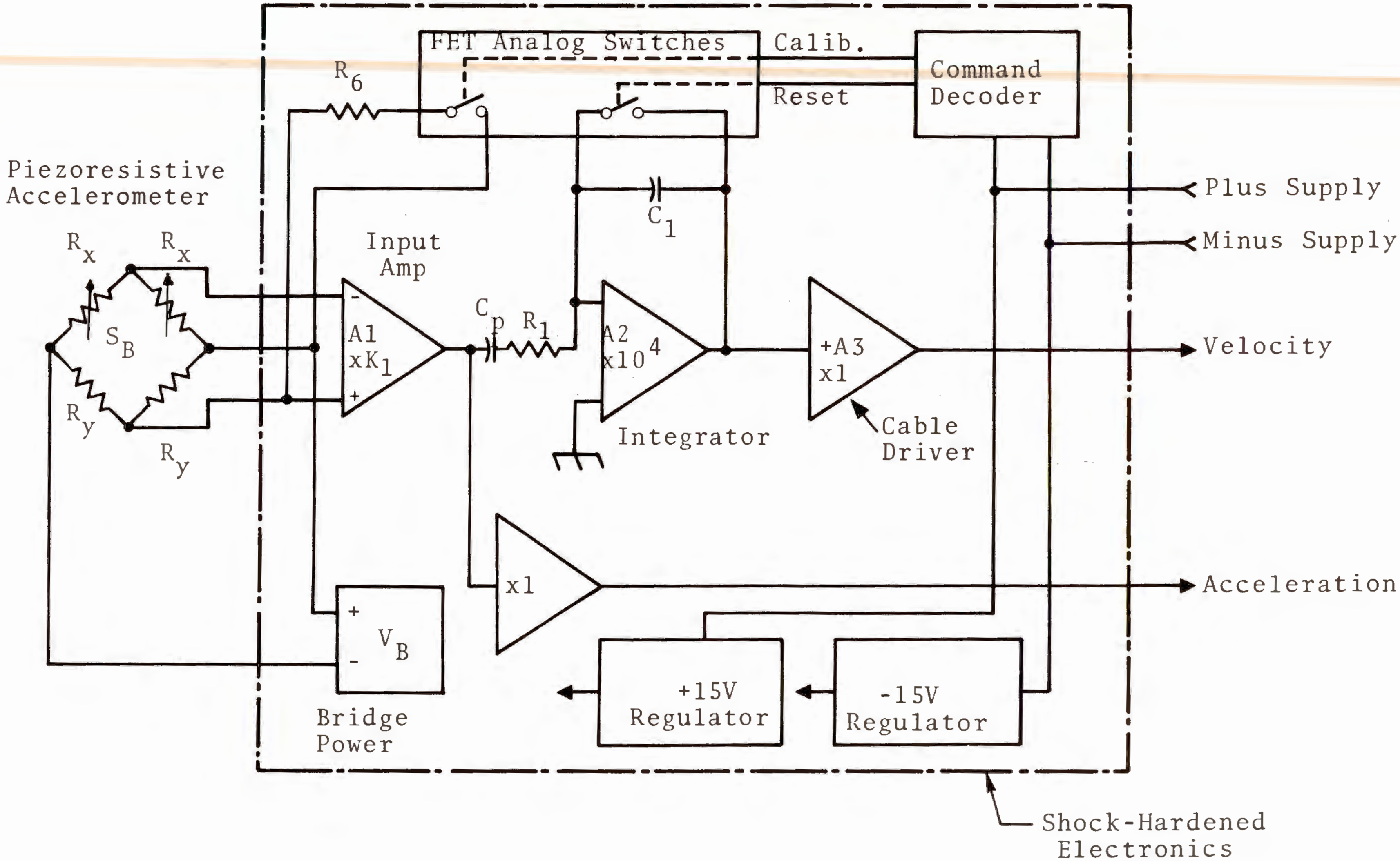

Figure 1. Block diagram of signal conditioning circuitry contained in particle velocity gauge package.

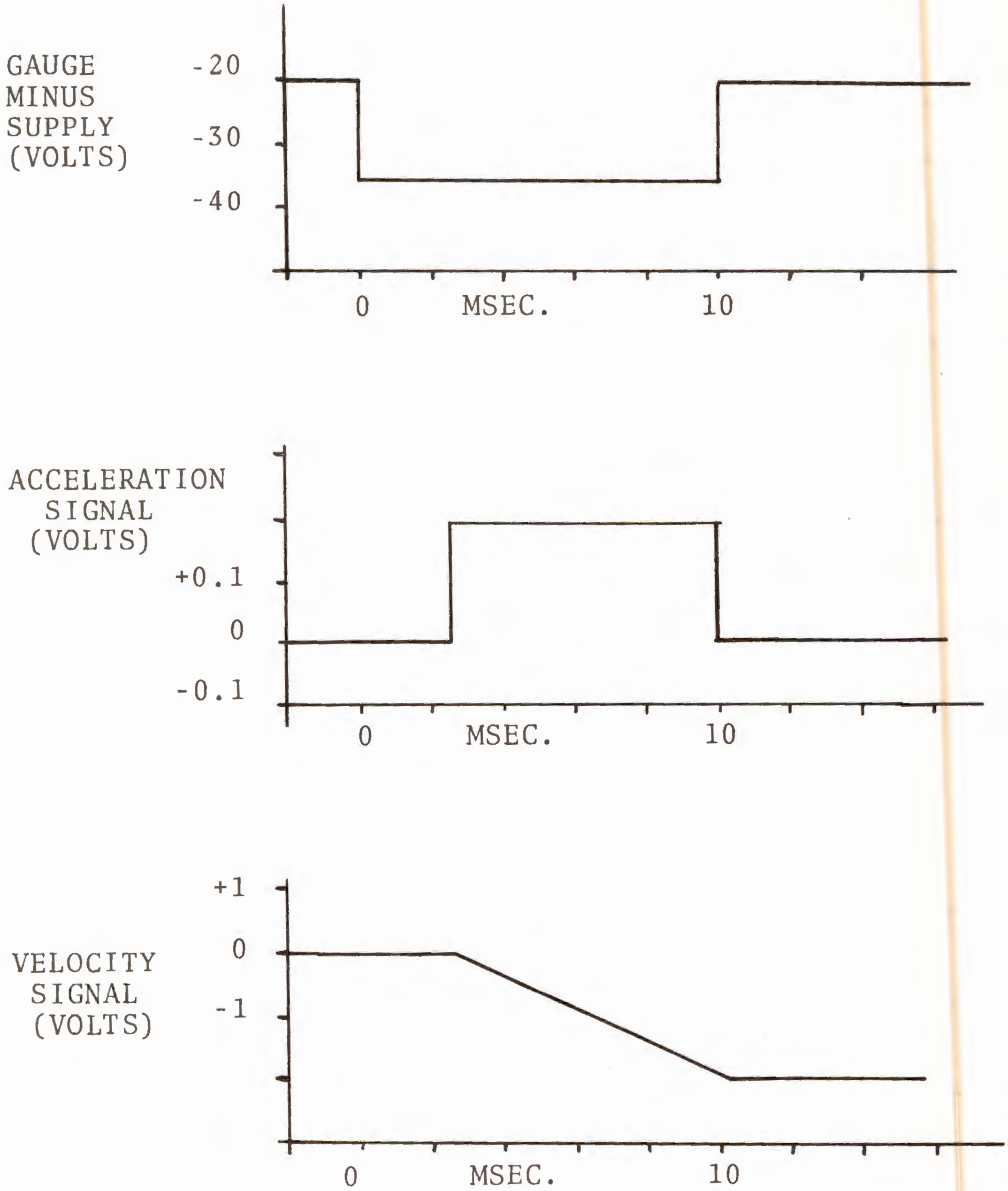

Figure 2. Typical Calibrate Command Signals

Finally, an outside layer of aluminum mass filled epoxy leads to an overall gauge density of about 2 gm/cc. (See Fig. 3).

On a routine basis, we test all instruments with a "drop-bar" apparatus (Fig. 4). This consists of a meter-long lucite, aluminum or steel bar dropped from heights of up to 3 meters onto the gauge. A dual light-beam system measures the bar velocity just before and just after the impact. With the gauge resting on a soft cushion, conservation of momentum then provides a velocity calibration point (Fig. 5). Typically we can achieve velocities of up to 4 meter/sec. In addition, the 1/2 millisecond, 800g impact checks for canister and accelerometer resonances plus bad solder joints and construction defects.

For testing at higher velocities and accelerations, we have made use of a 75mm Howitzer to accelerate the gauges to velocities over 100 m/s and at accelerations of from 5 to 10 thousand g's. Figure 6 shows an example where peak acceleration was 7kg's. We used an S^3 laser velocity interferometer ("VISAR") to independently monitor the instrument's motion.

Our experiences to date have been primarily with Endevco piezoresistive accelerometers. While we discuss below several of their limitations, we must point out that the Endevco units have basically performed well, and few commercially available alternatives exist. We are beginning to explore the use of quartz devices made by Kistler, PCB Piezotronics and others.

We have had relatively good results from our initial field experiences with this first model. For the ESSEX test series during the summer of 1974, S^3 fielded about 50 of these gauges. Figure 7 shows an example of operation in a very severe environment. The risetime of this waveform corresponds to an acceleration of about 2×10^5 g's, which is four times

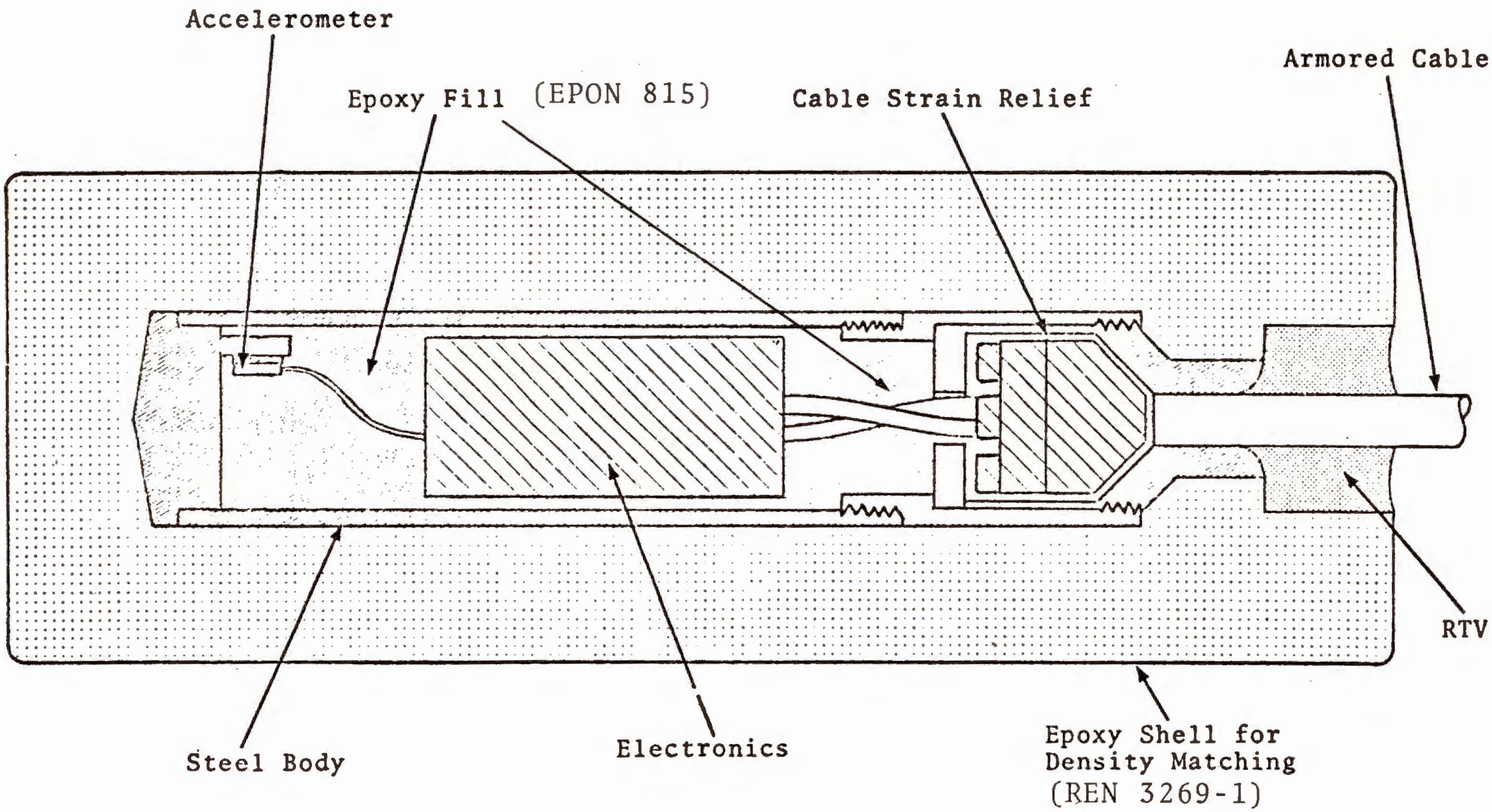

Figure 3. Cross-section of "high stress" velocity gauge canister. Accelerometer mounting illustrated is for measurement of acceleration and velocity in direction perpendicular to canister axis.

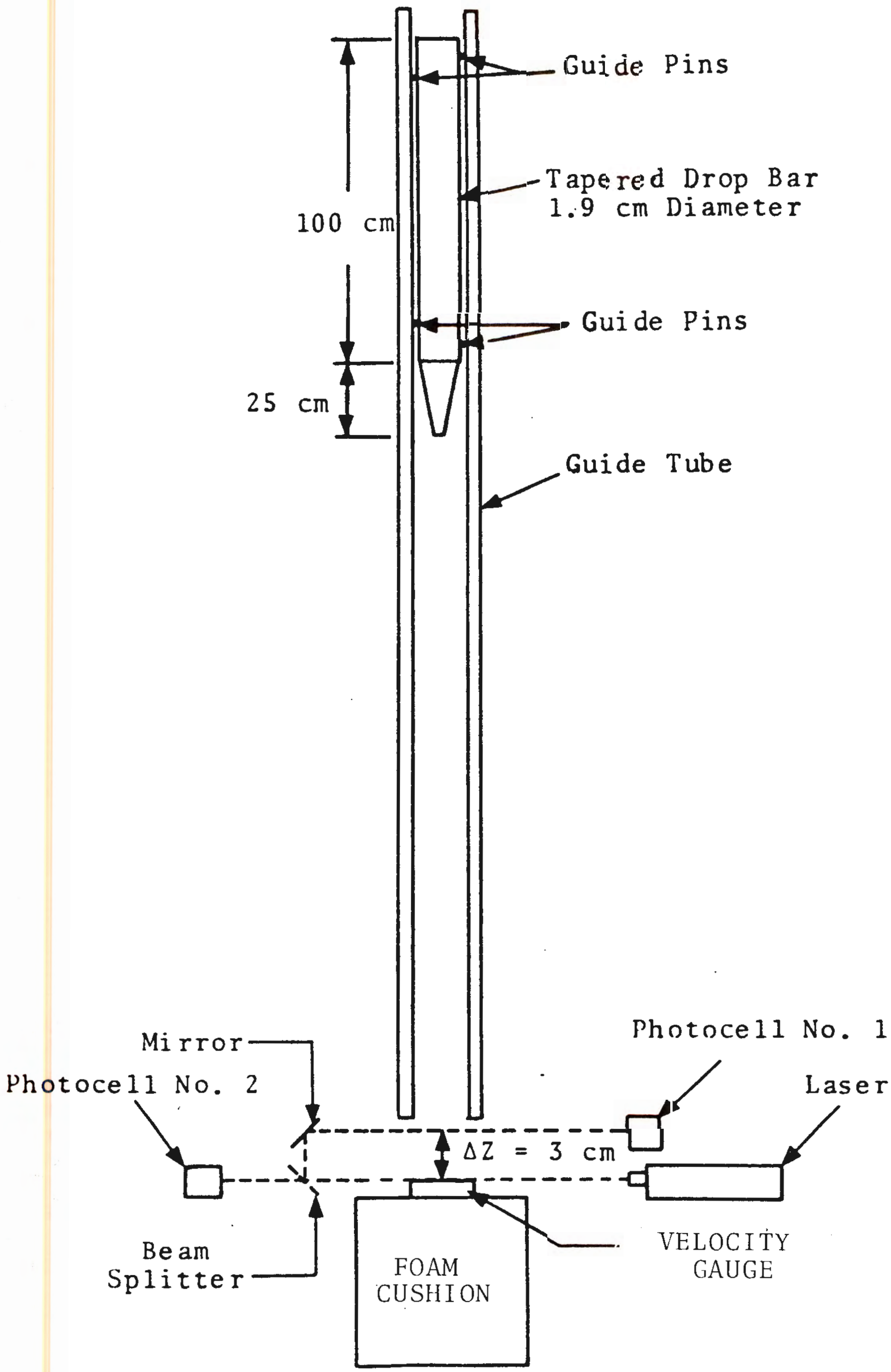

Figure 4. Drop bar assembly and laser system.

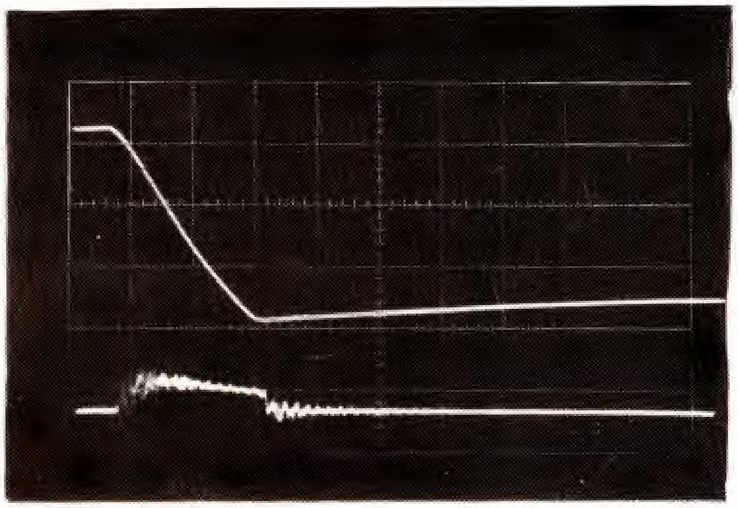

Figure 5. Typical signals from a drop bar test. The top trace is velocity, 2.1 m/sec peak to peak. The bottom trace is acceleration, 250 g's peak. Impact duration = 1.2 msec. Lucite drop Bar mass = 0.42kg; Initial bar velocity = 4.9 m/s; Rebound bar velocity = -1.6 m/s; Gauge mass = 1.3 kg.

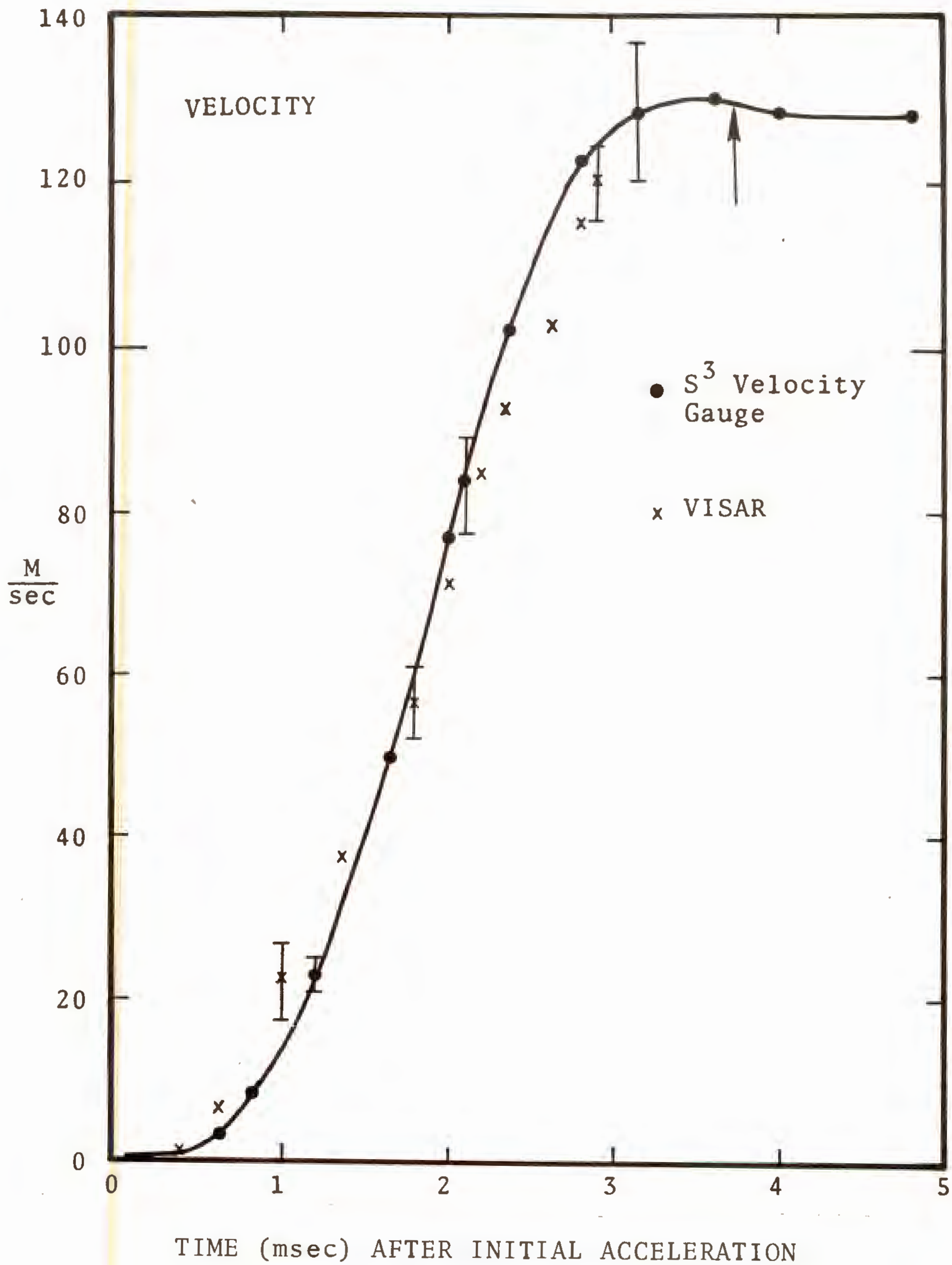

Figure 6. Comparison of velocity gauge and VISAR results for howitzer test of 4/26/74.

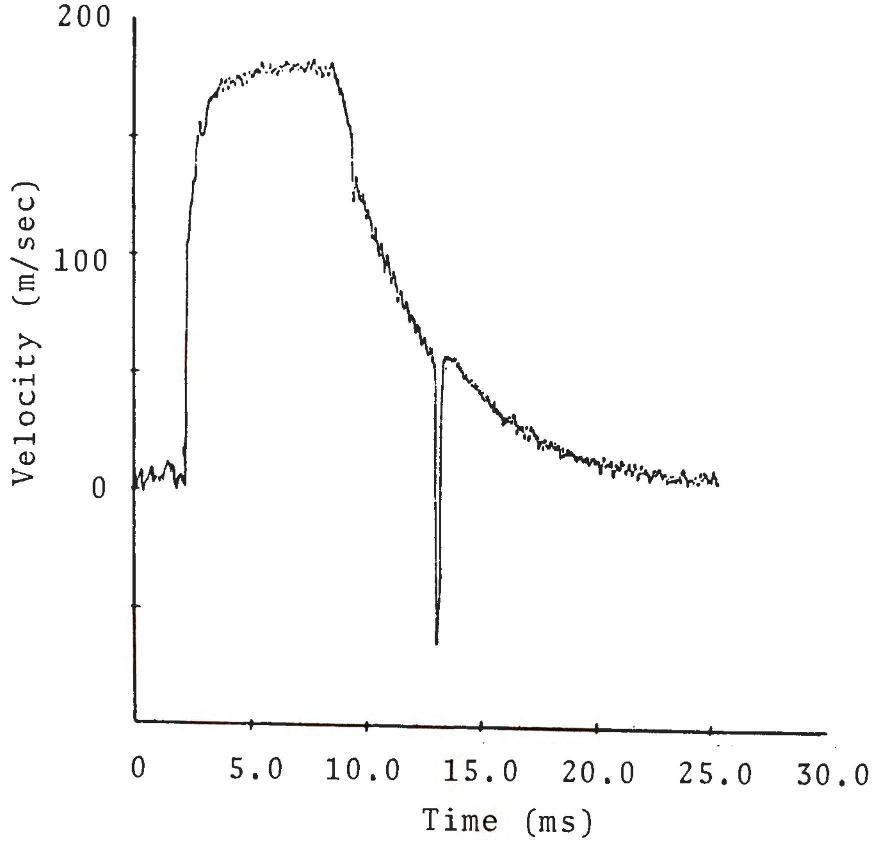

Figure 7. Example of Velocity Gauge Response in Severe Environment.

the rated range of the Endevco accelerometer used. Endevco does claim that selected samples of this model survive and respond linearly to such overranges. A stress profile measured at a nearby location confirms the risetime and initial peak velocity shown for this gauge. Hence we believe this is a good measurement. For the balance of the motion shown, accelerations range from a few hundred to 4,000 g's.

Figure 8 shows a lower g but longer duration motion. Here an accelerometer rated at 4500 g's full-scale observed an initial rise at about +300 g's followed by the gauge's fall in the earth's -1 g field. Note how difficult it would be to record directly the very wide dynamic range of the acceleration signal.

These instruments are not without their problems, however. In particular, the accelerometers are subject to several limitations. One problem is their very low frequency noise output. For example, a very "quiet" Endevco piezoresistive accelerometer rated at $\pm 5 \times 10^4$ g's will have an output stable to ± 1/5 g from second to second; a very "noisy" unit will be stable to ± 5 g's. During a one-second integration, the latter variation means that the velocity gauge output will be uncertain to ± 50 m/s. Hence for a long duration measurement, care must be exercised in the selection of the particular accelerometer used. The origin of this noise is not clear.

Zero shifts are another limitation of accelerometers. All piezoresistive types have a small dc output signal (typically less than ± 50mV) for zero acceleration input. This "zero" signal is of little consequence to our dynamic measurements in which only a change in accelerometer output is of interest. However, it is possible that the magnitude of this zero signal can change after a shock near the unit's

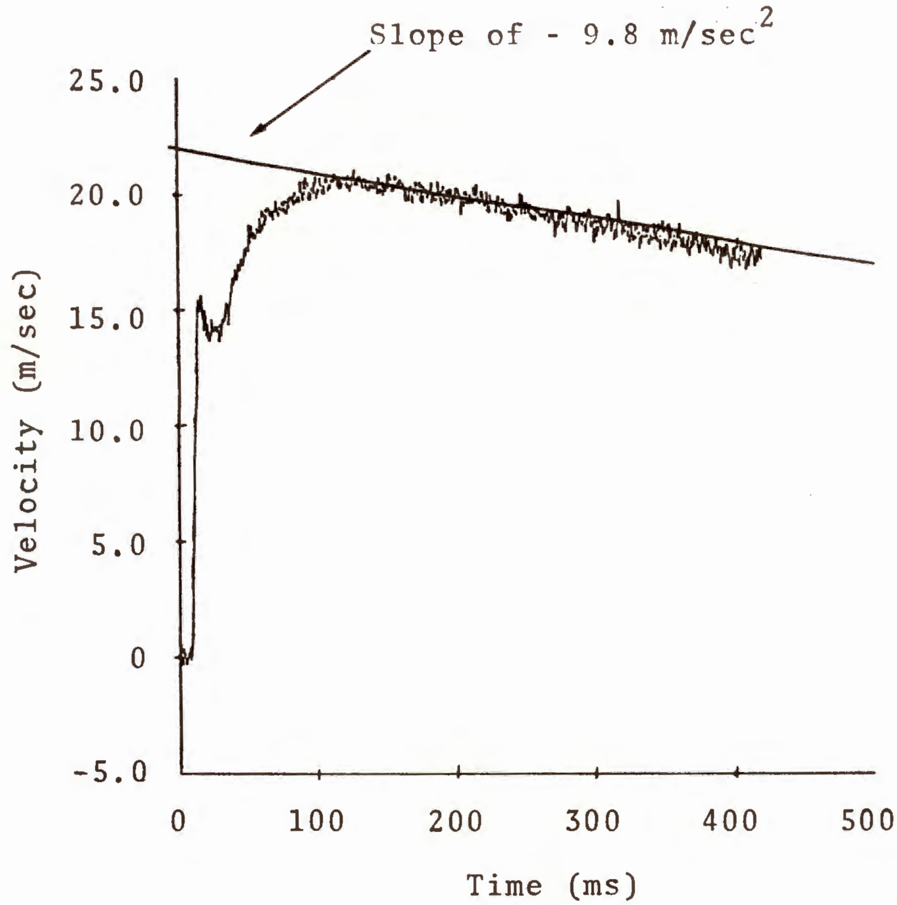

Figure 8. Example of Velocity Gauge Response over Long Time Base.

full scale rating. Such a change would introduce a systematic linear drift in the velocity subsequent to the ground motion's peak acceleration (See Fig. 9). Since this is a dc change in accelerometer output, the magnitude of its effect on the velocity signal depends on the low frequency cutoff of the integrator, the integrator time constant and the size of the zero shift. The Endevco accelerometers have an upper limit specification for zero shift of a few percent of full-scale for a shock at full scale; Endevco claims that the typical zero shift is a few percent of this maximum specification. For example, a 20 kG model could have a maximum zero shift of ± 400 g's due to a shock at 20,000 g's. Over a 10 millisecond interval after the peak shock, this would lead to a velocity signal error of ± 40 m/s. A partial solution to this problem is to use, when available, an accelerometer with a rated range at least ten times the expected peak acceleration. Perhaps a different accelerometer design would completely eliminate zero shift.

A third problem is that no accelerometers exist with ranges above 100 kg's. In the water-saturated media of the ESSEX tests we observed velocity profiles of moderate amplitude (under 100 m/s) and long duration (over a few milliseconds) with initial accelerations above 10^5g's. To measure these, high output and high range sensors are required. Some designs for accelerometers usable to 10^6g's have been proposed, and their development would be desirable. For the ESSEX series, most of our close-in gauges gave us only time-of-arrival because such an accelerometer was not available.

We have also had some experience with these instruments on nuclear tests. Figure 10 shows an example from the HYBLA FAIR experiment. For this gauge, the "RESET" switch was replaced by a fixed high-value resistor because we were concerned about the radiation resistance of the FET analog

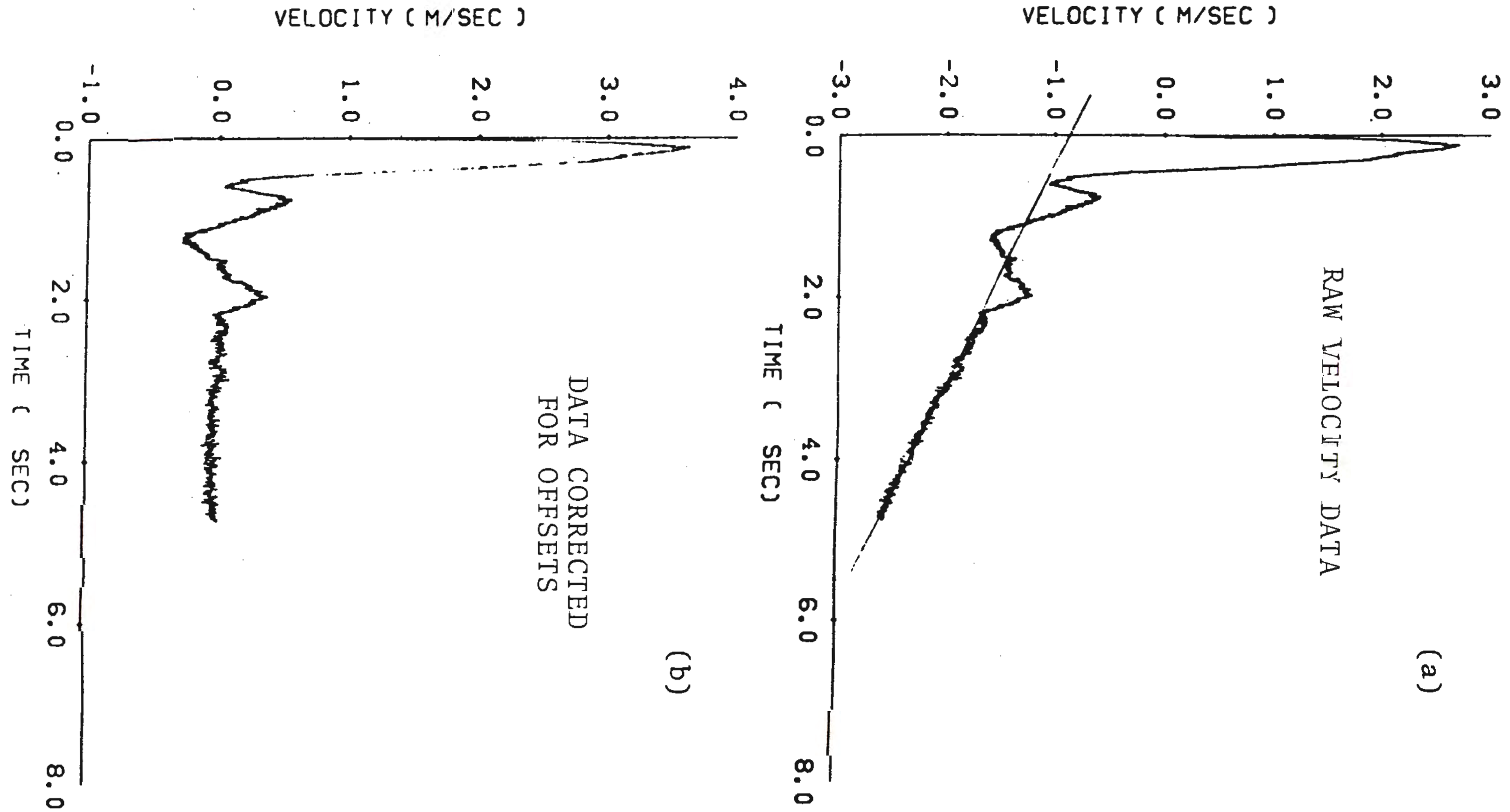

Figure 9. Example of Effects of Acceleration (and unexplained velocity) Zero Shift. Accelerometer is Rated at 250 G's. Offset is - 0.04G. Peak Acceleration is about 20 G's.

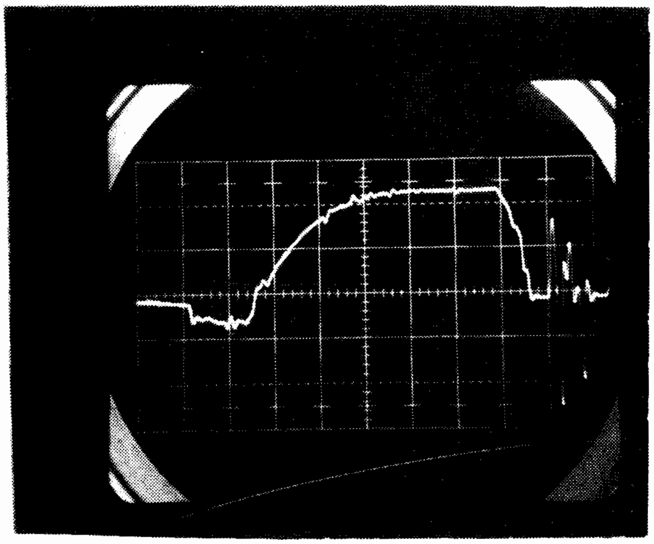

Figure 10. Observed Ground Motion in the Tunnel Wall for the HYBLA FAIR event. Peak velocity is about 70 m/s. Horizontal scale is 5 ms/div. Tϕ = 5.5 ms.

switches. An offset occurred at time zero due to electromagnetic pickup. Such effects complicate the data analysis, especially if the signal is not large compared to the offset or other noise pickup.

The principal problem with our integrating electronics seems to be that when the accelerometer fails, there is not an immediately obvious, corresponding anomaly in the velocity signal. Hence it is sometimes difficult to decide when to stop believing the velocity profile. Partial solutions to this problem are either to simultaneously record the acceleration signal as a diagnostic tool, or to field two independent gauges at each location. We are also considering the design of built-in error-sensing electronics with fault conditions added to the velocity signal output.

SESSION III

DISCUSSION SUMMARY

Session Chairman: Paul Lederer

Papers: Schelby, Harting, Rosenbluth, Shay, Coleman

DISCUSSION:

John Ramboz, National Bureau of Standards: You mentioned measuring velocity with a laser beam equipment called "Visar." Would you comment on that? Second, you said there seemed to be a need to have a million g accelerometer. Are people thinking about getting into that?

Phil Coleman, Systems, Science and Software (S^3): Visar is an instrument S^3 makes. It is basically like a Michelson interferometer used with an argon laser. By looking at interference fringes, we can estimate velocity.

The need for a million g accelerometer comes from a fellow named Howard Crafts at S^3. He has some preliminary ideas on how he would make such an accelerometer. The ideas are in a primitive stage, and I haven't seen any details. I understand someone at Sandia or LASL feels they have a way to make a million g accelerometer. I would be happy to explore these ideas with you afterwards.

Paul Lederer, National Bureau of Standards: I have been interested in finding out what in your opinion integral signal conditioning in transducers holds for us in the future.

Coleman: From the S^3 point of view, we have had pretty good success putting electronics as close as possible to the transducer itself. Many channels of data are required in our work, and we simply aren't rich enough to have 14-bit fast A-D transient digital analyzers for recording. We must record on tape recorders which do not have the dynamic range required to capture the initial shock motion levels and the subsequent lower levels which make up a lot of the velocity and even more of the displacement signal.

It is certainly valuable to be able to combine electronics with transducers as much as possible. One limitation we found in the S^3 velocity approach: if something goes wrong with the accelerometer, there is no completely unique way of seeing the break in the velocity data. So we record acceleration also to see if something has gone wrong with the transducer.

Robert Bunker, Kirtland Air Force Base: We are working toward the goal of putting conditioners down-hole with the transducers. I think the future potential is very good, especially with small, integrated circuits and low-cost devices. It would appear, especially from the S^3 approach, a velocity system transmitting lower signal frequencies has advantages for long-line transmission. You would not have the high frequencies that you do with acceleration.

One of our goals is to put integral electronics with our packages because of noise generated on the cables. We have to get the signal-to-noise ratio up. The only way to do that is to put electronics down-hole with the gage.

Bruce Wilner, Becton-Dickinson Laboratories: I am fascinated by this looking down the dragon's throat. Does anyone have views on how to better hold together such things as cables? For instance, should we use hard line cables? It would help if we had transducers in the configuration of paint, i.e., virtually zero thickness and zero mass. Just what suggestions can you make for holding things together in wild environments like these?

Coleman: With transducers you think of making the conductors very thin and very low mass. We have quartz stress gages with a range of several kilobars. Question: how to get the signal out of the quartz disk? We use a printed circuit conductor, very thin and flat, oriented perpendicular to the principal motion. It is very difficult for that to pass through any insulating material between it and the case. If you have solid, small diameter wire with a square or circular cross section, it is much easier for that (in very severe environments) to pass through things we normally think of as hard.

Wilner: How about the Livermore team?

James Morrison, Lawrence Livermore Lab (L^3): We have done some work at high acceleration levels. The current approach uses 10-mil Formvar-insulated twisted pair wire. In one case we tried Microdot cable for a 15,000 g, 15 ms half-sine pulse and the center conductor extruded out.

We are trying to develop a fuse tester for the hard structure munitions (HSM) program. Copper ball accelerometers tell us the acceleration level is 340,000 g. A zero mass conductor is truly what we need.

Pierre Fuselier (L^3): We were talking about preconditioning accelerometers with repeated shocks. We did some work on that a few years ago. Richard Larder mounted a 10-ft Hopkinson bar to protrude into an environmental chamber. The accelerometer was then shocked several times at levels and temperatures well above those expected in working conditions. We found that the accelerometers did hold that preconditioning for a period of a few days and then gradually recovered. There is an excellent paper on zero shift in piezoelectric crystals by a man named Ralph Plumlee, formerly of Sandia, Albquerque.

I have two questions for Darrell Harting. How did you compensate for transient temperature effects, and tell us more about Rene 41 wire?

Darrell Harting, Boeing Aerospace Company: Transient temperature compensation is accomplished through differential thermocouples connected between the compensating rod of the gage and the specimen surface. We measure the difference in temperature between the rod and specimen surface and multiply by the coefficient of expansion of the material being tested. Then you have an error term which can be added to or subtracted from the measurement made by the capacitance gage. Rene 41 wire we found to be the best material to build gages for the Flight Research Center at Edwards Air Force Base.

Peter Stein, Arizona State University, to Schelby: What is the requirement for a bias range on your amplifiers? How do you use that in your instrumentation?

Frederick Schelby, Sandia Laboratories, Albuquerque: The bias range sets the zero reference level of the signal, usually some place in the middle of the expected range.

Stein: You start out with a deliberately off-set zero level?

Schelby: Yes.

Stein: A question at large. Piezoelectric accelerometers have been documented as having zero shift after the first cycle. Coleman indicated piezoresistive accelerometers do that, too. Have any of you worked on that phenomenon to make a peak recording accelerometer?

Coleman: We haven't worked with artificial ceramic accelerometers because of large zero shifts. Zero shift in piezoresistive accelerometers is a 1/2 to 1% effect. It would be rather difficult to use it as a peak recording accelerometer.

Stein to Harting: You talked about and recommended a strain measuring system. Do you care to say more about why that particular input conditioning you developed with Endevco needs to go with your strain gage to make a capability which either one separately could not achieve?

Harting: Previous attempts to make capacitive strain gages were done at rather high frequencies, because people were concerned about the small capacities involved and wanted to cut down impedance by using high frequency. Those systems operated at frequencies like 1 MHz, and you had trouble if leads were more than 6-in. long. The signal conditioner I talked about is different in that it is a carrier amplifier operating at a relatively low frequency of 3.39 kHz with a charge converter input. The shield of the signal lead is driven so that it looks to the system as though there is no cable capacity. This does away with the effects of a capacitive system where if you so much as handle the cable, everything goes ape.

Using a half-bridge system cancels out several kinds of errors and effects and leaves the signal fairly pure. Cable system excitation leads are separately shielded. The shield ground is handled separately and signal lead and signal ground are handled separately. 400 ft of instrumentation line is no particular problem. The signal-to-noise ratio gets a little worse as the gage gets farther from the system.

Robert Bell, Celesco Industries, of S^3: Did you try testing the piezo-resistive (PR) accelerometer without the signal conditioning to see if perhaps the zero shift were tied to signal conditioning as opposed to the PR accelerometer?

Coleman: No, we haven't, but we have done lab tests where the only thing we were shocking was the accelerometer with the electronics 3 ft away on the bench. In many cases I put the accelerometer signal through a dc operational amp, don't integrate anything, and yet I can see zero shift. It is tied to the accelerometer.

At this point some preselected boo-boos were read.

Richard Taylor, Wright-Patterson Air Force Base, of William Shay: Was the zip tubing hard conduit?

William Shay, L : No, it is vinyl. It is like the plastic bags you zip up, except infinitely more difficult to zip because it has an aluminum conductor inside to provide electrostatic shielding, and it can be grounded.

James Leaney, Kentron-Hawaii: I am interested in the talk by Harting. Is your system under production through Endevco?

Harting: No. The entire system was licensed to Hytec Corporation. The mode card is built by Endevco for Hytec. You can get the system, the gage or the signal conditioner from Hytec.

Leaney to Sires: When using black electricians' tape, does this actually create a heat barrier or does it cause absorption of heat? Does it disperse or dissipate heat over the entire area? I thought it would absorb heat.

Larry Sires, Naval Weapons Center: The idea of black electricians' tape is not essentially for isolation. It will absorb radiation. The idea is to increase the time for the heat pulse to go from the surface of the tape to the transducer crystal. If you can increase this time to beyond the time of the generated pulse, then you have done the job.

Bunker: My question: is it pyroelectric sensitivity you're closing off with the tape, or is it a long-term thermal problem on the crystal?

Sires: Essentially it is both. First, pyroelectric effect is a temperature gradient through the crystal caused by a high thermal pulse in the environment. The better a material is as a thermal insulator, the better job it does of slowing down the thermal gradient entering the crystal. We also find that synthetic crystals are photosensitive, and for that we must use opaque tape. In PCB crystal transducers with a metal diaphragm over the crystal, photosensitivity is no longer a problem.

Henry Freynik, L^3: I have been working with radiation thermometers recently. Things that are opaque in the visible range are not necessarily opaque in the infrared region. Silicon and germanium are transparent in the range slightly above visual and are often used in a radiation thermometer as a beam splitter. The splitter sends visible radiation to one side and transmits the infrared radiation through. This may be a problem with some tapes. They may look opaque in the visible range, but a high heat pulse may send a lot of infrared energy through.

Harting: Is there any advantage in using an aluminized tape?

Sires: We haven't tried that, but we are trying ordnance tape, which is similar. It is very important to select a material that will actually be a reflector in the spectrum region you are worried about.

Lederer: We have a thermal transient test technique using photoflash lamps. We got substantial zero shifts from transducers, including semiconductor strain gage pressure transducers. To investigate something we have seen traces of before, in some cases we did not excite the transducer, and yet we got the expected photoelectric response. Then we tested two identical transducers and got just as much output without excitation from the one with the metal diaphragm over the silicon as we did from the other with a bare silicon diaphragm. It puzzled us.

Allan Diercks, Endevco: We ran into that phenomenon ourselves and attributed it to surface heating expansion effects. The philosophy is that heating the surface of the material causes very rapid expansion, coupling mechanically back inside to the sensing element of the transducer.

Thomas Rodgers, Eglin Air Force Base: We also ran into the same thing with the pressure transducer on the ejector foot. The hot gases driving the foot make two right-angle turns, so no light reaches the transducer. But the pressure pulse didn't look the way it should. We didn't have any residual build-up effect because the gases are vented at the bottom of the structure. We used black electricians' tape again, which held the temperature gradient back until the gage vented. Later we obtained PCB transducers with a GE 580 ablative coating. They worked well, although in a long period of time the coating wears off because it is subject to extreme heat and ablation.

The session was concluded with Patrick Walter of Sandia Laboratories, Albuquerque, making a plea for using both proper and consistent terms in the literature.

SESSION IV

MANUFACTURER'S PANEL DISCUSSION

Peter Stein, Chairman

(No papers given in this session)

SESSION IV, MANUFACTURERS' PANEL

CHAIRMAN: PETER K. STEIN

There were no papers given in this session. It was solely verbal presentations and discussion. Each manufacturer had 6 minutes to describe his company, their products, and current developments in which they took pride.

The manufacturers who were invited to sit on the panel were chosen by a four-step process. Step 1 was a listing of all the principal transducer manufacturers, step 2 sort by measurand, step 3 sort by transduction, and step 4 select the minimum representative number of manufacturers.

PANEL MEMBERS	TOPICS
Endevco Allan Diercks, Chief Engineer Rancho Viejo Road San Juan Capistrano, CA 92675 714-493-8181	Gas damping piezoresistive accelerometers Triaxial accelerometer frequency limitations
Kulite Semiconductor John C. Kicks, Manager Sales and Product Engineering 1039 Hoyt Avenue Ridgefield, NJ 07657 201-945-3000	High performance piezoresistive pressure transducers
Kaman Sciences Eldine Cole, Research Scientist Allan Colton PO Box 7463 Colorado Springs, CO 80933 303-598-5880 (303-599-1500)	Eddy current displacement transducers for high frequency displacements in hostile environments
National Semiconductor Art Zias, Mgr., Transducer Eng. 1050 J Duane Avenue Sunnyvale, CA 94086 408-732-5000	Pressure transducer: simple mechanical device for flow and cumulative volume metering

Panel Members and Topics (continued)

Schaevitz Engineering R. D. Cloon, Rep. PO Box 505 Camden, NJ 08101 609-662-8000	Radiation-resistant displacement transducers
Statham Instruments Gene D. Goodrich, Marketing Manager 2230 Statham Boulevard Oxnard, CA 93030 805-487-8511	Thin film strain gage transducers
Sundstrand Data Control, Inc. Robert J. Underbrink, Sales Manager Dynamic Instruments Overlake Industrial Park Redmond, WA 98052 206-885-3711	Dynamic piezoelectric instrumentation for pressure, load, and acceleration measurements
Validyne Engineering Max J. Kopp, Director of Marketing 19414 Londelius Street Northridge, CA 91324 213-886-8488	Transducer kit with replaceable diaphragms
Rosemount Engineering John K. Myers PO Box 35129 Minneapolis, MN 55435 612-941-5560	Standardization of transducer specifications
Kistler-Morse Walter P. Kistler, President 13227 Northrup Way Bellevue, WA 98005 206-641-4200	Silicon semiconductor strain gage transducers

Attendees were requested to prepare written questions of the manufacturers for discussion. These questions were submitted in advance to the session chairman. After the various presentations, the program was guided by audience questions, to which each panel member could respond.

DISCUSSION

Lawrence Livermore Laboratory (L^3): A general question on conversion to SI: What are your plans? Are you talking about it? What are you going to do to convert?

Max Kopp, Validyne Engineering: We will do whatever you want us to do. The trend now is to SI, and units should be what are most convenient for the user.

John Kicks, Kulite Semiconductor: We are going to have to make some changes in equipment and in business before universal adoption. The people propagating SI are not universally agreed.

Gene Goodrich, Statham Instruments: The user still thinks in psi.

Art Zias, National Semiconductor: With our methods, we don't care what the units are. We make a reference unit, put it on the laser, and everything is trimmed to that. We had one request specifying that everything be in the metric system. The unit was scaled beautifully and shipped. Then we had a call from the customer asking, "What the hell are these threads?" Threads will be a problem.

Walter Kistler, Kistler-Morse: I think the theoreticians messed up a little bit. I think the simple names and units of 40 years ago were much better.

Peter Stein, Arizona State University: We have two parties submitting the same general questions. Looking at the industry as a whole, to what extent is R and D for new transducer initiated by the manufacturer and how many are spin-offs from efforts at individual facilities? What percentage does the manufacturer set aside as R and D funds? Are new products created to the need of the user or dreamed up in the lab?

Paul Lederer, National Bureau of Standards, stated that the transducer market seems to be between 150 and 300 million dollars a year, but that there are about 300 manufacturers involved. This indicates that there isn't much margin for R and D of new transducers. Five percent of sales invested in R and D doesn't give you very much to work with.

Kicks commented that most ideas originate with the customer. The manufacturers generally put out a substantial amount of money on R and D predicated on customer requirements in general and the potential market.

Zias said that their high production methods were a curse when it came to R and D.

The consensus was that R and D usually gets done by contract with a customer or the customer partially subsidizes the effort by a minimum quantity order at a high unit cost.

Lederer: We have the impression a lot of people are concerned about durability of transducers, the ability of a transducer to keep on performing its measurement function for a relatively long time. Is this your impression as manufacturers, and how do you establish durability of your transducers?

Allan Diercks, Endevco: In some industries durability is a very important factor, particularly airlines who would like to be assured they will last forever. In other quarters, durability is considered very high if a transducer survives for a short period of time at 1400°F. In others, it is considered very durable if it lasts for thousands of hours. Endevco tries to obtain feedback from users on the life and performance of our transducers.

Zias said that if the customer has a well-defined duty cycle, he can save money and use wider tolerance specifications. You can get a good transducer for very little money if the requirements for accuracy are realistic. The error band concept versus specified errors is also useful to reduce costs.

Gene Goodrich, Statham Instruments: Pressure transducers used on space probes are required to make very accurate measurements 3 years in the future. How do you assure that the transducer can do that 3 years from now? The typical approach is to eliminate concern over reliability of electrical components, and methods have been devised to take care of that. It does increase the cost by a significant factor. The Jet Propulsion Laboratory probe indicated it was worthwhile. The transducers functioned reliably many times over a several-year period.

Another area where durability is of key importance is in industrial process control, where 10 years is a short period of time. This time is in continuous useage. How does the manufacturer approach that? One way is to do the best design job possible. Another is to select proper materials and work these materials at low stress levels compared to their yield strength.

Robert Mikels, Detroit Diesel Allison: One of our principal concerns is how to test for long-term effects for an application where we need 3,000 hours of reliable performance with a calibration degradation of not more than 1/2% in a mild temperature environment of 30°-170°F.

Kicks: The answer is that you have to perform accelerated life-cycle tests. There are ways of describing the problem and there are environment specifications which you can call out to specify what needs to be done.

Specifications tend to be written in terms of performance. They should include conditions of use so that the manufacturer can design, package and test the transducer intelligently.

Allan Colton, Kaman Sciences: I agree with that.

Zias: Tests can cost more than the transducer.

Richard Hasbrouck, L^3: We specify a minimum time to failure of 30,000 hours for the pressure transducers our group uses. Even so, we still use redundancy for insurance. Aging of the electronic components helps to assure reliability. We are having some shelf failures of high level output pressure transducers after 2 or 3 years. How do the manufacturers feel about long-term warranties?

Goodrich: We monitor electronic components during the manufacturing cycle and do all electronic circuitry and tests before button-up and calibration.

Colton said Kaman ages their electronic components but would need to know the application before quoting a warranty longer than 1 year.

Kicks: We have several warranties in spacecraft work. One is a 3-year shelf guarantee. For those transducers, it is essential to use aging. Mortality seems to be in the electronic components.

Stein: The basic principle is that the transducer behavior is a function of its total past history. You must expose each part of the transducer to the maximum service conditions it will see in all environments--thermal, mechanical, chemical, magnetic, or whatever. Regarding shelf failures, the first step is to determine the mode of failure. What caused the failure?

Zias: Another point of view: Unless you age (burn-in) components at temperature under actual use conditions, it can be a meaningless exercise. We burn-in 100%.

Larry Sires, Naval Weapons Center: I have a gripe on manufacturer's specifications. Often they don't tell us what the price is, and that is a major decision in purchasing any transducer. Another point--I feel that the #10-32 Microdot coaxial connector ought to be superseded by a sturdier connector.

Kistler: Yes, the center conductor pulls out of the teflon insulation.

Diercks: Endevco makes an improved connector using glass as the insulator.

Kistler: Connectors are a very important question for manufacturers as well as users. Cost is significant, and our experience with connectors in general is not very good.

Robert Bunker, Kirtland Air Force Base: Don't use connectors. Connect wire to wire.

Melton Hatch, EG & G: We use the wire-to-wire connection technique.

Robert Underbrink, Sundstrand Data Control: When a customer asks for data sheets, we always send out price lists.

Zias: Pricing can be a problem because of changing costs to the manufacturer. In that case it is best to quote prices on request.

The session closed with a summation and comment by Stein and some boo-boos quoted from the 7th Transducer Workshop.

SESSION V

INFORMATION — UTILIZATION AND SOURCE

John Hilten, Chairman

INFORMATION AND INFORMATION CONVERSION: SOME NEW THOUGHTS ON THE SUBJECT FOR MEASUREMENT ENGINEERING PURPOSES

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Abstract

This paper separates the energy conversion discussion always seen in measurement and transducer discussions from the REAL THING, which is information processing.

The purpose of a measuring system is to convey information about physical or chemical processes or states. It has long been evident that for purposes of design, evaluation, analysis, synthesis, understanding and teaching of the engineering of measuring systems, the division of the world of information into ANALOG and DIGITAL is insufficient.

This is a progress report in a series of papers on the development of viable new concepts associated with the processing of information through a measuring system. The results so far have been useful design, evaluation, and teaching criteria proven in the field by industry acceptance and by several generations of successful graduates. It is hoped that the progress report presented here will stimulate further application of these concepts to as yet untapped areas in the measurement field.

INFORMATION AND INFORMATION CONVERSION: SOME NEW THOUGHTS ON THE SUBJECT, FOR MEASUREMENT ENGINEERING PURPOSES . . . .

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Brief presentation as panel member, Session 5: Information: Utilization and Sources, 8th Transducer Workshop, Transducer Committee, Telemetry Group, Range Commander's Council, April 22-24, 1975, Dayton, Ohio.

INTRODUCTION

The purpose of a measuring system is to convey information about physical or chemical processes or states. It has long been evident that for purposes of design, evaluation, analysis, synthesis, understanding and teaching of the engineering of measuring systems, the division of the world of information into ANALOG and DIGITAL is insufficient. This paper is a progress report in a series, (1,2,3,4) on the development of viable new concepts associated with the processing of information through a measuring system. The results so far, have been useful design, evaluation, and teaching criteria proven in the field by industry acceptance and by several generations of successful graduates. It is hoped that the progress report presented here will stimulate further application of these concepts to as yet untapped areas in the measurement field.

INFORMATION IN MEASURING SYSTEMS

It has been found helpful to consider information as existing on PATTERNS of PROPERTIES of WAVE SHAPES of active or passive MEASURANDS, starting either from an initial condition of BALANCE (0-out for 0-in) or UNBALANCE (reference-out for 0-in). Universally used patterns in time and space are shown:

TABLE 1: INFORMATION PATTERNS

		PATTERNS IN SPACE	
		LOCAL	REGIONAL
PATTERNS IN TIME	Events	LOCAL EVENTS represent the absence of patterns. Single-point observations at single instances of time.	REGIONAL EVENTS such as photos, are one of the two simpler pattern based information forms.
PATTERNS IN TIME	Processes	LOCAL PROCESSES, signatures or thumbprints are another of the two simpler pattern-based information forms.	REGIONAL PROCESSES are the most complicated of the pattern-based information forms.

Wave shapes in common use today include CONSTANT LEVELS, SINE WAVES and PULSE TRAINS. Should other wave shapes, such as triangular waves, ever be found useful in measuring systems, an extension of the scheme presented here would be very simple indeed. The proposals are all of an open-ended nature.

Table 2 presents a summary of the more common types of information carrying which are used in measuring systems today. It should be noted that the BALANCED and UNBALANCED initial conditions mentioned above, are possible for each type shown.

A significant fact is that if 11 (*) measuring systems were constructed, each operating according to one of the information carrying schemes listed in the LOCAL EVENTS column, they could very well present 11 different responses to the same input, even if all 11 measuring systems were carefully calibrated. Indeed, simple undergraduate experiments are used in the author's laboratory to emphasize this fact.

Table 3 shows a comprehensive summary of the differences among five different measuring systems designed for use with electric resistance-based transducers, when evaluated along four different performance-criteria dimensions. They represent three of the 11 possibilities shown in Table 2, combined with two INFORMATION CONVERSION processes to be discussed below. The detailed derivation and discussion of the material presented in Table 3 is given in various internal publications of Lf/MSE (#) which also present illustrative examples from the published literature, of how these principles have been used in industry and research to advantage when considered, and to great detriment when neglected or wrongly used through ignorance.

Table 1 presents 44 information-carrying methods: 11 based on local events, and four pattern possibilities; each of these may be used from an initially balanced or unbalanced condition. These 88 versions can be studied by considering 3 wave shapes, 7 properties (##), 4 patterns and 2 initial conditions: 16 items. This economy of knowledge-acquisition is enhanced by the proposition that for information-processing studies in measuring systems it is unimportant to consider the energy-related measurands on which the information is carried. Thus, whether the information is carried on the frequency of a mechanical, pneumatic, optical, or electrical zero-based pulse train is unimportant for studies of the advantages, limitations and idiosyncratic properties of zero-based pulse carrier systems as information processing means.

(*) The sine and pulse wave shape properties of PERIOD are listed in parentheses and not counted among the 11. The author is not yet clear in his own mind whether advantages would accrue to a separate listing of that property or whether consideration of periods as 360-degree phase-angle increments might be simpler.

(#) Lf/MSE Publ. 30, 38, 38-A, 66, of which 38 is a comprehensive undergraduate experiment on that topic.

(##) Amplitude, frequency or repetition rate, phase or position, polarization plane, propagation direction, wavelength or velocity, and duty cycle.

NOTE: The nomenclature used in this paper is defined in Reference 3, and is specific to the Unified Approach to Measurement Engineering.

TABLE 2

SOME INFORMATION CARRYING METHODS

WAVE SHAPE	INFORMATION ABOUT A PROCESS EXISTS ON: Individual Property	Pattern of Properties		COMMON NAME	SIMPLE EXAMPLES
	Local Event	Regional Event	Local Process		
Constant Level	Amplitude	Frequency Amplitude	Amplitude Frequency	Analog Data Wave Shape Analysis Signature/Thumbprint Analysis	Mercury/Glass Thermometer Black/White Photograph Strain-rate Tests Spectroscopy, Vibrations
Sine Wave	Amplitude Frequency Phase Plane of Polarization Direction of Propagation Wave Length or Velocity (Period)	Amplitude	Period Frequency	SAM - Amplitude Modulation SFM - Frequency Modulation SPM - Phase Modulation FCM - Frequency Code Modulation	AM Radio Vibrating Wires, Doppler Photoelastic Isochromatics Photoelastic Isoclinics, Laser modulation Prism Spectrometer Counting Processes Antenna Characteristics Temperature-Sensitive Paint
Pulse Trains	Amplitude Repetition Rate Position Duty Cycle (Period)	Amplitude	Period Amplitude Frequency	PAM - Pulse Amplitude Modulation PFM - Pulse Frequency Modulation PPM - Pulse Position Modulation PWM - Pulse Width Modulation PDM - Pulse Duration Modulation PCM - Pulse Code Modulation	FM Radio & Tape Recorder Counting/Incremental Proc. Digital Data Code Knock Computer Card

Local: at one point in space
Event: at one instant in time
Process: over a time interval
Regional: over a region in space

A regional process example would be a motion picture. This category is not included in the above table.
The table is open-ended, and other properties and patterns of these can be added as developed or needed.

TABLE 3

DESIGN AND PERFORMANCE CRITERIA FOR RESISTANCE-BASED TRANSDUCERS AS AFFECTED BY THE INFORMATION FLOW

(Information originally in analog form. Conversions to AM only)

DESIGN CRITERIA FOR INFORMATION FLOW		PERFORMANCE CRITERIA				
Wave Shape	Conversion from Analog to AM at:	SENSITIVITY TO CAPACITIVE UNBALANCE	SENSITIVITY TO SELF-GENERATING RESPONSES	SIGNAL UPPER FREQUENCY LIMIT	INFORMATION STACKING ABILITY	TYPICAL USA COMMERCIAL INSTRUMENTS
Sine	Interrogating Input	High. Can be balanced out initially. Changes in C during a test cause trouble. w_c should be low for lowest effect. (1)	Low. Frequency-selective filtering possible if (2) $w_{n_{max}} < w_c - w_{s_{max}}$ Time-domain separation is sometimes possible even if $w_{s_{max}} > w_c$	<u>Analog Output:</u> $w_{s_{max}} = k.w_c$ $k < 1/3$ usually. <u>SAM or PAM Output:</u> k may be any non-integer if signal is periodic with period marked on the record. No demodulation is possible.	Yes, along the frequency domain, around various center frequencies such as specified by IRIG.	BLH M, N, 120B Tektronix Q or 3C66 Sanborn 1100 Daytronix B&K 1516 Natel Units
	Output	Low if the transducer is DC-fed.	High. If noise and signal frequencies overlap, separation of self from non-self-generating responses is not possible			Allegany 307 or any Inverter type amplifier. For SFM also VCO's or SCO's
Pulse Train	Interrogating Input (4)	Low if w_c is low. Pulse on-time (3) should be $> 10\tau$. $\tau = \frac{1}{2}RC$ for voltage-fed bridges. $\tau = (3/4)RC$ for current-fed ones.	Same as for Sine Wave. Filtering will covert zero-based PAM to zero-centered sometimes desirable.	Same as above for zero-based pulses. For zero-centered pulses (eg. square waves) may be higher depending on demodulation method	Yes, along time domain. Commutating, multiplexing, sampling, etc.	Vishay P-350 Budd HW-1 BLH 120 C Endevco 96
dc	None	Low	High. Same as for Sine-wave-conversion at Output.	Limited only by amplifier and transducer.	No	Vishay-Ellis BAM-1, BA-13, B&K 1516.

w_n = a component frequency of the self-generating response, i.e., a noise level component
w_c = (carrier) frequency supplied at the Interrogating Input
w_s = a component frequency of the non-self-generating response, i.e. a signal level component
τ = a time constant as defined. R = sensor resistance C = capacitive unbalance
Note that a square wave is a pulse train with duty cycle of $\frac{1}{2}$
(1) depends also on quadrature rejection ratio of phase-sensitive detector, if any
(2) depends also on balance of phase-sensitive detector
(3) depends also on recovery time and linear range of amplifier, if gating is not used.
(4) peak/rms ratio of wave shape is controlled through duty-cycle; self-heating is controllable.

INFORMATION CONVERSION

Given the variety (n choices) of information carrying possibilities of Table 2, the information conversion possibilities which can be systematically studied is $n(n-1) = 7656$ for $n = 88$, all within a very simple framework for such a study. Table 3 includes three important cases for resistance-based transducers: no conversion (straight analog), analog to sine-wave-amplitude modulated, and analog to pulse-amplitude-modulated. It will be seen that the four important performance criteria shown are dramatically different and often incompatible, for the five design criteria shown. The first graduate course in the 7 semester-course sequence in Lf/MSE is devoted in part, to that topic.

Figure 1 illustrates an optical measuring system which involves FOUR information conversions, yet only ONE energy conversion. It illustrates an infrared measuring system which involves analog, SAM, O-based PAM, O-centered PAM information carrying and conversion methods, although only a single energy-conversion: optical-electrical, is involved.

Infrared radiation, in analog form, is converted to O-based PAM by means of a rotating slotted disc acting as optical chopper. Conversion to SAM would require a sinusoidally distributed optical density around the disc periphery -- in inconvenience.

The information conversion moves the low-frequency analog information to a higher frequency range, in PAM-form, so that the low-frequency cut-off of the IR-detector is not a hindrance. Filtering the low-frequency portion of the O-BASED PAM signal converts it to O-CENTERED, with attendant advantages of analog noise suppression possibilities not present in O-BASED PAM.

All of the important information is contained in ANY of the sets of side-band frequency-ranges stacked around harmonics of the pulse carrier frequency which emerges electrically from the IR-detector. Thus, filtering around the first set of side-bands centered around that frequency retrieves all the information and makes the signal look as though it had always existed in SAM-form in which only a single region of side-band information exists. This would have been the case for sinusoidally distributed optical density variations around the "chopper" disc. The PAM-SAM conversion through a narrow-band tuned filter-amplifier minimizes the amount of random noise (dark current) which affects the system. Bandwidth reduction is equivalent to random-noise reduction. A reference signal is shown so that the phase-sensitive demodulator may act as SAM-ANALOG information converter. Depending on its quadrature rejection ratio, the effect of random noise is further suppressed. Analog information emerges at the system output.

This system takes advantage of the simplicity of a O-based optical ANALOG-PAM conversion, the un-necessity of reproducing the low frequencies of such a signal -- indeed the inability to do so for many IR-detectors which are ac coupled -- and the narrow bandwidth of an SAM signal with its attendant advantages.

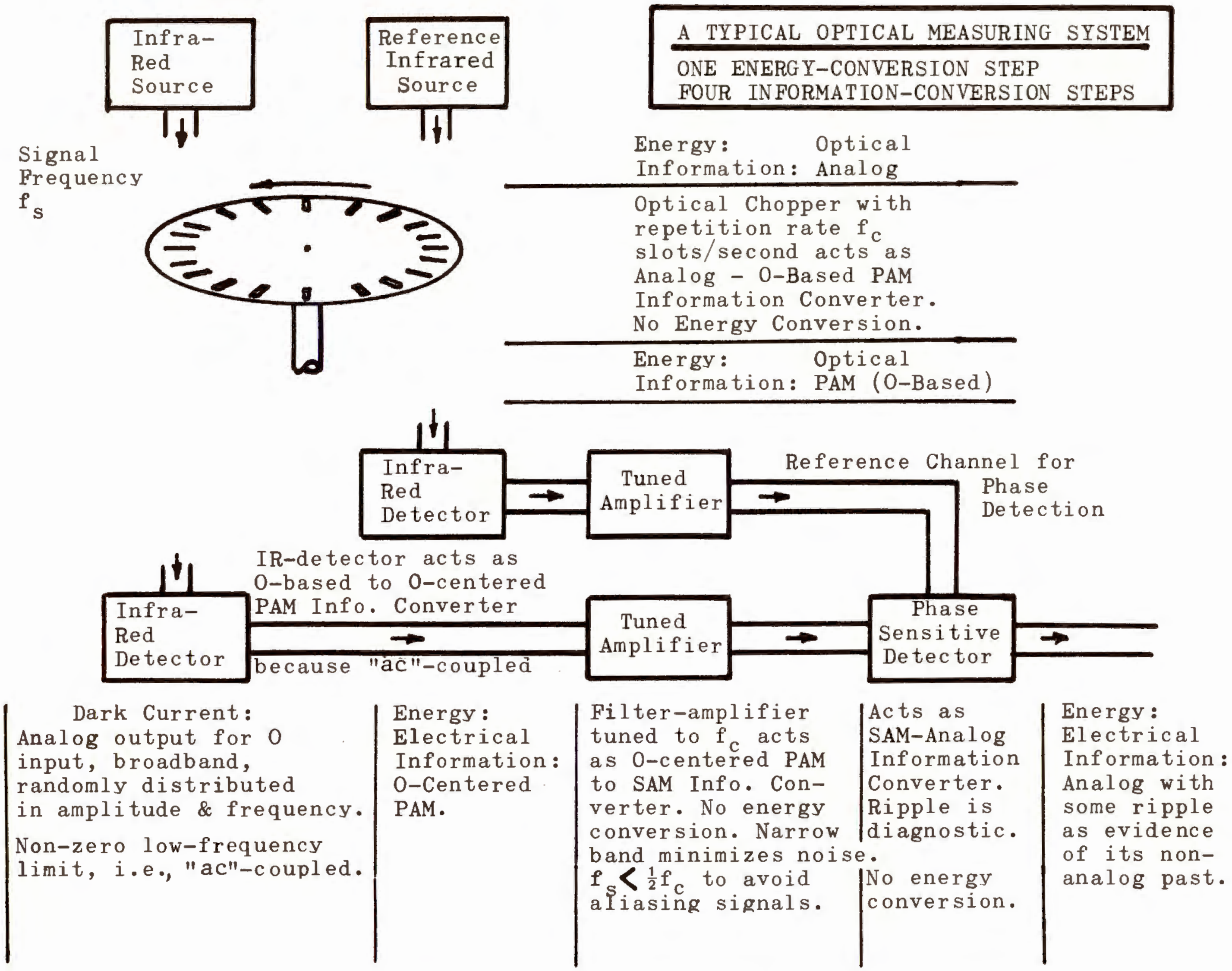

Figure 1. Optical measuring system involving four information conversions and one energy conversion.

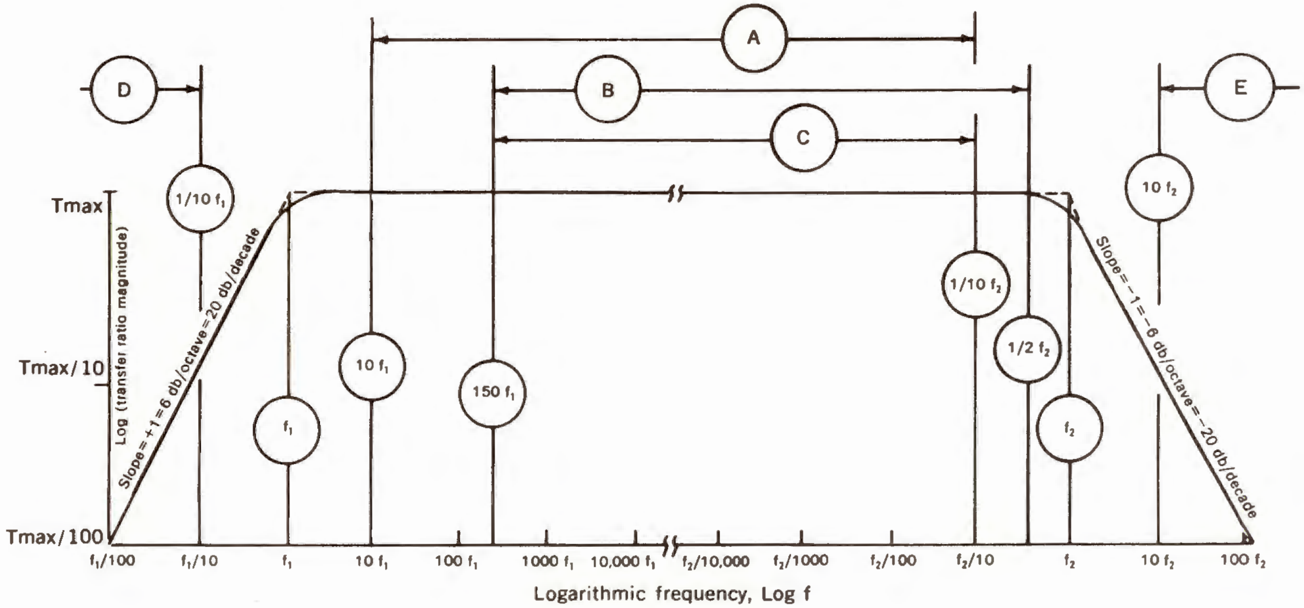

Figure 2. Criteria for reproduction or shaping of information.

For electrical resistance-based transducers a system which feeds the transducer with a pulse train to minimize cable capacitance effects, but which demodulates the transducer output as though it had always been a sine wave, would present great operational advantages. It does not yet exist, to the author's knowledge.

The above example is not cited as anything new -- only as a new way of looking at existing phenomena, with a new framework of reference which simplifies the understanding, teaching, analysis, synthesis and design of measuring systems from the information-flow point of view. This is only one of many fronts along which our concept-research program in measurement systems engineering is being carried out.

INFORMATION REPRODUCTION

The reproduction of information carried on or converted from any of the forms identified previously, is an important aspect of the engineering of a measuring system. Depending on the information form, different criteria for its reproduction apply. Fig. 2 illustrates three typical information-reproduction requirements. In Fig. 2, f_1 and f_2 are respectively the lower and upper half-power points. The discussion here is restricted to systems for which the upper and lower frequency-response roll-off's are governed by a single energy-storing element each (i.e., act as first order systems). In this case the asymptotic roll-off slope is +1 at the low end and -1 at the high end (corresponding to $\pm$ 6 dB/oct or $\pm$ 20 dB/dec) of the log-log "Bode" coordinate system. Criteria for other roll-offs can, of course, also be developed.

FREQUENCY-CONTENT REPRODUCTION: If the information is carried on the frequency content of a signal, such as in signature analysis and vibration analysis, then frequency range "A" in Fig. 2 presents the relationship required between the measuring system characteristics and signal frequencies for $\pm$ 1% amplitude reproduction of each frequency component. It should be noted that phase relationships here are not important, and that the human ear is an ideal frequency-content analyzer, not being affected by the relative phase relationships among the various frequency components of a signal. This capability of the human ear can be systematically exploited through aural monitoring of channels in a measuring system, and by deliberate training of the human ear (*).

PEAK-TO-PEAK REPRODUCTION OF A SQUARE WAVE: Measuring systems are often calibrated with square waves. Two typical examples are square-wave voltage insertion such as is common for cathode ray oscilloscopes, and square wave resistance variations produced by "chopper"-operated shunt calibration resistors in impedance-based transducers. The information is carried on the peak-to-peak value of the square wave, and wave-shape reproduction or frequency-content reproduction criteria do not apply. Frequency range "B" in Fig. 2 is the permissible range for the repetition rate of a square wave so that the desired criteria are met within $\pm$ 1%.

(*) The formalization of this technique as a standard measuring-system-design feature is due to L. S. Wirt; see "Acoustics as an Aid to Measurements"; L. S. Wirt, Strain Gage Readings, Vol. V No. 2, June-July 1962, which is also Ch. 10, Measurement Engineering, Vol. 1, P. K. Stein and contributing authors (1961 1st edition).

WAVE SHAPE REPRODUCTION: The most difficult goal to achieve among the commonly desired ones, is wave-shape reproduction. This criterion requires obeying the linear-phase-shift law as well as the frequency-content reproduction criteria (above). This combination yields the very restricted signal-frequency range "C", Fig. 2.

The above discussion covers only the FREQUENCY-RESPONSE considerations for various targets of information reproduction. There are also AMPLITUDE-RESPONSE criteria, often called linearity or non-linearity characteristics, which apply, but which will not be discussed in this paper.

INFORMATION SHAPING

The shaping of information may occur in the frequency or the amplitude domains. Typical examples are illustrated in Fig. 2.

INTEGRATION: A typical frequency-domain operation is the integration with time of a signal. All integrators must present to the signal, a straight line of slope -n for n-th order integration, with a phase shift of $-n\pi/2$ in the Bode-presentation, for all frequencies in the signal. This requirement is illustrated in Region "E" in Fig. 2, in which it is fulfilled to $\pm$ 1%.

DIFFERENTIATION: Another typical frequency-domain operation is the differentiation of a signal. All differentiators must present to the signal a straight line of slope +n for n-th order differentiation, with a phase shift of $+n\pi/2$ in the Bode representation of frequency-response characteristics. This requirement is illustrated in Region "D" in Fig. 2, in which it is fulfilled $\pm$ 1%.

Many other frequency-domain-based shaping operations exist, including compensation for lack of desired frequency response characteristics of any part of a measuring system.

LINEARIZATION: Typical amplitude-domain information shaping operations would be the linearizing of a signal such as from thermocouples, resistance thermometers, etc., or the deliberate nonlinearization to follow special requirements such as square laws for example. For all information reproduction, conversion, and shaping examples cited in this paper, it is vital that the measuring system exhibit linearity between the input and output. Nonlinear systems are frequency-creative, producing at their outputs frequencies not present at the input. Non-linear systems are required for purposes of frequency-multiplication, modulation, etc., but not for such operations as have been discussed here. In the analog-amplitude-modulation information conversion examples cited in Table 3, certain kinds of non-linearities for modulation, are required. It should be noted, however, that single-frequency excitation of a non-linear system, even with the use of tracking filters tuned to excitation frequency, will not solve the frequency creation problem: any cubic non-linearities will create an undesired frequency component at the signal frequency, which is then included in the filter output.

A TRANSDUCER INFORMATION CENTER

By

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ABSTRACT

A Transducer Information Center consisting of a data base, automated retrieval system, and a search and dissemination service is being established at Bendix. The data base is comprised of scholarly literature, reports, evaluation studies, and manufacturer's product information. A controlled subject descriptor vocabularly based on the Instrumentation Society of America's Transducer Nomenclature Standard S37.1 is used to query the data base. Other access points include: author, title, manufacturer, and type of document. A citation analysis was conducted to determine the most productive sources of transducer information; journal productivity conforms to Bradford's distribution. A literature search service is available and the Center's document accession list is disseminated periodically to interested Corporate personnel. Progress in the development and operation of the Center is reported.

1. INTRODUCTION

The Bendix Corporation is a multi-national, diversified company with products spanning five major business areas - automotive, aerospace-electronics industrial, home systems, and recreational vehicles. The Bendix Research Laboratories is a central operation attached to the world headquarters and is charged with the mission of assisting various operating divisions with their product requirements through research and development leading to new products and processes.

A key element of many of these business areas is control systems. Automatic devices, aircraft instrumentation, flight and engine controls, and industrial controls are a few application examples. Because it is expected that the present trends of increasing functionality and lower cost will continue for digital electronics, it can be anticipated that more and more control systems will be implemented using digital electronics. Thus, new and greater demands will be made on the sensor and actuator portions of the system. Increased performance and lower cost will constitute the major goals for these devices. A future mission of the Laboratories is the development of sensors and actuators matching as naturally as possible to interfaces of basically digital systems. In this paper we will be concerned with the sensors and discuss our progress in the establishment of a Bendix Transducer Information Center.

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WAVE SHAPE REPRODUCTION: The most difficult goal to achieve among the commonly desired ones, is wave-shape reproduction. This criterion requires obeying the linear-phase-shift law as well as the frequency-content reproduction criteria (above). This combination yields the very restricted signal-frequency range "C", Fig. 2.

The above discussion covers only the FREQUENCY-RESPONSE considerations for various targets of information reproduction. There are also AMPLITUDE-RESPONSE criteria, often called linearity or non-linearity characteristics, which apply, but which will not be discussed in this paper.

INFORMATION SHAPING

The shaping of information may occur in the frequency or the amplitude domains. Typical examples are illustrated in Fig. 2.

INTEGRATION: A typical frequency-domain operation is the integration with time of a signal. All integrators must present to the signal, a straight line of slope -n for n-th order integration, with a phase shift of $-n\pi/2$ in the Bode-presentation, for all frequencies in the signal. This requirement is illustrated in Region "E" in Fig. 2, in which it is fulfilled to $\pm$ 1%.

DIFFERENTIATION: Another typical frequency-domain operation is the differentiation of a signal. All differentiators must present to the signal a straight line of slope +n for n-th order differentiation, with a phase shift of $+n\pi/2$ in the Bode representation of frequency-response characteristics. This requirement is illustrated in Region "D" in Fig. 2, in which it is fulfilled $\pm$ 1%.

Many other frequency-domain-based shaping operations exist, including compensation for lack of desired frequency response characteristics of any part of a measuring system.

LINEARIZATION: Typical amplitude-domain information shaping operations would be the linearizing of a signal such as from thermocouples, resistance thermometers, etc., or the deliberate nonlinearization to follow special requirements such as square laws for example. For all information reproduction, conversion, and shaping examples cited in this paper, it is vital that the measuring system exhibit linearity between the input and output. Nonlinear systems are frequency-creative, producing at their outputs frequencies not present at the input. Non-linear systems are required for purposes of frequency-multiplication, modulation, etc., but not for such operations as have been discussed here. In the analog-amplitude-modulation information conversion examples cited in Table 3, certain kinds of non-linearities for modulation, are required. It should be noted, however, that single-frequency excitation of a non-linear system, even with the use of tracking filters tuned to excitation frequency, will not solve the frequency creation problem: any cubic non-linearities will create an undesired frequency component at the signal frequency, which is then included in the filter output.

CONCLUSION

It is the author's personal conviction that the study of information processing and conversion in measuring systems has lagged behind the study of energy processing and conversion, with which so many instrumentation text books are filled. Since the business of measurement is obtaining the maximum amount of information with the minimum expenditure of energy, it is hoped that this contribution will stimulate additional work along these lines. Much remains to be done! This is the organization to do it!

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A Transducer Information Center

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Presented at the Eighth Transducer Workshop
Sponsored by
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Dayton, Ohio 22 - 24 April 1975

Bendix Research Laboratories

A TRANSDUCER INFORMATION CENTER

By

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ABSTRACT

A Transducer Information Center consisting of a data base, automated retrieval system, and a search and dissemination service is being established at Bendix. The data base is comprised of scholarly literature, reports, evaluation studies, and manufacturer's product information. A controlled subject descriptor vocabularly based on the Instrumentation Society of America's Transducer Nomenclature Standard S37.1 is used to query the data base. Other access points include: author, title, manufacturer, and type of document. A citation analysis was conducted to determine the most productive sources of transducer information; journal productivity conforms to Bradford's distribution. A literature search service is available and the Center's document accession list is disseminated periodically to interested Corporate personnel. Progress in the development and operation of the Center is reported.

1. INTRODUCTION

The Bendix Corporation is a multi-national, diversified company with products spanning five major business areas - automotive, aerospace-electronics industrial, home systems, and recreational vehicles. The Bendix Research Laboratories is a central operation attached to the world headquarters and is charged with the mission of assisting various operating divisions with their product requirements through research and development leading to new products and processes.

A key element of many of these business areas is control systems. Automatic devices, aircraft instrumentation, flight and engine controls, and industrial controls are a few application examples. Because it is expected that the present trends of increasing functionality and lower cost will continue for digital electronics, it can be anticipated that more and more control systems will be implemented using digital electronics. Thus, new and greater demands will be made on the sensor and actuator portions of the system. Increased performance and lower cost will constitute the major goals for these devices. A future mission of the Laboratories is the development of sensors and actuators matching as naturally as possible to interfaces of basically digital systems. In this paper we will be concerned with the sensors and discuss our progress in the establishment of a Bendix Transducer Information Center.

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2. TRANSDUCER INFORMATION CENTERS

An important aspect of the Laboratories' work in sensors is the development of a Transducer Information Center (TIC) consisting of a data base, retrieval system, and search and dissemination services. The objective of this Center is to maintain a current awareness of key transducer concepts, available hardware, and trends. The data will serve system design engineers on a Corporate-wide basis, as well as provide BRL staff with state-of-the-art information against which to test new concepts in future developmental work on radical and improved new sensors.

The TIC is a central collection of documents on transducers which can be searched by a computer-based document retrieval system. Documents are acquired, analyzed, indexed, and filed for prompt retrieval (Figure 1). The Center's document accession list is disseminated periodically to interested Corporate personnel.

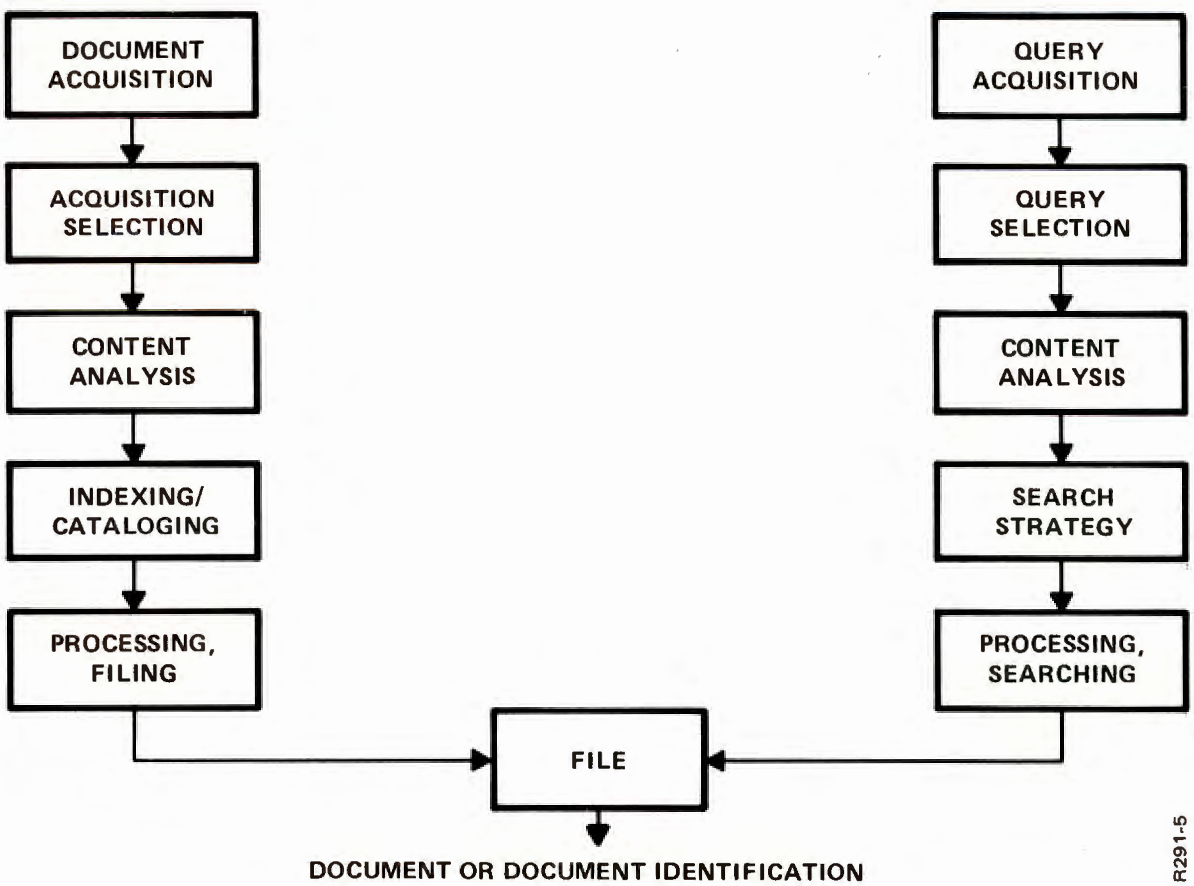


Figure 1 - A Generalized Information Retrieval System.

2.1 Past and Present, Non-Bendix Transducer Information Centers

2.1.1 Harry Diamond Laboratory

A project entitled "Research in Transducers" was initiated in 1957. The goal of this work was the classification of transducers into categories on the basis of transduction principle, physical magnitude measured, and energy conversion process. Scientific literature was searched, commercially available sensors catalogued, bibliographies compiled, and critical as well as state-of-the-art services conducted. This project was discontinued in the 1960's. However, although the data is antiquated, the method used to analyze transducer literature is relevant.

2.1.2 Battelle Memorial Institute

Battelle established a pilot TIC in 1963 under an Air Force contract. During the four years of its existence, this center collected and processed about 6000 pieces of information dealing with transducers. Commercial documents, data, scholarly literature, and reports were placed in a storage and retrieval system and disseminated to the transducer technology community on request.

2.1.3 National Bureau of Standards

An Inter-Agency Transducer Project was initiated by NBS in 1951. Transducer performance characteristics are compiled and testing procedures for selected transducers are developed and evaluated. The results of this work are published, including over 100 performance and characteristic descriptions of transducers.

2.2 Bendix Transducer Information Center

A TIC consisting of a data base, automated document retrieval system, and a search and dissemination service is being established at the Bendix Research Laboratories (Figure 2). The data base is comprised of scholarly and trade literature, reports, patents, evaluation studies, and manufacturer's product information. A controlled subject descriptor vocabulary, based on the Instrument Society of America's Electrical Transducer Nomenclature and Terminology Standard S37.1 is used to query the data base. Other access points include: author, title, manufacturer, and type of document. A citation analysis was conducted to determine the most productive sources of transducer information; journal productivity conforms to Bradford's distribution. (See Section 3.) A literature search service is planned and the Center's document accession list is to be disseminated quarterly to interested Corporate personnel.

2.2.1 Data Base

A data base is a set of files applicable and available to a given problem or user group. Criteria used for selection of materials to be added to the set constitute the acquisition policy.

The Bendix TIC's short-range acquisition policy in 1974 was to identify, locate, select, order and receive materials relating to

1. DATA BASE

   a. Journal Literature

   b. Manufacturer's Product Literature

   c. Corporation Literature

   d. Monographs

   e. Standards

   f. Patent Literature

   g. Conference and Meeting Information

2. RETRIEVAL SYSTEM: AUTOMATED

   a. Controlled Subject Descriptor Vocabulary - ISA Standard S37.1

   b. Controlled Type of Document Descriptor Vocabulary

   c. Access Points Into Data Base:

      Subject -- Faceted Descriptor
      Author
      Title
      Manufacturer
      Type of Document

3. SEARCH AND DISSEMINATION SERVICE

   a. Conduct Literature Searches for Bendix Personnel

   b. Quarterly Dissemination of Document Accession List

Figure 2 - Bendix Transducer Information Center,

pressure sensing; specifically, both professional and trade journal literature, manufacturer's product information, Corporation literature, books, standards, patent literature, conference and meetings information, and proceedings.

To execute the acquisition policy, a bibliography of transducer information resources was developed. Books, journals, indexing and abstracting services, select dissemination of information (SDI) and search services, relevant societies and meetings information, and a selected list of Buyers' Guides constitute the bibliography. Figure 3 outlines these resources. The flow of these materials through the data base's acquisition function is presented in Figure 4. A citation analysis of the journal literature is given later.

2.2.2 Automated Retrieval System

The purpose of the retrieval system is to ensure prompt access to documents in the Center's data base. This system consists of three processes: document analysis, terminology control, and a routine for retrieval of the Center's documents.

2.2.2.1 Document Analysis

Prior to entry in the data base, documents are analyzed to determine their subject content. The documents' main points pertinent to potential users are indexed. Once a document is evaluated for pertinent information, it is processed by translating its highlights into the system's vocabulary. The Bendix TIC indexing policy permits subjective decisions on the indexer's part as to what subjects in the document should be indexed. Within limits, a document is indexed under as many descriptors as the indexer believes pertinent to the potential interest of the Center's users.

2.2.2.2 Terminology Control

In order to ensure consistency in the assignment of descriptors to documents, it is necessary to use an indexing or vocabulary authority. This authority is an aid when searching for appropriate words, it provides a record of authoritative decisions on word usage, and it helps in error control.

Two vocabulary authorities are used in indexing documents, namely, Instrument Society of America's (ISA) Electrical Transducer Nomenclature and Terminology Standard S37.1 and the DDC Retrieval and Indexing Terminology.

2.2.2.3 Retrieval System

The Library Information Retrieval System (LIRS) (Figure 5) is an indexing system for the retrieval of documents in a library by one or more of the following:

(a) Subject

(b) Title

BOOKS:

The bibliography lists 23 books dealing with all types of transducers and their applications.

JOURNALS:

A total of 79 journals are identified as pertinent to transducers; 44 professional journals and 35 trade. Journals particularly relevant are starred and should be regularly scanned; approximately 60 journals.

INDEXING AND ABSTRACTING SERVICES:

These services index over 64% of the bibliography's journals, and are access points into government, report, and patent literature.

SDI AND SEARCH SERVICES:

A SDI service is a current awareness function. Citations of articles relevant to a user's "profile" are periodically sent to the requestor. On-line computer-assisted search of scientific literature is now available, and will be used at the Bendix TIC.

SOCIETIES AND MEETINGS:

Societies interested in transducers are listed with addresses, phone numbers, and their publications. Two journals that list conferences, meetings, and proceedings availability are included.

BUYERS' GUIDES:

Five buyers' guides covering transducer manufacturers are listed.

Figure 3 - Transducer Information Resources.

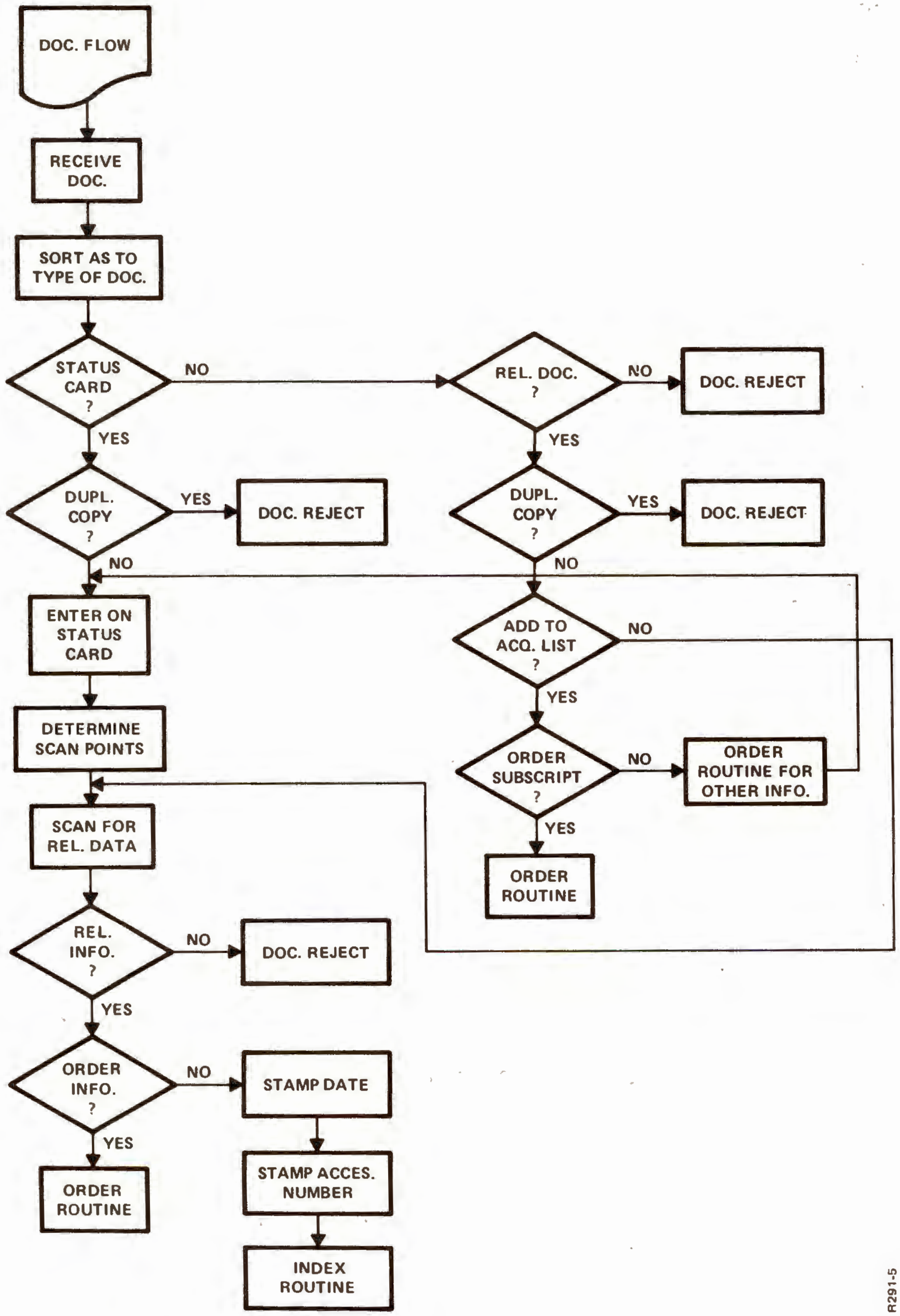


Figure 4 - Acquisition Flow of Materials Through Data Base.

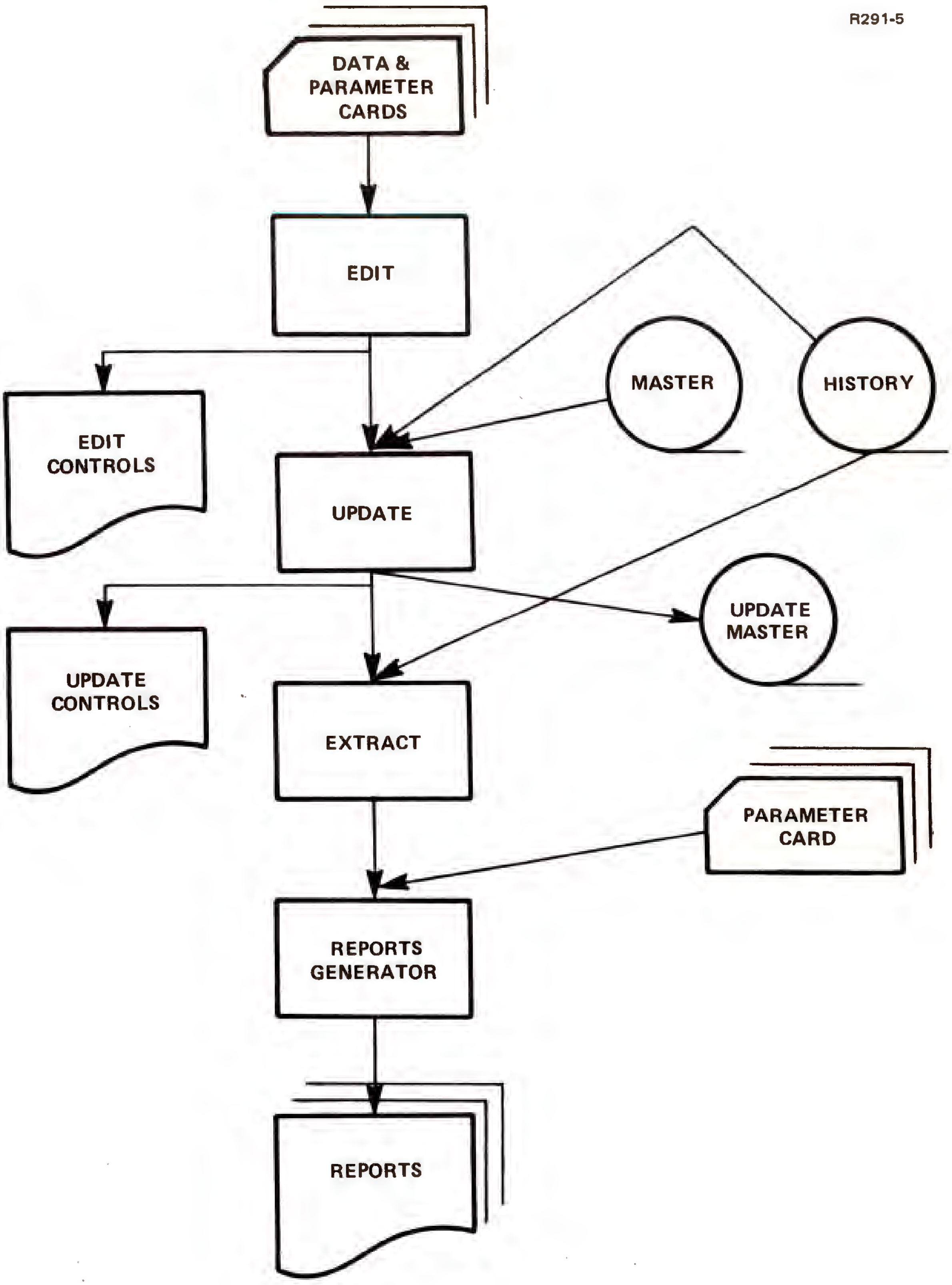


Figure 5 - Library Information Retrieval System, Summary Flow Chart.

(c) Authors or Editors

(d) Source

(e) Contract Number of Publisher

(f) Type of Document

The primary purpose of the LIRS is to report, on request, a library's holdings classified in the above terms. The secondary purpose is to retrieve documents by using a logical search, according to Subject Terms, to narrow the range of possible documents.

Coding forms are used for the parameter and input cards of this system. The parameter cards are used to control computer processing and consist of the following cards: (1) control, (2) report, (3) header search, and (4) detailed search. The data cards represent the input information which modifies and updates the existing files (Figure 6).

The LIRS contains the four classic elements of a maintained and reported file and a utility sort program. These elements are the following programs: (1) edit, (2) update, (3) extract, and (4) report generating. Figure 7 outlines these programs. The output of the system is a maximum of 11 requested reports (#02-12, see Figure 8) with 3 additional reports which are always printed.

The hardware requirements include an IBM 360 OS; peripheral equipment such as card reader, direct access, tape discs, and printer; and core requirements of ∿150 K. The program language is Cobol F.

2.2.3 Document Storage

Data base documents are stored sequentially by an accession number stamped on the document, and on the tab of its swing folder; both are stored in a filing cabinet. The descriptors under which the document is indexed are also written on the document. Books and other oversize materials are stamped with an accession number and stored elsewhere.

2.2.4 Search and Dissemination Service (SDS)

2.2.4.1 Literature Searches

As the acquisition process inputs data into the Center, so the search and dissemination process is its output. The objective of the Bendix TIC SDS is to conduct literature searches for Bendix personnel. The data base can be searched in two ways: using a logical search, or by searching the Center's categorized reports. The former, by coordinating descriptors, can limit the range of possible relevant documents. However, because LIRS is designed as an index-compiler, it is possible to locate documents by searching the categorized reports as an index. The nature of the query determines the way in which the data base is utilized once a document relevant to the query is located. Its information is transmitted verbally or copied and sent to the requestor. Figure 9 is a flow chart of the steps used to search the classified reports.

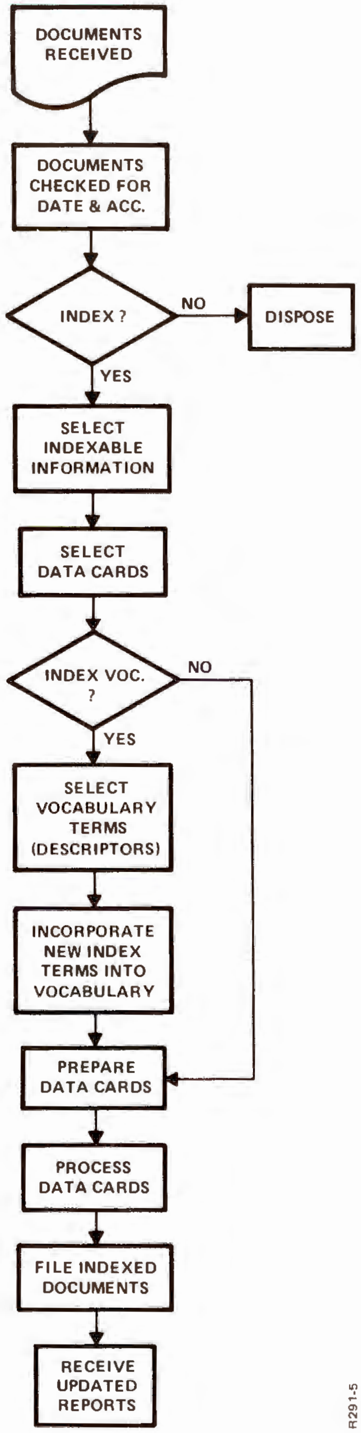


Figure 6 - Flowchart of Steps in Indexing a Document.

1. EDIT Program (EDITLIRS)

   Internally sorts input data

   Edits input data

   Writes control report

2. UPDATE Program (UPDTLIRS)

   Updates the Master File

   Updates the History File; if requested

   Changes Subject Terms on Master File; if requested

   Searches the Master File for Subject Terms requested in the Questions

   Creates Source Code File

3. EXTRACT Program (EXTRLIRS)

   Extracts reporting information from the Master and/or History File

4. SORT Program (Utility)

   Sorts data extracted from the Master File for reporting purposes

5. REPORTS GENERATOR PROGRAM (RPTSLIRS)

   Formats the 12 various reports

   Writes the 12 various reports

Figure 7 - LIRS Programs.

CATALOGING REPORTS

01 Acception and Exception Register - always printed

02 Library Additions Report

03 Accession Number Reports

04 Master Information Report

REFERENCE REPORTS

05 Master Record

06 Subject Term and Title Report

07 Authors/Editors and Source Report

08 Contract Report

09 Source Code Report

10 Source Description Report

11 Thesaurus Report

LITERATURE SEARCH REPORT

12 Document Retrieval Report

CONTROL REPORTS

13 Edit Control Report - always printed

14 Update Control Report - always printed

Figure 8 - Output Reports of LIRS.

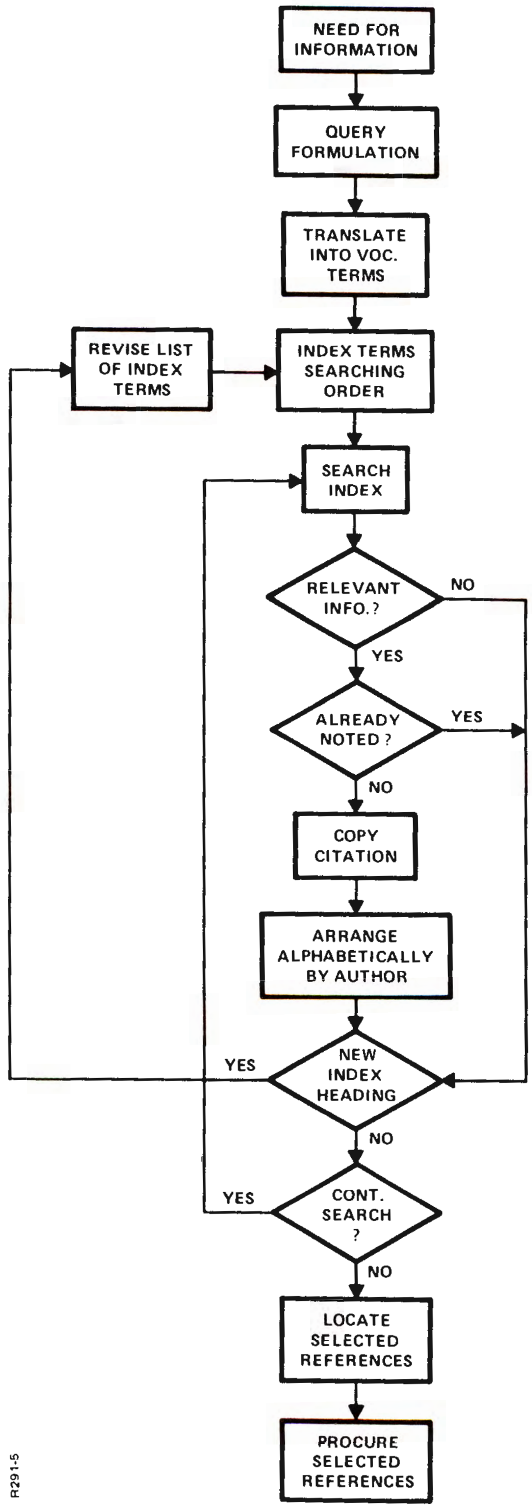


Figure 9 - Flowchart of Steps in Searching an Index.

2.2.4.2 State-of-the-Art Search (SAS)

An ideal system for an SAS query would be a true information retrieval system. Unfortunately, computerized information retrieval systems (which could, for example, answer directly the question "what is the density of mercury at 0°C?") are in the future. Also, unfortunately, inquiries defining the state-of-the-art are couched in terms of performance, environment, price, etc. The inquirer does not ordinarily specify his need in terms useful for document retrieval.

Because the LIRS does include a large number of unallocated subject descriptors, it is possible to code a selected subset of documents by stylized subject descriptors to permit a limited retrieval of documents including the information desired. The TIC is experimenting with such a stylized descriptor code for manufacturer's product data based upon key functional, environmental, and other factors. Since the LIRS is limited to selecting only by descriptor match, the descriptors must define categories and subcategories unambiguously. For example, gage pressure might be coded 0-1 psig, 1-10 psig, 10-100 psig, etc. The task of coding a document includes selecting the special characteristics of the sensor and matching them to the descriptor set. In retrieval, again the desired characteristics must be matched to the descriptor set. Thus, the reason why the descriptors must be stylized lies in the limitations of the LIRS retrieval; this constraint also dictates that the coding/retrieval interface must be assigned to an individual both intimately familiar with the LIRS descriptors and also possessing technical judgment.

3. CITATION ANALYSIS

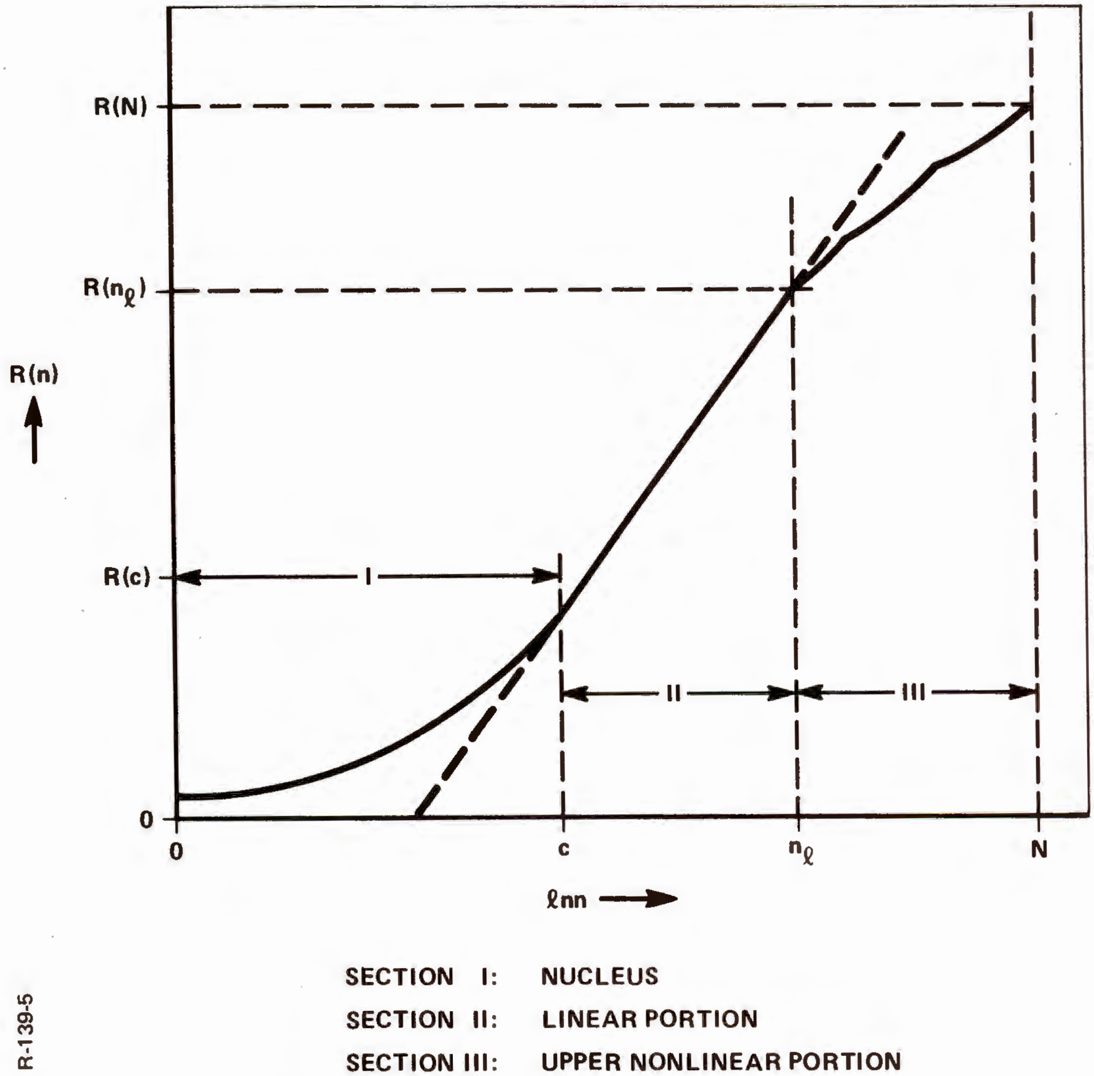
Because journal literature is a current source of transducer information, a citation analysis was conducted to determine how this information is scattered in the scientific literature. Each journal in the scientific literature contributes a certain number of papers to the total bibliography on a given scientific subject. In 1948, S. C. Bradford found that if the journals are ranked according to their productivity, a semilogarithmic plot of the cumulative total number of papers R(n) versus the number of journals n, in decreasing order of productivity, yields in many cases a characteristic stretched S-shaped curve (Figure 10). The initial nonlinear zone contained the most productive sources and is called the nucleus (Section I). It is followed by a linear section (Section II) and another nonlinear portion (Section III) at the end. This graph is commonly referred to as Bradford's distribution. The nucleus and the linear section are expressed respectively as:

$$A(n) = R(1)n^{\beta} \qquad 1 \leq n \leq C \tag{1}$$

and

$$R(n) = k \, \ell n(n/s) \qquad C \leq n \leq n_{\ell} \tag{2}$$

BRADFORD DIAGRAM



SECTION I: NUCLEUS
SECTION II: LINEAR PORTION
SECTION III: UPPER NONLINEAR PORTION

Figure 10 - Bradford Distribution.

where β, k, and s are constants which can be determined for any Bradford distribution. The nonlinear section at the end of the distribution (Section III) contains the least productive sources. It has been shown recently that the previously held notion that this latter deviation from linearity is due to an incomplete bibliography is not necessarily true, but rather is an intrinsic feature of the Bradford distribution. The details of this work which gives rise to a more accurate approximation to the bibliographic distribution are given in a paper by Bräunlich and Kroll.* Two bibliographies were analyzed. The Bradford distribution for the bibliography on transducers gathered from four years (1970-1973) of Engineering Index is shown in Figure 11.

It can be concluded from the citation analysis that over three-quarters of the transducer literature can be accessed by scanning the first 25 or so journals in Figure 12. However, because the majority of these sources are professional in nature — 20 of the 25 journals -- they have little or no advertising. Therefore, a number of trade publications must be regularly examined to keep abreast of current innovations in transducer manufacturing. The more important trade journals are listed in Figure 13.

Because a citation analysis is a purely quantitative method, the frequency of appearance of core journals central to a subject area will probably be a reflection of the number of articles they publish. As more bibliographic knowledge is gained of transducer literature, refined decisions can be made as to what journals published the most relevant articles in the core area -- the relative positional importance of the journals can then be adjusted accordingly. Until such time, scanning the professional core of journals -- Figure 12, the first 25 or so journals -- and the more important trade journals -- Figure 13 -- should reveal the majority of current transducer literature. What information that is missed in this process can be acquired by regularly scanning the Indexing and Abstracting services.

4. CONCLUDING REMARKS

The Bendix TIC as presently envisioned has been described in some detail. At the present, the descriptor vocabulary for pressure sensors is being revised in order to make the Center more useful. Also, a bibliography on pressure sensors is nearing completion. Future work includes introduction of flow sensors and liquid level sensors in the data base, as well as other key transducers as they are identified.

ACKNOWLEDGEMENTS

Discussions with Dr. P. F. Bräunlich and C. Ahern are gratefully acknowledged.

Peter Braunlich and Michael Kroll, "Bradford's Distribution and the Bibliometric Analysis of Scientific Literature," a paper which is being submitted for publication. Draft copies are available at Bendix Research Laboratories.

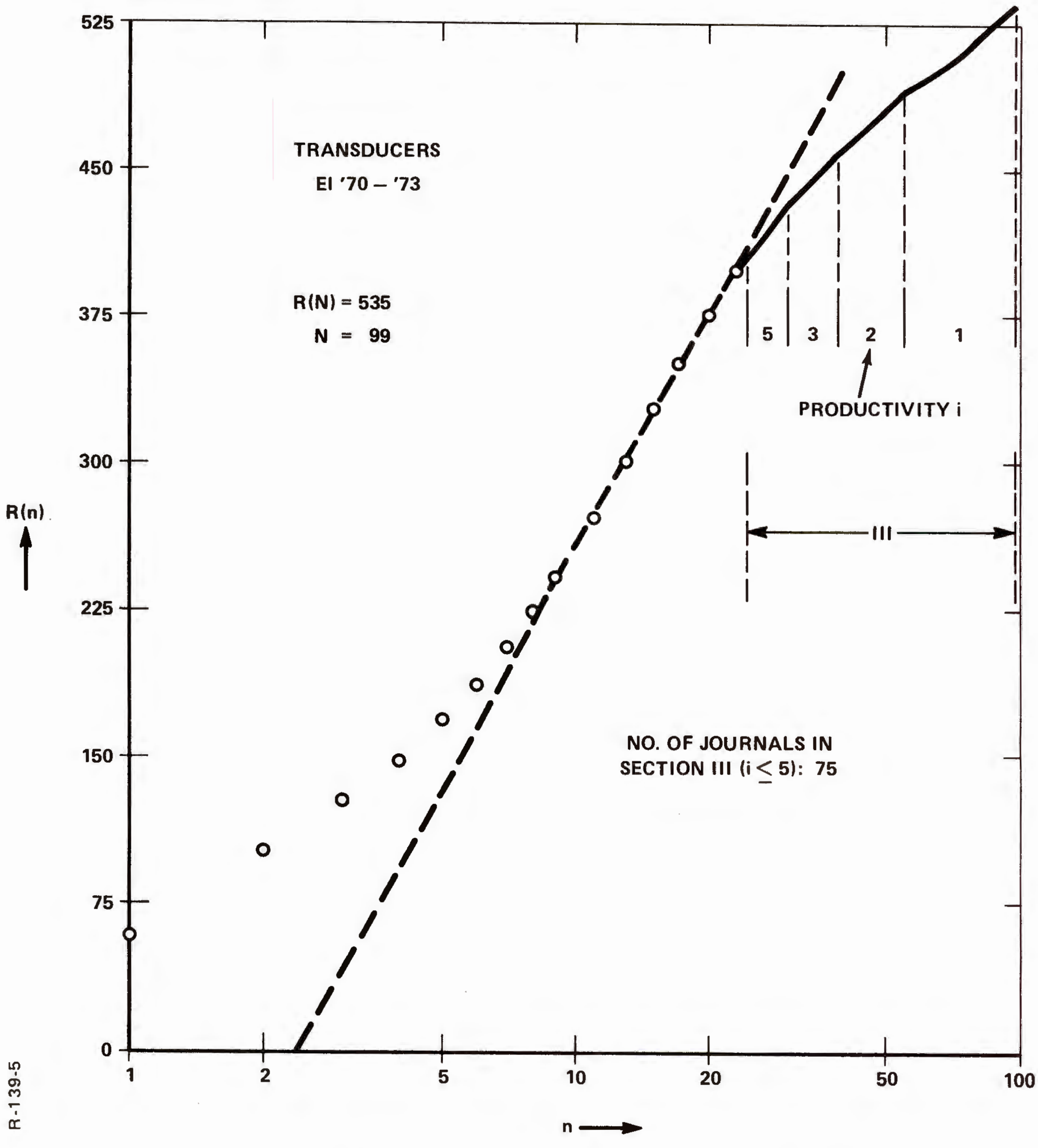


Figure 11 - Bradford Distribution of <u>Engineering Index</u> Transducer Bibliographic.

Measurement Techniques (P)
Review of Scientific Instruments (P)
Experimental Mechanics (T)
IEEE Transaction Sonics and Ultrasonics (P)
Instruments and Experimental Techniques (P)
Journal of Acoustical Society of America (P)
Journal of Applied Physics (P)
Journal of Physics E: Scientific Instruments (P)
Soviet Physics: Acoustics (P)
Instrument Society of America, Transactions (P)
Strain (T)
Instruments and Control Systems (T)
Vacuum (T)
Electronics Letters (P)
Soviet Journal of Nondestructive Testing (P)
IEEE Transactions: Industrial Electronics and Control Instrumentation (P)
American Society of Mechanical Engineers, Quarterly Transactions (P)
Applied Physics Letters (P)
IEEE Transactions: Electron Devices (P)
Ultrasonics (T)
Electronics and Communications in Japan (P)
IEEE Transactions: Instrumentation and Measurement (P)
IEEE Proceedings (P)
Acoustica (P)
Control and Instrumentation (T)
Radio Engineering and Electronic Physics (P)
Instrumentation Technology (T)
Journal of Environmental Sciences (P)
Journal of Strain Analysis (P)
Pomicery Aulomatyka Kontrola (P)
Electronics (T)
IEEE Transactions: Bio-Medical Engineering (P)
Instrumentation (T)
Engineering (T)
Medical and Biological Engineering (T)
Solid-State Electronics (P)
Automation and Remote Control (P)
Electromechanical Design (T)
IEEE Proceedings (P)
Measurement and Control (T)
Microtecnic (P)
Process Instrumentation (T)
Soviet Journal of Instrumentation and Control (P)
Journal of Dynamic Systems, Measurement and Control (P)
Journal of Engineering for Industry (P)
Journal of Physics C: Solid State Physics (P)
Automation (T)
Aviation Week and Space Technology (T)
Control Engineering (T)
Design News (T)
EDN (T)
Electronic Instrumentation (T)
Research/Development (T)
Industrial Research (T)
Instrument and Apparatus News (T)
Measurement and Automation News (T)
Measurements and Data
Process Engineering (T)
Electronic Design (T)

Figure 12 - Key Professional (P) and Trade (T) Journals Listed According to a Priority Rate.

1. Control and Instrumentation

2. Control Engineering

3. Design News

4. EDN

5. Electronic Design

6. Experimental Mechanics

7. Instrumentation Technology

8. Instruments and Apparatus News

9. Instruments and Control Systems

10. Measurement and Automation News

11. Measurements and Data

12. Process Engineering

13. Strain

14. Ultrasonics

Figure 13 - Key Trade Journals.

A REVIEW OF TRANSDUCER RELATED STANDARDS

Dale W. Rockwell

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Abstract

The benefits derived from standardization include mass production, uniformity, interchangeability, quality control, reduction of sizes and shapes required, etc. Two types of standards exist: military and voluntary. The latter includes such organizations as ANSI, ISA, ASTM, and ASME.

The effect of standards is to make world trade feasible. Product certification procedures are being proposed for imports/exports.

The need for additional standards is evident in areas such as flow meters, servo transducers, temperature sensors, and shock testing of accelerometers among others.

"Standardization Documents Relating to Transducers" was compiled at the Seventh Transducer Workshop and appended for the Eighth Transducer Workshop.

A REVIEW OF TRANSDUCER RELATED STANDARDS

By Dale W. Rockwell

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In discussing standardization documents it is worthwhile to briefly review their benefits which include uniformization of products which facilitates mass production, interchangeability, and testing; streamlining of inventories by eliminating uneconomic sizes, shapes, etc.; and increasing the market through production of standardized "acceptable products." An example was recently cited which illustrates the benefits of standardization. J. W. Landis, President of the American National Standards Institute, reported that standardization on the new optimum metric fastener system would call for 25 standard thread sizes instead of the present 59 with a resultant estimated savings of more than $500 million a year, reference (1).

There are basically two types of standards - those produced by government (e.g., Military Standards, Military Specifications, etc.) and those produced by voluntary standards organizations (only the second type are considered in this presentation). The voluntary transducer standards are produced by numerous organizations including the American National Standards Institute (ANSI), the Instrument Society of America (ISA), American Society for Testing Materials (ASTM), and the American Society of Mechanical Engineers (ASME). As you may know ANSI is a federation of organizations including representatives from professional organizations, industry, trade organizations, consumer interests, and standards organizations. ANSI coordinates development of National Standards, establishes national consensus standards, is the official United States member to ISO and to IEC through ANSI's affiliate U.S. National Committee for IEC.

The importance of international aspects should be considered since standards approved by ISO (International Organization for Standardization) and IEC (International Electrotechnical Commission) are vital to the world market. An example of the importance of international standardization was pointed out in a recent publication which described a proposal made in Europe that international standards be coupled with product certification procedures such that products not certified according to international standards would effectively be barred until proper certification was secured, reference (2). While America's participation in international standards is voluntary, many countries are actively working to influence the outcome of future standards. If our point of view is to be properly presented an increased effort and better support from industry is required.

A list of approved and draft transducer related standards has been compiled and is provided as a handout. The compilation will also be included in the minutes of this Transducer Workshop. (NOTE: This list does not include standards by the Range Commanders Council as they are covered in another session of this Transducer Workshop). A review of the 1975 compilation compared to a 1972 listing (reference 3) reveals that approximately 30% of the approved standards listed are new or have been revised since 1972. While that figure represents a substantial amount of activity it is also noted that approximately 35% of the 1975 approved standards are in excess of ten years old - there is more to be done. A few actions worthy of note are: several revised and new ANSI standards in acoustics and vibration, updated ASTM standards in termperature/thermocouples, and several ISA standards have been or are being written or revised. ANSI's MC88 (formerly B88) Committee has several standards dealing with calibration of transducers (pressure, force, temperature, flow, etc.) in preparation and is preparing the final draft of "A Guide to the Static Calibration of Pressure Transducers" which follows their "Guide to the Dynamic Calibration of Pressure Transducers" which was approved and published in 1972.

There appears to be a substantial need for a number of additional or revised transducer related standards covering certain types of flow meters (as well as their calibration and use), servo accelerometers and their calibration, some of the newer types of temperature sensors, shock testing, shock accelerometers, etc. Additional standards are also required in some of the newer signal conditioning instruments and the new microprocessor based "smart" instruments are beginning to show up and will require future standardization. Straying a little farther from transducers, but somewhat related, is the need for standards on the calibration of particle counters, gas analysis equipment, etc.

There is much to be done in the transducer related areas of standardization and each of you can contribute in some way toward standardization in transducers and their related instruments. In closing I would like to remind you that standards are of no value unless they are used. Each of us must make a conscious effort to maximize our use of standards if we expect to receive the benefits of standardization.

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(1) "Metrication's Profit Opportunities Stressed," ANSI Reporter Vol. 9, No. 7, 28 March 1975.

(2) Zerfas, J., "International Standards... The Key or Barrier to Trade," Quality Management and Engineering , February 1975, pp 31.

(3) Rockwell, D. and Rogero, S., "A Report on the Activity of Committees Involved in Standardization of Transducers and Related Measurements," Minutes Seventh Transducer Workshop of the Telemetry Group Range Commanders Council, 4-6 April 1972, pp 257-270.

411

STANDARDIZATION DOCUMENTS RELATING TO TRANSDUCERS

COMPILED BY:
DALE ROCKWELL
NAVY METROLOGY ENGINEERING CENTER
POMONA, CALIFORNIA

8th TRANSDUCER WORKSHOP OF THE TELEMETRY GROUP
RANGE COMMANDERS COUNCIL
DAYTON, OHIO
22 - 24 APRIL 1975

AMERICAN NATIONAL STANDARDS INSTITUTE
1430 BROADWAY
NEW YORK, NY 10018

B88.1-1972	Dynamic Calibration of Pressure Transducers, Guide for	
MC88 --	Static Calibration of Pressure Transducers, Guide for	Final Draft Being Prepared (Other Drafts Are Being Prepared On Calibration of Pressure, Force, and Other Transducers).
C96.1-1964 (R1969)	Temperature Measuring Thermocouples	
C96.2-1973	Temperature-Electromotive Force (EMF) Tables for Thermocouples (ASTM E230-72)	
S1-1-1960 (R1971)	"Acoustical Terminology (Including Mechanical Shock and Vibration)"	
S1-2-1962 (R1971)	"Physical Measurement of Sound, Method For"	
S1.4-1961 (R1971)	"General-Purpose Sound Level Meters, Specification for"	

S1.8-1969	"Preferred Reference Quantities for Acoustical Levels"
S1.10-1966 (R1971)	"Calibration of Microphones, Method For The"
S1.12-1967 (R1972)	"Laboratory Standard Microphones, Specifications For"
S2.2-1959 (R1971)	"Calibration of Shock and Vibration Pickups, Methods for the"
S2.10-1971	"Analysis and Presentation of Shock and Vibration Data, Methods for"
S2.11-1969 (R1973)	"Calibrations and Tests for Electrical Transducers Used for Measuring Shock and Vibration, Selection of"

AMERICAN SOCIETY OF MECHANICAL ENGINEERS
UNITED ENGINEERING CENTER
345 EAST 47th STREET, NEW YORK, nY 10017

PTC 19-2	"Instrument and Apparatus: Pressure Measurement," 1965.	
PTC 19.3-1974	Temperature Measurement Instruments and Apparatus. Performance Test Codes	1974 Rewrite - Presents a Summary discussion of temperature measurement as related to Performance Test Code work with particular emphasis on basic sources of error and means for coping with them.
PTC 19.5.2,	"Instrument and Apparatus: Volumetric (Displacement) Meters," 1966	
PTC 19.5.3,	"Instruments and Apparatus: Fluid Velocity Measurement," 1965	
PTC 19.5.4,	"Instruments and Apparatus: Flow Measurement," 1959	
PTC 19.5.5	"Instrument and Apparatus: Special Methods of Flow Measurement," 1966	

PTC 19.16 "Determination of the Velocity of Liquids," 1965

American Society for Testing Materials
1916 Race Street
Philadelphia, PA 19103

E 220-72 Calibration of Thermocouples by Comparison Techniques

E 230-72E Standard Temperature-Electromotive Force (EMF) Tables for Thermocouples

E 235-73E Specification for Thermocouples, Sheathed Type K, for Nuclear or for Other High Reliability Applications

E 344-74 Definitions of Terms Relating to Temperature Measurement.

INSTRUMENT SOCIETY OF AMERICA
400 STANWIX STREET
PITTSBURG, PA 15222

ISA-S31.1	Turbine Flowmeters	Standard approved 1972 has been submitted to ANSI for approval as an American National Standard
ISA-S37.1	Electrical Transducer Nomenclature and Terminology	1969 Standard - Submitted to ANSI for approval as an American National Standard
ISA-S37.2	Specifications and Tests For Piezoelectric Acceleration Transducers	1964 Standard - To be revised.
ISA-S37.3	Specifications and Tests for Strain-gage Pressure Transducers	1970 Standard - Submitted to ANSI for approval as an American National Standard
ISA-S37.4	Specifications and Tests for Resistive (Platinum-Wire) Temperature Transducers	Presently in Preparation

ISA-S37.5	Specifications and Tests for Strain-Gage Acceleration Transducers	1971 Standard - Submitted to ANSI for approval as an American National Standard
ISA-S37.6	Specifications and Tests for Potentiometric Pressure Transducers	1975 Revision Released
ISA-S37.8	Specifications and Tests for Strain-Gage Force Transducers (Load Cells)	A revised (1975) draft has been prepared and is presently being reviewed.
ISA-S37.10	Specifications and Tests for Piezo-Electric Pressure and Sound Transducers	Standard approved 1969 has been submitted to ANSI for approval as an American National Standard.
ISA-S37.11	Specifications and Tests for Servo Acceleration Transducers	Presently in Preparation
ISA-S37.12	Specifications and Tests for Potentiometric Displacement Transducers	1974 draft has been distributed for review.
ISA-S37.13	Specifications and Tests for High-Level DC-Output Pressure Transducers	Prepared in draft form final not yet released.

SCIENTIFIC APPARATUS MAKERS ASSOCIATION
1140 CONNECTICUT AVENUE, N.W.,
WASHINGTON, D.C. 20036

SAMA:	II 1 & 2 Load Cell Terminology and Recommended Test Procedures, 2nd edition, 1964
RC 5-10	"Resistance Thermometers," 2nd Edition, 1963
SAMA:	RC 8-10 "Thermocouple Thermometers (Pyrometers)," 2nd Edition, 1963
SAMA:	RC 20-11, Measurement and Control Terminology, 1964
SAMA:	RC 21-4-1966, Temperature-Resistance Values for Resistance Thermometer Elements of Platinum, Nickel and Copper, 1966

SESSION V

DISCUSSION SUMMARY

Session Chairman: John Hilten

Papers: Stein, Kroll and Carrico, Rockwell

DISCUSSION:

Pierre Fuselier, L^3: I am interested in the transducer information center. Is the Bendix library available to other people or is it solely for in-house use?

John Carrico, Bendix Research Laboratories: For the present it is solely for Bendix. As it matures and is supported by a much larger base, it will open up to outsiders. Once it is working on a small scale, we will seek outside interests, although its main function is to support our divisions. The center does have a charter to sustain itself with outside contracts, and we are looking to the transducer community to help us. We asked ourselves, "Could either Battelle or Stanford Research Institute (SRI) do the task for us?" They could for a fee which we feel would be better spent in Bendix.

You have my name, and if you would like information, we could run it through the computer once we are set up. Companies will be able to subscribe to it at a date in the future. Cataloging manufacturing product information is an horrendous undertaking. We are still looking at how we will handle that.

Darrell Harting, Boeing Aerospace to Dale Rockwell of Navy Metrology: You asked for inputs on additional standards: American Society for Testing Materials (ASTM) has tests for strain gages.

Harting to Kroll: You said that 75% of the transducer information is in 25% of the transducer journals. Did you list them?

M. J. Kroll of Harper Hospital, Detroit: Yes. (Kroll showed slides with analysis of the techniques used and discussed methods used in organizing data).

Harting to Stein of Arizona State University: You didn't have time to talk about patterns. Can you do that now?

Stein: Apparently the mind of western man breaks patterns down in terms of time and space. We normally think of patterns in time and call them "processes" and patterns for an instant in time we call "events." Patterns in space are local or regional. A photograph would be a regional event. It does carry information, does not fit the normal definition in information theory as carrying information, yet it does convey something to you in patterns of grey or various colors. We refer to that as a regional event.

The local process is where signature analysis is classified according to this scheme, for example: from a submarine, or something in the ocean, you record the set of the pressure waves over a period of time. You then frequency analyze those, and the pattern obtained from one point in space over a period of time carries information to you. The motion picture is an example of a regional process. In tape recording you're taking things happening over a period of time--that would be a local process--putting it on tape, and looking at one instant in time.

We are talking about four different kinds of patterns and eleven wave shape property combinations, making fifteen different things to study. Then all these combinations and permutations are at your feet for teaching and analyzing more easily and effectively.

Howard Grant, Pratt and Whitney Aircraft: A question for Kroll and Rockwell together: Do you have standards in your libraries?

Kroll: Yes, we carry transducer standards. We have American National Standards Institute (ANSI), Instrument Society of America (ISA), and others applicable to the field.

Grant: Is there a standardization of standards going on? Can we go to ANSI and find all the world's standards at one source?

Dale Rockwell, Naval Metrology Center: I'm not sure if it's an up-to-date one. In 1972, there was a document by the National Bureau of Standards (NBS) which listed all the standards at that time. I assume it has been up-dated.

Paul Lederer, NBS: ISA brought out a new edition of preprints, abstracts and standards related to instrumentation. It is a reprint of all their own standards and a listing of many other related standards. I imagine it will be republished each year. ISA is currently trying to get their transducer-related standards accepted as ANSI standards.

Rockwell: ANSI does take the standards of other organizations and establishes them as ANSI standards. ANSI does put out a directory on all the standards they have and lists international standards in that. I don't think there is a charge for this directory.

Roger Noyes, EG & G, to Rockwell: Can you say a word on the Government and Industry Data Exchange Program (GIDEP)?

Rockwell: There may be someone here more familiar with that than I am. I believe it is a document that lists calibration and test procedures. The isolated instances I have run into have been disappointing.

Thomas Rogers, Eglin Air Force Base: The service is provided basically free by the Navy, but you have to respond with a procedure to become a user of the program. In addition to calibration procedures, it lists other types of papers on subjects of interest to the aerospace industry.

Audience to Rockwell: We talked last night about the many standards that are presently available. We should use them and specify them instead of writing our own specifications, some of which are lousy and open to interpretation. The transducer community should use the standards that are available.

Robert Bunker, Kirtland Air Force Base to the Bendix team: I personally find this literature search business very discouraging. If a thing is old, it is not retrievable, even though it is the best past literature on that subject. What is your basis for throwing things out?

Kroll/Carrico: We appreciate the problem. We have gone back to the 1940's for monographs, and that's most of the information. We have journal articles for the last 4 years. Product information collection started last year; that's an interactive program with our engineers. Most of the technical information appearing in the trade magazines is available by looking up listings of abstracts.

We concluded the session with a coffee break.

SESSION VI

IMPLEMENTATION OF WORKSHOP GOALS
AND
TRANSDUCER COMMITTEE AIMS

Patrick Walter, Chairman

SESSION VI: IMPLEMENTATION OF WORKSHOP GOALS AND TRANSDUCER COMMITTEE AIMS

Patrick Walter, Chairman, Transducer Committee
Sandia Laboratories

Panel: Transducer Committee Members

As noted above, this session was different from the others in that no formal paper presentations were made. Several members of the transducer committee reported on various phases of committee activities and in each case asked for feedback from attendees, both at the moment and in the future. As in the other sessions, discussion came at the end.

Several changes were made in this session from the program as printed. For that reason a revised agenda is provided here.

1000 Paul Lederer, National Bureau of Standards (NBS),
IRIG 106, "Transducer Standards."

1010 William Anderson, Naval Air Test Center (NATC),
IRIG 118, "Transducer Based System Calibration."

1025 "Proposed Standard Terminology for Telemetry
Transducer Amplifiers"
Patrick Walter and Fredrick Schelby, Sandia Laboratories
William Anderson, NATC

1040 William Anderson, NATC
"Directory of Transducer Users, July 1973."

1050 Paul Lederer, NBS
"Interagency Transducer Project Activities."

1120 Charles Thomas, Wright-Patterson Air Force Base
"Future Task Definition for NBS."

1200 End of Workshop.

Patrick Walter informed the group on size and composition of the transducer committee, how it fits into the Telemetry Group and subsequently the Range Commanders Council. He discussed the mechanics for the output of the committee, using IRIG 106 and 118 sections as examples, and explained how these documents can be obtained and used by people in the transducer community.

The first speaker was Paul Lederer who spoke on that portion of document RCC 106 listing a collection of standards related to transducers. He commented that after hearing Dale Rockwell's presentation in session 5, the committee would be able to make several relevant additions to that section. He also pointed out that NBS has several technical notes which describe methods and procedures (not standards) that are potentially useful to users of transducers.

William Anderson of NATC talked about that portion of document RCC 118 titled "Transducer-Based System Calibration." There are many standards and procedures for calibrating the individual elements in a data acquisition channel. There is a real need for methods and standard procedure by which the entire signal channel of such a system can be checked from end to end. The ideal is to apply the measurand to the transducer and through the entire system. When this is not possible, substitution and simulation techniques are suggested and outlined.

Next was a three-part presentation. Patrick Walter stated that the field of transducer calibration standards was in good shape and so was the status of telemetry recording standards; however, there was a need for standards for the link between those two elements, i.e., telemetry transducer amplifiers. The subcommittee on amplifier proposed standard terminology was formed to remedy that.

Joe Haden of Holloman Air Force Base is the chairman. In developing his committee two ad hoc groups were formed: one headed by Fred Schelby for charge amplifiers with Allan Diercks of Endevco and Joe Winters of the Naval Weapons Center. A second group is headed by Bill Anderson for dc amplifiers with Elvis Skidgel from I. E. D. Conic and Earl Cunningham from Ectron. Schelby and Anderson each gave a brief resume of how they see their tasks and summarized their individual efforts.

William Anderson spoke on the "Directory of Transducer Users" dated July 1973, told us how it came into being and how people could use it to get help, or to help each other, in the field of transducer applications. The directory is presently in process of updating. Reference sheets were distributed to the audience and they were requested to submit them for inclusion if they desire to participate.

Paul Lederer of NBS spoke on "Interagency Transducer Projects Activities" to date (see appendix.) The group is interested in areas which they feel have not been sufficiently covered and in which a need exists for more knowledge. Some examples are the dynamic characteristics of transducers, environment effects on transducers, and reliability and durability. Some work has been done in developing new principles for improved transduction. A necessary adjunct to these efforts is applying the information gathered to voluntary standards efforts. The basic objective can be stated as the investigation of performance characteristics of electromechanical transducers required for meaningful measurement of physical quantities and the dissemination of knowledge thus obtained.

One of the group's most useful functions is the development of techniques and assistance to other people in using them. Some examples can be seen under "Use of Project Results" and "Measurement Method Development and Application."

Lederer gave some very interesting technical details on the development and use of several procedures and equipments originated by the group.

The final presentation was made by Charles Thomas of Wright Patterson Air Force Base. He stated that the transducer committee activities are partly dependent on responses from groups such as this Workshop. He mentioned a questionnaire that was distributed to attendees and the need for pro or con feedback on work currently in progress or being planned. This feedback provides guidance to the committee and what the committee asks NBS to do. Some elements are how to space Workshops so that they are fruitful, promote exchange between us and transducer manufacturers, and topics that should be covered at the next Workshop.

The committee also needs input from the transducer community as to additional items of concern high on the individual's list of priorities. Some examples follow:

Do you think the thermal transient test methods should be incorporated as a test procedure in document RCC 118?

Do you feel that development of a mechanical filter for shock measurements by acceleration is an item that should be covered by the interagency group at NBS?

How do you rate the importance of investigating the effects of line pressure on low differential pressure transducers?

The need for methods for evaluating performance limitations imposed by the presence of signal conditioning within the transducer.

All of the foregoing is very helpful in long-range planning.

At this point the open discussion began with Pat Walter asking the attendees to voice their present concerns.

Howard Grant, Pratt and Whitney Aircraft: We are concerned with rotating systems and particularly high g loading acceleration, and methods of transferring signals from these rotating systems by slip rings and near-field telemetry.

Douglas Marker, Dahlgren Naval Weapons Lab: One of our problems is instrumentation in gun barrel work, that is, instrumentation of projectiles. Getting signals from the transducers and making sure that they will withstand the gun environment is quite difficult. We are concerned about transducer responses and noise pick-up in the gun barrel environment.

Dale Rockwell, Navy Metrology Engineering Center: I'm typical of most people here in that my basic interest is in calibration. We are interested in development of portable, on-site, semiautomatic calibration systems--for example, micro processor control systems, a system with maximum operator-machine interaction where we can put a calibration procedure in the instrumentation and make things easier for calibration people. For this work you need very good transducers with high accuracy that have very good repeatability and resolution. Linearity is no problem, since the computer process can take care of that. It can take a nonlinear transducer, put it in a processor and come out with a beautiful end result. Hysteresis can be taken care of to some extent. I'm interested in obtaining information on newer transducers, and anything that anyone, including NBS, may be doing along the line of evaluating very accurate portable transducers.

Thomas: We are also interested in that field. We have a problem in calibrating microphones which are installed in many systems including aircraft in a flush mounted configuration. It is difficult to do in-place calibrations or get access to the wires for insertion calibration techniques. We don't believe the procedures we are currently using are what they should be. We'd like to improve on the procedures we are currently using.

Robert Bunker, Kirtland Air Force Base: I'd like to support that also. For end-to-end calibration there has to be a technique available to apply the forcing function to the transducer, if we would like to know the response transfer function of the system. Often there is nothing available to apply the forcing function that would allow us to do that.

Another area that seems to have been overlooked is velocity and a standard for calibrating velocity transducers. In connection with your linear system for signal conditioning, we have a very difficult time in prediction of ranges and have therefore gone to logarithmic amplifiers. You might want to try one in your system.

Thomas: What we did was to develop, on contract and in-house, an automatic gain changing amplifier that will sense output and change gain in 10-dB steps to keep data centered between two adjustable bands. You can set a high limit and a low limit which is compatible with your recording system. If the signal is outside tolerance longer than 0.3 seconds, the amplifier will shift in less than 1 microsec and move to where you need it. It has seven steps, allowing wide range coverage. Transducers are switched in flight without worrying about the signal amplitude. This amplifier decreased the number of flights we had to fly by a factor of three.

Melton Hatch, EG&G: Much of the time we are trying to design a flow measurement system without causing stream interference. I wonder if there is any good literature on standards one would be able to use to design probes for other than air flow? I have noticed that volumes of data exist which are not in the literature. It seems there may be an area here for dissemination of standards.

Lederer: There is a publication by NBS that came out last year giving a basic exposition of methods of measuring flow. It is a summary-type report with lots of references.

John Ramboz of NBS: I'm interested in the mechanical filters to be used with shock accelerometers. How well do you want it to work, and how much money do you have? This would be a low-pass mechanical filter to keep accelerometer resonance from being excited. Damping would have to play an important role in this design. Common damping materials would not fill the bill because they are temperature and rate sensitive. I recently ran across reference to an experimental manganese-copper alloy. Perhaps this material can be applied for the filter. This material has properties similar to mild steel and may have application as the diaphragm of pressure transducers. I'd like to have any inputs from the audience.

Bunker: I would hate to use damping in any way other than as a protection for the device. I like to do my filtering electronically after the data is acquired. The transducer should be a faithful reproducer of what is there.

Ramboz: Let me cite an example. Velocity measurement is valid to the point where you approach transducer resonance, where distortion sets in. If we can keep from distorting and we know what the filter response characteristics are, then mechanical filtering has advantages.

Thomas: Signal conditioning systems have limited range. If you hit that system with high frequency, high level inputs, you're going to miss the kind of thing you're most interested in. A lot of that is just noise you would like to be rid of. Since you have to make the impedance transfer early in the game, then you must contend with all the noise generated in the signal conditioning. That is a bad time to go into a filtering operation. If you could have a calibrated mechanical filter with a known cut-off, it would simplify the signal conditioning. We have tried in-flight electrical filters and all they did was add to our headaches.

Ramboz: In the case of electrical filtering you're indeed trying to suppress a design fault. Now rather than having a separate piece of hardware as a filter, this ultimately could be designed as part of the base of the accelerometer. When bought, these characteristics would already be accounted for in the design and calibration of the transducer.

Peter Stein, Arizona State University: There are other factors as well. If you allow the transducer to resonate and then filter, you have to be prepared to have twice the linear range normally used, which means half the gain. If you don't do that, the tops of the signal tend to get cut off, and if you filter them, you in effect are averaging a distorted signal. Averaging of a distorted signal results in a distorted average. You cannot recover the data ever again.

Audience: It would appear that the most desirable thing this group could be working on is materials research to be applied to a solution. Design of mechanical filtering is a user's job in a sense. It would seem to me that we are getting into the area of "how do you apply, what do you select, how do you pick a transducer with high enough frequency to do all that?" I'd rather see work on basic materials that would make it possible for us to have better transducers.

Walter: I have a comment on cross-axis sensitivity of accelerometers. We are used to seeing this specified but each manufacturer has his own testing procedure for it. In all the cases I know, it is done with a rectilinear input device with very low frequency and small amplitude levels. In testing such as Douglas Marker has mentioned, a calibration at much higher levels is required. For instance, in measuring gun barrel slap of 1,000 g, the forward acceleration is 10,000 g, and if you have 5% cross-axis sensitivity, then half your desired signal will be noise. We need standards for determining the cross-axis sensitivity of accelerometers specifying both amplitude and frequency at which the test is to be made.

Harry Clarke of NATC: I am concerned with angular measurements in rotation, especially acceleration. There is a deficiency of low range angular accelerometers on the market, and calibration methods could be improved. I would like to see some technique other than gyros developed for angular acceleration.

Thomas: We have needs in a similar area. Angular vibration is becoming increasingly important since we are making measurements for optical systems, of which there is a large proliferation. We are looking into buying several samples of other than conventional angular accelerometers for evaluation.

James Leaney of Kentron-Hawaii: We are just establishing calibration and evaluation capabilities and facilities. I favor the in-situ approach, not the cloistered cell of metrology.

Stein: There are inputs that only you can provide. Various sections of NBS come under review of an evaluation panel once a year. Paul Lederer's group is in the electrical technology division, of which transducers are just a small part. People's knowledgeability in transducers was nonexistent on the panel until a very few years ago. Transducers are probably the least understood element in the whole measurements chain. Any enlightenment you can give people who don't know anything about transducers would be of help to all of us. The more information you can provide in groups such as this, the better your needs will be represented.

Lederer: If you have any kind of problem in calibration or application of transducers, or if you see a need for calibration techniques to meet requirements for measurements, if you can foresee anything like that, it would be useful if you would call me at NBS. We can then come up with the kind of task outline that will be most effective in the future.

At this juncture Charles Thomas polled the attendees to establish priorities on seven of many suggestions generated by the session. In the final program presentation, "Future Task Definition for NBS," he had listed four projects either being or to be considered as tasks for the NBS transducer group. Thomas enumerated nine additional potential projects which had been suggested in the course of the session.

PRIORITY BY VOTES			ITEMS	
1st	2nd	3rd		
8	3	1	A.	We need more variety of choice in low range angular accelerometers.
7	4	3	B.	Standard method for testing cross-axis sensitivity of accelerometers at high frequencies and amplitudes.
5	10	7	C.	Damping of resonant transducers (mechanical filters).
4	5	16	D.	Portable on-site semiautomatic calibration systems.
0	5	2	E.	Evaluate transducer performance limits imposed by integral electronics.
2	1	1	F.	Better dissemination of information on flow measurement and system design.
1	1	1	G.	Instrumentation of artillery projectiles.

ITEMS NOT POLLED

H. Develop protection schemes for pressure transducers in thermal transient environments.

I. Recommended method for calibration and evaluation of velocity transducers.

J. Use of logarithmic amplifiers versus automatic gain changing amplifiers.

K. Effects of line pressure on performance of low differential range pressure transducers.

L. Adoption of recommended test methods for the effects of thermal transients.

M. Investigate problems of high g acceleration of rotating systems and signal retrieval (slip rings, near-field telemetry, etc.)

Pat Walter asked the audience for help by correspondence in the transducer committee's work of defining tasks and identifying problems. In closing the session he expressed appreciation to members of the committee and also to all the people who worked on the Workshop. A special vote of thanks was given to Charles Thomas, our host, for the smooth and efficient operation of all the Workshop accommodations, and to Pierre Fuselier, our chairman, for a very productive Workshop.

END EIGHTH TRANSDUCER WORKSHOP

22 April 1975

REPLY TO ATTN OF: William D. Anderson, Transducer Committee, Telemetry Group (TG)
Technical Support Directorate
Naval Air Test Center, Patuxent River, Maryland 20670

SUBJECT: Directory of Transducer Users

TO: Transducer Users

The Transducer Committee of the Telemetry Group/Range Commanders Council coordinates transducer activities between national test ranges, range users, RDT&E activities of DOD, and aerospace contractors.

The first Directory of Transducer Users was published during July 1973. The directory was published to promote the exchange of information between transducer users with common problems. The Transducer Committee is planning to publish a revision of the directory during 1975.

It is requested that you fill out the enclosed form listing one or more key employees at your activity engaged in transducer activities. This can include transducer users or personnel involved in transducer calibrations or evaluations. In each case, it is requested that the names listed not be higher level management personnel, but those most directly responsible for transducer applications at your activity. Those listed in the 1973 printing of the directory should submit a form indicating that the information in the directory is correct or making corrections where necessary.

A completed sample is enclosed to assist you in filling out the form. It is requested that the submission be returned by 2 July 1975.

Very truly yours,

William D. Anderson

William D. Anderson
Transducer Committee, TG
Phone (301) 863-4271
Autovon 356-4271

SAMPLE

DIRECTORY OF TRANSDUCER USERS

ACTIVITY: Sandia Laboratories, Albuquerque, N.M.

TRANSDUCER CONTACTS:

	(1)	(2)
Name	P. L. Walter	L. L. Lathrop
Address	Sandia Laboratories	Sandia Laboratories
	Division 7511	Division 7511
	P. O. Box 5800	P. O. Box 5800
	Albuquerque, N.M. 87115	Albuquerque, N.M. 87115
Phone	AC 505 265-5785	AC 505 265-5785
Autovon	(FTS) 843-2520	(FTS) 843-2520

TRANSDUCER CONTACT FUNCTIONS:
Calibrator X Evaluator X User ___ Other Consultant

SUMMARY OF USAGE:

Sandia Laboratories Albuquerque instruments a variety of components/assemblies for design verification testing. These component/assemblies include electro-mechanical devices, mechanical structures, projectiles, parachutes, etc. Test environments utilized are vibration exciters, centrifuges, drop towers, ballistics, rocket sleds, sheet explosives, flyer plates, shock tubes, and underground nuclear detonations. Both radio link and hard wire telemetry are employed.

SPECIAL EXPERTISE, FACILITIES, COMMENTS:

Sandia Laboratories Albuquerque makes a large quantity of acceleration measurements in impact type environments where levels in the ten's of thousands of g's are frequently encountered. Some knowledge is also present in measuring blast and ballistic type pressure environments where very short pressure rise times are encountered and pressure levels from a few hundred to ten's of thousands of psi are experienced.

(Use Back For Additional Contacts or Comments)

SAMPLE

DIRECTORY OF TRANSDUCER USERS

ACTIVITY: ____________________

TRANSDUCER CONTACTS:

Name (1) ____________________ (2) ____________________

Address ____________________ ____________________

____________________ ____________________

____________________ ____________________

____________________ ____________________

Phone ____________________ ____________________

Autovon ____________________ ____________________

TRANSDUCER CONTACT FUNCTIONS:

Calibrator ___ Evaluator ___ User ___ Other ____________________

SUMMARY OF USAGE:

____

SPECIAL EXPERTISE, FACILITIES, COMMENTS:

____

(Use Back For Additional Contacts or Comments)

EIGHTH TRANSDUCER WORKSHOP

(22-24 APRIL 1975)

1. Are you aware of any other standards, concerning transducers, which have not been listed in RCC 106?

2. Are there any transducer related areas in which you think standards are needed? (Describe)

3. After having reviewed RCC 118, are there any recommended changes or additions?

4. Are you aware that the Directory of Transducer Users was published in 1973?

5. Do you wish to be included in an up-date of this directory? If so, please provide the required following information:

   Name ______________________________

   Address ____________________________

   Phone Number _______________________

   Type of Transducers __________________

6. Are you willing to serve on a review board for transducer related standards generated by the Transducer Committee? If so, provide name and address and check area of expertise/interest.

   ______ Charge Amplifiers

   ______ RCC 118/Transducer Board Sys. Calibration

   ______ dc Amplifiers

   ______ Excitation Power Supplies

7. What would you like to see covered in the next Transducer Workshop?

8. Comments: (Additional items of concern, in areas of test and evaluation of transducers, for the Transducer Committee. New areas of need such as combined transducer/amplifier.)

9. Items either being, or to be considered as products by NBS. (Add any additional items.)

A. Develop a thermal transient test method for investigating the effect of short duration thermal transients on pressure transducers.

B. Develop protection schemes for pressure transducers to mitigate the effects of thermal transients without degrading the dynamic performance of the transducers.

C. Develop mechanical filters for shock accelerometers to prevent data degradation from spurious shock excited resonances.

D. Develop methods for evaluating the effects of line pressures on the performance characteristics of differential pressure transducers.

E. Develop methods for evaluating the performance limitations imposed by the presence of integral semiconductor signal conditioning in transducers.

Return completed questionaire by 1 June 1975 to:

CHARLES E. THOMAS
AFFDL/FYT
WPAFB, OHIO 45433

APPENDIX A

REPORT ON ACTIVITIES OF THE INTERAGENCY TRANSDUCER PROJECTS GROUP OF NBS

APPENDIX A

REPORT ON ACTIVITIES OF THE INTERAGENCY TRANSDUCER PROJECTS GROUP OF NBS

Edited by Pierre F. Fuselier, Workshop General Chairman

Report* on activities of the Interagency Transducer Projects Group of NBS by Paul Lederer.

1. Highlights of the oral presentation.
2. Illustrations of equipment.
3. Summary report for Executive Committee, TG/RCC, 5 February 1975

*[NOTE: this report was originally designed by the author for verbal presentation. The editor felt that its content warranted wider distribution.]

NBS INTERAGENCY TRANSDUCER PROJECT

PROJECT ESTABLISHED: 1951

SPONSORS

- NAVY	BUREAU OF AERONAUTICS NAVAL AIR SYSTEMS COMMAND NAVAL AIR TEST CENTER
- ARMY	WHITE SANDS MISSILE RANGE ABERDEEN PROVING GROUND
- AIR FORCE	WRIGHT AIR DEVELOPMENT CENTER ARMAMENT DEVELOPMENT AND TEST CENTER
- NASA	OFFICE FOR ADVANCED RESEARCH AND TECHNOLOGY

OBJECTIVES

- INVESTIGATE THE PERFORMANCE CHARACTERISTICS OF ELECTROMECHANICAL TELEMETERING TRANSDUCERS REQUIRED FOR MEANINGFUL MEASUREMENTS OF PHYSICAL QUANTITIES
- DEVELOP TECHNIQUES AND APPARATUS FOR THE DETERMINATION OF THOSE CHARACTERISTICS
- DISSEMINATE EFFECTIVELY THE KNOWLEDGE OBTAINED THROUGH PUBLICATIONS AND PARTICIPATION IN TRANSDUCER STANDARDIZATION ACTIVITIES

SOURCES OF FUNDING

- JOINTLY SUPPORTED NBS INTERAGENCY TRANSDUCER PROJECT
- NBS STRS CONTRIBUTION

STAFF

- FOUR PROFESSIONALS

NBS INTERAGENCY TRANSDUCER PROJECT

DIRECTIONS OF PROJECT EFFORT

MEASUREMENT METHOD FOR:

- DYNAMIC CHARACTERISTICS
- ENVIRONMENTAL EFFECTS
- RELIABILITY AND DURABILITY
- NEW PRINCIPLES AND IMPROVED MATERIALS - FEASIBILITY
- VOLUNTARY PERFORMANCE AND EVALUATION STANDARDS
- EVALUATION OF NEW TRANSDUCERS

OUTPUTS

- 13 NBS TECHNICAL NOTES
- 7 PAPERS
- 53 PERFORMANCE TEST REPORTS
- 1 PATENT
- 4 STANDARDS
- 1 RECOMMENDED PRACTICE
- 8 TALKS
- 2 TRANSDUCER WORKSHOPS
- PARTICIPATION IN 8 STANDARDS COMMITTEES
- NBS-DEVELOPED TECHNIQUES IN USE AT 12 LABORATORIES

NBS INTERAGENCY TRANSDUCER PROJECT

USE OF PROJECT RESULTS

DEVICE	UTILIZATION
STEP-FUNCTION PRESSURE CALIBRATOR	NASA LANGLEY RESEARCH CENTER SANDIA LABORATORY GENERAL MOTORS RESEARCH LABORATORY NAVAL AIR TEST CENTER
EARTH'S FIELD DYNAMIC ACCELEROMETER CALIBRATOR	NAVY METROLOGY ENGINEERING CENTER NAVAL AIR TEST CENTER
SHOCK TUBE FOR PRESSURE TRANSDUCER EVALUATION	GENERAL DYNAMICS/FORT WORTH NAVAL PROVING GROUND
HYDRAULIC SINUSOIDAL PRESSURE CALIBRATOR	NASA LANGLEY RESEARCH CENTER NASA MARSHALL SPACE FLIGHT CENTER
DUAL CENTRIFUGE	AVAILABLE COMMERCIALLY FROM TWO MANUFACTURERS

HIGHLIGHTS OF FY 1974

MEASUREMENT METHOD DEVELOPMENT AND APPLICATION:

- INITIATED DEVELOPMENT OF THERMAL TRANSIENT TESTER FOR PRESSURE TRANSDUCERS

STANDARDIZATION AND DISSEMINATION:

- DRAFTED SECTION OF ANSI GUIDE FOR STATIC CALIBRATION OF PRESSURE TRANSDUCERS
- REVIEWED OTHER SECTIONS OF ANSI GUIDE
- DRAFTED SECTION OF TG/RCC TRANSDUCER-BASED END-TO-END CALIBRATION STANDARDS
- REVIEWED OTHER SECTIONS OF TG/RCC STANDARDS
- REVISED ISA STANDARD ON POTENTIOMETER PRESSURE TRANSDUCERS

NBS INTERAGENCY TRANSDUCER PROJECT

CURRENT PROGRAM

FY 1975

MEASUREMENT METHOD DEVELOPMENT AND APPLICATION

- COMPLETE DEVELOPMENT OF THERMAL TRANSIENT TESTER FOR PRESSURE TRANSDUCERS
- INITIATE DETERMINATION OF BASIS FOR PRESSURE TRANSDUCER PROTECTION AGAINST THERMAL TRANSIENTS
- INITIATE DEVELOPMENT OF EVALUATION TECHNIQUES TO ASSESS EFFECTS OF THERMAL TRANSIENT PROTECTION ON PRESSURE TRANSDUCER PERFORMANCE

STANDARDIZATION AND DISSEMINATION

- REVISE ANSI GUIDE FOR STATIC CALIBRATION OF PRESSURE TRANSDUCERS
- REVISE TG/RCC TRANSDUCER-BASED END-TO-END CALIBRATION STANDARDS
- RE-AFFIRM ISA STANDARD ON POTENTIOMETER PRESSURE TRANSDUCERS
- PARTICIPATE IN TRANSDUCER WORKSHOP OF TELEMETRY GROUP, RANGE COMMANDERS COUNCIL

FUTURE ACTIVITIES

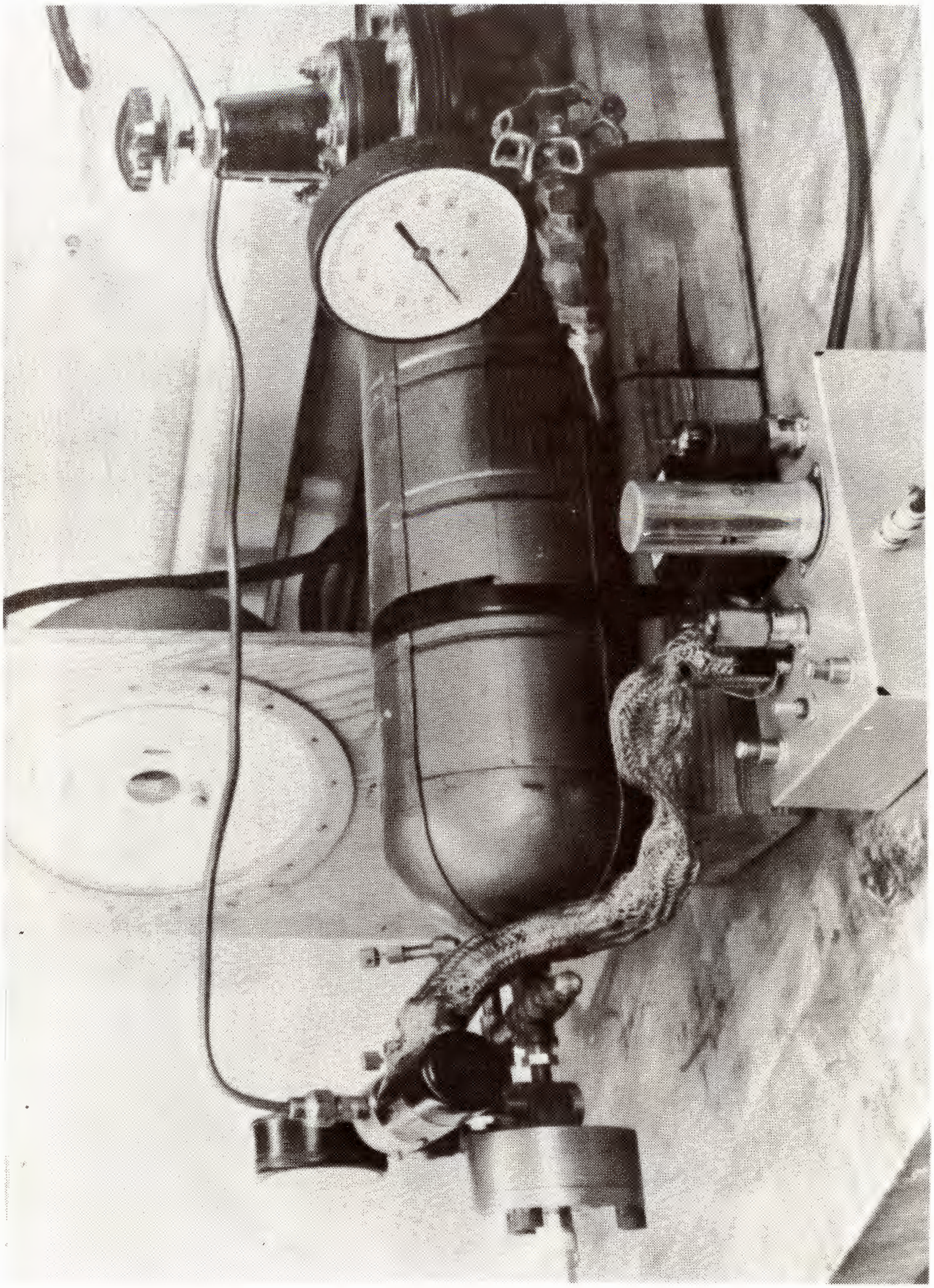
FY 1976

MEASUREMENT METHOD DEVELOPMENT AND APPLICATION

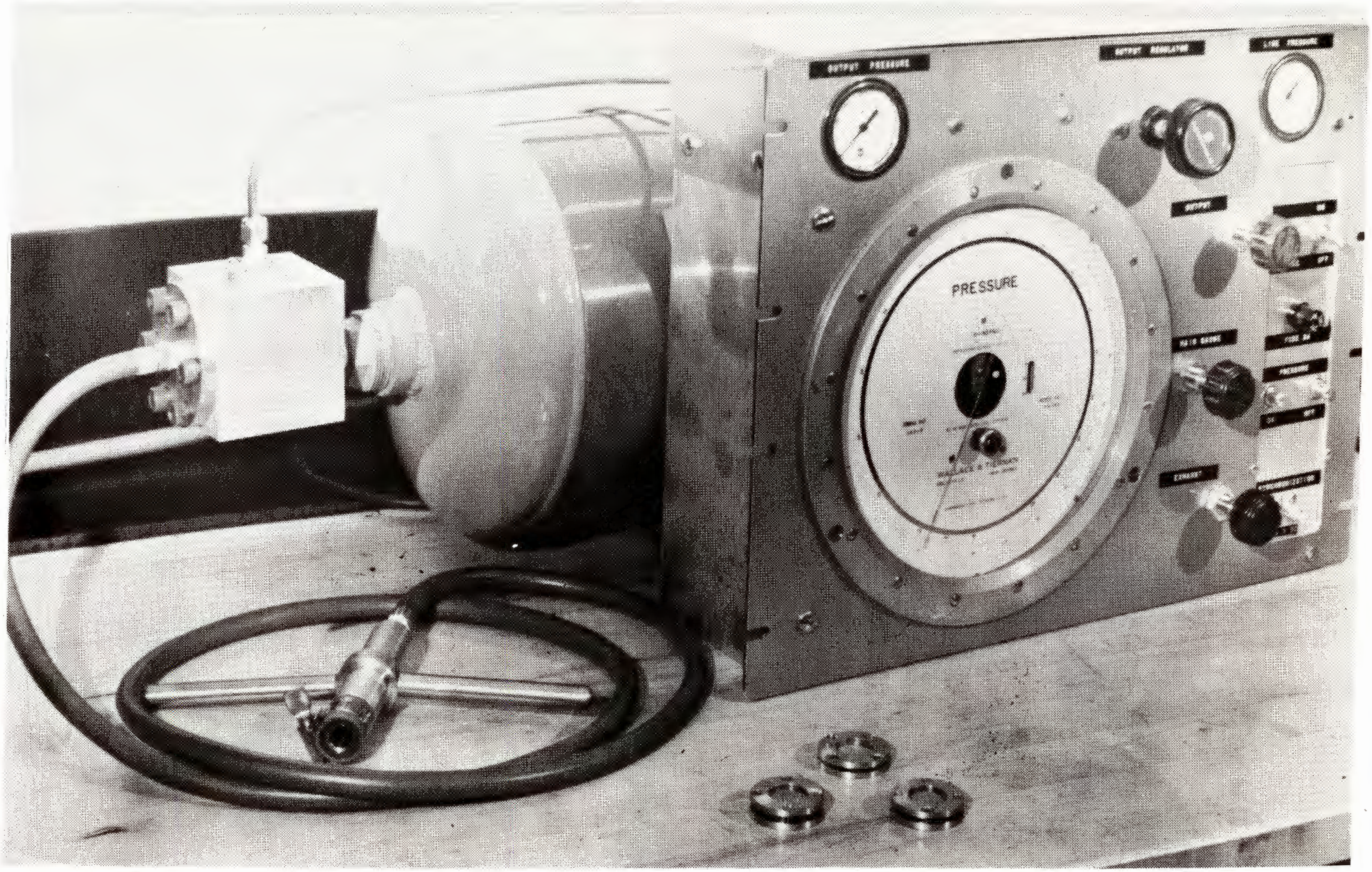
- CONTINUE DETERMINATION OF BASIS FOR PRESSURE TRANSDUCER PROTECTION AGAINST THERMAL TRANSIENTS
- CONTINUE DEVELOPMENT OF EVALUATION TECHNIQUES TO ASSESS EFFECTS OF THERMAL TRANSIENT PROTECTION ON TRANSDUCER PERFORMANCE
- INITIATE EVALUATION OF THERMAL TRANSIENT PROTECTION FOR PRESSURE TRANSDUCERS
- INITIATE DEVELOPMENT OF METHODS FOR THE CALIBRATION OF LOW RANGE DIFFERENTIAL PRESSURE TRANSDUCERS AT HIGH LINE PRESSURES
- INITIATE DEVELOPMENT OF MECHANICAL FILTERING SCHEMES FOR ACCELEROMETERS

STANDARDIZATION AND DISSEMINATION

- PUBLISH FINAL REPORT ON THERMAL TRANSIENT TESTER FOR PRESSURE TRANSDUCERS
- CONTINUE PARTICIPATION IN ANSI AND ISA STANDARDIZATION ACTIVITIES



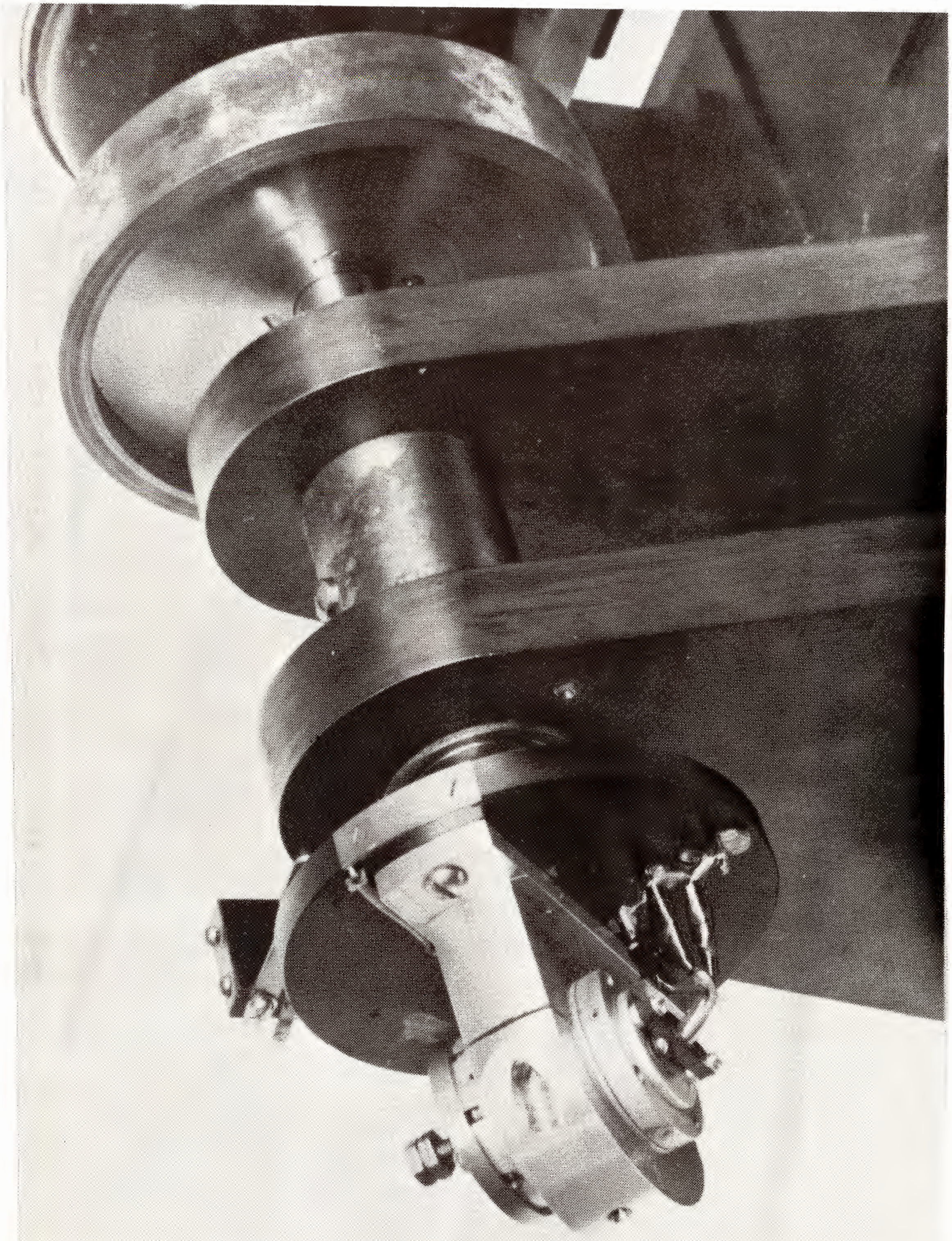
PROTOTYPE PNEUMATIC STEP FUNCTION PRESSURE CALIBRATOR



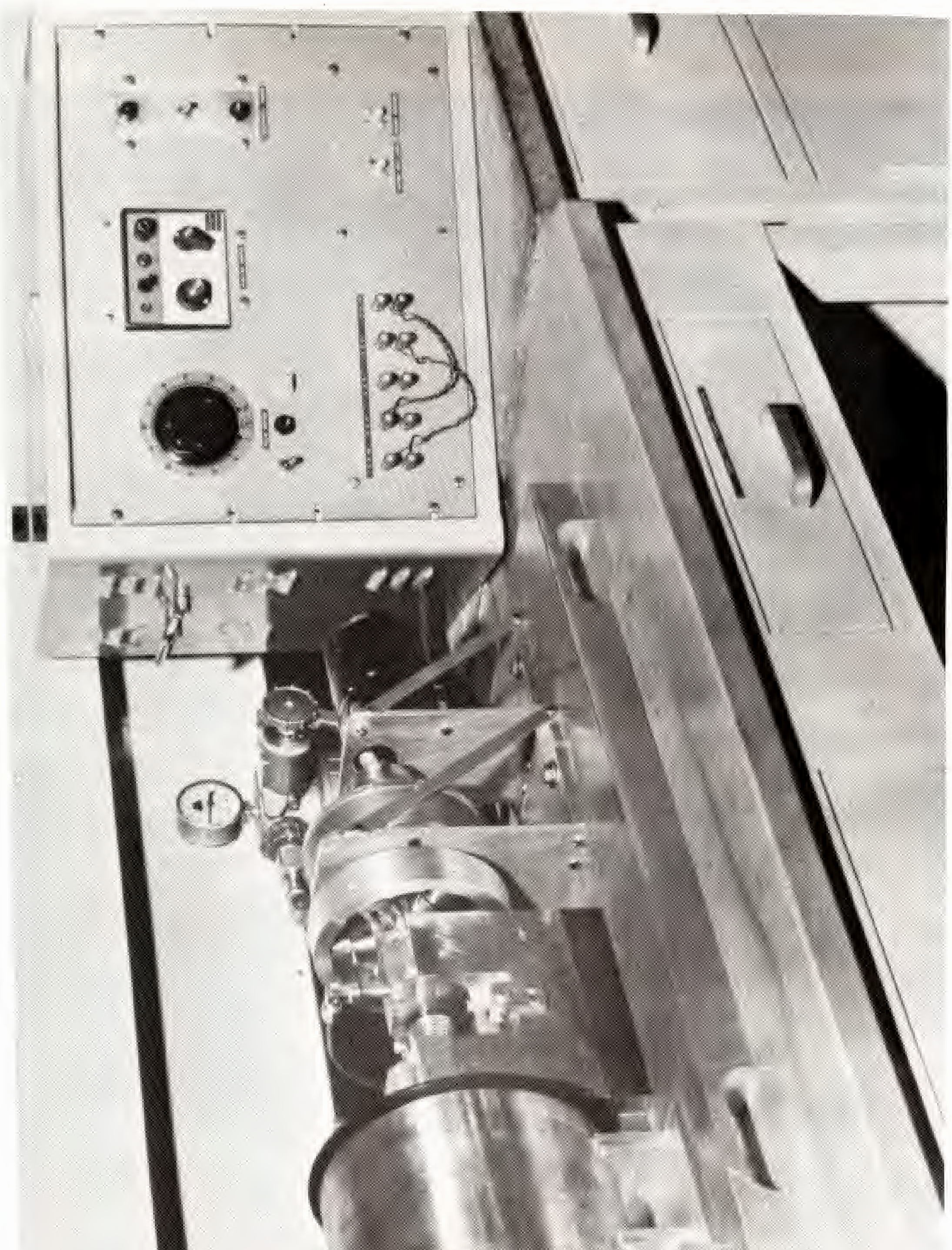
IMPROVED PNEUMATIC STEP FUNCTION PRESSURE CALIBRATOR

PROTOTYPE EARTH'S FIELD STATIC CALIBRATION FOR ACCELEROMETERS

IMPROVED EARTH'S FIELD STATIC CALIBRATOR FOR ACCELEROMETERS



PROTOTYPE EARTH'S FIELD DYNAMIC CALIBRATION FOR ACCELEROMETERS



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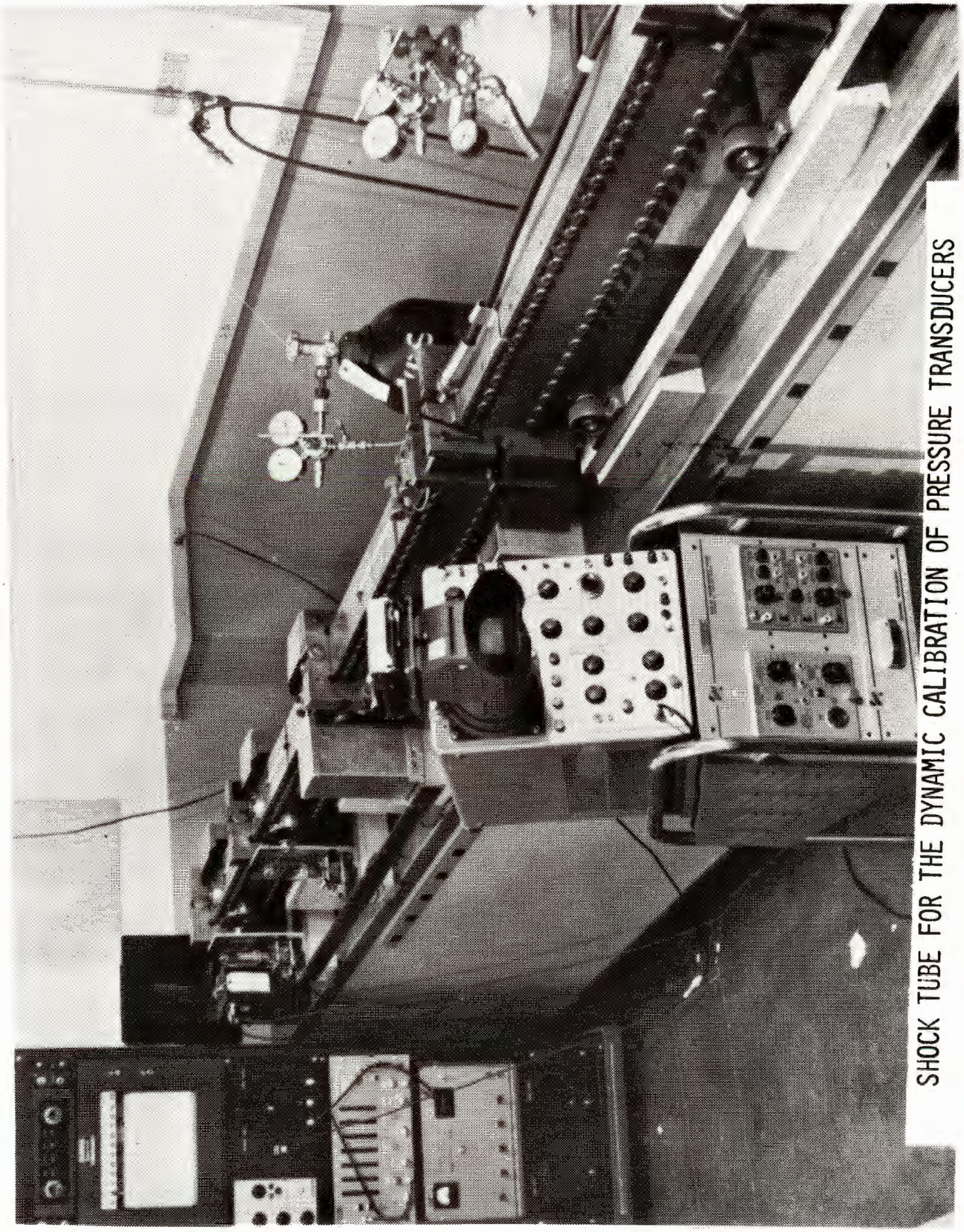
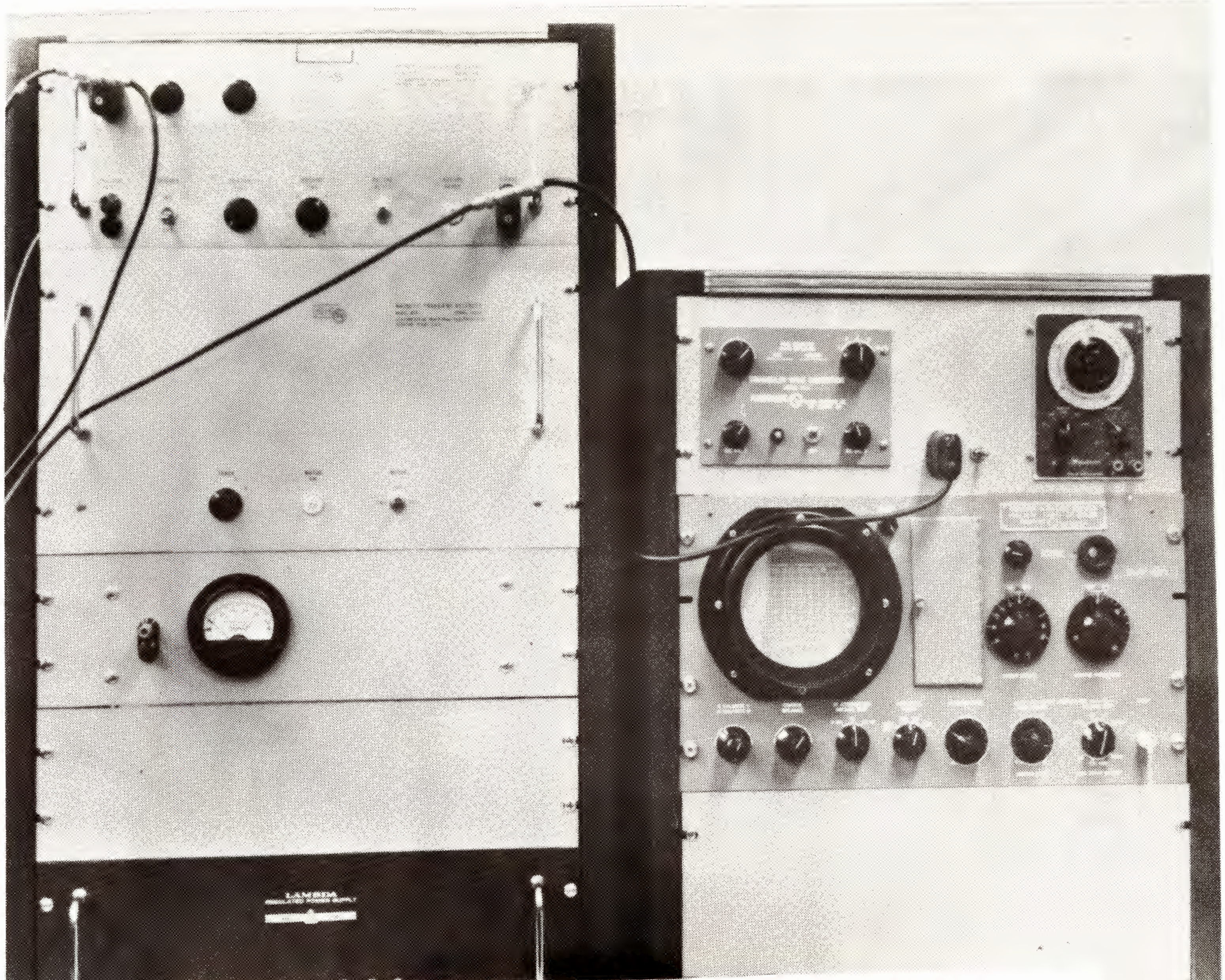
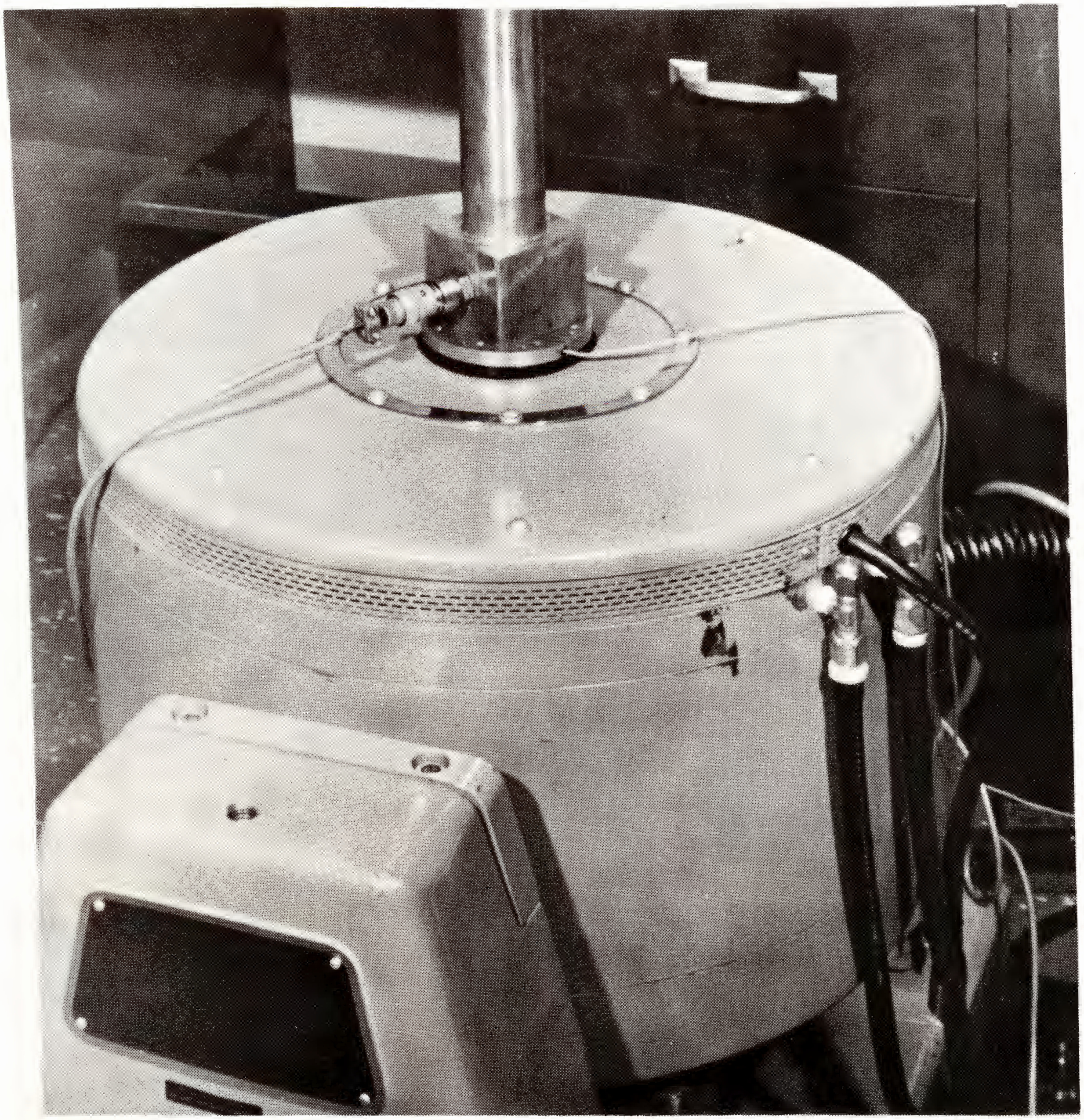


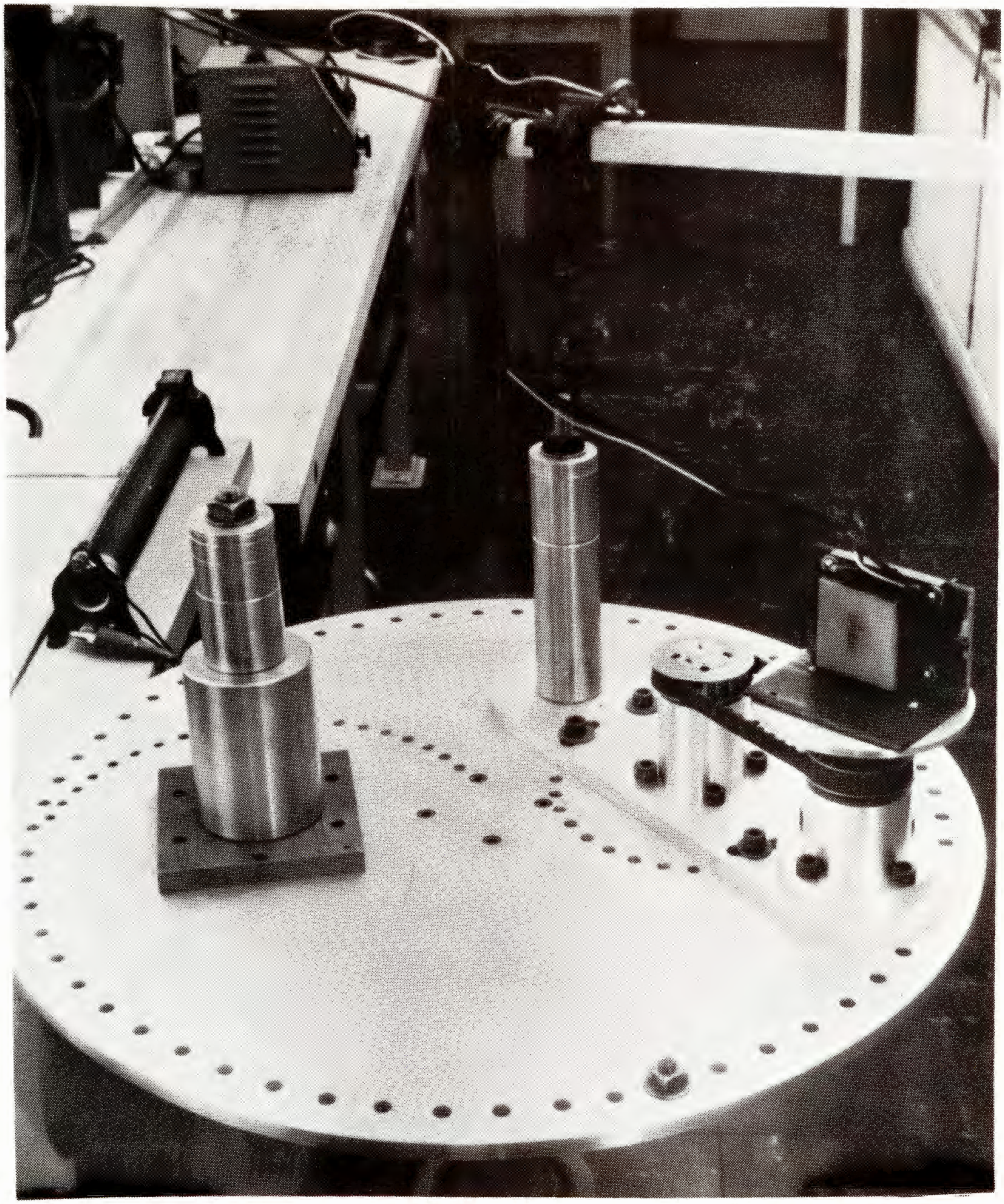
SHOCK TUBE FOR THE DYNAMIC CALIBRATION OF PRESSURE TRANSDUCERS



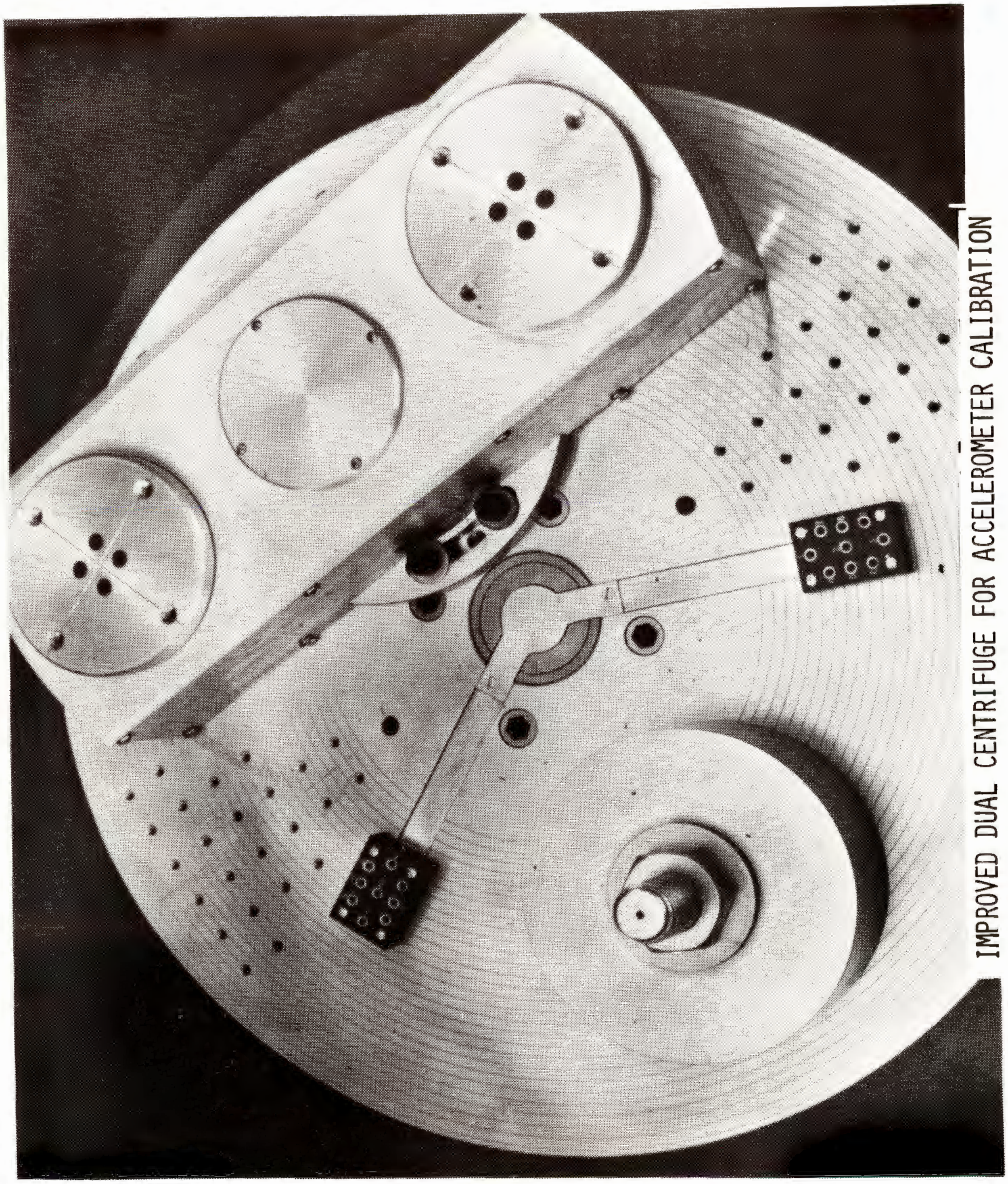
TRANSIENT RECORDER AND FREQUENCY ANALYZER FOR THE DETERMINATION OF THE DYNAMIC CHARACTERISTICS OF PRESSURE TRANSDUCERS



PROTOTYPE HYDRAULIC SINUSOIDAL CALIBRATOR FOR PRESSURE TRANSDUCERS



PROTOTYPE DUAL CENTRIFUGE FOR ACCELEROMETER CALIBRATION



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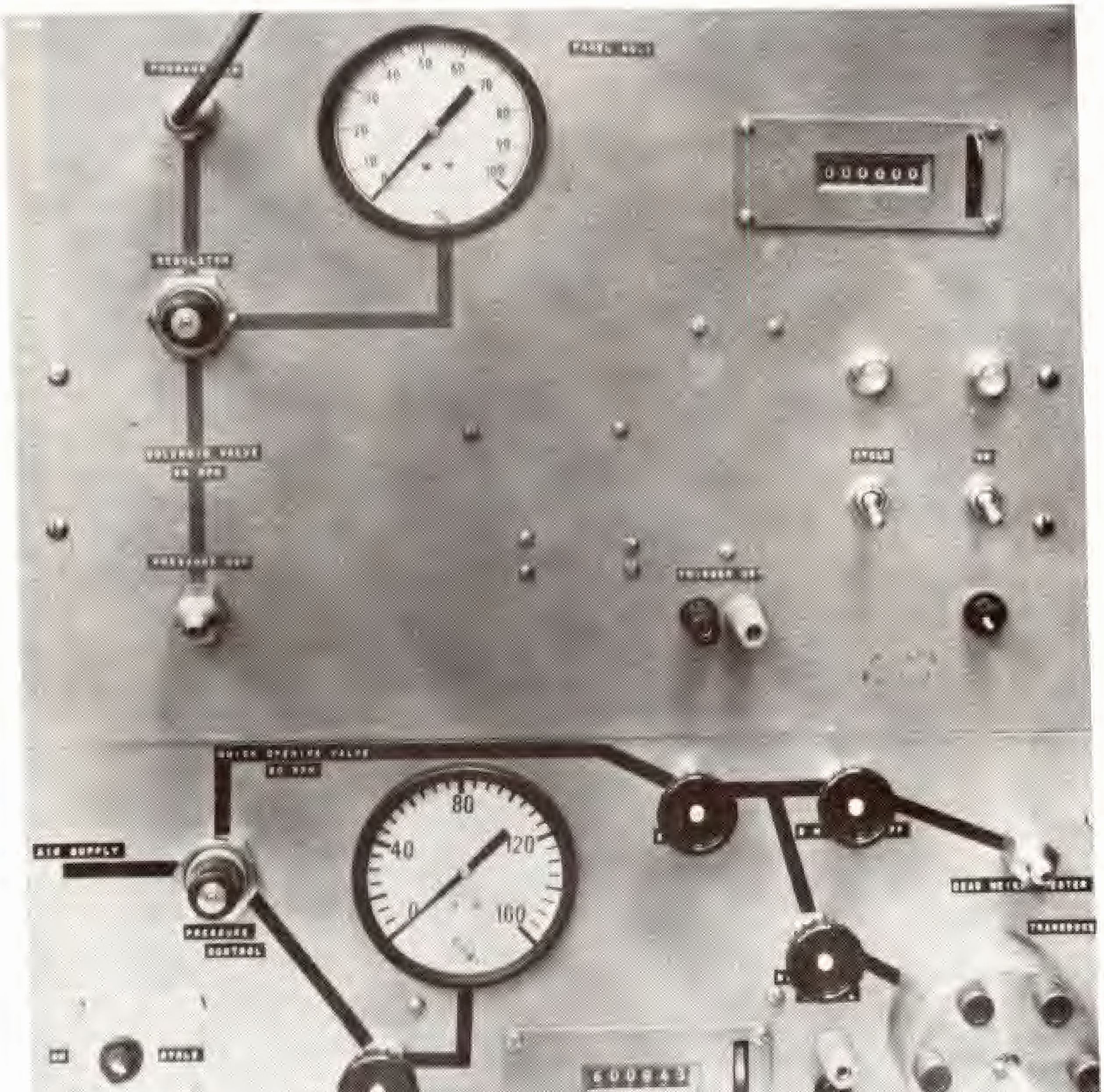
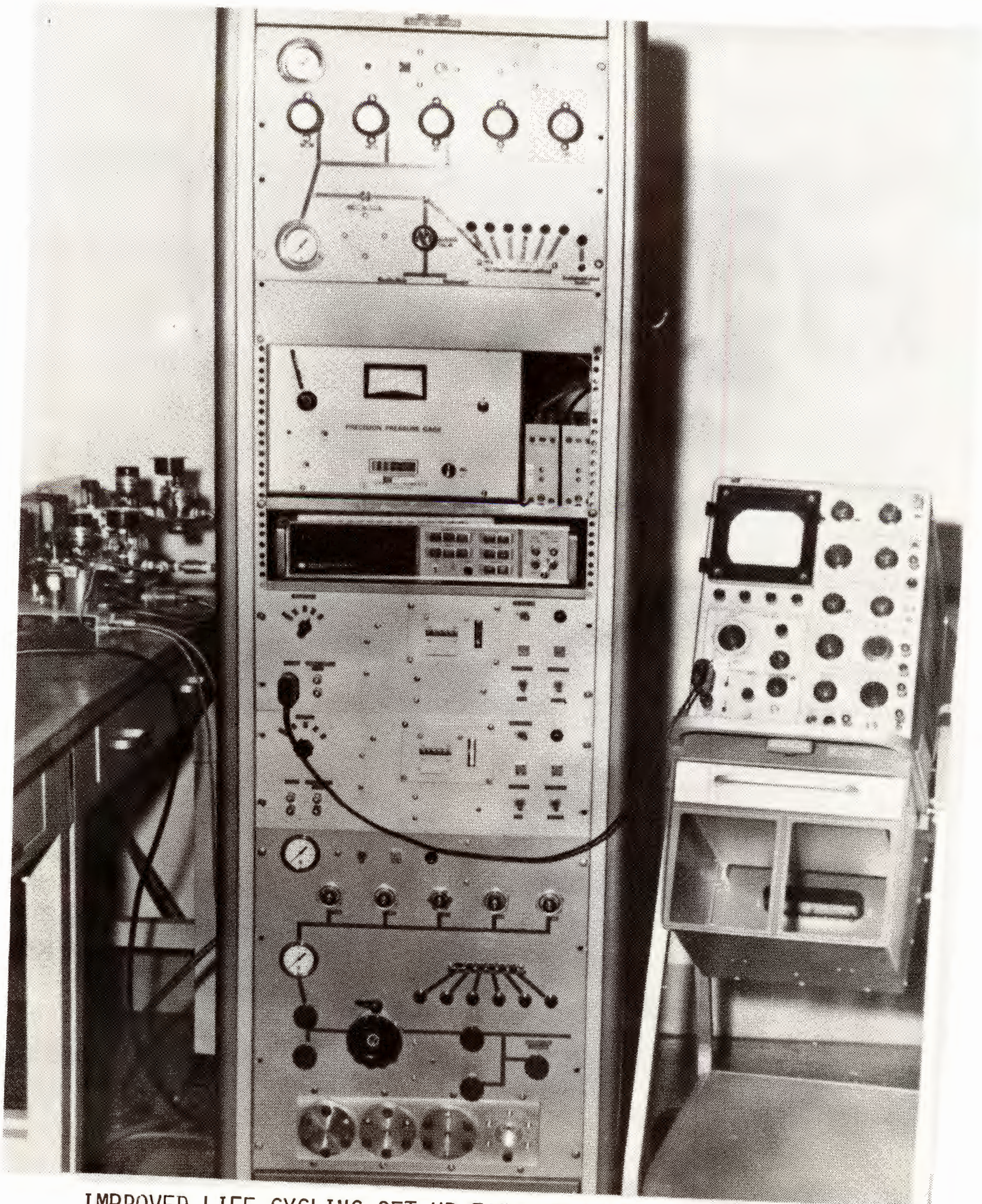
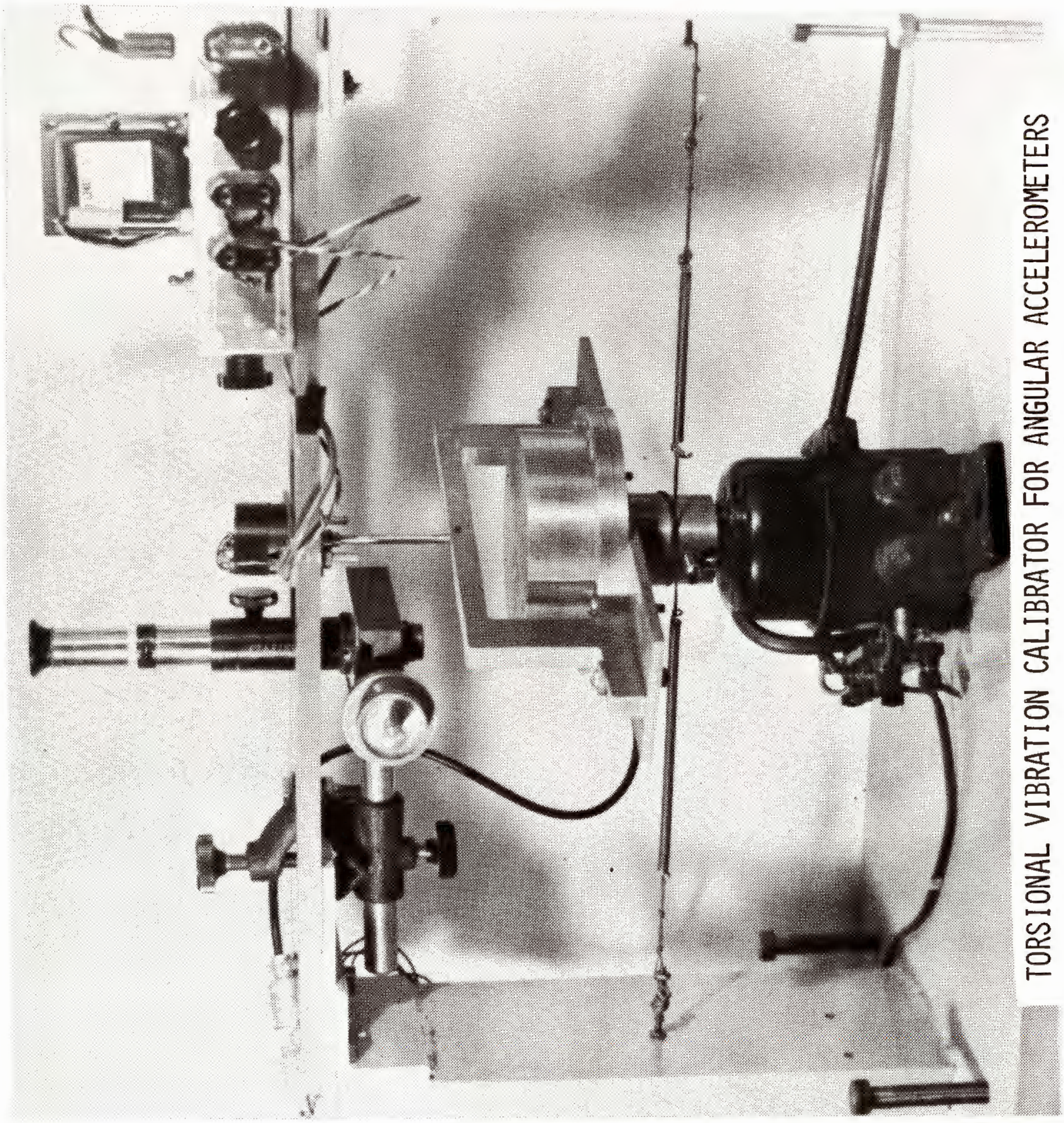


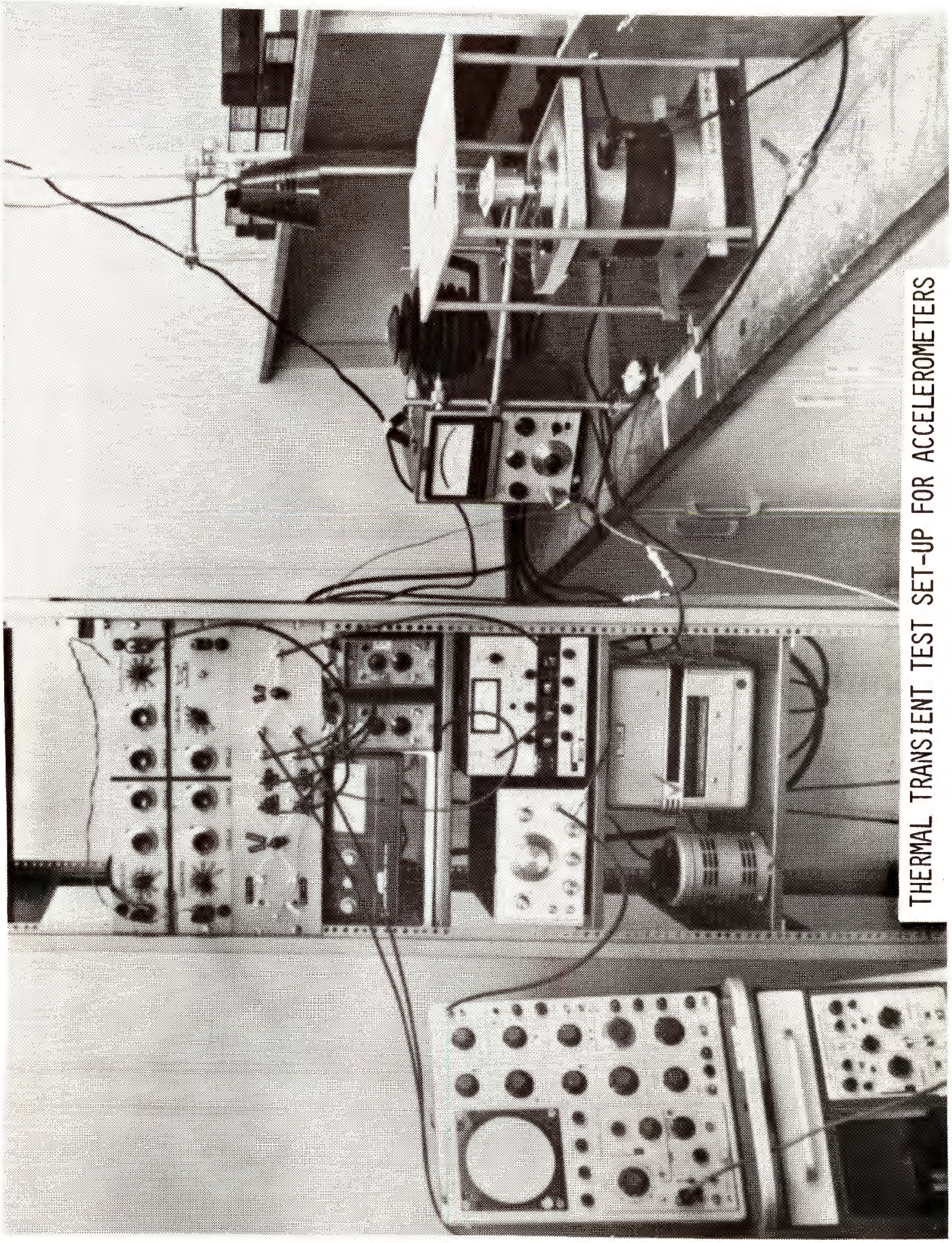
PROTOTYPE LIFE CYCLING SET-UP FOR PRESSURE TRANSDUCERS



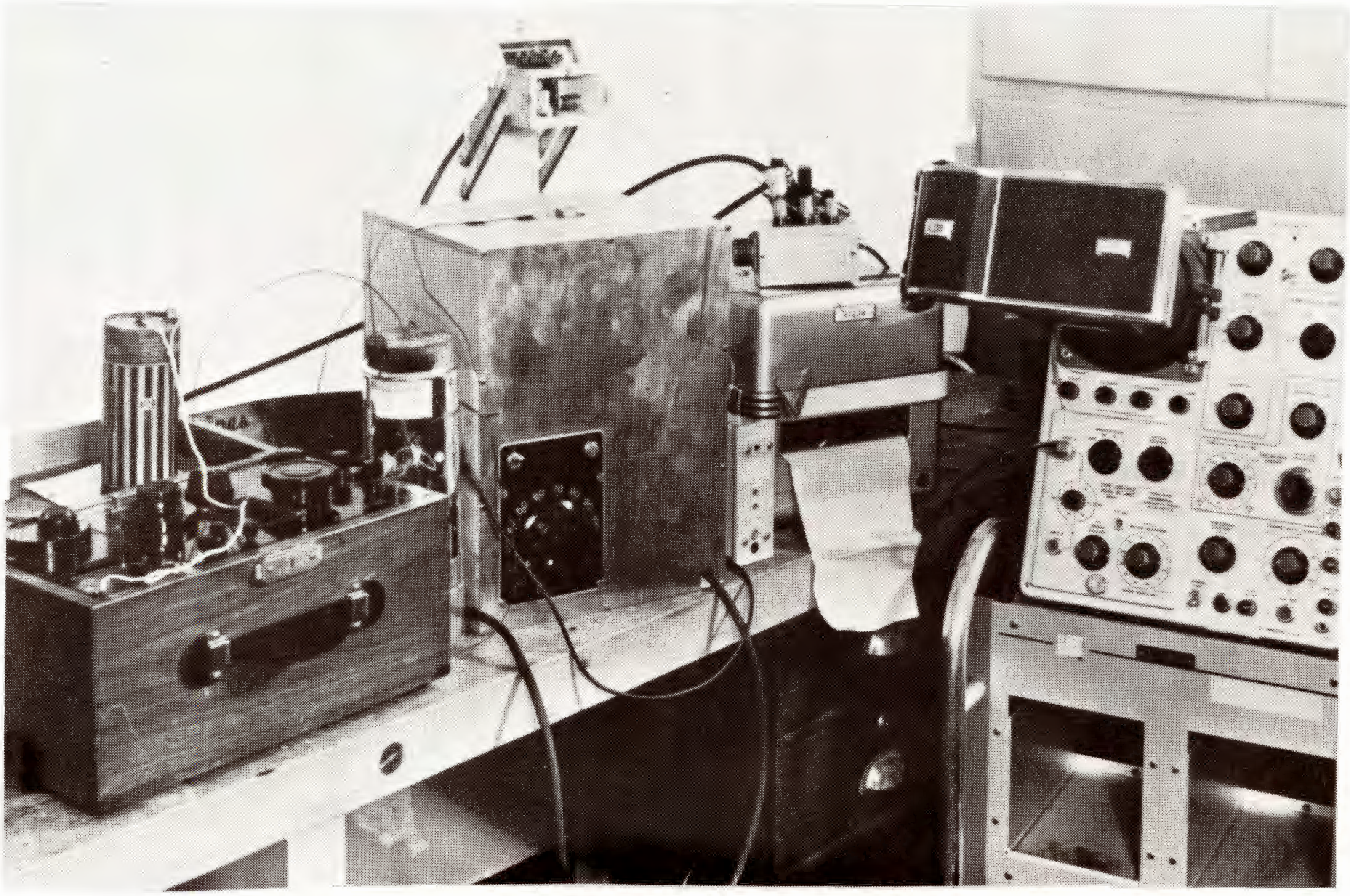
IMPROVED LIFE CYCLING SET-UP FOR PRESSURE TRANSDUCERS



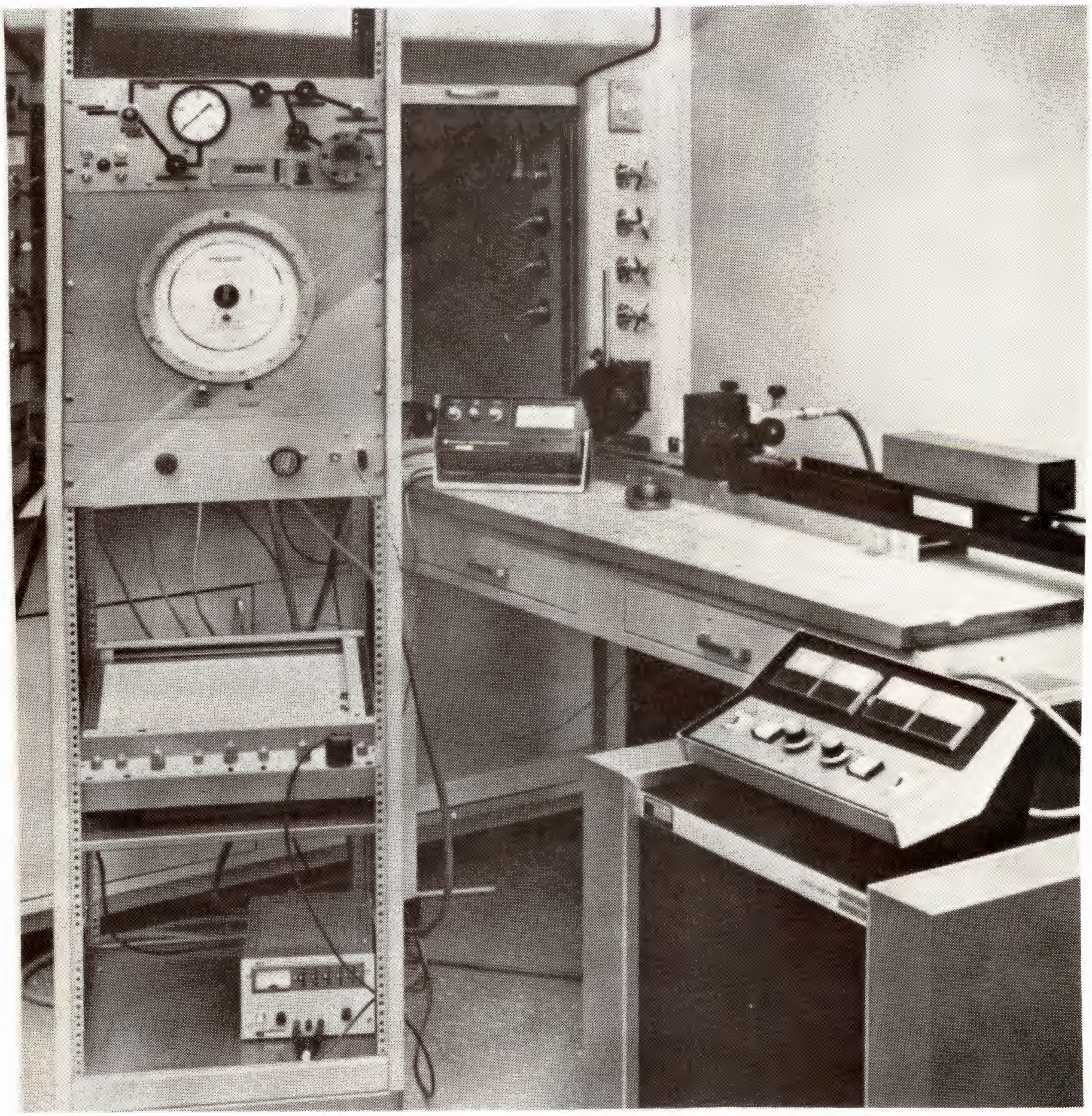
TORSIONAL VIBRATION CALIBRATOR FOR ANGULAR ACCELEROMETERS



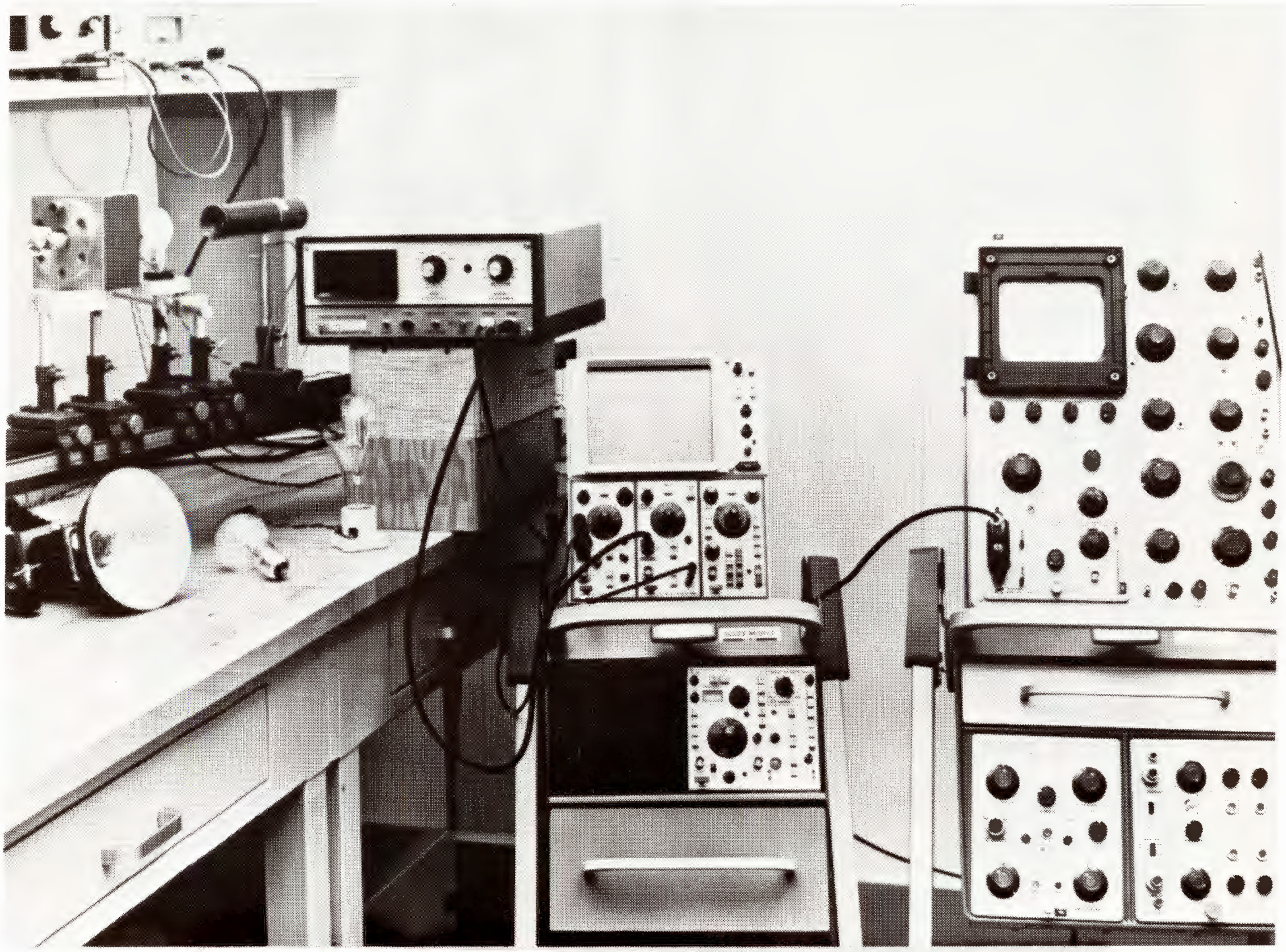
THERMAL TRANSIENT TEST SET-UP FOR ACCELEROMETERS



PROTOTYPE THERMAL TRANSIENT TESTER FOR PRESSURE TRANSDUCERS



IMPROVED THERMAL TRANSIENT TESTER FOR PRESSURE TRANSDUCER



FLASHBULB THERMAL TRANSIENT TEST SET-UP FOR PRESSURE TRANSDUCERS

National Bureau of Standards

NBS Interagency Transducer Project

Notes for

Summary Report

For Executive Committee, TG/RCC

Report Number 174

February 5, 1975

This is a progress report. The work is incomplete and is continuing. Results and conclusions are not necessarily those that will be included in a final report. Performance test data were obtained from one or two samples of several transducer types, and do not necessarily represent the characteristics of all transducers of a given type.

Funding: NAVAIR SYSCOM Purchase Request N00019-75-IP-59001
White Sands Missile Range (Supplemental Funding)

NBS Interagency Transducer Project

1. Current Assignment

The Transducer Committee of TG/RCC has assigned the following task to the NBS InterAgency Transducer Project: "Develop a test device and generate a test procedure to impinge thermal transient inputs on pressure transducers. The requirements of the test device should include:

a. Inexpensive to build;
b. Simple to operate;
c. Easily reproducible by transducer manufacturers, test ranges, or range users;
d. Capable of impinging thermal transients of any duration greater than 1 millisecond;
e. Controlled heat flux inputs capable of being quantized.

Documentation of this test procedure and the devices constructed should be formalized in report form. In addition, this report should relate the heat flux capabilities of the test device to actual thermal transient environments. Quarterly progress reports should be submitted to the TG Transducer Committee."

2. Experimental Method and Apparatus

A method for generating and applying thermal transients to pressure transducers was described in an oral presentation to the Executive Committee TG and to the Transducer Committee at the July 1974 TG/RCC meeting. The method in brief consists of exposing the pressure transducer to radiation resulting from the ignition of a photographic flashbulb or from the discharge of an electronic flash while monitoring transducer output.

The experimental arrangement is as follows: The flashbulb or flashtube is mounted in a vertical position at the center of an optical bench; mounted on the bench on opposite sides are an energy meter and the transducer mounting fixture. The diaphragm of the mounted pressure transducer and the sensing element of the energy meter are aligned with and equidistant from the center of the flash unit. The energy meter and transducer may be moved along the bench to vary the respective distances between them and the flash unit, which is held fixed. Also fixed in position is a photodiode mounted at right angles 15 cm from the bench center and used as a flash output monitor to check the operation of the energy meter. All four elements are adjusted in position vertically to be coplanar.

In a test the quantities monitored are as follows: (a) the output of the pressure transducer displayed on an oscilloscope, (b) the digital reading of the energy meter (which displays the total pulse energy in joules, (c) the energy meter output displayed on an oscilloscope (peak amplitude is proportional to the energy input), and (d) the photodiode output also displayed on an oscilloscope.

3. Experimental Results

When the energy meter and electronic flash were received in September 1974, experimental work began. Most of the work was exploratory in nature to determine parameters for future experiments.

The approximate amount of energy available from the electronic flash at the 150-W·s setting was measured with the energy meter a few cm away from the flash (within the range over which there was little variation observed with change in meter-flash distance). A level of from 0.3 J to 0.4 J was measured by the 1-cm^2 circular sensing area of the energy meter. Using the same experimental arrangement with a #22 flashbulb, approximately 1 J was measured.

A number of tests were conducted to establish the repeatability of the flash energy from various sources. The standard deviation for repeated flashes from the electronic flash was found to be about 2%, for the photo flash bulbs about 5%.

An energy-distance investigation showed that the data obtained follow closely the well-known inverse square law governing radiation from a point source.

These tests indicated that energy levels ranging up to 2 J could be obtained with this test method using #22 flash bulbs, about 800 mJ using #5 bulbs, and about 100 mJ using the electronic flash, at distances of 6 to 7 cm. The minimum working distance is set by the location of the sensing element of the energy meter, which is located inside a protective shroud 2.5 cm from the front aperture in the shroud and by the distance from the outside of the flash bulb to its center line.

An investigation of the duration of the thermal transients from various sources showed values of about 6 ms for the electronic flash and 29 ms and 37 ms for two type of photoflash bulbs.

A transducer was tested using the method described. The maximum transducer zero shift observed amounts to roughly 0.027% FS/mJ, and 0.031% FS/mJ, and 0.029% FS/mJ for electronic flash, #5 and #22 flash bulbs, respectively, for transducer X, a flush diaphragm semiconductor.

These results suggest that the transducer response to a thermal transient is directly proportional to the energy content of the transient and that transient duration has little bearing on the response.

4. Future Plans

In addition to tests on sixteen commercial pressure transducers representing seven different models, the following experiments are planned:

a. Measurement of the response of selected transducers to energy incident at an angle other than normal to the exposed surface

b. Measurement of the response of selected transducers with the transducer itself measuring full-scale pressure
c. Measurement of the response of selected transducers with the transducer itself measuring vacuum pressure
d. Measurement of the energy transmission loss through a glass window.
e. Determination of the effect of aperture size on the energy measurement
f. Measurement of the effect of line-voltage changes on electronic flash energy
g. Measurement of the effect of battery-voltage changes on flashbulb energy

h. Measurement of the output of selected semiconductor strain-gage pressure transducers when exposed to thermal transients and with no transducer (electrical) excitation

PUBLICATIONS 1974-75

1. Lederer, P.S.; Development of a Dynamic Pressure Calibration Technique - A Progress Report, NBSIR 73-290 (October 15, 1973).

2. Vezzetti, C.F., Lederer, P.S., and Hilten, J.S.; Development of a Dynamic Pressure Calibration Technique - A Progress Report, NBSIR 74-503(R) (June 15, 1974).

3. Hilten, J.S., and Lederer, P.S.; Space Shuttle Pogo Pressure Measuring System - A Progress Report, NBSIR 74-562 (July 15, 1974).

4. Hilten, J.S., and Lederer, P.S.; Space Shuttle Pogo Pressure Measuring System - A Progress Report, NBSIR 74-604 (December 20, 1974).

5. Lederer, P.S., and Hilten, J.S.; Space Shuttle Pogo Pressure Measuring System - A Progress Report, NBSIR 75-560 (to be published).

6. Lederer, P.S., and Hilten, J.S.; NBS InterAgency Transducer Project - A Progress Report, NBSIR 75-654 (to be published).

NBS TECHNICAL NOTES

1. Vezzetti, C.F., and Lederer, P.S.; An Experimental Technique for the Evaluation of Thermal Transient Effects on Piezoelectric Accelerometers, NBS TN 855 (January 1975).

2. Kraft, R.; Note on a Vibratory Phenomenon Arising in Transducer Calibration, NBS TN 856 (February 1975).

OTHER

Lederer, P.S.; Transducers in the Real World, Joint Measurement Conference, NBS, Gaithersburg, MD (November 1974).

STANDARDS ACTIVITIES 1974-75

1. RCC STD 106, Chapter 9 "Transducer Standards" reviewed September 1974.
2. RCC 118 "Transducers Based System Calibrations" reviewed July 1974.
3. ANSI MC88.X-1975 "A Hydraulic Sinusoidal Calibration Method for Low Range Pressure Transducers" prepared, revised December 1974.
4. ANSI MC88.Y-1975 "A Guide for the Static Calibration of Pressure Transducers" draft reviewed December 1974.
5. ISA S37.6 "Specifications and Tests of Potentiometric Pressure Transducers" revised for reaffirmation, September 1974.
6. ISA S37.8 "Specifications and Tests for Strain Gage Force Transducers" reviewed January 1975.
7. ISA 37.12 "Specifications and Tests for Potentiometric Displacement Transducers" reviewed January 1975.

APPENDIX B

BITS AND PIECES

8TH TRANSDUCER WORKSHOP

22-24 April 1975, Dayton, Ohio

INTRODUCTION OF MILLS DEAN, III, BY HENRY FREYNIK, CHAIRMAN, SESSION I

Last but not least is our sixth speaker, Mills Dean. He has been with the Naval Ship Research and Development Center for 30 years as a member of the Instrumentation Department. He is best known for his work in reporting. He edited the first reference book of semiconductor and conventional strain gages in the early 1960's. He is also widely known for his pioneer work and continuing efforts in strain gage waterproofing.

As Pierre Fuselier mentioned, Mills has an unusual document in his possession--official travel orders marked "NO COST TRAVEL ORDERS." Total money granted for trip: zero--in every appropriate bureaucratic place.

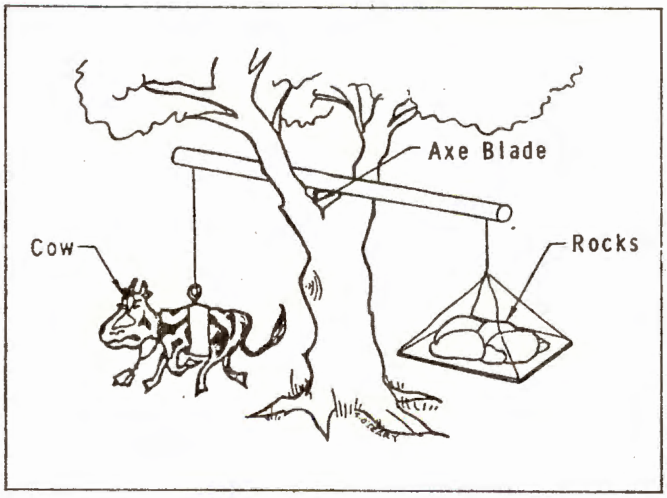
I couldn't help thinking, here's a man who has 8-10 years of testing on destroyers and has recently installed 100 strain gages on a propeller, ran this propeller in sea tests and lost only 4 out of 100 gages, and you would think a grateful nation could send him here--a nation that can afford to send Henry Kissinger's 4,000-lb car to California could well afford to send 200-lb Mills Dean to Dayton.

I'd like to briefly introduce a very important member of Dean's group, Marty Dean, in the back row. She bears the secret burden of hearing all the things we never hear about, the waterproofing which didn't go.

AN ANECDOTE

In measurements engineering we sometimes lose sight of that all too rare quality called "common" sense. Let's see if we can recognize part of ourselves in this account of a measuring procedure.

EDITORIAL: BALANCED PRECISION



While I was in graduate school, I worked part-time for a wise old consulting engineer, who had grown up in Russia. One of his favorite stories dealt with how the peasants in his former homeland used to weigh a cow. They would locate a suitable tree and place an axe blade in its fork to serve as the knife edge of a balance. They would then carefully trim a pole for use as the balance beam. Then they would hang a harness for the cow from one end of the pole and a platfrom for holding weights from the other, and they would whittle away bits of the platform so that it just balanced the empty harness. After these preparations were completed, they would attach the cow to the harness, place rocks on the platform progressing from large ones to smaller ones, and even to sand, until they achieved perfect balance. Then they would simply guess at the weight of the rocks.

Eric E. Ungar
Contributing Editor

An extract from Sound and Vibration, March 1975 by permission from Jack K. Mowry, publisher.

BOO-BOOS

8th TRANSDUCER WORKSHOP

APRIL 22-24, 1975

1. To set up for an unexpected flight load survey calibration of an airplane, it was necessary to build some simple tension load cells in a hurry. The load cells were calibrated in a warm room in the laboratory complex and used in a relatively cold hangar.

   Because of the urgency of the job, I carried the cells to the hangar in my car and piled them on the floor just inside of the door, where the temperature was near freezing, while I worked on my instrumentation.

   As soon as the load cells were installed, I checked out the loading system, and found what appeared to be errors in my loads when checked by other methods. The errors were large enough to require a thorough check of the instrumentation system - which was operating exactly as it should have been.

   The next step was to recalibrate (back at the lab, in a warm room). The calibrations all checked, so I brought the load cells back to the hangar, unloaded, and repeated the entire sequence - including finding apparent errors in the system.

   The problem? The strain gages on the load cells had been protected with a tarry substance which, in itself, should not have caused any problem over the temperature ranges encountered. The difficulty arose because the material touched the load cell covers, gluing them in place when cold, thus providing a parallel load path. In the warm calibration lab, the problem went away because the material was too soft to provide noticeable restraint.

2. Physics Law #8

   It works better if you plug it in.

3. During a critical test, the Zero-line on a cathode ray oscilloscope developed a sudden strange desire to angle up the screen at about 45 degrees. During coffee breaks everything worked fine only to go off again after the break. Finally it was determined that for that model cathode ray oscilloscope this 45-degree zero line would occur at high sensitivity if the line voltage dropped below 90 volts. During coffee breaks with everything else shut off the line voltage returned above 90 volts. Use of an autotransformer to bring voltage up near 110 volts cured the problem.

4. In the course of developing a pressure transducer embodying an LVDT as the displacement sensor, the happy fact of intrinsic zero temperature compensation presented itself.

Since both the transformer and core were to be mounted on equal length sections of the same material, displacement between them due to temperature variations would be essentially nonexistent.

However, when the first temperature tests were conducted, the zero shift was very large. When rational thought once again became possible, after the usual string of unprintable epithets followed by doubts about such basic physical parameters as thermal expansion coefficients, it became sadly apparent that we had not considered the multitude of different thermal coefficients existing within the LVDT assembly. A copper transformer wound on a ceramic bobbin, contained within an aluminum sleeve, which was epoxied in a stainless steel housing. All this resulted in a null position which varied significantly with temperature.

Needless to say, considerable time was spent developing a temperature compensating scheme.

And, once again, the immutable laws of Edsel Murphy were proven to be alive and well.

5. This measurement "Boo-Boo" occurred while recording acoustic data during a fatigue test. For this test, an array of microphones had been placed in front of the section of aircraft structure being tested and had been connected by way of coaxial cables to voltage amplifiers and recording equipment located some distance from the test area. With a sound pressure level of about 160 dB on the structure, the microphone signals were being recorded and simultaneously monitored on an oscilloscope. Strangely, one mike signal was observed to have a normal spectrum but the level for this channel was a good 20 dB lower than the rest. We weren't sure why. Was it the amplifier? Something that went wrong during calibration? Or had the transducer failed?

   After the test, we were shocked to find the coaxial cable for the questionable microphone channel lying on the floor. Oh yes, this was the extra channel (and cable) not being used on this particular test. Nevertheless, the open circuited cable in the high intensity noise environment had acted like a transducer. It even looked like a mike signal, just a bit low.

6. When measuring blast pressures with piezoelectric transducers, we typically use a layer of black plastic electricians tape over the transducer face to act as a thermal barrier. In an effort to improve the performance of this thermal shield a roll of pressure sensitive Teflon tape was obtained, after much moaning over the cost ($15.00 per roll). Obviously the Teflon should provide a better thermal shield than electricians tape, when used in a test; however, the pressure records appeared to have a strong thermal pulse superimposed on the pressure signal. The transducers used were Susquehana Model ST-2. Laboratory

tests were conducted using a flash bulb as a thermal source. These tests revealed that the ability of a material to provide "thermal" shielding depended on its optical opacity rather than on any thermal characteristics of the tape. Thus, the effect we observed was some type of photo effect rather than a thermal effect. We are still using black plastic electricians tape.

7. At a certain laboratory, a sinusoidal calibration technique for pressure transducers was under development. Being poor and using unsophisticated equipment, during the frequency response determinations both amplitude and frequency were adjusted manually at each point. When a resonance was approached, the amplitude of the pressure stimulus was reduced so as not to overrange the transducer. Having suddenly inherited some money, we bought an automatic control system including a frequency sweeping amplifier with automatic input amplitude control to assure a constant input at all frequencies. During the first calibration run, the automatic system swept through the resonance and overranged and destroyed the transducer under test.
   Moral: Think before you push that button.

8. I was life testing some pressure transducers at room temperature by applying and releasing the pressure at the rate of five times a second. About a week later I happened to touch the cycling apparatus and found out that my room temperature test fixture was hot. A quickly applied thermocouple showed a sizzling 150°F. I was 3 million cycles late in making what ought to have been an obvious check.

9. A routine installation of thin semiconductor strain gage dynamic pressure transducers on the inner duct wall of a ducted fan (well downstream from the fan) was intended to monitor the small pressure disturbances expected at blade-passing frequency.

   The same instrumentation had been used before with perfectly satisfactory results. An outdoor test stand was being used for the first time, however. The test engineers were more surprised than pleased to find that some of the transducers reported enormous pressure fluctuations (at blade-passing frequency), orders of magnitude larger than any experienced in the past.

   The cause was traced to the photosensitivity of the transducers. Sunlight, striking at an angle, was being chopped by the fan blades. Lab tests confirmed the behavior.

   The transducers in this case had only a very thin "opaque" coating of RTV covering the diaphragm, and this coating turned out to be not opaque to strong sunlight.

   The general conclusion to be drawn from this experience is simply to light-test every installation where a photosensitive semiconductor may see intense visible radiation.

10. In designing transducers for use at 650°F to 1300°F, success depends on the materials selected being compatible with one another in various ways. The Boo-boo related below is an illustration of one type of problem noted:

Use of Aremco Product Co. #505 (Briar Cliff Manor, New York), ceramic cement in a small volume enclosure can lead to disastrous results because the 505 generates at least 1500 psi pressure when its temperature is raised above about 700°F. Thin diaphragms, bellows or other structural components not intended to be exposed to such pressures are thus caused to fail. Careful pre-baking of the 505 to its end-use temperature before sealing its enclosure does not eliminate the generation of gas. Aremco 505, though, is a product quite useful to temperatures well above 700°F if not sealed in a gas tight enclosure.

Saureisen #8 ceramic cement (Pittsburgh, Pa.) serves similar uses as Aremco #505, but does not generate high pressures after pre-baking.

11. In using a pressure transducer in a high temperature environment (especially a transient one), it must be remembered that the sensing element will change its output both in magnitude and in time if a proper ablative coating is not used on the sensing surface. Oversight of this fact will lead to erroneous pressure readings.

12. A wet-wet ΔP transducer was specified as a sensor in an airborne engine diagnostic system. The unit was specified for 28 VDC excitation, 1500 ohm bridge resistance, and zero balance trimmed to 0 mv ±1% F.S. Due to input circuit restrictions it was later found necessary to change from the grounded 28 VDC supply to an alternate 20 VDC isolated supply and operate at reduced sensitivity. When the system went into operation it was found to be in error at the zero end by nearly 5% in some cases.

The problem was a balance shift due to variations in bridge heating at the lesser excitation voltage. Solution was to have the manufacturer trim the bridge balance at 20 VDC rather than at 28 VDC.

13. In an attempt to provide one kilovolt isolation between a pressure transducer and a water medium, I introduced a 3 mil Lexan film between the face of the transducer and the water. The film was made to conform to the transducer face (Endevco 8503), but was not bonded to it. Film thickness was selected to give about 1% decrease in sensitivity.

Behavior was fine at room temperature, but the shift of zero with temperature was enormous. The Lexan had been clamped at its edges, constrained to the thermal expansion of the metal case. Its middle was free to follow its own large thermal expansion, and buckled with increasing temperature.

Possible cures would have been the use of very compliant rubber film, or provision that the film be perfectly flat. Actual cure was that Endevco put the required isolation inside the case.

14. ±100 g accelerometers were installed in the aircraft wheels to measure the acceleration experienced during aircraft landings. It was found that the actual peak acceleration was ±18 g with corresponding output of ±25 mV.

Signal conditioning was required to make output signals compatible with the recording systems. Due to the high gain of the amplifiers, noise was also amplified to a significant level.

Instead of low-pass filtering the unwanted signals, rubber pads were used to chock-mount the accelerometers to eliminate noise or spikes. Hence, the peak acceleration at landing was considerably reduced.

In the course of the test, aircraft wheels were raised. In doing so, the 14-month instrumentation installation, as well as the mounted transducers, were wiped out.

15. Failure of the power generator on an A4M aircraft required measurements to determine whether vibration had caused the failure.

A bracket was fabricated to mount a triaxial accelerometer on the front of the generator. The three axes were calibrated to ±10 g. The first tests showed that the accelerometer outputs were saturated and the predominant frequencies were 1 kHz and 3 kHz. The accelerometer was recalibrated to ±20 g and the next test showed saturation in some phases of the test. Again the predominant frequencies were 1 kHz and 3 kHz.

After much discussion someone finally thought of checking the accelerometer mounting bracket. When the accelerometer was recalibrated with the bracket, very definite resonances were found at 1 kHz and 3 kHz. The bracket was redesigned and the following tests showed no high peaks at those frequencies.

The reasons given for not originally checking the bracket were (1) it looked strong and bulky, and (2) installation was on a tight schedule which didn't allow for tests.

16. <u>Test Objective</u>. To study the plastic response of beams to impulsive loads.

<u>Arena Layout</u>. The arena was a 5 ft. x 30 ft. concrete pad with a 4 ft. x 4 ft. x 2 inch armor plate mounted vertically at one end. The armor plate had a one ft. square window through it across which was clamped the 1-inch wide beam to be tested. A 4 ft. x 4 ft. x 20 ft. FAE bag was placed on the pad to serve as the explosive forcing function. Due to physical limitations the bag could not be placed flush against the vertical plate, thus an air space of approximately 3 inches was present.

Instrumentation. Four PCB Model 102M24 pressure transducers were mounted in the vertical armor plate, one just above, below, and to either side of the window, in such a configuration as to measure the face-on pressure at the plate. Kistler Model 504D Dual Mode Amplifiers were used as signal conditioning and set such that the expected 800 psi at the transducer would produce 5 volts out to the analog recorder.

Test Conduct. Upon detonation of the FAE bag the entire system saturated and rang. The beam being tested had ripped loose from its mounts and was found in the grass some distance from the test pad. It was obvious that the pressure experienced at the plate was greater than calculated.

Explanation. The reason for the unexpected high pressure was found by conducting subsequent tests with the FAE bag placed varying distances from the plate. At separation distances of several feet it was noticed that two separate and distinct pressure fronts were present at the transducers. The first front was found to be an air shock while the second, which occurred sometime later, was the decaying Chapman-Jouquet detonation front. The fronts added algebraically at the transducer. As the separation distance of the plate and FAE bag was lessened the separation distance of the two fronts did likewise. At a distance of less than one foot the algebratic sum of the two peak pressures became greater than the peak pressure of either of the two. At a separation distance of 3 inches there was no noticeable time lag between the two pressure fronts and the peak pressure was about one and one-half times the expected calculated pressure from this type of explosive.

17. We tried to make air flow measurements to determine wind speed behind a jet engine. The measurement technique employed was to measure the differential pressure with a Pitot tube and the flow temperature in order to calculate the velocity. The measurements were made about 120' behind the engine which was about 8' off the ground. The measurement program was a disaster due to the turbulence behind the engine. We have as much negative as positive differential pressure as a function of time.

18. In setting the taper on subcarrier oscillators it must be remembered that the input threshold of a frequency counter may be too high to register the output from the low level oscillators. This oversight of counter characteristics could lead one to believe that the oscillators themselves were defective.

19. While this account is not in the measurements field, it is certainly a classic boo-boo.

YOU SEE, SIR, IT HAPPENED THIS WAY -

According to the International Woodworker, the following letter from a brick layer in Barbados, West Indies, was written to the employing firm in England. It was verified as true by the British newspaper, "Manchester Guardian."

Respected Sir, when I got to the building, I found that the hurricane had knocked some bricks off the top. So I rigged up a beam with a pulley at the top of the building and hoisted up a couple of barrels full of bricks. When I had fixed the building, there was a lot of bricks left over.

I hoisted the barrel back up again and secured the line at the bottom, and then went up and filled the barrel with extra bricks. Then I went to the bottom and cast off the line.

Unfortunately, the barrel of bricks was heavier than I was and before I knew what was happening the barrel started down, jerking me off the ground. I decided to hang on and half-way up I met the barrel coming down and received a severe blow on the shoulder.

I then continued to the top, banging my head against the beam and getting my finger jammed in the pulley. When the barrel hit the ground, it bursted its bottom, allowing all the bricks to spill out.

I was now heavier than the barrel and started down again at a high speed. Half-way down I met the barrel coming up and received several injuries to my shins. When I hit the ground I landed on the bricks, getting several painful cuts from the sharp edges.

At this point I must have lost my presence of mind, because I let go of the line. The barrel then came down giving me another heavy blow on the head and putting me in the hospital.

I respectively request sick leave.

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