TWG

DOCUMENT 112-70

RCC

SIXTH TRANSDUCER WORKSHOP

22–24 October 1969
NASA Langley Research Center
Hampton, Virginia

TELEMETRY WORKING GROUP
INTER-RANGE INSTRUMENTATION GROUP
RANGE COMMANDERS COUNCIL

KWAJALEIN MISSILE RANGE
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Transducer
Workshop

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Telemetry Working Group
Inter-Range Instrumentation Group
Range Commanders Council

Published by

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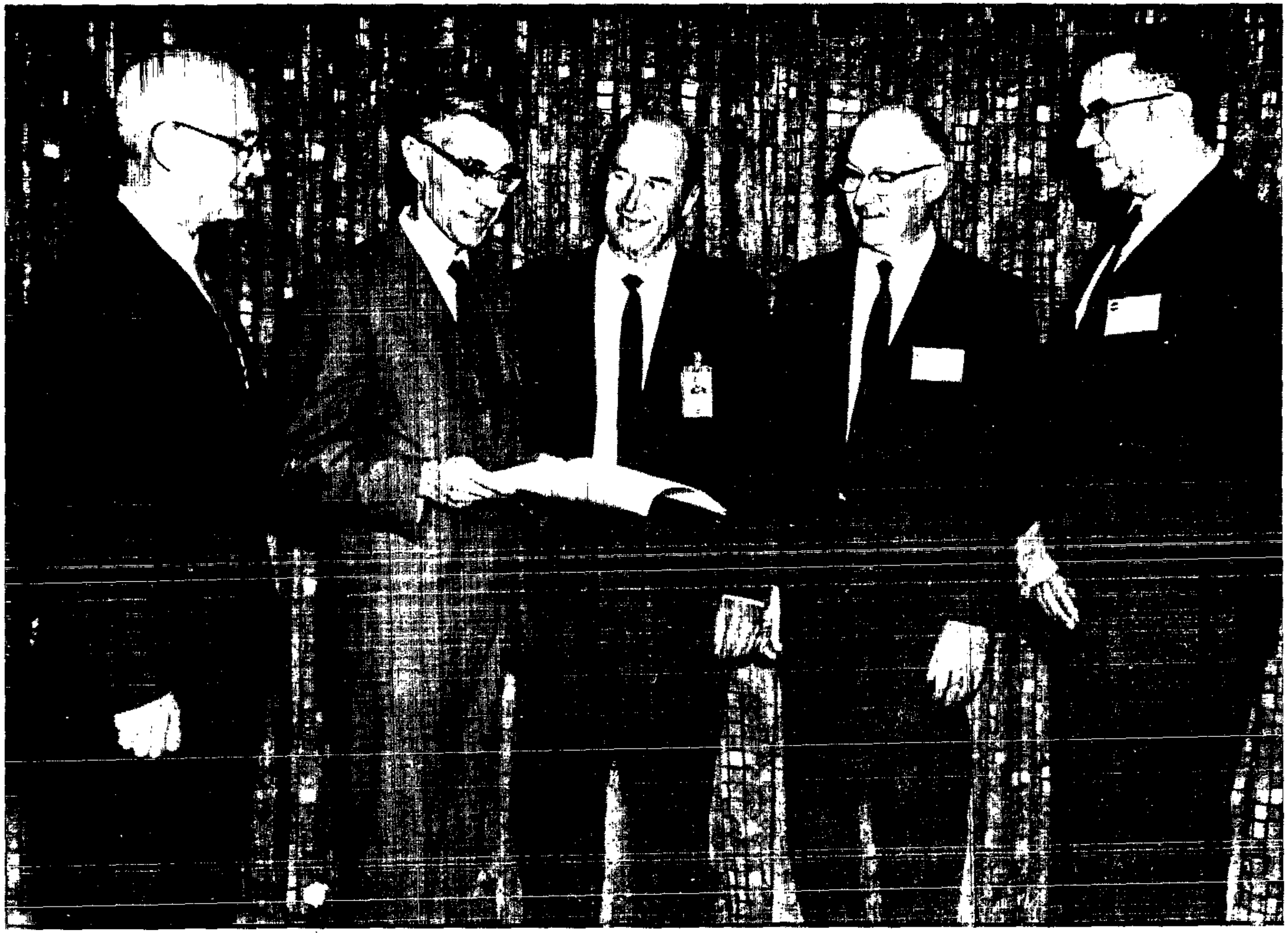

Sixth Transducer Workshop Participants
O. Ingebritsen, Local Arrangements; R. Naylor, Canadian Guest; C. Nelson, Assistant Director, Langley Research Center; L. L. Lathrop, Chairman Transducer Committee, TWG-IRIG; P. S. Lederer, General Chairman, Sixth Transducer Workshop.

transducers to physical measurement.

6TH TRANSDUCER WORKSHOP

General Chairman:

Paul S. Lederer
National Bureau of Standards
Washington, D. C.

PRELIMINARY PROGRAM

Wednesday, October 22, 1969

7:00 P.M. — Buses leave Holiday Inn, Hampton, Virginia for NASA tour

7:30 P.M. — Joint guided tour of selected NASA Langley Laboratories with attendees of 40th Shock and Vibration Symposium

Thursday, October 23, 1969

8:00 A.M. — Buses leave Holiday Inn, Hampton, Virginia

8:15 A.M. — Registration **Morale Activities** Building (No. 1222), NASA Langley Laboratory. Coffee and doughnuts will be served during registration.

9:00 A.M. — Introductory Session
Welcome:
Mr. Edgar M. Cortright, Director
NASA Langley Research Center
or his representative

Transducer Committee Activities
Loyt L. Lathrop
Chairman, Transducer Committee,
TWG-IRIG

9:30 A.M. — Session I "Thermal Measurements"

Chairman: Paul Freeze
National Bureau of Stand

"High Temperature Measurement in Rocket Nozzle Ablative Materials"

H. I. Binder, Air Force Rocket Propulsion Laboratory

Panel Members:

William Harvey, NASA Langley Research Center
Jack Barber, Sandia Corporation

10:30 A.M. — Coffee Break

11:00 A.M. — Session I Continued

12:30 P.M. — Lunch NASA Cafeteria

2:00 P.M. — Session II "Measurement of Pressure and Flow"

Chairman: Dale Rockwell
Navy Metrology
Engineering Center

"Internal Rocket-Engine Probes for use in a Combustion Instability Environment"

S. Rogero, Jet Propulsion Laboratory

Panel Members:

ards

3:00 P.M.	Coffee Break
3:30 P.M.	Session II Continued
4:30 P.M.	Adjournment — Buses return to Motel

Friday, October 24, 1969

8:00 A.M.	Buses leave Holiday Inn, Hampton, Virginia
8:30 A.M.	Session III "General Measurement Problem Areas"
	Chairman: W. G. James AFFDL, Wright-Patterson AFB
	"Transducer Instrumentation used in Bio-Engineering Measurement"
	Prof. Robert M. Jacobs, Newark College of Engineering
	"Noise Levels"
	Prof. Peter Stein, Arizona State University
	Panel Members:
	Loyt Lathrop, Sandia Corporation E. K. Yager, General Dynamics J. Kowalick, Frankford Arsenal
10:00 A.M.	Coffee Break
10:30 A.M.	Session III Continued
12:30 P.M.	Lunch NASA Cafeteria
1:30 P.M.	Session IV "Measurement of Force and Acceleration"
	Chairman: Leon Horn National Bureau of Standards
	"Turbopump Vibration Measurements at Cryogenic Temperatures"
	B. Washburn, Los Alamos Scientific Laboratory
	"Dynamic Error Analysis of H.E.S.T. Program"
	J. Baca, AFSWC, Kirtland AFB
	Panel Members:
	Otis Ingebritsen, NASA Langley Research Center John S. Hilten, National Bureau of Standards
2:45 P.M.	Coffee Break — Bus leaves for Airport
3:00 P.M.	Session IV Continued
4:30 P.M.	Adjournment — Bus leaves for Airport

INTRODUCTION

The Sixth Transducer Workshop co-sponsored by NASA Langley Research Center and the Telemetry Working Group-IRIG was held at the NASA Langley Research Center, Hampton, Virginia on 22-24 October 1969. Paul S. Lederer, National Bureau of Standards, Washington, D.C. was General Chairman of this workshop. Mr. Lederer is a member of the Transducer Committee-TWG-IRIG which has as its Chairman, Mr. Loyt L. Lathrop. Sandia Corporation.

Otis Ingebritsen was coordinator for the NASA Langley Research Center and organized the tour of center facilities.

This workshop was conducted in a somewhat different manner from preceding ones. There were not more than two papers at each session, primarily to set the stage for the following panel discussion with audience participation. The speakers were invited to join the panel at the conclusion of their talks. Each panel had a "recorder" who noted down pertinent questions, answers, and comments as they occurred during the session. The notes appear in these minutes immediately following the papers which initiated each session.

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SIXTH TRANSDUCER WORKSHOP
Langley Research Center
October 23-24, 1969

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Transducer Workshop

Tour of the NASA Langley Research Center

Introductory remarks by Dr. George W. Brooks,
Assistant Director

Assignment of Guide by Mr. Ingebritsen

Flight Instrument Division

Reliability Test Equipment
Sensor Development
Telemetry Receiving Station

Rocket Combustion Test Area

Supersonic Planetary Entry Decelerator (SPED II)

Rocket Test Cells

Instrument Research Division

Light Beam Deflectometer
Accelerometer Continuous Comparison Static Calibration
3 Component Balance for Extremely Small Loads

TRANSDUCER WORKSHOP

Welcome
Clifford Nelson
Assistant Director
NASA Langley Research Center

Mr. Nelson welcomed the group on behalf of the NASA Langley Research Center. He discussed the mission of this center in aero-space research and the large role played by instrumentation in this mission. The instrumentation requirements of the center demand a knowledge of the performance characteristics of a large number of various transducer. An important activity at Langley is the evaluation and calibration of these transducers. Mr. Nelson expressed the hope that this workshop would be most beneficial for all participants.

Transducer Committee Activities
Loyt L. Lathrop
Chairman, Transducer Committee, TWG-IRIG

Good morning. I am Loyt Lathrop, Chairman of the Transducer Committee. Thank you, Mr. Nelson, for your warm welcome and for co-sponsoring and hosting the Sixth Transducer Workshop. Some of you probably wonder, "What is the Transducer Committee?" Briefly, the transducer committee is one of ten sub-committees in the Telemetry Working Group of the Inter-Range Instrumentation Group, commonly referred to as IRIG. Those of you who work with telemetry are probably familiar with the FM/FM subcarrier channels referred to as IRIG subcarrier channels.

The objectives of the transducer committee are to disseminate information on transducers including calibration, evaluation and techniques of measurement. To partially fulfill these objectives the transducer Committee has already held five transducer workshops; the first conducted in February 1960. We try to hold one about every two years. We are grateful to NASA Langley Research Center for co-sponsoring this Sixth Transducer Workshop and serving as host. If any of you think that your facility would be willing to host a future workshop please contact me or Paul Lederer.

Minutes of the Fifth Transducer Workshop can still be obtained from the RCC Secretariat. If you wish a copy write to:

Secretariat
Range Commanders Council
ATTN: Mr. E. E. Froemel
STEWS-SA-R
White Sands Missile Range, New Mexico 88002

The remainder of this meeting will be under the guidance of Paul Lederer of the National Bureau of Standards. Paul is also a member of the Transducer Committee and is General Chairman of this Sixth Transducer Workshop.

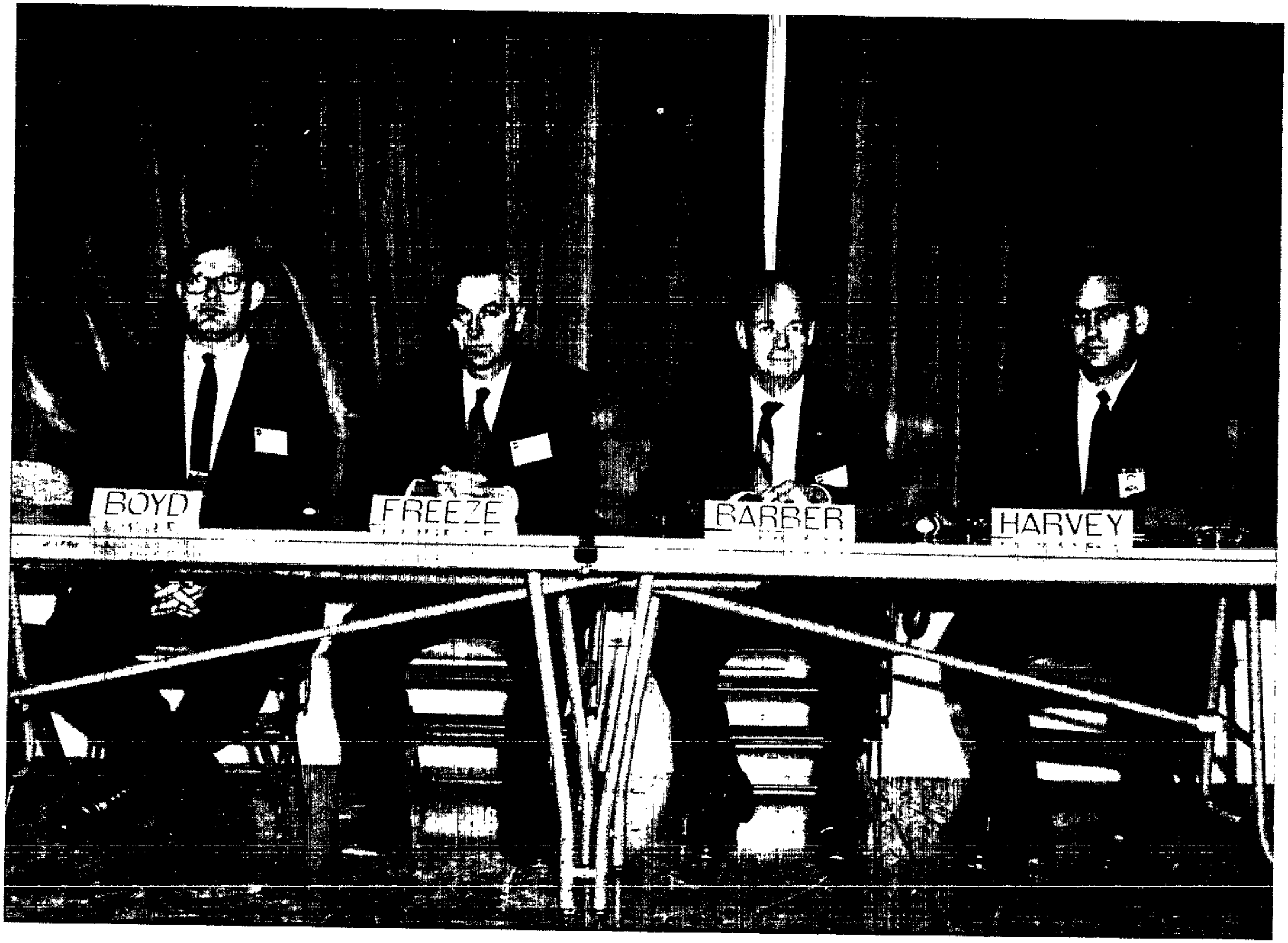
SESSION 1

Thermal Measurements

Chairman: Paul Freeze, National Bureau of Standards

Recorder: W. D. Harvey, NASA Langley Research Center

Panelists: J. S. Barber, Sandia Corporation
A. Boyd, AF Rocket Propulsion Laboratory



Panel Session I "Thermal Measurements"
A. H. Boyd; P. D. Freeze, Chairman; J. A. Barber; W. E. Harvey, Recorder.

68-537

HIGH TEMPERATURE MEASUREMENT USING PASSIVE TEMPERATURE INDICATORS

Presented at the 1968 ISA Annual Conference and Exhibit
October 28-31, 1968
NEW YORK CITY

INSTRUMENT SOCIETY of AMERICA
530 William Penn Place
Pittsburgh, Pennsylvania 15219

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ISA activities include programming forums, disseminating information, providing educational opportunities and materials, developing standards and recognizing individual technological achievement.

Supplementary to all ISA activities are the following major publications: Journals-***Instrumentation Technology*** (monthly), ***ISA Transactions*** (quarterly), Translations of Russian Journals; ***ISA Index;*** Symposia Proceedings; ***ISA Transducer Compendium;*** ISA Standards; Training and Educational Aids. The Society also publishes monographs on specific applications and types of instrumentation.

ISA welcomes both users and manufacturers of instruments and controls in all spheres of industry and science. Members may participate in a diversified program of meetings, publications and activities.

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530 William Penn Place
Pittsburgh, Pa. 15219

68-537
HIGH TEMPERATURE MEASUREMENT USING PASSIVE TEMPERATURE INDICATORS

Harold I. Binder
Electronic Engineer
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Edwards Air Force Base, California

ABSTRACT

A novel approach for the measurement of high temperatures in rocket nozzle ablative materials has been developed and successfully demonstrated. The technique is based on the use of implanted microcapsules containing metal-carbon or carbide-carbon compositions which undergo distinctive and irreversible changes upon reaching their respective melting points. Fifteen different compositions are used to span the range from 3150°F to 6233°F and to provide accurate indications of temperatures attained at a point. A discussion of the theory of operation of the technique is presented together with a description of the instrument's design and characteristics.

INTRODUCTION

This paper describes the theory of operation, design and characteristics of a new instrument which, upon post-test analysis, indicates the maximum temperatures attained at a point within rocket nozzle ablative materials. Accurate measurement of temperatures above 4200°F is required to predict surface regression rates and thermal insulation performance characteristics of such ablative materials.

Over the past decade, much effort has been spent on developing thermal instrumentation capable of providing reliable data in the severe environments of ablative materials. Most of this research has concentrated on thermocouples so that temperatures might be determined as a function of time. Such instrumentation, however, is subject to several difficulties and limitations. No metallic thermocouple which will operate above 5000°F is currently available. A W-5%Re/W-25%Re thermocouple is capable of providing reproducible temperature measurements to about 4900°F in a vacuum and to about 4250°F, for very short durations, in a carbonaceous environment. This is almost 1000°F below the temperature of the charred surface. A second limitation involves degradation of insulative coatings at the temperatures of interest. For example, the resistivity of berrylium oxide, one of the best insulators, approaches the resistivity of plastic ablative materials above 4200°F. Another problem inherent in the use of thermocouples is the fact that their presence causes a distortion of local thermal patterns because of heat conduction away from the junction. Since the quantity of heat withdrawn by the thermocouple is uncertain, it is impossible to obtain a true reading of the actual temperature at the junction.

Because of problems such as these it was decided to depart radically from conventional concepts and to develop a technique that would use to advantage the high temperature characteristics which rendered the most advanced thermocouples ineffective. This new method involves the implantation into the ablative material of microscopic temperature indicators composed of precalibrated eutectic mixtures of refractory metals and carbon encapsulated within graphite containers. Upon being subjected to their respective melting point temperatures, the indicators undergo distinctive and irreversible changes in their shape, size and internal microstructure. These changes are detectible by radiographic and metallurgical analysis, and indicate that the melting point rating of a given indicator has been attained. A temperature time-history is not obtained since the measurements are event-dependent only and not a function of time. The success of this approach has significantly extended temperature measurement capability and makes it practically feasible, for the first time, to accurately measure temperatures in the range of 4200°F to 6200°F within ablative materials.

THEORY OF OPERATION AND DESIGN

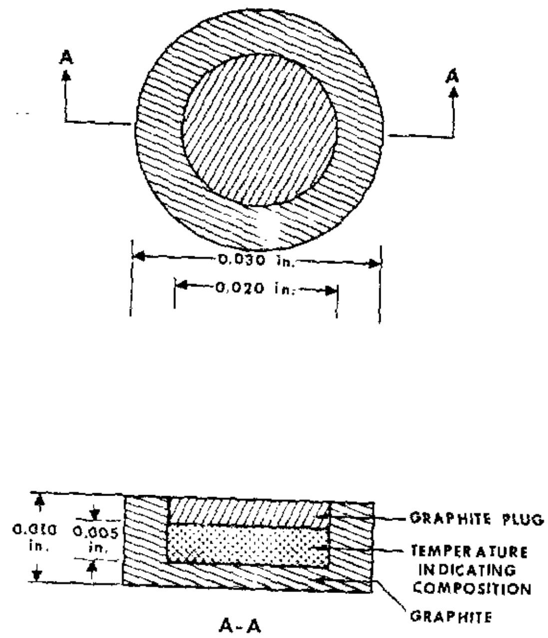
Table 1 lists the chemical constituents and melting point temperatures of fifteen metal-carbon and carbide-carbon eutectic powder compositions that melt between 3150°F and 6233°F. These eutectic compositions are in the form of finely mixed powders in the order of 325 mesh containing impurities in the range of 100 to 500 PPM. Temperature measurement is accomplished by encapsulating such precalibrated compositions in graphite microcapsules and then implanting these containers into the ablative material whose temperature is to be measured.

Utilizing eutectic melting in such binary systems, as opposed to pure melting in single component systems for the temperature reference point, reduces the probability that carbon, a major

TEMPERATURE- INDICATING MATERIALS

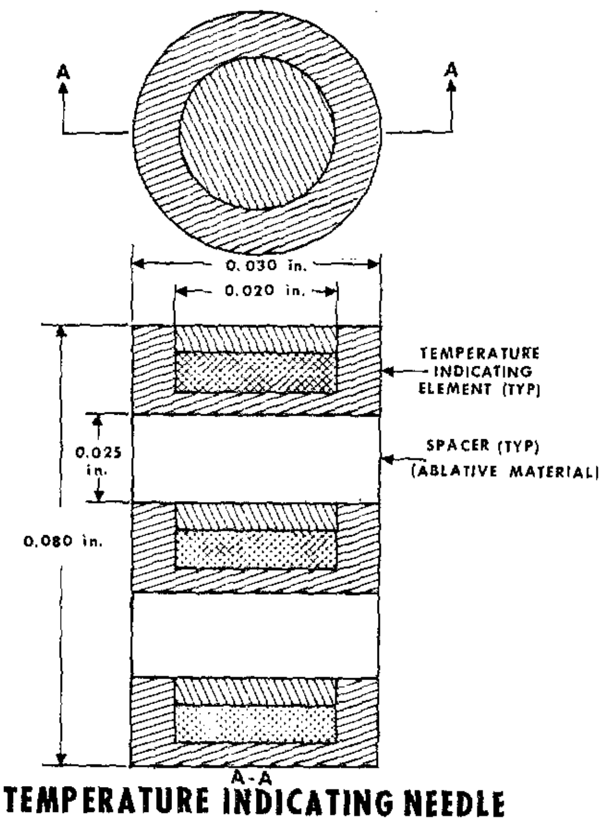
EUTECTIC COMPOSITION	CARBON CONTENT	MELTING TEMPERATURE °F
Pt + C	3 At. % C	3150 ± 27
Zr + ZrC	5 At. % C	3335 ± 27
Mo + α-Mo_2C	17 At. % C	3992 ± 9
Nb + βNb_2C	10 At. % C	4267 ± 18
ZrB_2 + C	33 At. % C	4334 ± 27
HfB_2 + C	38 At. % C	4559 ± 18
α MoC_{1-x} + C	45 At. % C	4683 ± 9
VC + C	49 At. % C	4757 ± 22
WC_{1-x} + WC	41 At. % C	4928 ± 18
TiC + C	63 At. % C	5029 ± 11
Ta + βTa_2C	12 At. % C	5149 ± 27
ZrC + C	64 At. % C	5272 ± 22
HfC + C	65 At. % C	5756 ± 36
NbC + C	60 At. % C	5981 ± 36
TaC + C	61 At. % C	6233 ± 47

TABLE 1



TEMPERATURE INDICATING ELEMENT

FIGURE 1



TEMPERATURE INDICATING NEEDLE

FIGURE 2

constituent of the ablative char, will interfere chemically or depress the melting point of the system. Instead, carbon is used to advantage in the temperature indicating materials as one of the components. A number of such indicators which melt at different temperature levels can be implanted within ablative materials in a predetermined fashion in order to obtain an accurate temperature profile for the material being tested. Radiographs taken of the implanted indicators both before and after the test for comparison analysis determine which indicators melted during the rocket motor firing. When temperatures exceeding the melting points of the encapsulated powders occur, the melt wets, reacts with, and erodes the cavity of the graphite microcapsule by taking more carbon into solution. Such temperature excursions in excess of the eutectic composition melting temperatures only result in increased solubility of carbon and does not alter the fact that melting has occurred. When comparing radiographs of the indicators before and after melting, the radiographs of the melted indicators exhibit an enlarged or swollen appearance because of the additional carbon dissolved by the melt. Indicators which do not melt exhibit no such change in their shape. If, for any reason, a radiograph does not clearly disclose whether or not melting occurred, the indicators can be examined microscopically to determine their condition.

The governing criterion for the selection of the microcapsule is chemical compatibility. An analysis of potential candidate materials that could be used to encapsulate the eutectic compositions indicated that only graphite could maintain its integrity at the temperatures under consideration and had the necessary chemical compatibility with both the carbonaceous charred ablative materials and the carbonaceous eutectic compositions. All indicating compositions are of materials whose eutectic melting points have recently been accurately measured with optical pyrometers directly traceable to calibration by the National Bureau of Standards.

In accordance with standard practice developed for thermocouples, temperature indicating elements are first implanted within cylindrical plugs of the same ablative materials as those in which temperature measurements are desired. In turn, these instrumented plugs are inserted into the actual rocket nozzle ablative liner material. The location and identification of each indicating element is established by reference marking the base of each instrumented plug and radiographing the entire assembly prior to insertion into the rocket nozzle liner. After firing, the instrumented plug is removed from the nozzle liner, oriented in accordance with the reference mark and again radiographed. The condition of each indicator is thus revealed. It is also possible to section the instrumented plug after firing and determine the condition of the indicators by metallurgical techniques.

Figure 1 depicts a cross-section of a temperature indicating element, showing a eutectic composition enclosed within a disk-shaped cylindrical microcapsule with a hollow interior. The container is machined from POCO graphite, a non-porous, fine-grained, high-purity grade graphite with impurities of less than 10 PPM. The temperature indicating compositions are hand packed into the cavity of the container and sealed in by a press-fit graphite plug. The graphite has a density of 1.88 grams/cm which is sufficient to exclude, and therefore eliminate interference from, pyrolysis gases generated by the host ablative materials. A capsule size of 0.030 inch in diameter and 0.010 inch in thickness was found to be an upper limit and still not cause a temperature disturbance greater than the melting point accuracies of the enclosed eutectic compositions. To further decrease their distortion of the local isothermal patterns the elements are oriented so that the capsule diameters are normal to the direction of heat flow.

Figure 2 shows a cross-section of three stacked temperature indicating elements arranged in the form of a needle. The intervening spacers are identical to the host ablative material. The elements are bonded to the spacers with a conventional epoxy adhesive and the entire needle assembly is implanted and bonded into a cylindrical plug of ablative material, as indicated previously. The depth of char in which the temperature range of interest occurs progresses during the firing, and as regression occurs from its initial position to a location below the original surface, all temperature indicating elements located in the regressed region are lost during the firing. Consequently, multiple, identical indicating elements in depth are required. Any number of such elements can be stacked and each indicator will respond independently of its neighboring element. Figure 3 pictorially summarizes the operations involved in applying this temperature measurement technique to rocket nozzle ablative liners.

This technique, in addition to being the only method available to indicate temperatures within ablative materials in the range of interest, offers the following advantages:

1. The indicators are permanently and accurately calibrated prior to implantation and melt at definite temperature levels which are not subject to alteration. The indicators are chemically stable for indefinite periods of time on the shelf or at elevated temperatures up to their respective melting points, at which time their response delay is of the order of milliseconds. Their performance is unaffected by super-heating above their fusion temperature, and by prolonged heat soak or cooldown periods. The microstructural appearance of the indicating compositions before melting is distinctively different from their appearance after melting, and they remain permanently altered after resolidification.

2. The indicators are metal-carbon and carbide-carbon compositions encapsulated within graphite containers which are chemically compatible with carbonaceous ablative materials at elevated temperatures. Furthermore, the performance characteristics of the indicators are unaffected by pyrolysis gases generated during ablation.

3. The indicators are passive devices and do not require active, real-time, auxilliary instrumentation such as power supplies and recorders.

4. The indicators register essentially point measurements of temperature and do not appreciably distort the normal thermal patterns. The indicating elements cannot conduct a significant amount of heat away from the region being measured because of (a) their small size, (b) their isolation within the host material, and (c) the fact that their activation mechanism is such that a negligible amount of thermal energy is absorbed during the fusion process.

CONCLUSIONS

A method has been developed to measure temperatures in rocket nozzle ablative materials in the range of 3150°F to 6233°F. The method is based on implanting microscopic indicators with calibrated melting points which register the attainment of temperature levels by undergoing fusion. The temperature indications are distinct, irreversible and detectible by radiographic or metallurgical techniques.

ACKNOWLEDGMENT

The author gratefully acknowledges the assistance and constructive criticism given by R. E. Anderson, D. R. Hornbaker, H. B. Hurtt, Dr. E. Rudy, and W. C. Severin.

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TEMPERATURE MEASUREMENT TECHNIQUE APPLIED to ROCKET NOZZLE ABLATIVE LINERS

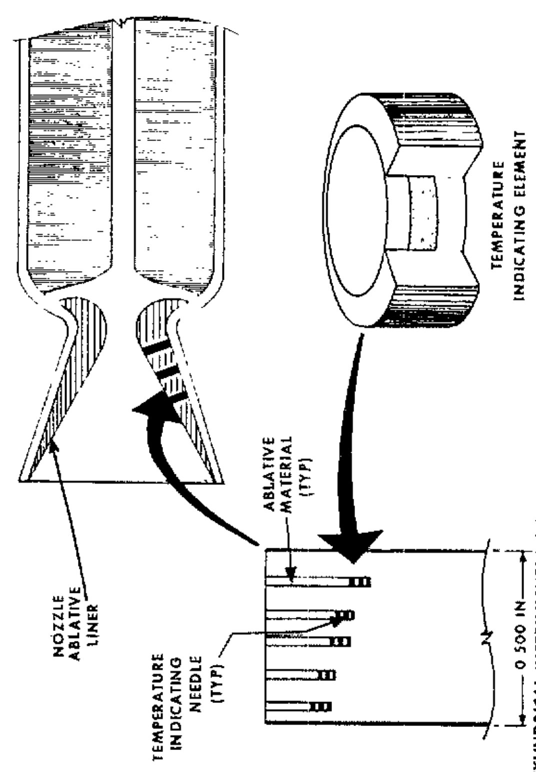

FIGURE 3

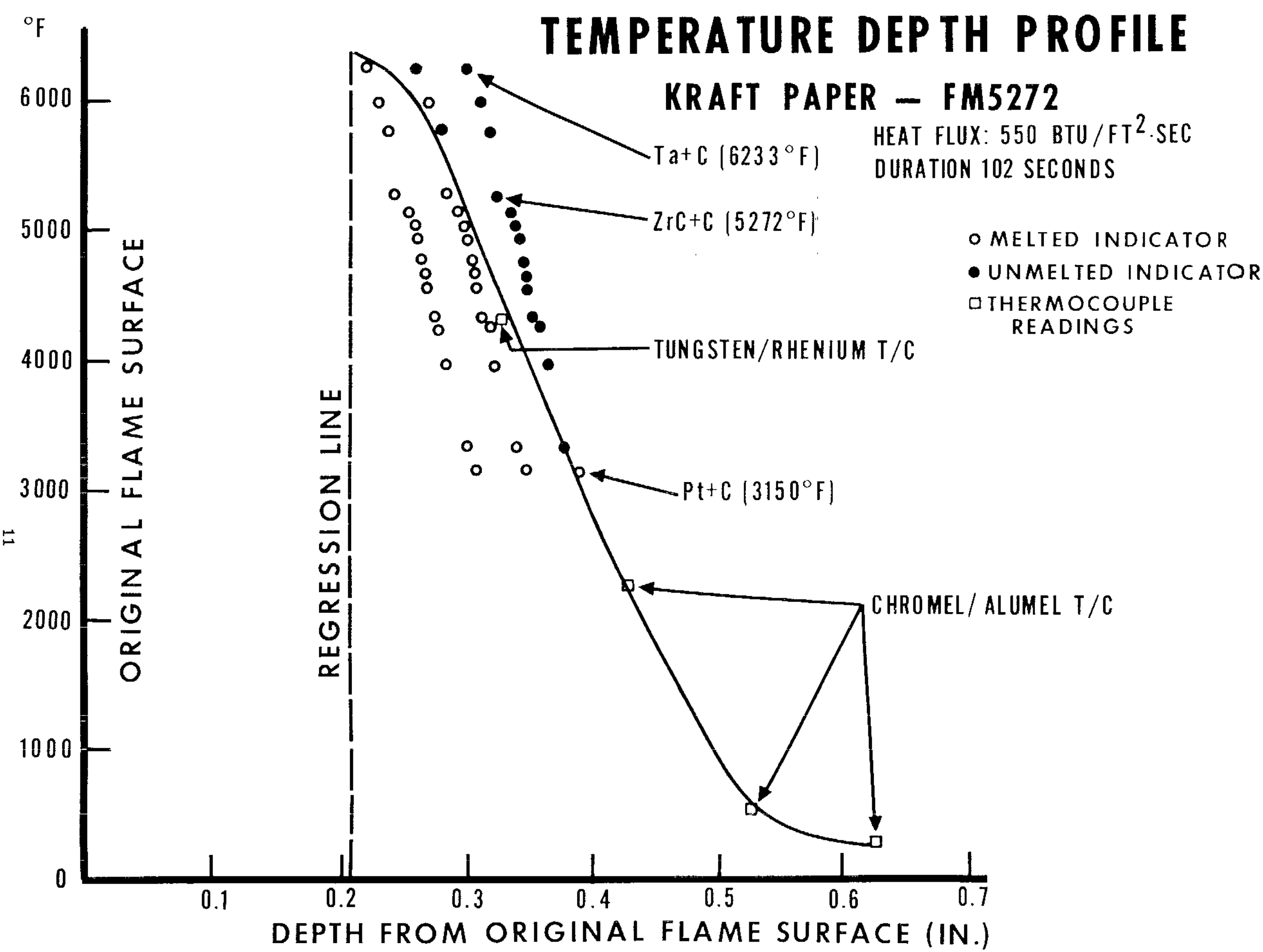
TEMPERATURE DEPTH PROFILE
KRAFT PAPER — FM5272
HEAT FLUX: 550 BTU/FT2·SEC
DURATION 102 SECONDS
○ MELTED INDICATOR
● UNMELTED INDICATOR
□ THERMOCOUPLE READINGS
Ta+C (6233°F)
ZrC+C (5272°F)
TUNGSTEN/RHENIUM T/C
Pt+C (3150°F)
CHROMEL/ALUMEL T/C
°F
6000
5000
4000
3000
2000
1000
0
ORIGINAL FLAME SURFACE
REGRESSION LINE
0.1
0.2
0.3
0.4
0.5
0.6
0.7
DEPTH FROM ORIGINAL FLAME SURFACE (IN.)

FIGURE I

NOZZLE 1 TEMPERATURE DEPTH PROFILE

CARBON PHENOLIC -SP8050 DURATION: 24 SECONDS

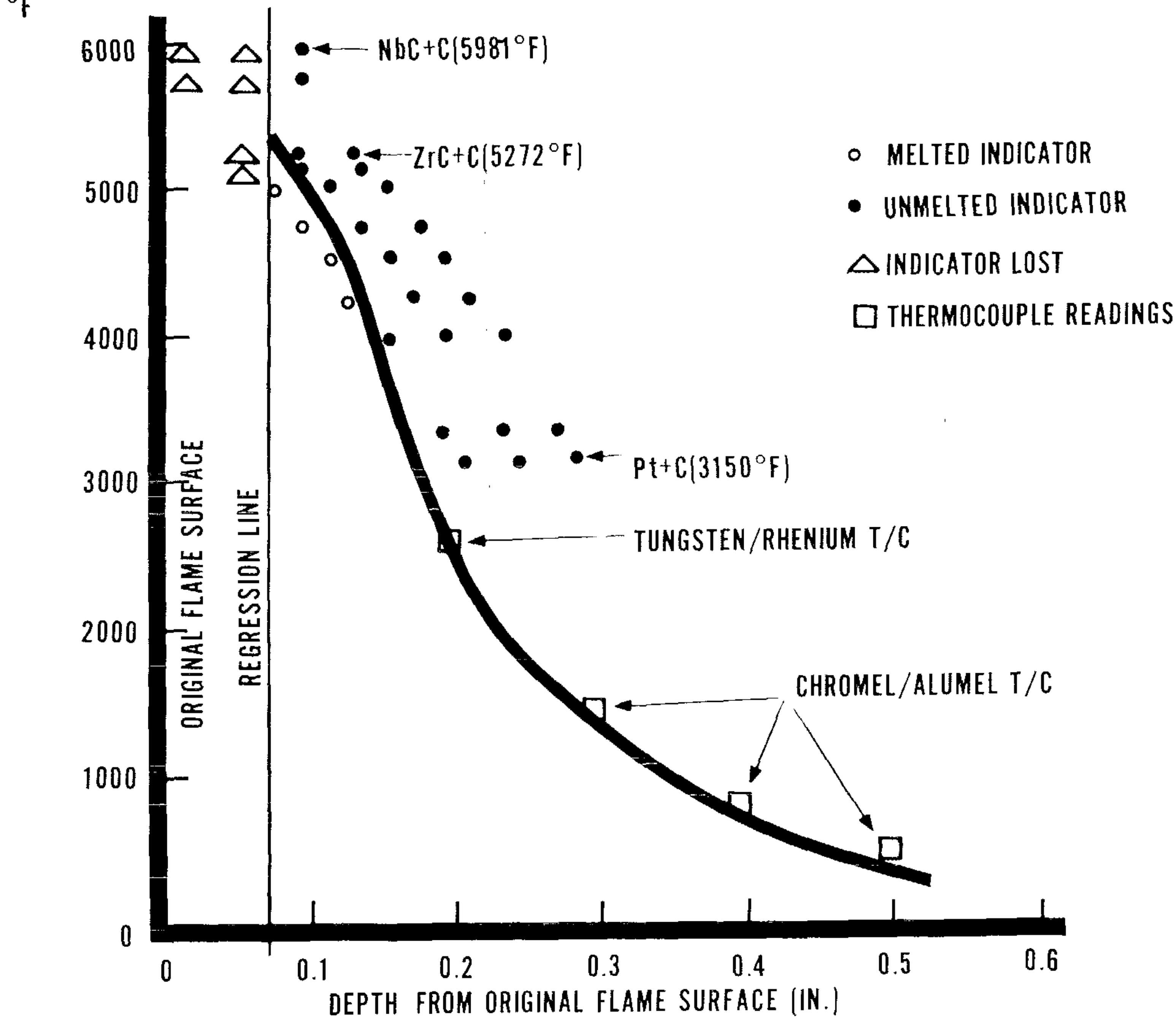

FIGURE II

PASSIVE TEMPERATURE INDICATOR TEST RESULTS

1. Test results of the Passive Temperature Indicators described in ISA Paper 68-537 are shown by two graphs.

2. Figure I shows the results of tests of a Kraft Paper FM 5272 plug which was instrumented with 45 passive indicators, three Chromel/Alumel thermocouples and one Tungsten Rhenium thermocouple. The heat source for this test was a plasma arc furnace.

3. Figure II shows the results of an actual field test of a carbon phenolic SP 8050 plug which was instrumented with 33 passive indicators, three Chromel/Alumel thermocouples and one Tungsten Phenium thermocouple. This plug was tested in a rocket nozzle which was fired for 24 seconds. The design of the plug was not ideal and several passive sensors were lost in regression of the plug surface. However, the test did prove the feasibility of using the technique to obtain high temperature data in-situ in an ablative rocket nozzle.

4. The data obtained from these two tests accurately established the temperature profiles within the ablative materials. This technique advances the state-of-the-art in high temperature measurements in ablative materials and provides information which cannot be obtained with other measurement techniques.

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REMARKS AND ANSWERS FROM SESSION I, "THERMAL MEASUREMENTS," OF THE SIXTH TRANSDUCER WORKSHOP

Reference 1: Presentation entitled "High Temperature Measurements in Rocket Nozzle Ablative Materials," by Al Boyd, AFFTC Edwards

1. Q: (Origin unknown) Is temperature measuring device of reference 1 a steady state one? – Did you (Al Boyd) determine any transient conditions for device?

A: (Al Boyd) No – see report (ref. 1). (Boyd) – Expect device has an order of milliseconds response.

2. Q: (Paul Lederer, NBS) How do you (Boyd) find plugs after test - location, etc. of reference 1?

A: (Boyd) We obtain x-rays before and after testing.

3. Q: (Origin unknown) Would tests of reference 1 repeat and check with thermocouples - would the thermocouples, which are recording at the low temperature end of the overall distribution, scale or extrapolate up the temperature scale to serve as check?

A: (Boyd) Only a one-time test has been made on the plugs (ref. 1) - possibly the thermocouples used along with the plugs can be extrapolated with assurance - I'm (Boyd) not sure if they can or if they have already been.

4. Q: (Origin unknown) Did you (ref. 1) apply corrections to thermocouples or plugs such as done by Sandia Corp.?

A: (Boyd) No - I'm not sure if co-workers have.

5. Q: (Origin unknown) Did you use same materials in plugs as that existing in liner of nozzle?

A: (Boyd) Yes.

6. Q: (Origin unknown) Can you give the audience a cost evaluation of project?

A: (Boyd) Yes, approximately $45,000.

7. Q: (Loyt Lathrop, TWG-IRIG) How do you tell when you reach the correct temperature?

A: (Boyd) The pill box or capsule plugs contain a powder form substance (see ref. 1) or evtectic material serving as the sensor from which an actual physical change of the pill box can be detected by x-rays.

8. Q: (Paul Freeze, NBS) Does the diffusion of graphite into the capsule box change the calibration of the sensor?

A: (Boyd) No.

9. Q: (Paul Freeze, NBS) Do you get repeat melt point between batches of plugs - and can plugs be made to repeat exactly for each batch?

A: (Boyd) Large amounts of the mixtures of materials used to make the plugs are calibrated and they usually remain the same. Reference 1 quotes accuracies of $\pm 22^{\circ}$ F at 5000 $^{\circ}$.

10. Q: (Paul Freeze, NBS) Have you used any other thermocouples at lower temperature ranges?

A: (Boyd) No answer recorded.

11. Q: (Ken Myers, Edwards) How do you measure response time of fast temperature sensors - say in the millisecond range?

A: (Paul Freeze, NBS) Shuttering of heat sources to obtain pulse type input to sensors and seem to be good up to 63 percent.

A: (Dale Rockwell, Navy Met. Engr. Center) Have used zenon lamp source as an impulse function to sensors such as thermocouples and thin films in a range of microseconds.

A: (W. D. Harvey, NASA Langley) Have used a heat pulse calibrate unit constructed to produce a low heating rate from about 1-20 Btu/ft^{2}sec with good repeatability. This unit allows a dynamic pulse of known heat rate to be applied to a gage to be calibrated. The unit consists of a heater coil and attached blower. A nozzle was designed and used to reduce the airflow across the heater coil from 1.5 inches to 0.5 inches cross section. The nozzle was equipped with a mixing screen and radiation shield. A slotted disk was mounted on a spring-loaded shaft in line with the nozzle, such as to give a pulse type input of flow to the sensor. A standard calorimeter was used to calibrate the airstream.

Comment: Lawrence Radiation Laboratory has attempted to evaluate fast response sensors in reactors. These studies are essentially time constant studies.

(Pat Walters, Sandia) China-Lake does thin film work.

12. Q: (W. D. Harvey, NASA Langley) Do plugs remain fixed in original position in the nozzle test or how do you know if or when they may change position during test? (Ref. 1)

A: (Boyd) Plugs remain fixed during test. Only if they are blown out of the nozzle do they change position.

13. Q: (Paul Lederer, NBS) What are you, Paul Freeze, doing at NBS?

A: (Paul Freeze, NBS) 1. Using nobel metal thermocouples; 2. We have detected chemical effects in some thermocouples called "catalaysis" effects especially in Pt-Pt-13% Rd; 3. Studying effects of radients on thermocouples.

14. Q: (Bruce Ness, Boeing Co.) to Mr. Freeze, NBS - Do you expect much error in velocity corrections to probes - what are catalaysis effects like at about 1500°.

A: Non directly

15. Q: (Bruce Ness, Boeing Co.) Anyone doing control temperature work in joining thermocouples at control temperatures of say $1\text{-}2^{\circ}$ over a very small area - on the order of the wire diameters to be jointed together?

A: Non directly.

16. Q: (Loyt Lathrop) What time constant do you quote to a manufacturer for a particular temperature, pressure, etc., measuring project?

A: (Paul Freeze, NBS) Must be defined in each case.

A: (Peter Stein, Arizona State Univ.) You may use for example a strain gage to detect temperature changes - time constant vary with temperature level.

17. Q: (Origin unknown) There is a need for simplicity, reliable systems, and low power requirements for long range space travel vehicles and packages - what is recommended along space travel vehicles and packages - what is recommended along these lines especially in line with low power requirements? And to resolve small temperature changes?

A: (Peter Stein) Beware of chromel-alumel thermocouples having possible piezoelectric effects, etc. Must know instrument and not rely on venders quoted data.

A: (John Russell) Be sure to use control temperature reference box for reference temperature data.

A: (W. G. James. AFFDL, Wright-Patterson) See Mr. Roberts at Wright-Patterson about high temperature thermistors and related tests.

18. Q: (Otis Ingebritsen, NASA Langley) What sort of gradients (under gravity conditions) would be expected due to orientation of temperature sensing instruments - especially in case of gyroscopes, where these sensors are employed and utilized to correct the gyro?

A: Non recorded - only general comments available.

SESSION II

Measurement of Pressure and Flow

Chairman: Dale Rockwell, Navy Metrology Engineering Center

Recorder: A. H. Boyd, AF Rocket Propulsion Laboratory

Panelists: Mills Dean III, Naval Ship Research and Development Center
T. D. Carpini, NASA Langley Research Center
J. Z. Inskeep, Jet Propulsion Laboratory

Panel Session II "Measurement of Pressure and Flow"
A. H. Boyd, Recorder; D. W. Rockwell, Chairman; Mills Dean III; T. D. Carpini; J. Z. Inskeep.

INTERNAL ROCKET-ENGINE PROBES FOR USE IN
A COMBUSTION INSTABILITY ENVIRONMENT*

Steve Rogero — ISA Member
Senior Research Engineer
Jet Propulsion Laboratory
Pasadena, California

ABSTRACT

Recent advances in the heat-transfer capabilities of water-cooled pressure probes now permit the measurement of high-frequency pressure variations utilizing the third-dimensional variable of the rocket-motor chamber (radially with reference to a cylindrical combustion chamber). This paper describes two types of internal rocket-motor probes used in a JPL Resonant Combustion Program. Early probes were uncooled models designed and built by JPL. Later, two cooled probes were designed and built by the Greyrad Corporation. The Greyrad probes can be adjusted within their adapters to measure high-frequency pressure variations at locations 1/2 in. to 5-1/2 in. from the inside of the chamber wall. Thermal protection is provided by high water-flow rates through inner and outer tube bundles. Approximately two-thirds of the water is used to cool the outer tube bundle and exits above the 90-deg bend in the probe. The remainder is forced across the sensing area of an internally acceleration-compensated transducer (Kistler Model 603A) and out into the motor chamber. In addition to the water cooling there is a 0.020-in. coating of RTV 580 on the transducer diaphragm to provide protection against thermal radiation. The probes have been used in a series of instability tests at various longitudinal locations and insertion lengths. Information on testing and evaluation of the probes, actual pressure data obtained during instability firings, and conclusions drawn from this information are presented.

INTRODUCTION

The JPL Propulsion Division has, for several years, been involved in a study of the resonant combustion (or instability) phenomena as related to liquid-propellant rocket engines. In support of this program, the Instrumentation Section has directed considerable effort toward the development of a high-response pressure-measuring system, which is necessary to define the characteristics of the resonant combustion phenomena. These efforts have resulted in a system with frequency response in the neighborhood of 100 kHz, capable of withstanding the severe environmental conditions present during resonant combustion(1). To discuss the use of pressure probes in this type of application it is necessary first to explain the characteristics of the resonant combustion phenomena and some of the problems associated with making three-dimensional pressure measurements in such an environment.

CHARACTERISTICS OF THE RESONANT COMBUSTION PHENOMENA

The resonant combustion phenomena may be described as a steep-fronted detonation-like pressure wave rotating with supersonic velocity about the combustion chamber axis as shown in Fig. 1. This artist's conception envisions a shock wave rotating within the sensitive reaction zone near the injector(2). The wave amplitude diminishes at locations farther from the injector as the shock wave follows a possible helical path down the chamber. The wave is quite steep-fronted, and velocity measurements indicate that the transit time across a sensing area 0.25 in. in diameter is on the order of 3 μsec, which is sufficiently fast to excite the resonant frequencies of most transducers. Since the wave crosses the measurement location on the order of once every 500 μsec, the output of the transducer during resonance might be expected to look like a series of shock-tube tests.

The environmental conditions present during resonant combustion are quite severe. Although instantaneous heat-transfer measurements have not been made, steady-state measurements and other observations indicate that heat-transfer rates may be in excess of 50 Btu/in.^{2} sec. This is sufficient to burn through an engine chamber wall 1-in. thick in less than 1 sec. Vibration levels are in excess of 1000 peak g at frequencies above 2000 Hz. Because of the severity of these environmental conditions and the likelihood of damage to any instrumentation system, the run durations are limited to very short times. Typical run durations are less than 0.5 sec, of which approximately 0.1 sec is resonance.

*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

Superior numbers refer to similarly-numbered references at the end of this paper.

PRESSURE-MEASURING SYSTEM

The pressure transducers used to define the resonant combustion wave characteristics at the chamber boundaries generally consisted of Kistler Model 603As (manufactured by Kistler Instrument Corp., Clarence, N.Y.) in uncooled near-flush mounting configurations with a thin coating of ablative material to protect the transducer diaphragm[1].

Figures 2a and 2b show the shock-tube response of an optimized pressure-measuring system as recorded on an oscilloscope and on magnetic tape. The transducer itself has a rise time on the order of 1 μsec and a ringing frequency of approximately 500 kHz. The transducer was flush-mounted on the end of the shock tube and had a thin coating of RTV 580 (manufactured by General Electric Silicone Products Dept., Waterford, N.Y.) over the diaphragm. As may be noted in Fig. 2b, the response of this system to a pressure step input is basically that of the recording system. The trace in Fig. 2c is data as recorded by this transducer configuration during a resonant combustion firing. It should be possible to assume, within the 7-μsec rise-time limitation of the recording system, that the data as recorded are a faithful reproduction of the pressure disturbance. It is known that the pressure-wave amplitude is at least 950 psi and that its transit time across the transducer diaphragm is less than 7 μsec[3].

Measurements made with this system have proved satisfactory for determining the characteristics of the resonant combustion wave at the chamber boundaries. To further define the phenomena, however, it became desirable to make measurements three dimensionally toward the center of the chamber.

UNCOOLED JPL PROBE

The first probe used in the Resonant Combustion Program is shown in Figs. 3 and 4. This was an uncooled probe consisting of a stainless steel tube with a Teflon coating. The end coating Teflon could be removed for access to the transducer, a Kistler Model 603A protected with a 0.80-in.-thick coating of RTV 580. The probe is inserted through the nozzle and held in place by three struts attached to a nozzle plate. The lower end of the probe is attached to a camera housing used to record movies during a firing[4].

This probe was used in several firings and was useful in obtaining data to support the resonant combustion theories. There were, however, several shortcomings, one of the more serious being low-frequency response due to the coupling configuration and thick coating of ablative material in front of the transducer diaphragm.

COOLED GREYRAD PROBE

To extend the capabilities of the probing system, the Greyrad Corporation was contracted to design and build two water-cooled probes for use in this program. The Greyrad probes (manufactured by the Greyrad Corporation, Princeton, New Jersey) are shown in Fig. 5. Water enters the probe through the upper end and flows through tube bundles down the probe body. Approximately two-thirds of the water (0.2 lb/sec) exits above the bend. The remainder is used to splash-cool the transducer diaphragm. The upper portion of the probe body is brass and copper, 0.5 in. in diameter. The lower portion is stainless steel, 0.375 in. in diameter. The probe can be adjusted within the mounting adapter to measure pressure at locations from 0.5 to 5.5 in. from the inside chamber wall. In addition to water cooling, a 0.20-in. coating of RTV 580 is used to protect the transducer sensing element against the effects of thermal radiation.

Figures 6 and 7 show the Greyrad probe installed on the engine and ready for a firing. The flex line in Fig. 6 connects the probe with a solenoid valve so that cooling water flow can be started approximately 0.5 sec before ignition. Water pressure is normally maintained at least 200 psi above steady-state chamber pressure. The probes are designed to withstand internal water pressures in excess of 1000 psi. Figure 7, a view up the chamber nozzle, shows the probe in the fully retracted position with the sensing element oriented toward the injector. Other transducer locations can be seen longitudinally along the chamber wall and in the injector face.

These probes have been used in a series of nine resonant combustion firings without damage. At the completion of this phase of evaluation the probes were returned to Greyrad for minor modification.

ANALYSIS OF FIRING DATA

Data shown in Fig. 8 were obtained during a resonant combustion firing in which both Greyrad probes were installed. The lower trace is 10 kHz time base. The second trace is the output of a reference transducer described earlier (flush-mounted Kistler 603A with a 0.10-in. coating of RTV 580). The output of the fully retracted probe is shown next. In this configuration the probe and reference transducer sensing areas are 0.5 in. apart and should, within their frequency-response limitations, have the same output. In general, this is the case with both the probe and the reference transducer measuring the same wave amplitude and shape.

The upper trace in Fig. 8 is the output of the fully extended probe. As was expected and verified in other firings, the amplitude of the resonant combustion wave is quite low near the center of the engine. The wave amplitude does, in fact, drop off faster at locations toward the chamber center than at locations along the chamber wall downstream from the injector.

Information on the probe transducer thermal-drift rate during resonant combustion was also obtained during the firings. In general, the zero drift rate for the probes was low. These tests gave further emphasis to previous conclusions on the use of ablative coatings[5]. High water-flow rates are necessary to protect transducers during long-duration firings and to maintain the structural rigidity of probe-type devices during short-duration firings. The primary cause of zero drift during short-duration firings, however, is thermal radiation, and the best way to reduce this effect is to apply an opaque coating over the transducer sensing area. If this coating can be kept intact, the zero drift rate will almost always be within tolerable limits.

CONCLUSIONS

The Greyrad probes will be used on future resonant combustion firings in a further evaluation of their capabilities and more extensive determination of the characteristics of the resonant combustion phenomena. At this time, however, the following conclusions have been reached.

1. The frequency response of the probe is satisfactory for making high-response pressure measurements during resonant combustion.

2. The mechanical design of the probe allows it to operate for extended periods in the severe environment of resonant combustion.

3. Measurements made with the probe support earlier JPL theories as to the characteristics of the resonant combustion phenomena.

4. The use of ablative coatings, however thin, is desirable even on fluid- or gas-cooled transducers when making measurements in areas of high heat-transfer rates. In most instances, the effect of an opaque coating will be the predominant factor in reducing zero drift due to thermal radiation.

REFERENCES

(1) Clayton, R. M., and Rogero, S., Experimental Measurements on a Rotating Detonation-Like Wave Observed During Liquid Rocket Resonant Combustion, Technical Report 32-788, Jet Propulsion Laboratory, Pasadena, California, August, 1965.

(2) Clayton, R. M., Rogero, S., and Sotter, J. G., "An Experimental Description of Destructive Liquid Rocket Resonant Combustion," AIAA J., Vol. 6, No. 7, pp. 1252-1259, July, 1968. Also available as Technical Report 32-1293, Jet Propulsion Laboratory, Pasadena, California.

(3) Rogero, S., Measurement of the High-Frequency Pressure Phenomena Associated With Oscillatory Combustion in Rocket Engines, CPIA Publication No. 138, Vol. I, Chemical Propulsion Information Agency, The Johns Hopkins University, Applied Physics Lab., Silver Spring, Md., February, 1967.

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KEY WORDS

Pressure-measuring system
High-frequency pressure
Instability
Thermal protection
Water-cooled probe
Rocket engine probe
Pressure probe

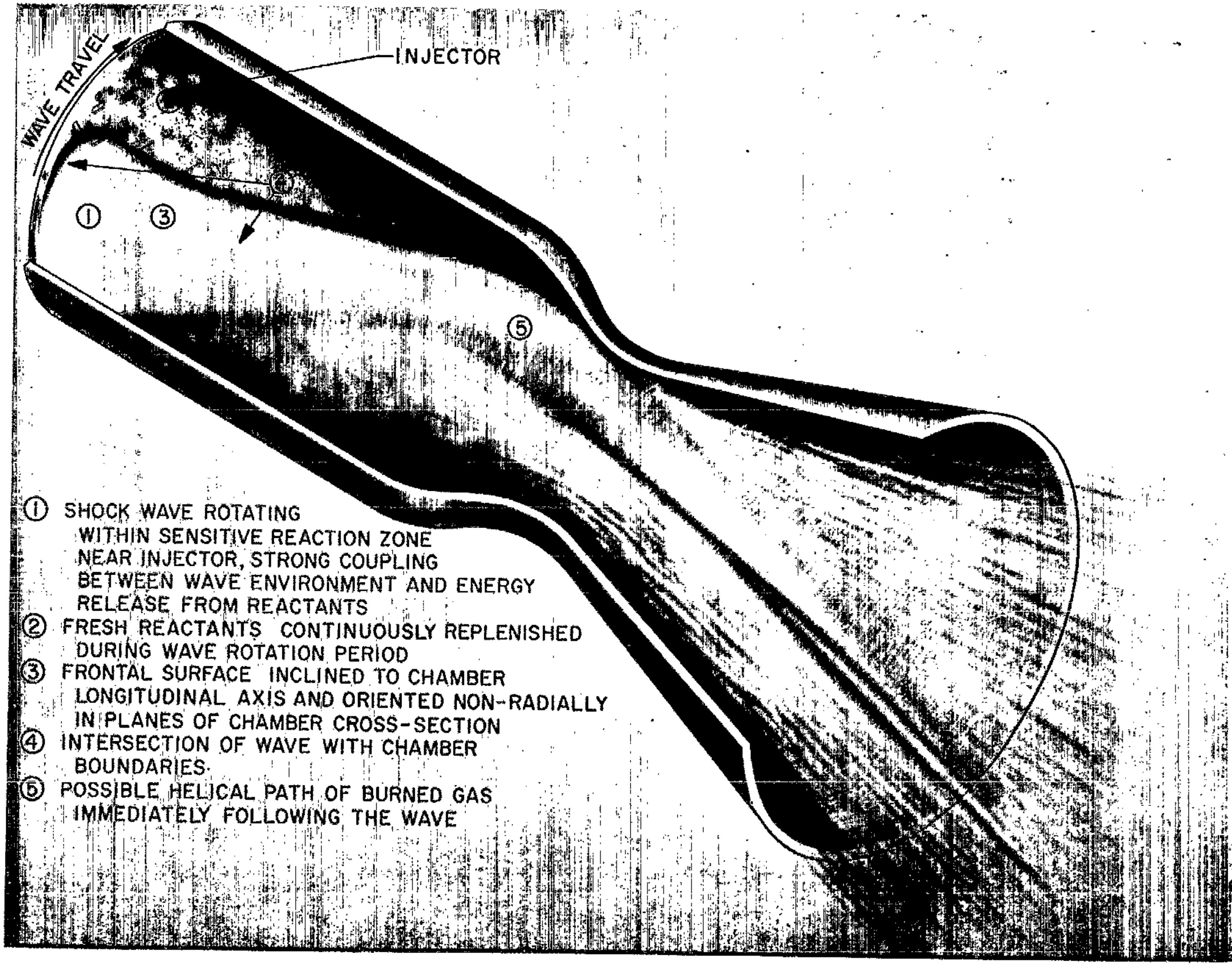

Fig. 1. Artist's conception of rotating detonation-like wave front

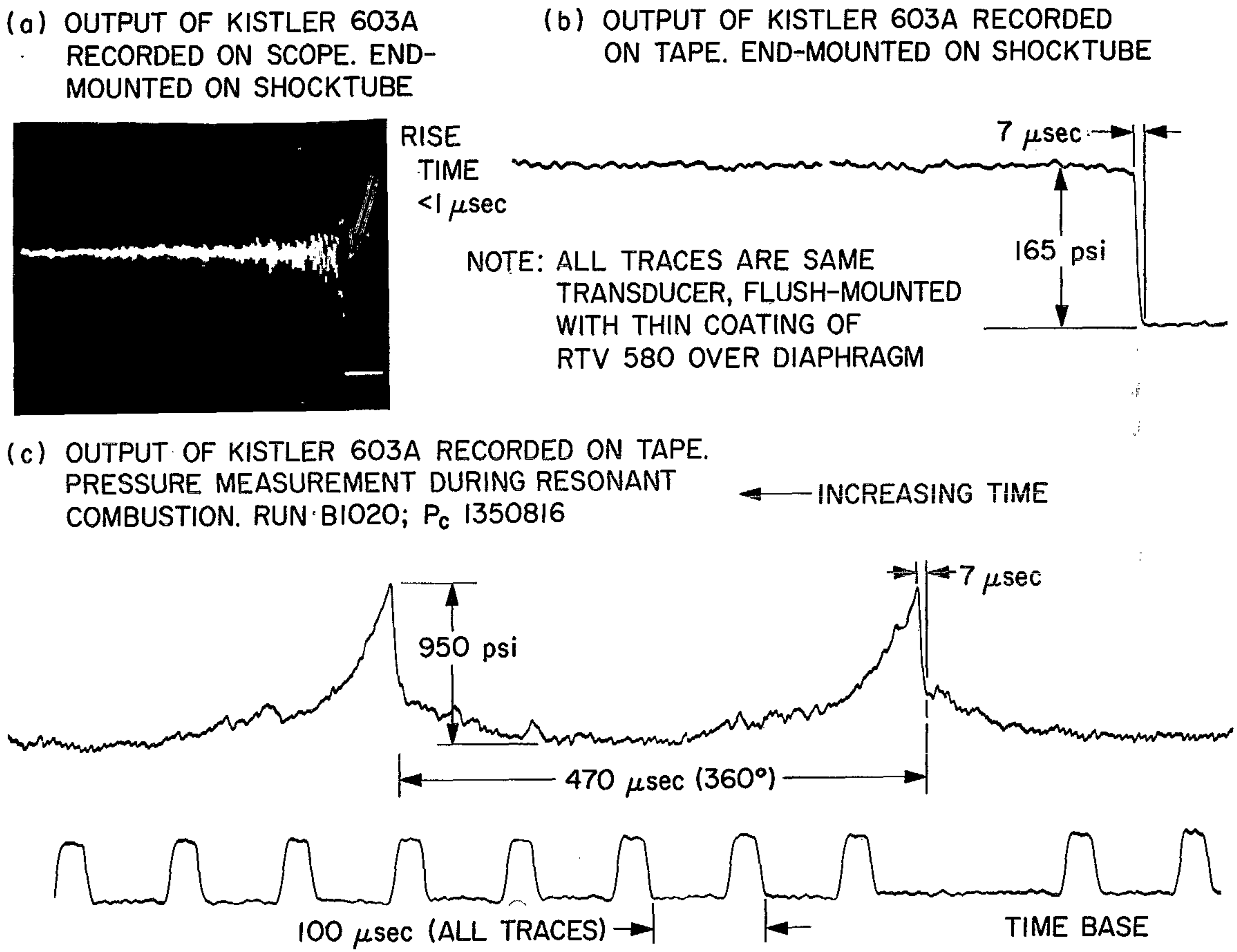

Fig. 2. Response of optimized pressure-measuring system: shock tube and resonant combustion firing

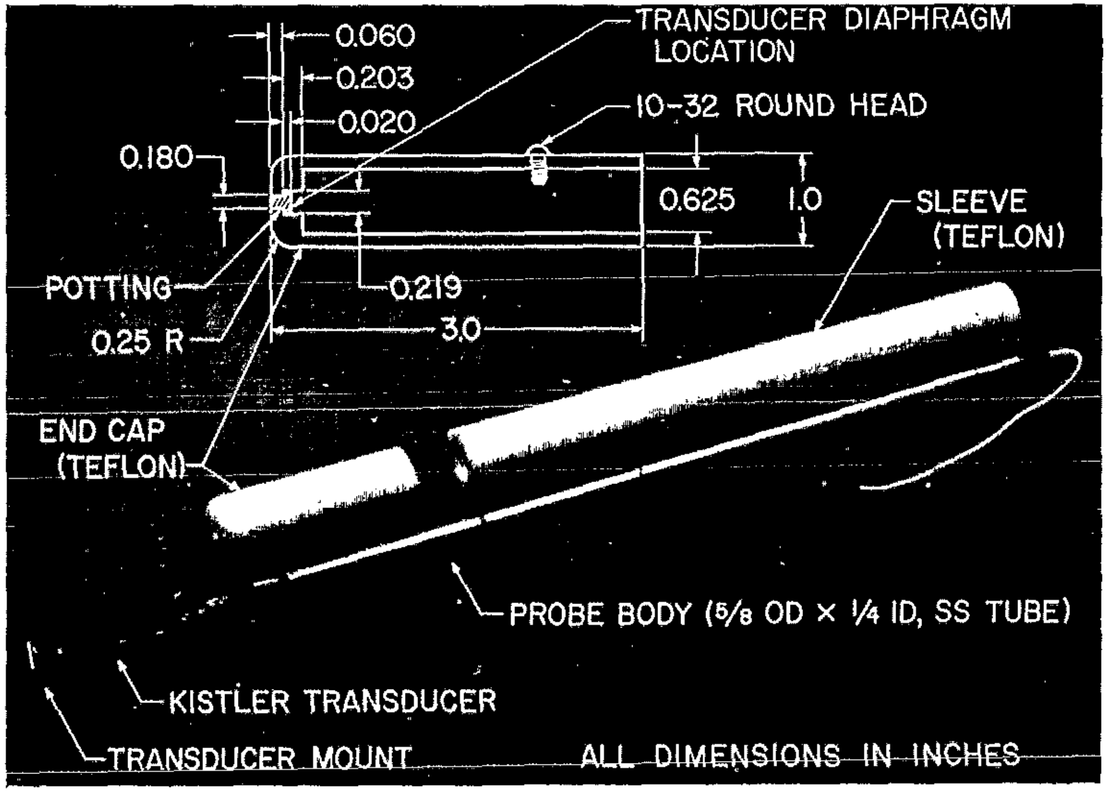

Fig. 3. Construction details of JPL probe

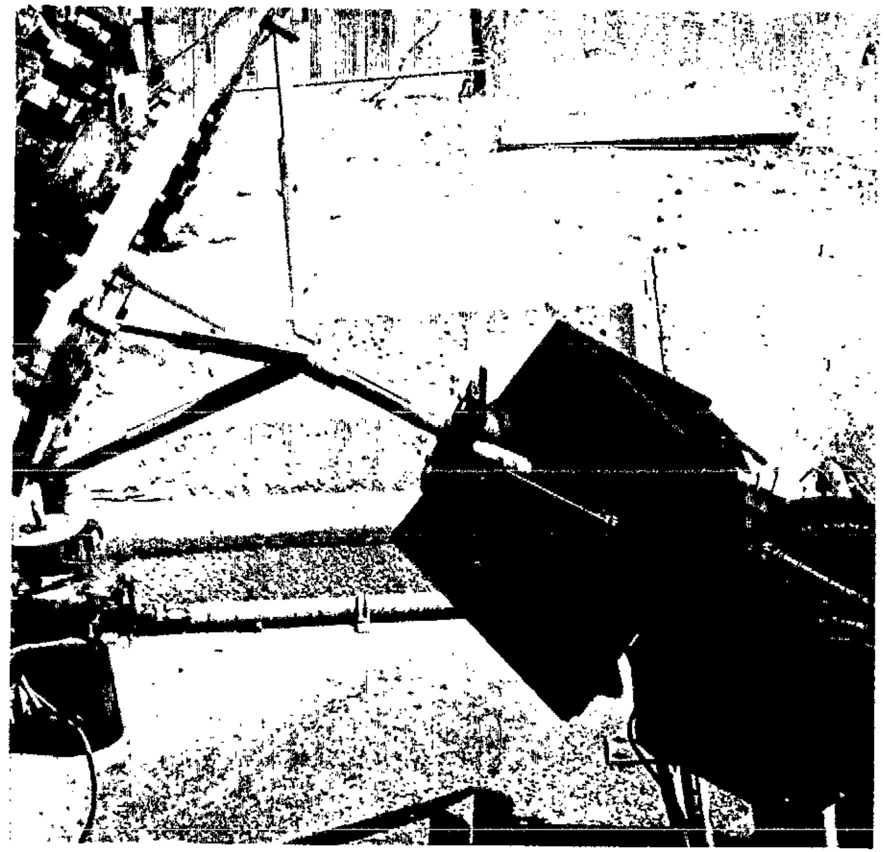

Fig. 4. JPL probe installed for firing

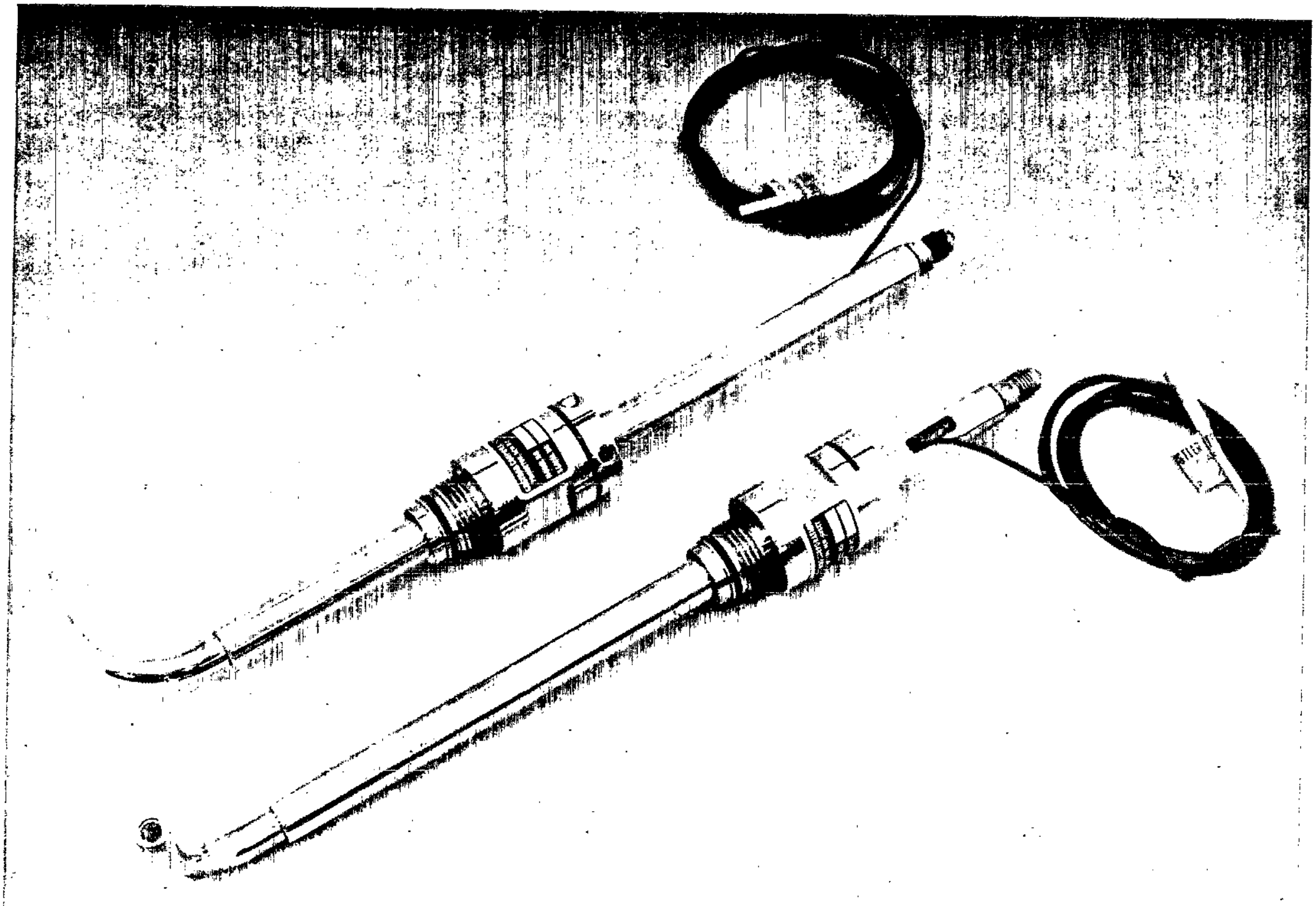

Fig. 5. Water-cooled probe — Greyrad design

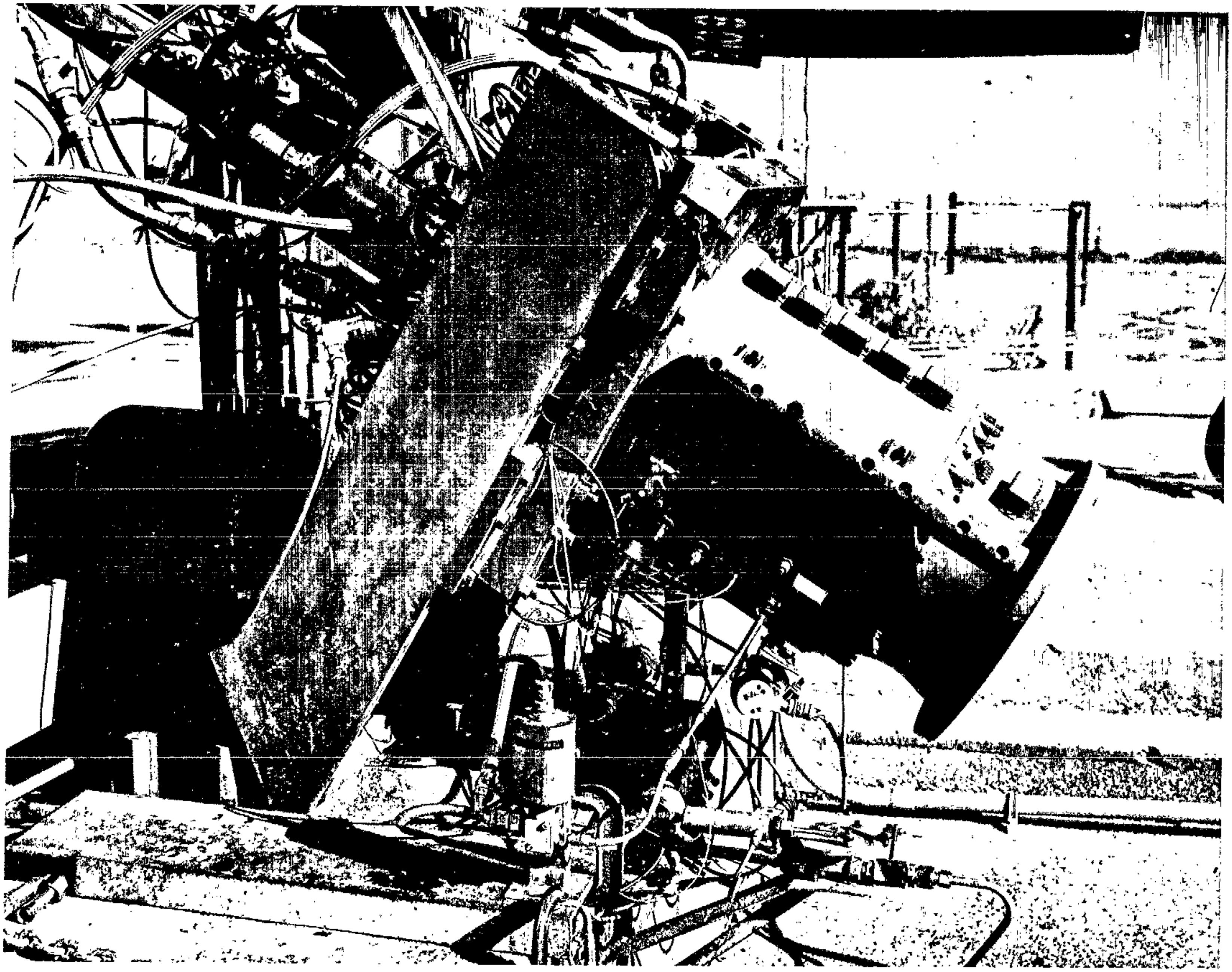

Fig. 6. Greyrad probe installed for firing

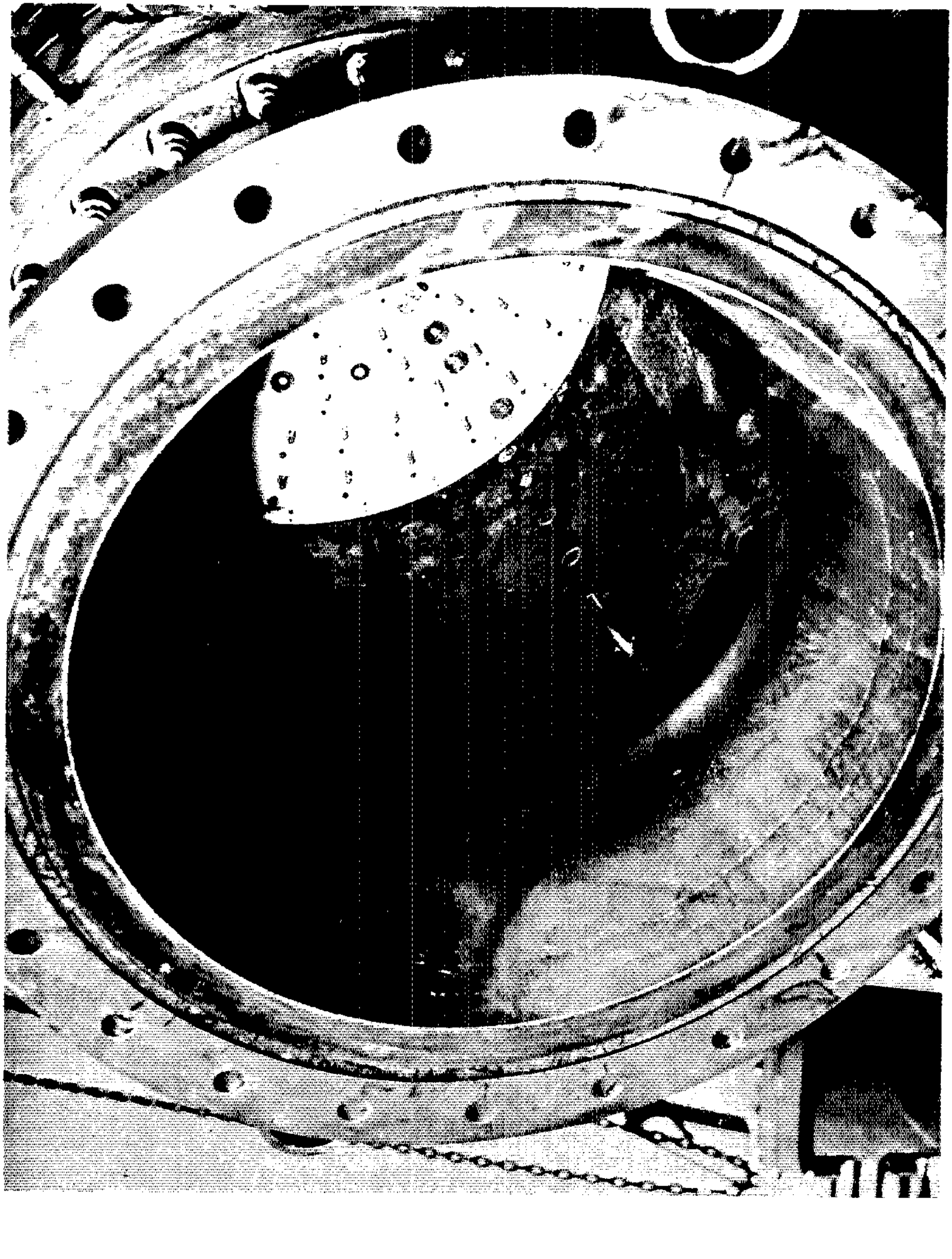

Fig. 7. View up nozzle showing Greyrad probe

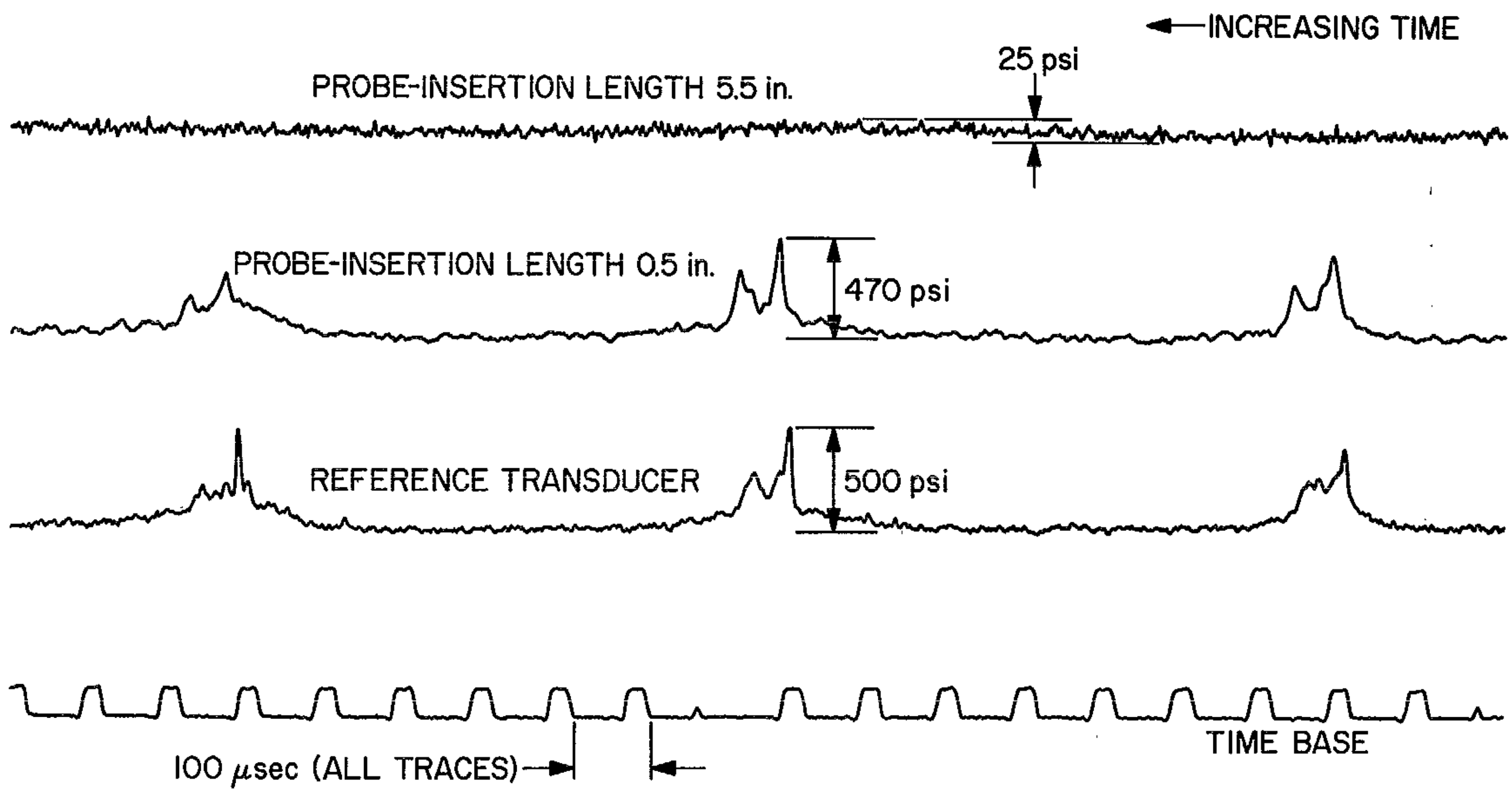

Fig. 8. Comparison of resonant combustion data from probes and reference transducer

FLOW MEASUREMENT TRANSDUCERS AT LRC

By Thomas D. Carpini

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Hampton, Virginia

Presented at the Sixth Transducer Workshop of the Telemetry Working Group of the Inter-Range Instrumentation Group

Hampton, Virginia
October 23-24, 1969

FLOW MEASUREMENT TRANSDUCERS AT LRC

By Thomas D. Carpini
Langley Research Center

SUMMARY

A brief review is made of the flow rate measurement transducers in current use at the Langley Research Center. These include electronic in-line turbine and thermal transducers that directly sense volumetric and mass flow, and differential pressure transducers which are used to infer the flow rate through head-type flowmeters (orifice, nozzle and laminar). Experience shows that the turbine flowmeter, because of its accuracy, rangeability, and ease of application, is best suited to measure nearly all the liquid flow rates. Gas flow rates, depending on test requirements, are measured with a variety of flowmeters, including the turbine type.

INTRODUCTION

The importance of accurate flow rate measurements has grown steadily at this Center in recent years. This importance is linked directly to the development of space-oriented tools like the arc-heated tunnels for probing reentry phenomena, plasma accelerators for studying new methods of space propulsion, and regenerative life support test beds for developing life-sustaining systems for long-mission space craft. Furthermore, flow rate information is essential to experiments involving jet engine performance, gas concentration determinations, thrust and lift augmentation and gas mixing for ablative materials and hypersonic combustor studies. In meeting the flow measurement needs of these diverse research projects, the Instrument Research Division (IRD) has investigated the suitability of a variety of flowmeters and has adopted some for general use. Others are still under test in a continuing program to upgrade the Center's flow measurement capability. A summary of the scope and diversity of LRC's flow measurement activity is presented along with a brief discussion of some current flow transducers and examples of their application.

DISCUSSION

The summary is developed around a list (fig. 1) of the essential factors underlying the selection of a flowmeter for any project application, namely:

1. Fluid to be metered; this includes considerations of viscosity, density, homogeneity, and corrosiveness.

2. Flow range; this implies meter size, meter rangeability, and meter units required.

3. Flowing conditions; these include the operating static pressure, fluid temperature, and acceptable pressure drop.

4. Accuracy expected; this is influenced by factors of calibration, installation, environment, secondary measurements, signal conditioning, and recording media.

Fluids

Wide-spread requirements for measuring a variety of liquids and gases exist. Water at ambient temperature is the fluid in 90 percent of the liquid measurements. Other liquids are JP-4, propane, aqueous propylene glycol, Dow Corning DC 331, 90 percent concentration hydrogen-peroxide, hydrazine, and nitrogen-tetroxide. These fluids vary considerably in viscosity, corrosiveness, lubricity and toxicity. Gas flow measurements (other than air which is the fluid in most cases) often involve the inert fluids, helium, nitrogen, and argon. Other gases are hydrogen, oxygen and the hydro-carbons methane and ethane. Probably the most exotic of metered fluids have been molten lithium and a hydrazine-aluminum powder slurry. The lithium was used (after vaporizing) in a plasma accelerator and a description of the flow measuring system appears later in this discussion; the slurry (30 percent aluminum by volume) was tested as a rocket propellant by the Applied Materials and Physics Division and was measured with a 30-gpm magnetic flowmeter.

Flow Range

Liquid flow rate measurements range from about 5.3×10^{-5} gpm (0.2 cc/min) to 500 gpm. Covering the low range is a resistance type thermal mass flowmeter that measures the rate of water consumption of a water electrolysis unit in a regenerative life support system. Turbine flowmeters ranging in diameter from 3/16" to 2-1/2" handle most liquid flows from about 0.01 to 500 gpm.

Gas flows range from about 3.5×10^{-6} scfm (0.1 cc/min.) encountered in leak rate determinations to 12,000 scfm (15 lbs/sec.) air required to generate thrusts for the 16-foot transonic tunnel testing of jet powered models. The lower ranges are usually associated with gas mixing and combustion experiments, space equipment leak rates, and life support systems. Gas flows are measured with thermal, head-type, and turbine flowmeters.

Flowing Conditions

Flowing pressure and temperature conditions are as diverse as the Center's research projects. Some fluid temperature extremes have been -150°F of liquid nitrogen boil off flows and 600°F of the molten lithium mentioned previously. Most flows, however, are measured at ambient temperatures. Pressure conditions vary more than those of fluid temperature. Some notably uncommon pressures are 1000 psi required to force CO_2 flows to the high enthalpy arc of the Applied Materials and Physics Division, 15,000 psi behind the nitrogen gas flows of the Mach 19 hypersonic nitrogen tunnel, and 1.0-to-10 torr absolute pressures for air flows of experimental planetary enthalpy probes. Some facility water and hydrogen-peroxide pressures reach 1000 psi.

Accuracy

Generally the accuracy requirements vary with the experiment. Liquid measurements in the field can be made to 1.0 percent of reading with careful installation and recording techniques. With gas measurements, the uncertainty is about 1.0 percent of full scale. Here the accuracy has strong dependence upon the pressure and temperature measurements required for fluid density determinations, with pressure exerting the greater influence. Pressure transducers yielding 0.5 percent measurements are generally used, and open-bead thermocouple probes with ±1° tolerances are used to measure fluid temperature.

The most demanding accuracy requirements at LRC are of H_2O_2 and air measurements to thrust simulators used in correlating jet and nozzle performances. More is said of this later.

Liquid flowmeters are calibrated with a Brooks Instrument Co. dynamic time-weight standard certified by NBS to have an uncertainty of 0.15 percent (fig. 2).

Gas flowmeters are calibrated with a Cox Instruments, Inc. sub-sonic nozzle stand with an uncertainty believed to be less than 0.75 percent. Low-flow units (less than 1.0 scfm) are calibrated with a Brooks (George K. Porter) time-volume stand with an uncertainty of ±0.5 percent.

TURBINE FLOWMETER

Because of its accuracy, ease of application and recordability, the turbine flowmeter is the most widely used flow instrument at LRC. Over 400 units exist, all of stainless steel, with measuring capabilities of 0.0125 gpm to 500 gpm for liquid and 0.1 to 250 acfm for gases. Most standard turbines have rotors suspended on ball bearings and operate at pressures to 3000 psi.

The turbine's working principle is simple yet precise (fig. 3). The fluid drives a freely turning rotor (C) suspended in a flow passage (A) of constant area. The rotor (B) turns at a speed proportional to volumetric flow rate. As each helical rotor blade interrupts the magnetic field of a closely coupled pickup coil (D), one cycle of alternating voltage (typically sinusoidal) appears at the coil terminals. The frequency of the generated voltage is a measure of the flow rate while the sum number of cycles is a measure of total flow. A convenient, universally used calibration factor for this system is K = cycles/gallon (for liquids) or cycles/cubic ft (for gas). The linear operating range (constant K) depends on design, size, and fluid viscosity. A 10-1 linear range is common with transducers having full-scale capacities of over 1 gpm for liquid, and 1 acfm for gas. In smaller transducers, small bore, low flow, and fluid viscosity combine to generate non-linear calibrations. Repeatability, however, for all properly functioning turbines is better than 0.25 percent. For gas measurements, recorded values of fluid temperature and pressure are required to determine fluid density which is multiplied by the volumetric flow rate (given by the turbine's output frequency) to compute mass flow rate.

Most LRC turbines have full scale output frequencies of 1200 Hz at output voltages ranging to 1000 millivolts peak-to-peak. These outputs are fed to frequency-to-analog convertors which respond only to variations in frequency and are insensitive to waveshape or changing amplitude. The convertors emit useful low impedance millivolt signals suitable for recording and square-wave signals, which are synchronous with input frequencies, for driving counters. The standard conversion uncertainty is ±0.1 percent of full scale at steady-state flow conditions.

Liquid Applications

A typical facility requirement is recording the history of water coolant flow rates to the electrodes and other elements of any arc heater which is used for studying low density, high temperature, reentry phenomena. Mass flow data are required to assure adequate cooling, perform heat balance calculations and determine test gas enthalpy. Fig. 4 shows a group of 2-inch, 250 gpm turbines in the 20-megawatt arc heated facility of the Aero-Physics Division. They measure 800 psi water flows to the arc electrodes, nozzle, and test section wall. The convertors for these flowmeters (and others) are shown in the control room view of fig. 5. Some have capability for driving meter relays designed to operate emergency shut-down equipment in the event of inadequate cooling.

Another application of the turbine flowmeter is shown in fig. 6. This system was used in the RAM C flight test conducted by the Flight Instrumentation Division for studying radio blackout during reentry. A simple sketch of the vehicle is also shown. A 1/2-inch turbine flow transducer measured the flow rate of water that was injected into the flow field near the nose of the vehicle in an effort to reduce the detrimental plasma effect on radio communications. The water droplets served as recombination centers for positive ions and electrons resulting in signal strength enhancement up to about 30 db. The program called for injection of rapid spurts of water (up to 0.66 lb/sec.) at vehicle speeds of 27,000 ft/sec. and at heights of 300,000 ft. To meet the flow system response requirement of 5 milliseconds, the usual frequency convertor was omitted and the turbine's output, after clipping, was fed directly to a 40 kilocycle voltage controlled oscillator (VCO) for telemetering to ground receivers. The flow rate was obtained from oscillographic readings of the frequency.

Gas Application

An example of gas turbine flowmetering is shown in figs. 7 and 8. Fig. 7 shows a 3-inch diameter, 12-bladed turbine flow transducer which measures up to 15 lb/sec. of air to jet simulators. Fig. 8 is a schematic diagram of the complete flow metering run including the turbine flow transducer. The jet simulators are used for correlating aerodynamic data obtained from jet-powered models in the 16-foot transonic and 4-foot supersonic wind tunnels. Thrusts up to 1000 lbs are generated by exhausting the compressed air through the test jet nozzles. Accurate flow measurements are required since jet thrust coefficients are determined directly from mass flow measurement values. The system accuracy approaches 1.0 percent of flow rate over much of the 10-1 metering range.

The air is regulated down from 1800 psi and heated to 90°F to prevent jet nozzle geometry changes from frost accumulation. Flowmeter static pressure is maintained at 800 psig and measured with a 0.25 percent wsg transducer. The temperature is measured with an open-bead copper-constantan thermocouple probe. The pressure and temperature values are needed to determine fluid density. The mass flow rate is the product of density and volumetric flow rate.

Two-inch flowmeters were first applied in an attempt to restrict system size. However, these meters failed after 15 hours of operation because of accelerated bearing wear due to excessive metering velocities. The 3-inch meter now gives about 100 hours of trouble free operation before bearing replacement is necessary. This life extension resulted from (1), reduced velocities inherent in the larger diameter and (2), an improved bearing system where the 440C stainless steel balls are sealed with stainless steel shields and are silicone-lubricated. Four-inch diameter flowmeters lubricated with light oil have operated for 200 hours without performance loss.

These flowmeters were originally calibrated at the Colorado Engineering Experiment Station which is headed by Professor Tom Arnberg, and were checked at LRC on the Cox flow stand up to 2 lb/sec. On-site meter verification (after bearing change) is made with sonic flow nozzles also calibrated at the Colorado Engineering Experiment Station.

THERMAL MASS FLOWMETERS

Small gas flow rates (<1 scfm) are often measured with thermal mass flowmeters that employ heat transfer sensing mechanisms. Their output (both visual and electrical) are related directly to the convenient engineering mass flow units of lbs/sec., lbs/min., or scc./min., the latter being a volumetric term which defines the gas density at standard atmospheric conditions. Thermal mass flowmeters are useful for (1) monitoring and recording small gas flows into plasma accelerators, (2) determining leak rates of space chambers and inflatable satellites (3), studying the combustion reaction of gases, and (4) determining the relative porosity of acoustical and ablative materials. These flowmeters indicate the true mass flow rate without requiring correction for temperature and pressure variations over fairly wide ranges of these flow conditions.

Several manufacturers market various forms of thermal flowmeters using resistance bridge, thermocouple, thermistors, hot-wire elements for sensing mechanisms. All include some form of in-line transducer and a signal-conditioner meter unit. This discussion will cover two types (fig. 9) in use at Langley: The thermocouple type and the thermistor type, both of which emit output voltages which are a function essentially of mass flow and gas heat capacity.

Thermocouple Type

Simple sketches showing the thermocouple-type flow transducer's basic sensing mechanism appear at the top of fig. 9. At zero flow the differential thermo-electric output of the two thermocouples on the heated tube is also zero. When gas flows through the tube, the assymetrical cooling at the thermocouples produces a differential voltage that is directly proportional to mass flow rate. The approximately 100 units at Langley vary in flow range from 0-5 scc/min. to 0-20,000 scc/min. Some units of higher ranges using laminar by-pass elements also exist for flows to 5 scfm.

These flowmeters are accurate to about 2 percent of full scale and do not require pressure and temperature corrections between 0.1 to 250 psia and 40° to $140^{\circ}F$, respectively. With calibration over narrower pressure and temperature ranges, the accuracy is 1.0 percent of full scale at better than 1/2 percent repeatability. Other advantages are their minimal pressure drops (typically 1" - 2" H_2O for most units) and low-impedance linear output, (0-5 millivolt to 0-10 volt). These meters require reasonably delicate handling, periodic calibration and upstream filtering in order to maintain a desirable level of performance.

Lithium Flow System

Fig. 10 depicts the use of the thermocouple flowmeter in a system which was used to meter molten lithium to a Hall current plasma accelerator of the Aero-Physics Division. Most magneto-plasmadynamics experiments for deep space propulsion had been performed by ionizing and accelerating a variety of gases. Thought was later given to vaporizing and ionizing the alkalai metals because of their lower ionization potential.

Lower ionization potential reduced the energy requirements for the ionization process and made more energy available for accelerating the plasma. Lithium was chosen for the first experiments because its outer ring single electron could be readily dislodged. For optimum correlation with the gas tests, however, the lithium flow rates were fixed at the gas flow rates of .010

to .025 grams/sec. At molten lithium density of .544 grams/cc, the maximum volume flow rate was 2.75 cc/min., a minuscule rate which posed formidable measurement problems. The 600°F molten lithium temperature and the corrosiveness of the lithium compounded the measurement problems.

The chosen flow system, shown in simplified form, comprises a volume displacement technique where flow of an inert gas (helium because of its insolubility in lithium) displaces the lithium in the reservoir. Consequently, by the Law of Continuity, a measure of the helium volume flow rate is precisely that of the lithium forced from the reservoir. The helium pressure and temperature above the lithium were carefully monitored, with the pressure maintained at three atmospheres and the lithium temperature at 600°F. Preset flow rates were controlled with a modified Brown Electrik servoamplifier, motor and gear train which drove the high-resolution, copper-seated metering value. A 0-5 scc/min. thermocouple mass flowmeter was calibrated with helium under test flowing pressure and temperature conditions.

The flow curves show flowmeter readings plotted against lithium mass flow rate. The upper curve is the lithium flow rate inferred from the flowmeter readings and computed from the equations of continuity and state. The lower curve represents the actual flow determined by the timed collection of molten lithium. The flowmeter generally indicated 85 percent of the actual flow rate in repeated calibrations. The systematic error was mostly attributed to the helium calibration of the flowmeter. The time-volume standard used to perform the calibration employed a mercury-sealed piston driven by the helium gas and was designed to handle much larger flows than the 0-5 scc/min. Thus the standard would tend to minimize the effects of small leaks. However, the on-site flow metering system was found to be repeatable to about 2 percent and constituted a major improvement over previous nozzle methods used to measure flows of alkalai metals.

Thermistor Type

In the thermistor mass flow system (fig. 9) a self-heated bead thermistor loses heat to the fluid stream and the electrical power required to maintain the thermistor at a fixed resistance (temperature) is related to mass flow rate. A second thermistor compensates the sensor's non-linearity so that the 5 volt dc output is linear with mass flow rate. A panel meter provides instant readout of mass flow in percent of rated flow capacity. Units are available with capacities of 3.3×10^{-3} to 50 lb/min. Again, like the thermocouple types, these flowmeters impose negligible pressure drop and indicate true mass flow rates over fairly wide pressure and temperature ranges without correction when careful application techniques are practiced.

PRESSURE TRANSDUCERS FOR HEAD-TYPE FLOWMETERS

High Pressure Flows

At this center, wire strain gage and potentiometer type transducers (fig. 11) are generally used to measure the flow-proportional differential pressure (ΔP) across the restricting element in head-type compressed gas flow systems. All emit output signals that are compatible with LRC's data aquisition systems and perform with combined hysteresis and non-linearity errors of less than 0.75 percent of full scale. Typical ΔP ranges are from 0-10 to 0-250 paid in transducers operating at line pressures from 150 to 5000 psi.

Experience with head-type compressed gas flow measurement systems shows that the ΔP transducer must be able to sustain over-loads many times its design ΔP range because of high pressure transients that are often generated within these systems. Most of the center's ΔP transducers have adequate overload characteristics for nearly all of the high-pressure flow work at line pressures to 1500 psi. Some (the potentiometer type included) can sustain ΔP overloads to 6000 psi without degrading significantly their performance. Important design features of the most reliable transducers are (1) hydraulically damped force-summing devices, (2) effective mechanical stops, and (3) insensitivity to high common-mode pressures.

A major disadvantage of the potentiometric transducer, however, is the wire-wound potentiometer with its inherent resolution and mechanical problems. Currently, IRD's Force Measurement Section has adopted a Hall effects transducing system to this unit in place of the potentiometer. Results from early laboratory and field tests are highly encouraging.

Low Pressure Flows

For small gas flows both in the atmospheric and sub-atmospheric pressure flow regions, capacitance pressure transducing systems are often used. In the atmospheric case, laminar flow elements are used to reduce the Reynolds numbers to values less than 2000 so that the pressure drop becomes linear with volume flow rate. The capacitance pressure systems with a 1000-to-1 rangeability are well suited for laminar flow elements whose ability to measure near-zero flows is limited only by the pressure instrument. In the sub-atmospheric case, repeatable flow-proportional pressure data from sonic nozzles operating at 1 to 100 torr pressure have also been obtained with the capacitance gage. This system employs a transducer consisting of a high precision, stable capacitance voltage divider of which the variable element is a thin, prestressed metallic diaphragm. Positioned between fixed capacitance plates, the diaphragm, when acted upon by pressure inputs, amplitude-modulates the carrier voltage which is applied to the fixed plates. After demodulation, the output appears as a 0-5 volt dc signal which is linear with pressure to within ±0.5 percent of full scale for each of 7 selectable ranges, and repeatable to better than 0.25 percent. Typical transducer ranges are ±10, 50, 100, and 1000 torr.

CONCLUDING REMARKS

A brief discussion was presented on the nature of fluid flow measurement requirements at LRC and the transducers which are currently being applied to meet these requirements. The following statements reflect the present flow measurement activity:

(1) Turbine flow transducers are used to measure about 90 percent of the liquid flow rates; most are used for water coolant flows in arc-heated facilities.

(2) Gas flow rates are handled with a variety of instruments including thermal mass flow transducers, turbine flow transducers, and differential-pressure transducers in head-type flow systems.

(3) Measurement capabilities range from 5.3×10^{-5} gpm (0.2 cc/min) to 500 gpm for liquid and from 3.5×10^{-6} scfm (0.1 cc/min) to 12,000 scfm (15 lb/sec) for gases.

(4) Measurement uncertainties for liquids are generally 1.0 percent of flow rate; those for gases, 1.0 percent of full scale flow rate.

1. FLUIDS (VISCOSITY, DENSITY, HOMOGENEITY, CORROSIVENESS)

LIQUIDS		GASES	
WATER	PROPYLENE GLYCOL	AIR	CARBON DIOXIDE
JP-4	DOW CORNING 331	NITROGEN	METHANE
PROPANE	NITROGEN TETROXIDE	HELIUM	HYDROGEN
HYDROGEN PEROXIDE	HYDRAZINE	ARGON	ETHANE
MOLTEN LITHIUM	HYDRAZINE-ALUMINUM SLURRY	OXYGEN	HYDROGEN SULPHIDE

2. FLOW RANGE (METER SIZE, RANGEABILITY)

5.3×10^{-5} gpm (0.2 cc/min.) TO 500 gpm	3.5×10^{-6} scfm (0.1 cc/min.) TO 12,000 scfm

3. FLOWING CONDITIONS (PRESSURE, TEMPERATURE, PRESSURE DROP)

PRESSURE: TO 1000 PSI	.02 TO 15,000 PSIA
TEMPERATURE: MOSTLY AMBIENT	$-150°$ TO $100°$ F

4. ACCURACY (CALIBRATION, INSTALLATION, SECONDARY MEASUREMENTS, SIGNAL CONDITIONING, RECORDING)

MEASUREMENT UNCERTAINTY:

1.0 PERCENT OF FLOW RATE	1.0 PERCENT OF FULL SCALE

CALIBRATION:

BROOKS 9910 DYNAMIC WEIGH STAND (300 gpm, ± 0.15 PERCENT UNCERTAINTY)	COX 610 AIR PRECISION NOZZLE STAND (2 LB/SEC., ± 0.75 PERCENT UNCERTAINTY)

FIG. 1 SUMMARY OF LRC FLOW MEASUREMENT ACTIVITY.

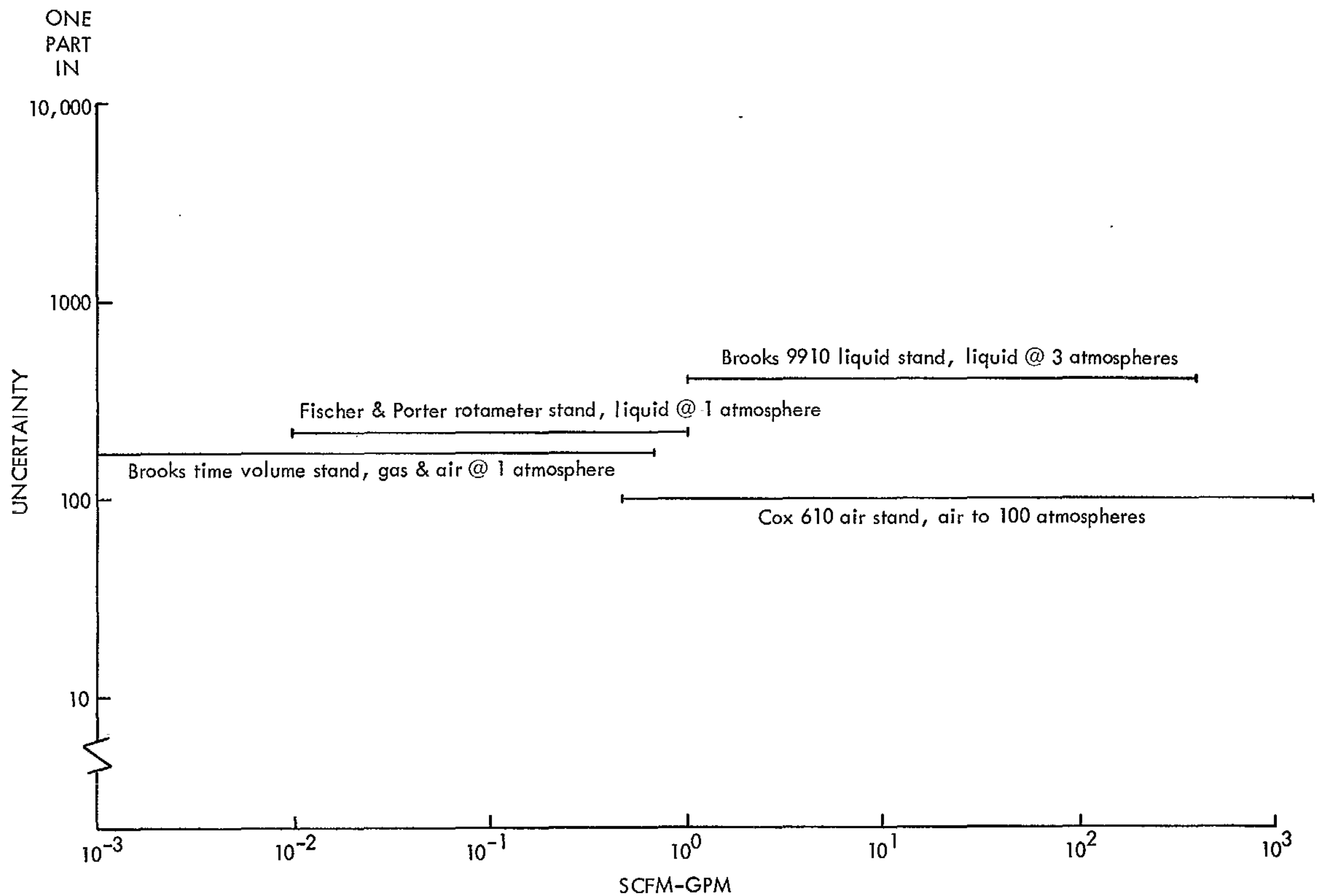

FIG. 2 SCOPE AND UNCERTAINTIES OF LRC FLOWMETER CALIBRATION EQUIPMENT

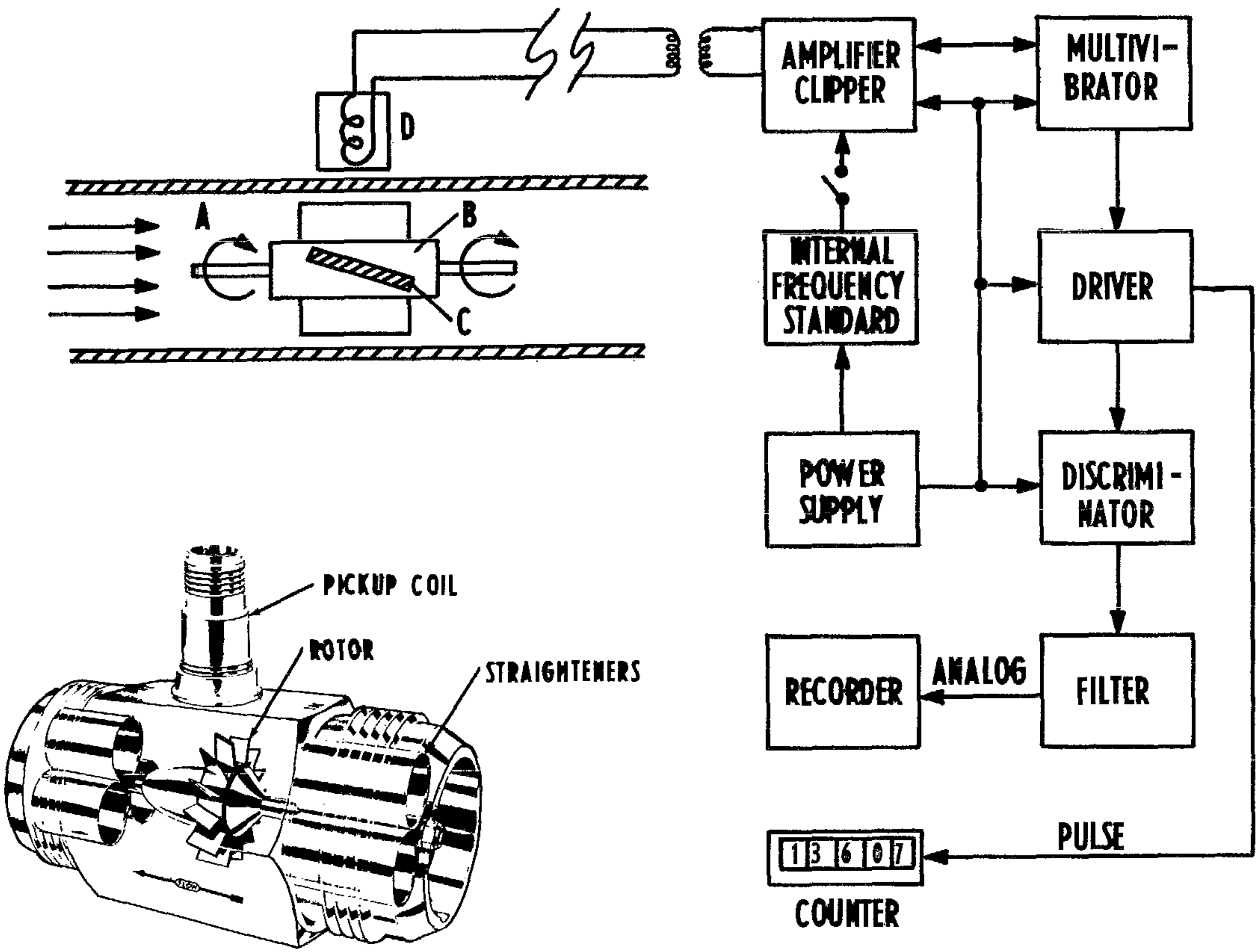

FIG. 3 TURBINE FLOWMETER SYSTEM.

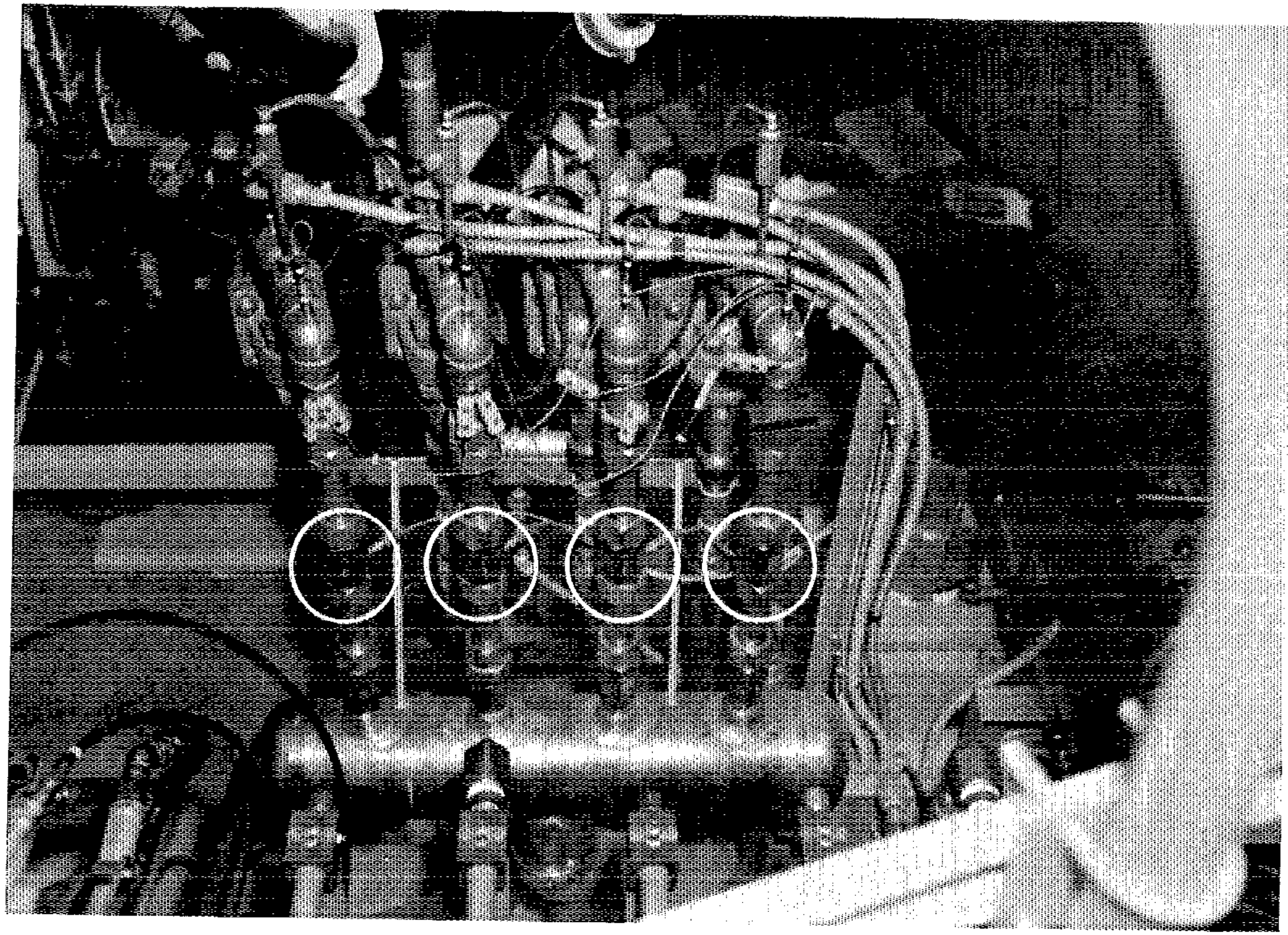

FIG. 4 TURBINE FLOW TRANSDUCERS MOUNTED IN THE WATER COOLANT SYSTEM OF AN ARC HEATER.

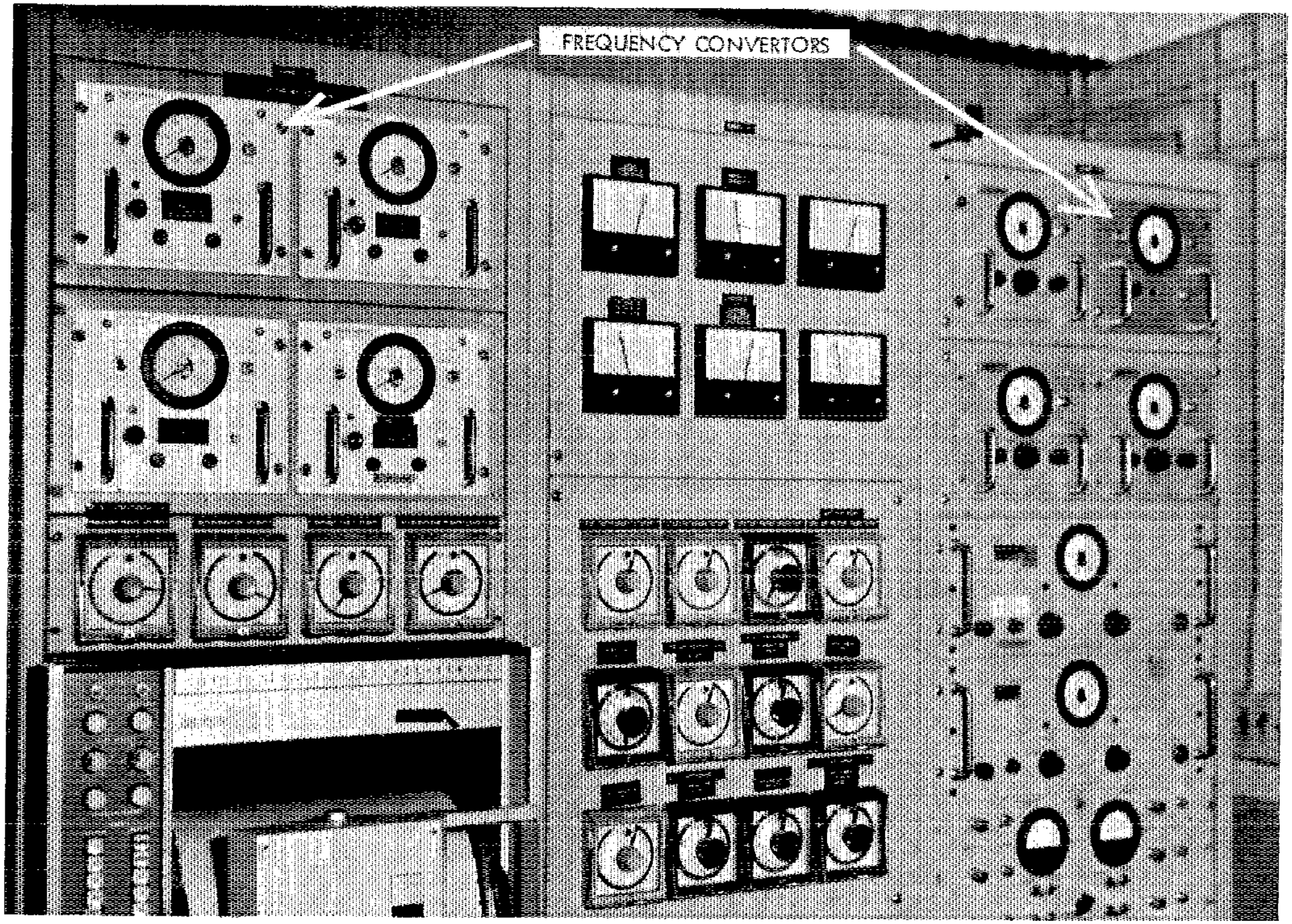

FIG. 5 CONTROL ROOM INSTALLATION OF FREQUENCY CONVERTORS

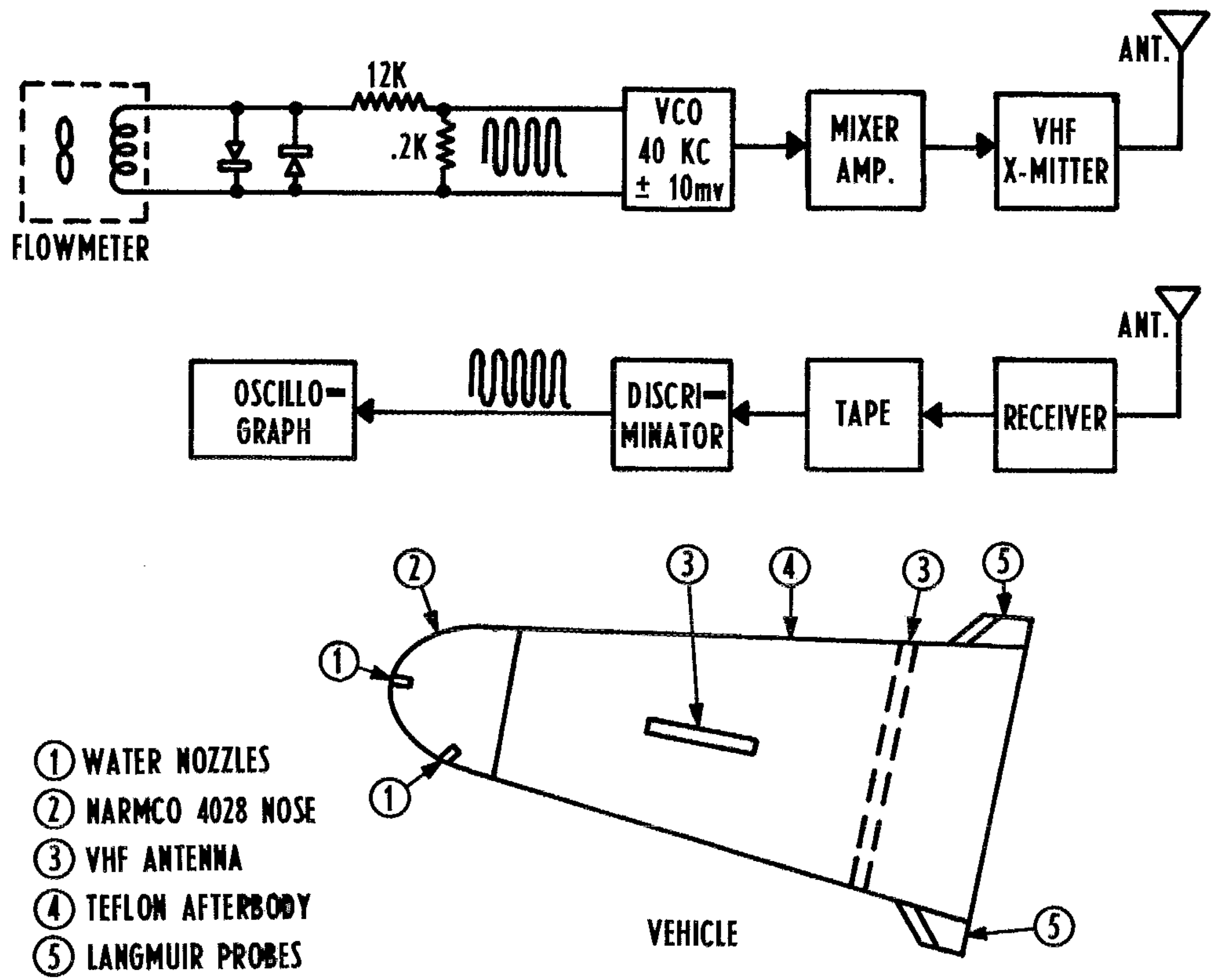

FIG. 6 RAM C WATER FLOW MEASUREMENT SYSTEM.

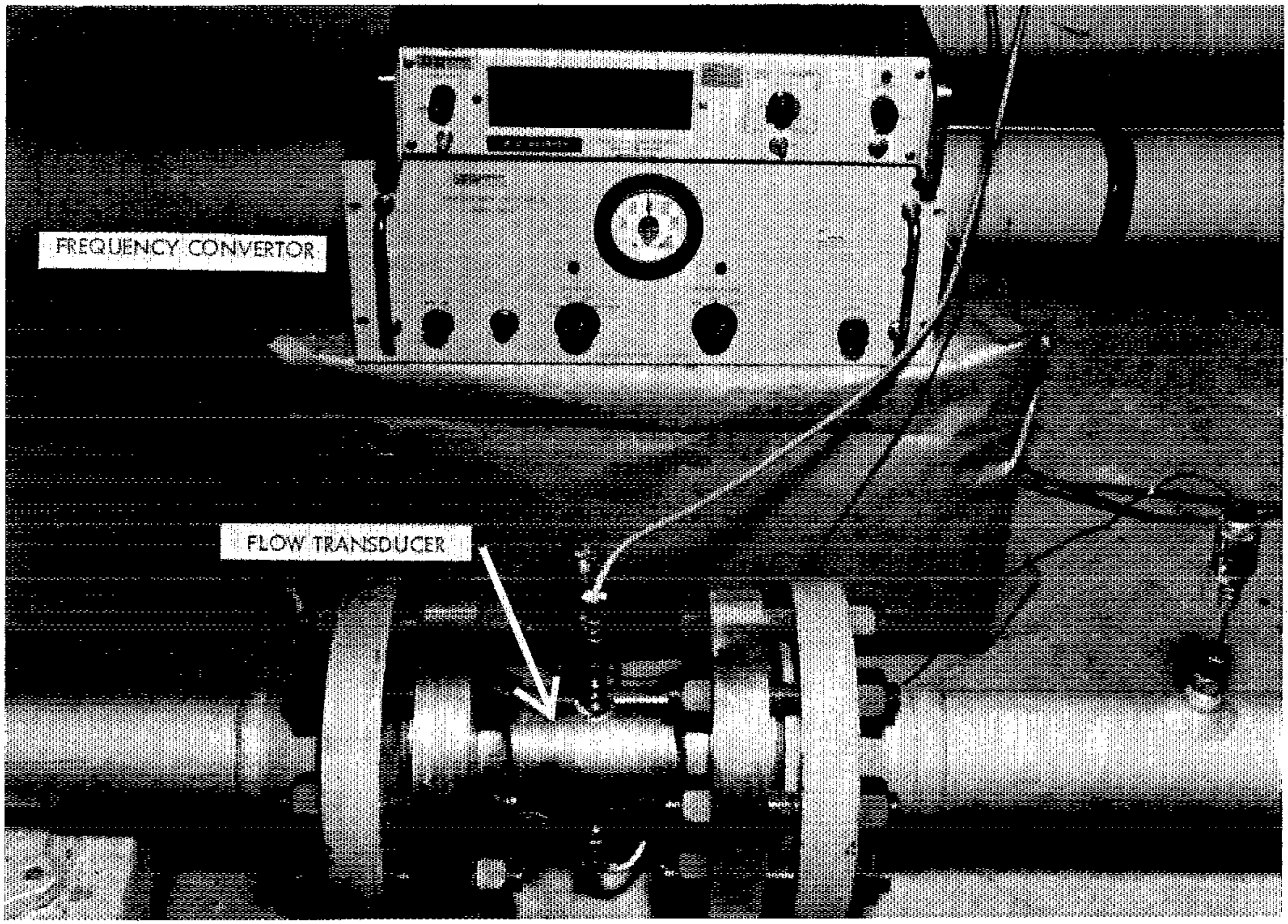

FIG. 7 3 - INCH, 15 LB./SEC. TURBINE FLOW SYSTEM FOR COMPRESSED AIR FLOWS.

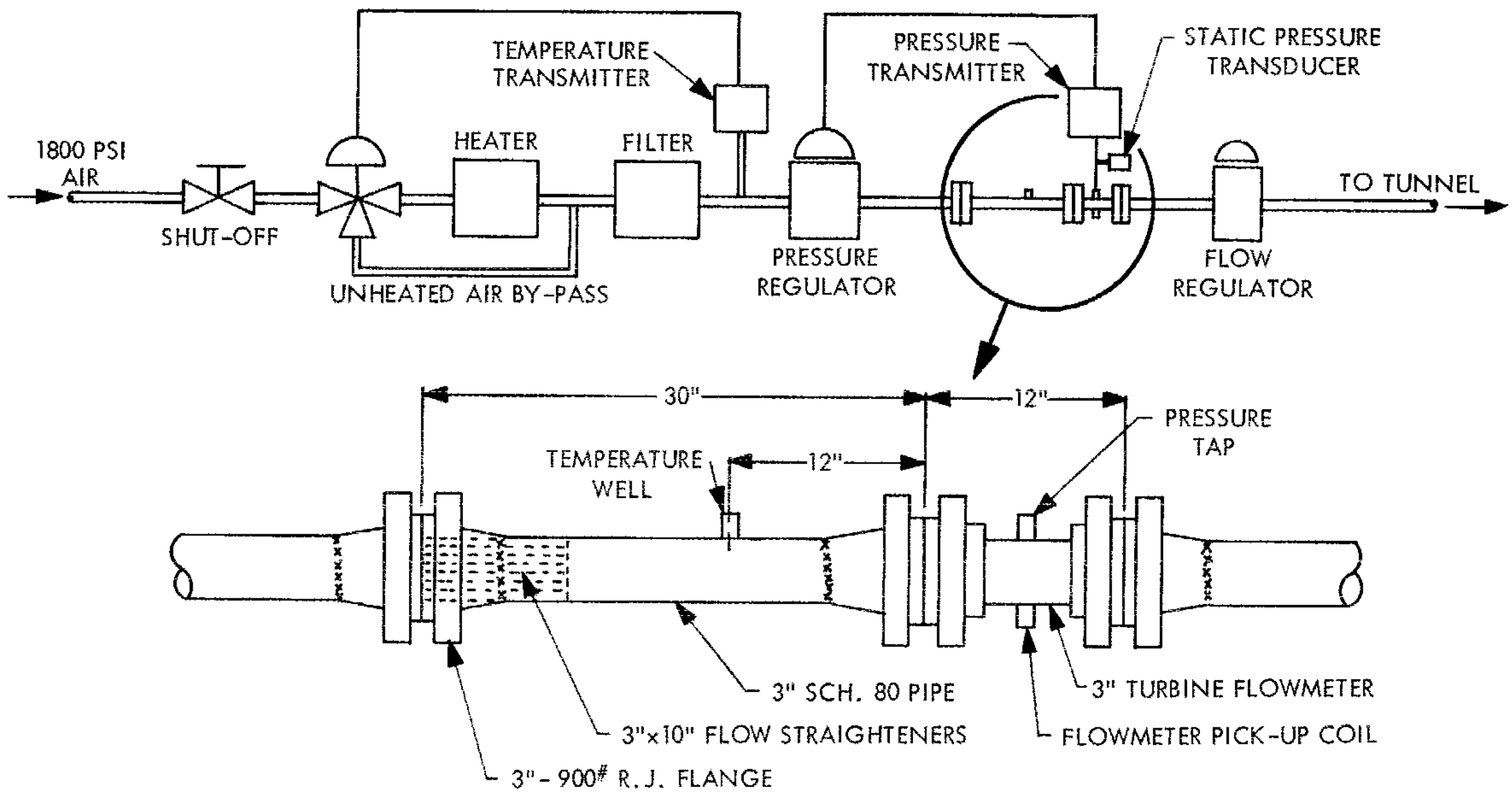

FIG. 8 - 16FT. TUNNEL HIGH PRESSURE AIR TURBINE FLOWMETER SYSTEM.

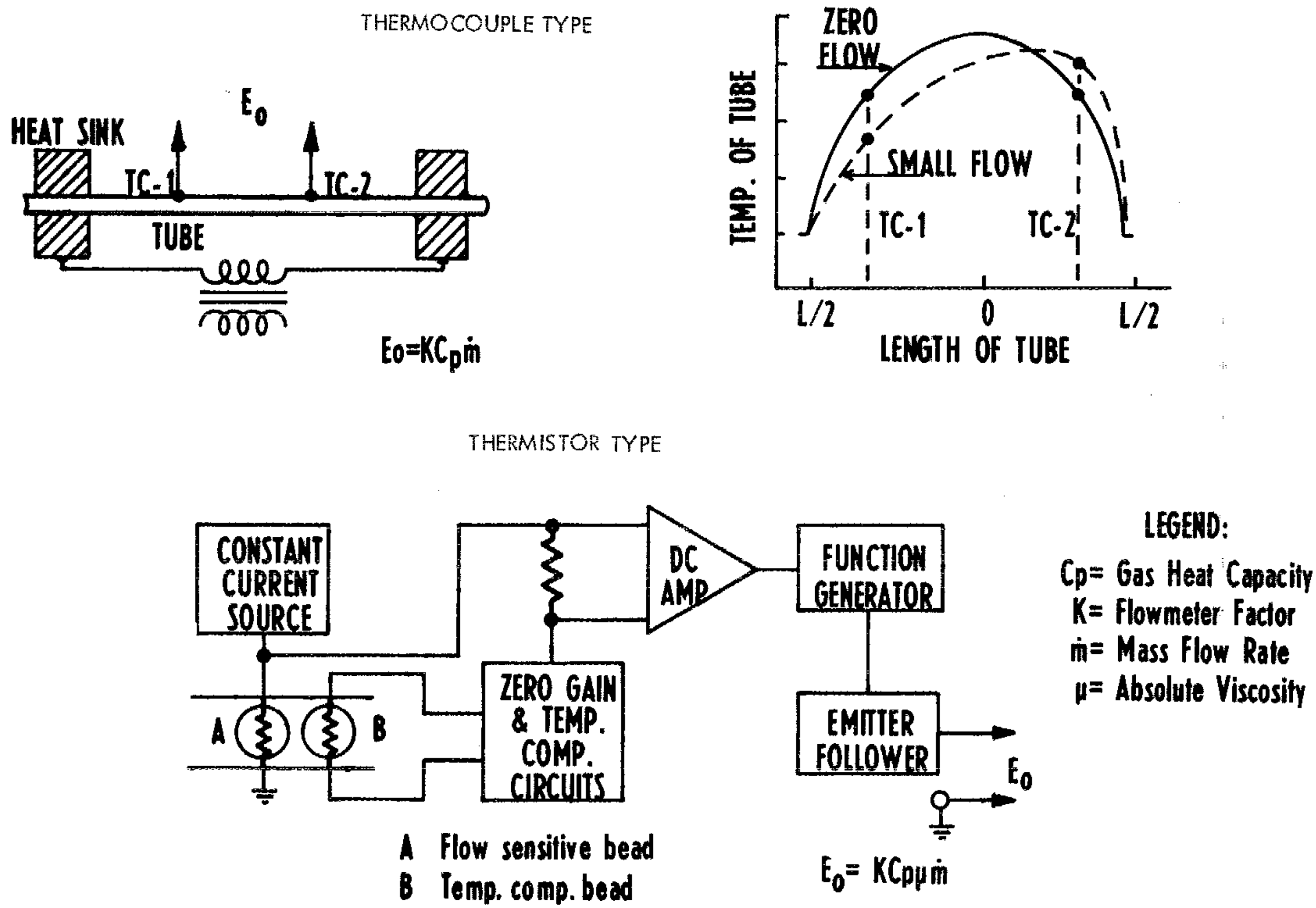

FIG. 9 THERMAL MASS FLOWMETERS.

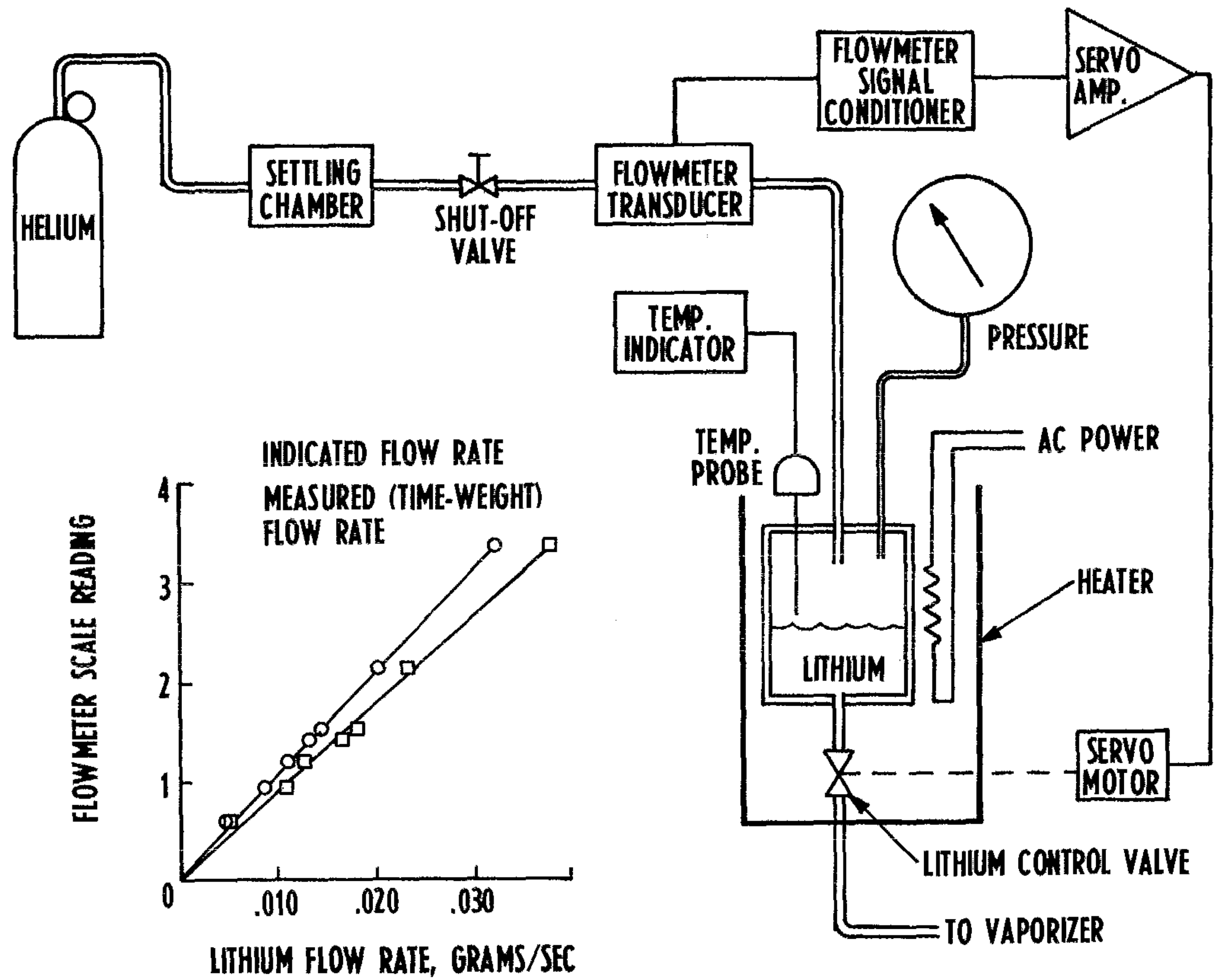

FIG. 10 MOLTEN LITHIUM FLOW SYSTEM.

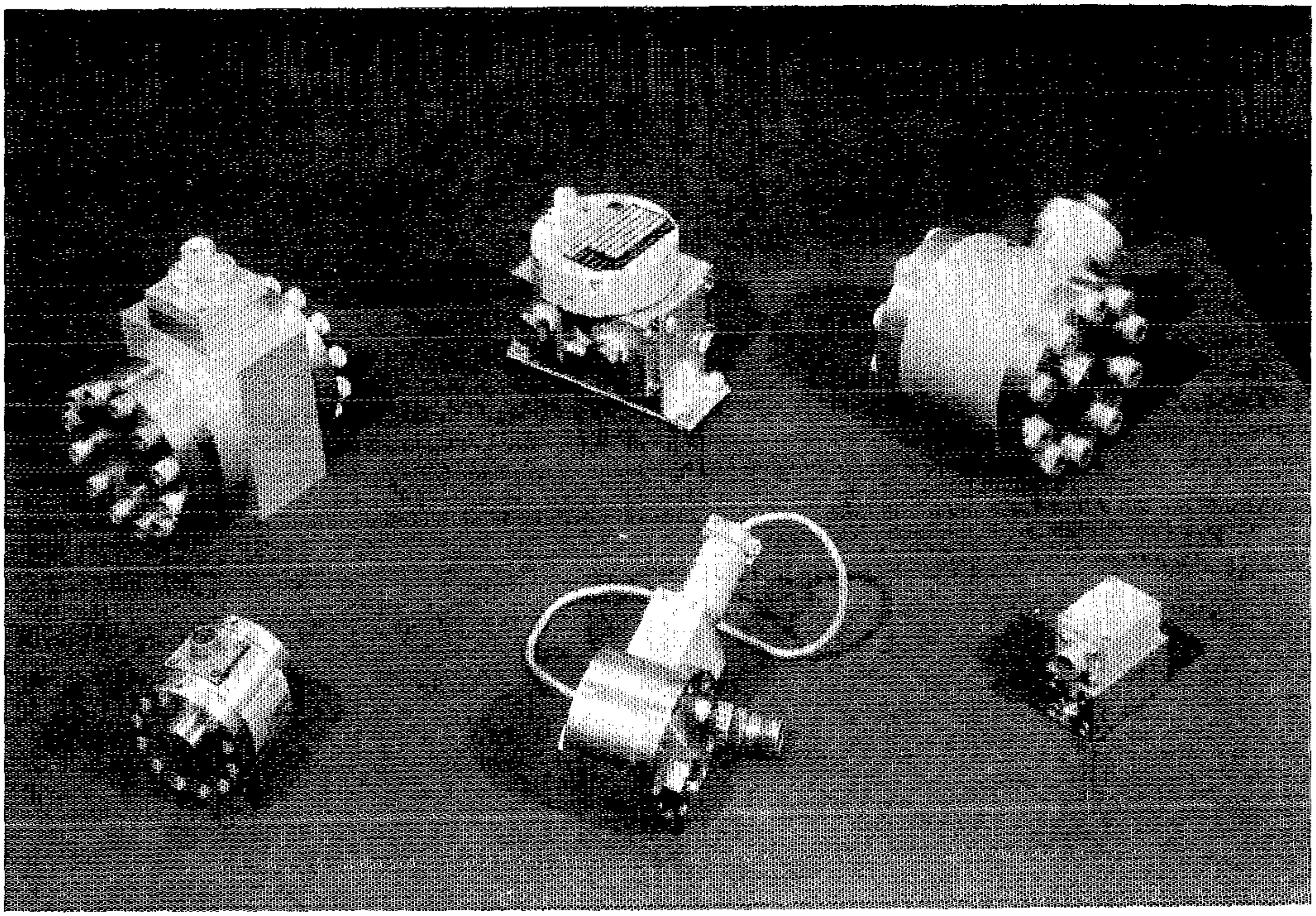

FIG. 11 DIFFERENTIAL PRESSURE TRANSDUCERS CURRENTLY USED AT LRC FOR COMPRESSED GAS FLOWS.

REMARKS AND ANSWERS FROM

SESSION II, "MEASUREMENT

OF PRESSURE AND FLOW"

Question 1: E. K. Yager

How are the pressure transducers calibrated?

Answer: With Shock Tube Facility.

Question 2: P. K. Stein - Arizona State University

What is the amplitude of the pressure step generated in the shock tube?

Answer: 150 PSI to 200 PSI.

Question 3: Warren Thomas - NASA - Langley

What was location of Reference Transducer? Was it flush mounted?

Answer: Inskeep showed where transducer was mounted, flush - near the Greyrad probe transducer.

Question 4: W. Thomas - NASA - Langley

Does orientation of reference transducer and probe transducer i.e. (90 degree) effect output of the two output tracer?

Answer: No, because pressure wave is in tangential mode and is moving across face of both transducers.

Question 5: On data presented there is a 30 psi difference between reference probe. Is this a calibration error?

Answer: No, the accuracy of the measurement is no better than $\pm$ 30 psi.

Question 6: Paul Lederer, NBS

Does the water cooling coming through the probe introduce errors?

Answer: No, the water is started before the engine and no shift in zero is observed.

Question 7: Paul Lederer - NBS

Was the cooling water supplied to the probe when it was calibrated in the shock tube?

Answer: Inskeep, "No, and that is a problem which has to be worked on. A means to handle the water in the shock tube has to be worked out."

Question 8: Thomas - NASA - Langley

How can you be sure peak pressure observed is not a result of transducer resonance?

Answer: The transducer resonance is about 500 KHZ and this frequency does not show up in the data. The rocket was fired with transducer capped so that any output would be due to mechanical excitation. Essentially, no response from the transducer was recorded. It is reasonable to assume that uncapped transducers response is from pressure only.

Question 9: Dale Rockwell

What is the 7 microsecond delay observed on the trace curve?

Answer: This is a response characteristic of the recording system. Data taken on an oscilloscope does not show this delay.

Question 10: Bill Harvey

How do you know output is not due to mechanical shock and vibration?

Answer: The transducer was installed in a tap which does not see pressure and the output observed. The data shows output of less than 10% of amplitude of pressure data.

Question 11: What about temperature sensitivity?

Answer: Zero shift due to temperature change is a low frequency phenomena and does not effect the high frequency data. The pressure pulses are on top of 200 psi average chamber pressure. This static pressure is not recorded by this transducer, i.e. the system is AC coupled.

Question 12: What was the property of the coating of RTV on the transducer?

Answer: The coating on the pressure diaphragm protects the transducer from the environment without the coating the data was always lost.

Question 13: Has the spectral analyses of the data from different parts located around the chamber been compared to identify the mode of oscillation?

Answer: No, it was not. The purpose of the probes was to demonstrate the existance of a heliz type pressure wave within the combustion chamber. The probe provides data out in the chamber away from the walls of the chamber. This data in addition to the data obtained from the flush mounted transducer will characterize the unstable combustion.

Question 14: What is the low frequency capability of the transducer?

Answer: The Kistler transducers have poor low frequency response. The Kistler transducer is used for High Frequency data only and a TABOR transducer is used to measure low frequency chamber pressure data.

Question 15: Thomas - NASA - Langley

What other type of transducer can be used to obtain the data?

Answer: Inskeep, "Water cooled Photocon Transducer but they are less rugged than the Kistler."

Question 16: Paul Lederer - NBS

Have you used the Princeton University Helium Bleed Transducer?

Answer: Yes, we use them when longer run times are required, but they have a lower frequency response than the Kistler Transducers under $10KH_2$.

Question 17: Alfred Boyd-AF Rocket Propulsion Lab

How many firings can you get on a probe?

Answer: Nine so far, without failure.

Question 18: How was the cooling water flow rate established?

Answer: Greyrad corporation established that two pounds per second water flow was required for the probe. Water pressure and flow rate was usually measured to insure cooling of the probe.

Question 19:	Was RTV charred or eroded?
Answer:	Yes, each time the probe was used the RTV required replacement.
Question 20:	What is the longevity of uncooled transducers?
Answer:	The transducers lose sensitivity and require replacement often. After each test some of the transducers require replacement average of 5 or 6 firing per transducer.
Question 21:	How often are the transducers calibrated?
Answer:	After each firing.
Question 22:	How was Heat Flux figure of 50 $BTU/in^2/sec$ determined?
Answer:	Early in the program heat transfer ratio of 10-15 $BTU/in^2/sec$ were measured. How specification of 50 $BTU/in^2/sec$ was reached is not known. From experience the rocket wall which is 1 inch thick stainless steel has burned through in one second.
Question 23:	TomCarpini - NASA - Langley What was the gas temperature in the chamber?
Answer:	Over 6000°F.
Question 24:	Lederer - NBS What is the accuracy of the measurement?
Question:	How does the Project Engineer feel about the accuracy?
Answer:	No complaint. He is looking for gross pressure changes, 30 psi is adequate.
Question:25:	Dale Rockwell Is the 500 KHz ring frequency of the transducers obtained with the RTV coating on the transducer diaphragm.
Answer:	Yes, it is.

COMMENT: Walt Patrick - Sandia Corporation

Explosive Driven Shock Tube produce temperature transients of two ms rise to 9000°F and Decay 26 ms.

Test of various transducers. With coating in explosive shock tube to measure the resonance frequency of the transducer with the explosive shock tube is necessary to protect the transducer from temperatures to avoid zero shift. Dynamic pressure and dynamic temperature go together. If transducer is evaluated without coating the data is not usable due to temperature induced zero shift. If transducer is in the 500 psi range or more, the mass of the coating does not change the resonance very much since the diaphragm mass is quite large compared to the coating. However, if transducer is a small one the coating introduce damping which causes phase distortion as well as reducing the resonance frequency.

Test at Sandia on small 10-32 inch diameter Kulite strain gauge transducers indicate that electricians tape provide suitable protection from temperature transients while introducing small amounts of damping and phase distortion.

Thin film transducers are available but they have a time smear problem when the temperature transient crosses the transducer face. Static test indicates they are better than strain gauge transducers by an order of magnitude insofar as zero shift with temperature is concerned.

The best results would be obtained if the transducer did not require a coating because then the transducer would be undamped and the highest resonance frequency would be observed.

Question 26: Tally - Marshall Spacelight Center, Huntsville

Does anyone know how to check the step flow response of a turbine flowmeter?

Answer: Carpini, "I think Jerry Grey did some of this work and I have some of his papers on it. We flew a 1/2 inch turbine on a RAM C package where one of the critical specifications was that it have a time constant of 5 milliseconds, or the time to reach full step flow was about 20-25 milliseconds. We have had some bad experience with a certain manufacturers flowmeter in that when the flow was suddenly increased, it wanted to increase speed and was reluctant to come down. It was worse the other way around."

Tom Corpini presented a short discussion of flow calibration and application at NASA-Langley to open discussions on flow measurement.

Question 27: How do you determine the response of a turbine flowmeter?

Answer: Quick acting valve.

Question 28: Tally-- NASA - MSFC Huntsville

Has anyone tested turbine flowmeter to determine their sensitivity to accelerations?

Answer: No.

Question 29: What techniques are available for measurement of mass flow rate of gas.

Answer: Tally - NASA - MSFC Huntsville

Injection of radio-active material.

COMMENT: Mr. Dale Rockwell

In the last few years the turbine flowmeter manufacturers have been putting out non-magnetic pick up. Those increased flow ranges from 10-1 to 50-1 or higher. These flowmeters are used for transfer standards. High Pressure-high temperature flowmeters for an air medium were purchased from Quantum Dynamics. These were specified to operate at 800°F for up to several hundred cubic foot minute. Our heat exchangers are not in operation and tests have not been completed at this date.

Question 30: P. K. Stein - Arizona State University

I would like to address this question to any member of the panel: Has anyone ever accessed the effect on the flow of placing a flowmeter, a turbine type or any other, in the flow stream? For instance, if a pump is forcing fluid through a pipe, you have one set of conditions. What happens to the pump, or any other driving force, when a flowmeter is put into the system. There has to be some effect, back pressure or something, that affects the pump operation that wasn't present when the flowmeter was absent.

Answer: Corpini, "When a flowmeter is calibrated against some standard, it puts out some signal that is proportional to mass flow and when it's in use, the pressure is always at a level to overcome or minimize any effects of back pressure."

Rockwell, "In my experience of monitoring calibration work by others, I feel that any effect is eliniated or minimized by calibrating under the exact conditions which the flowmeter will be actually working under during the measurement."

COMMENTS: Mr. Charles Brodey presented a discussion of Oscillating Gyroscope Mass flow of blood required to receive reflections at a given depth.

Question 31: Professor Jacobs

Does anyone have an approach for measuring flow environment in the human being in the main arteries of the body without requiring major surgery?

Answer: Al Boyd - AF Rocket Propulsion Lab

Someone at Ames Research Lab at Moffet Field, California is making measurements of blood flow with an ultrasonic doppler shift technique. They apply a cuff to the arm or leg and transmit a pulse of ultrasonic energy into the tissue. Professor Jacobs' comments that this technique may not be safe as the reaction of the blood to ultrasonic energy is not known.

COMMENTS: Mr. A. H. Boyd reviewed the Pulse Flow Measurement Technology at AFRPL. This included the status of the Laser Flowmeter, the Positive Displacement Flowmeter used to measure the total volume per pulse and new target type flowmeter for CLF_5 flow measurement.

Question 32: How do you generate your step junction of flow to calibrate the flowmeter?

Answer: A. H. Boyd - AF Rocket Propulsion Lab

We open a valve down stream with a pressurized tank feeding the system. Altitude control engine valve open 2 ms.

SESSION III

General Measurement Problem Areas

Chairman: W. G. James, AF Flight Development Laboratory

Recorder: J. F. Kowalick, Frankford Arsenal

Panelists: L. L. Lathrop, Sandia Corporation
E. K. Yager, General Dynamics - San Diego
Prof. R. M. Jacobs, Newark College of Engineering
Prof P. Stein, Arizona State University

Panel Session III "General Measurement Problem Areas"
Prof. R. M. Jacobs; J. F. Kowalick, Recorder; L. L. Lathrop; W. G. James, Chairman; Prof. P. Stein; E. K. Yager.

TRANSDUCER APPLICATION IN BIO-ENGINEERING

Robert M. Jacobs
Associate Professor

James L. Martin
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Newark College of Engineering
Newark, New Jersey

Presented at

6th Transducer Workshop
October 23, 24, 1969
Langley Field, Virginia

by

Robert M. Jacobs

The purpose of this paper is to present some applications of standard tranducers to the specialized area of Bio-Engineering. In our work at NCE we have used existing or "off-the-shelf" transducers in three research programs: The first, "The Evaluation of Left-Ventricular Work in Man By the Thermal Dilution Technique", essentially a temperature measuring problem; the second, "The Evaluation of the Friction Drag of Biological Fluids in Contact with Technological and Biological Surfaces", a drag or force measuring problem; and the third, "The Effects of High Pressure (50 atmos) and Dissolved Gases on the Viscosity of Blood, and Blood Derivatives" a pressure measuring problem.

The problem of temperature measurement in the left-ventricular work evaluation is that a rapid response, $T = 0.02$ sec, temperature sensor is required that has sufficient structural integrity so that it can be inserted into a catheter with an .050 ID and fed into the left-ventricle of a man from either the brachial artery, at the elbow, or the femoral artery, at the groin. The maximum distance the sensor has to travel within the body was 100 cm. In addition, the output from the sensor system has to be compatable with the existing instrumentation within the operating room of the Cardiac Catheterization Laboratory. Some of the literature referred to the use of thermistors in the thermal dilution technique in animals. Upon investigation it was found that the time constant for the devices used was 0.25 seconds or longer. The structural integrity or the thermistor assembly appears questionable because of the many components that could separate in sterilization, and in the relatively rough handling of insertion. In addition, a thermistor circuit requires a power source to be led into the body - a questionable practice. A commercially available thermocouple was found that appeared to meet all requirements -- structural integrity and a T < .02 seconds. This C/A thermal couple is 150 cm long, contained within a 0.020" S.S. Jacket tapering to .04" for 2: and reducing to 0.010" for the final 1/4". The time constant for the thermal couple, amplifier and recorder are shown in Figure 1. The trace on the bottom of the figure is for an ECG for an adult male undergoing a standard cathertization procedure. We were connected to one channel of the recorder testing the time constant by taking the junction from ambient air to a beaker of water 3° below ambient, the initial discontinuity in the trace is due to the changing film coefficient as the probe is moved through the air. The time constant evaluation had noting to do with the patient, we have left the ECG on to show that in time interval of one heart beat all changes can be followed. A normal heart rate is 70 beats a minute during cathertization it can go up 140 beats per minute, assuming equal time for diastole and systole, and that the flow assumes a square wave with diastole taking .2 to .4 seconds requiring the T = .02.

The output of the thermal couple is fed to the amplifier section of a strain gage bridge amplifier. An Ellis Bam-1 is available, the DC amplifier (500 gain, 2000 cps cut-off) was found to be stable and capable of amplifying the micro-volt signal for the Electronics for Medicine recording console in the Cathertization Laboratory operating room. An initial attempt was made to use the amplifiers within the E for M console but they did not have the required DC stability nor sufficient amplification without cascading which led to many difficulties.

The thermal dilution technique is relatively old. The early applications were used to determine volume of left ventricle before filling started (end systolic) and at the end of filling (end diastolic) and from these valves the volume of the left ventricle. The clinical procedure used is to insert a catheter through the brachial artery into the left ventricle, a second catheter is inserted into the femoral artery and is also inserted into the left ventricle, Figure 2. The catheter in the brachial artery is connected to a cold saline injector. The catheter in the femoral artery acts as a guide for the thermal couple. The position of the catheters and temperature probe are constantly monitored by x-ray and TV screen, photographic records can also be made. Once the probe and injecting catheter are positioned, 40 cc of cold (40°F) saline is injected over 3 or 4 heart beats, Figure 3. As the cold saline enters the left ventricle the bulk temperature decreases during systole (fluid ejection from the heart) and increases or remains constant during diastole (fluid filling the heart). At end of injectioning the cold fluid, a minimum bulk temperature is reached and each subsequent diastole increases the temperature and systole does not change the temperature. A normal heart will have 6 or 7 up to the original base temperature, others will take longer. Equations, Figures 4 and 5, have been developed for determining the instantaneous volume of the left-ventricle from the time-temperature curve and the initial body temperature, saline temperature and volume. This has been reported in the literature. All of the in vivo work to date has been done in the Cathertization Laboratory at St. Michael's Medical Center, Newark under the direction of Dr. R. Brancato.

In the evaluation of the effects of dissolved gases in blood on the viscosity at high pressure a transducer was required that could sustain 750 psi (50 atmos) and be sensitive enough to resolve a maximum of .050 inches of water, repeatedly. In addition to this requirement, the total volume of the test chamber and transducer has to be very smsll since human blood is to be evaluated. The test device consists of two blocks of Lucite connected, Figure 6, by a glass capillary having pressure taps bored into it. The Lucite blocks are the drive piston block and the floating piston block. The drive piston block has a 0.250 diameter ground glass piston rod activited thru a gear train and screw assembly. The gear train can be modified so that lead screw advance can be changed from 0.6 in/min to 5.5 in/min. The drive is from a reversible synchronous motor at 72 rpm. In the original device the floating piston block was to contain an 1/8 inch diameter ground glass rod acting as the piston of a "dead weight gage". The glass rod was found to be binding and alighnment was virtually impossible. It was therefore, discarded and replaced with a standard high pressure dead weight tester which could be isolated from the system, after the fluid within the test device was pressurized. In order to provide a closed system the drive piston block was modified so that a second piston within a new block would be retracted when the main rod was advanced. By connecting the fluid passages of the float piston block to the new piston chamber, the fluid system is closed and can be pressurized to any level by means of the external dead weight gage. It is planned to fill the large volumes with saline and use a limited quantity of blood (less than 20 cc) within the main drive cylinder and the capillary. All other spaces will be filled with the saline under pressure. For the drive piston rod diameter selected the shear rates possible are from 20 per/sec to 700 per/sec.

A statham PM 280 TC $\pm$ 2-350 pressure transducer was available at NCE. This transducer is capable of line pressure of 3000 psi and has a full scale differential pressure of 2 psi. An Ellis Bam-1 was used to power the transducer. The output of the BAM was read on a HP 490 AB DC vacuum tube voltmeter paralled with a Texas Instrument XY Plotter with a Signal Control module. An initial test was performed with the transducer to establish its sensitivity. It was placed on end, the system balanced to correct for diaphragm motion, one cavity of the transducer was filled with water, a head of approximately 1/4" water, which gave an output signal that was measurable. A test rig was then devised to test and calibrate the unit under ambient conditions. This contained a micrometer (.0001 inch) adjustment on one side of the transducer. The gain of the BAM was adjusted for 1 mv output for 0.01 inch water pressure differential, this permitted readings to the nearest .001 ± .0005 inch water on the XY plotter using 1 mv/inch Figure 7 is a calibration curve. With this range the noise was found to be approximately ± .1 mv (.001 inch water) and the drift over a 30 minute period to be .3 mv (.003 inch water). Since normal operating time, with human blood is limited to 60 to 90 seconds this drift is more than acceptable. Repeated cycling thru a rnage of ± .05 inch water indicated that the system had excellent repeatability and maintained the sensitivity of 1 mv/.01 inch of water.

To date a preliminary calibration of the test equipment with water has been made. For a shear rate of 34.1 /sec an output of 6.5 mv (.065 inch water) has been found this compares with .069/sec theoretically. We have also found that the viscosity of water does not change with pressure from ambient to 50 atmospheres.

The test is based on flow through a capillary viscometer with an initial assumption that

$$\Delta P = \frac{8 Q \mu L}{\pi R_0^4}$$

and

$$\left.\frac{du}{dR}\right|_{R=R_0} = \frac{1}{2\mu} \frac{\Delta P}{L} R_0$$

For a 1/4" diameter piston traveling 1/60 in/sec the volume flow rate is: $Q = \frac{\pi}{(60)(64)} \text{ in}^3/\text{sec} = 8.17 \times 10^{-4} \text{ in}^3/\text{sec}$

Using a 0.0625 in. diameter capillary 10 inches long results in a

$$\Delta P = 0.25 \times 10^{-2} \text{ psi} = 0.069 \text{ in. } H_2O$$

and $\left.\frac{du}{dR}\right|_{R=R_0} = 34.1 \text{ per sec}$ shear rate.

The volume float piston, chamber, drive piston chamber, capillary and intersections is approximately 10 cc.

A recheck of transducer calibration after use to 775 psi indicated that the original calibration of 1.0 mv/.01 inch water was maintained. The gain on the BAM was checked by means of the internal calibration circuit in the unit, with a calibrating resistor of 1 meg-ohm the output is 14.5 mv and this is checked on the TI Plotter. There is slight shift of the zero of the transducer as the pressure in the system is increased, not with increased pressure differential. Since we are not measuring dynamic changes over a range of system pressures but rather are measuring pressure differentials at discreet pressure levels this drift is unimportant and can be accounted for prior to testing.

This program has been supported by office of Naval Research Division of Physiology under contract N-00014-67-A-0225-0002 NR 101-732.

The friction drag of a blood system in contact with technological and biological surfaces was to be measured directly in order to observe any differences that exist in the magnitude of the friction drag per unit area in the physical situation. These were to be made with a minimum volume of blood - ideally 25 cc but not to exceed 50 cc.

An axi-symmetric geometry was chosen for the drag generating section of the system. The axisymmetric geometry provides a system with some of the independent variables found in the micro-circulation of humans (one conduit variable, variable shear rate, and relatively rigid boundaries). The device consists of two 0.250 inch diameter tubes connected to a 14 inch diameter well. The tubes differ in length by 5 inches, other than that, they have as near identical extrance and leaving conditions as can be fabricated. At the lower end of these tubes are 10 ml plastic syringes driven by a common drive system, Figure 8. Suspended into the two cylinders are 1/8" diameter spherical ended glass stings - one is 5" longer than other. The "stings" are mounted to cantilever beams by .008" diameter flexure wires and stabilized by a bearing. The beams are .060" x 0.500" x 5" long to the flexure wires. A capacitor plate mounted approximately 7" from the support of each beam. The two plates are within .010 inches of a common ground. Provisions have been made to adjust the gap of each beam independently.

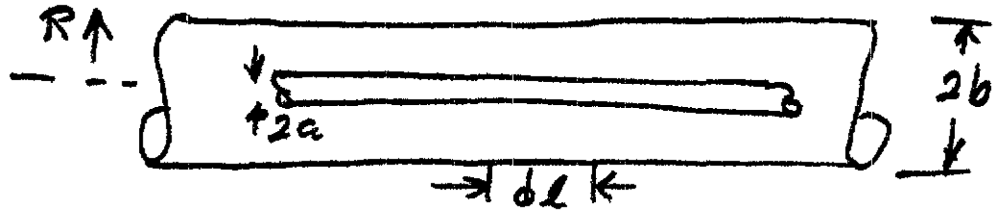
The capacitor plates are connected into a differential circuit through a Lion Research GP 311 "Capacitance to voltage Transducer" to a 202 A Driver Unit. The output from the Driver unit is read on a HP 3420A DC Differential Voltmeter capable of reading in the microvolt range, Figure 9.

The expressions governing the flow conditions at points far removed from the ends, more than 20 times the gap size, are for a Newtonian fluid in creeping motion are

Shear: $$\tau = \mu \frac{du}{dR}$$

Velocity: $$u = \frac{1}{4}\mu \frac{dP}{dl}\left[a^2 - R^2 + \frac{a^2 - b^2}{\ln b/a} \ln \frac{a}{R}\right]$$

Flow Rate: $$Q = \frac{\pi}{8\mu} \frac{dP}{dl}\left[(a^4 - b^4) - \frac{(a^2 - b^2)^2}{\ln a/b}\right]$$



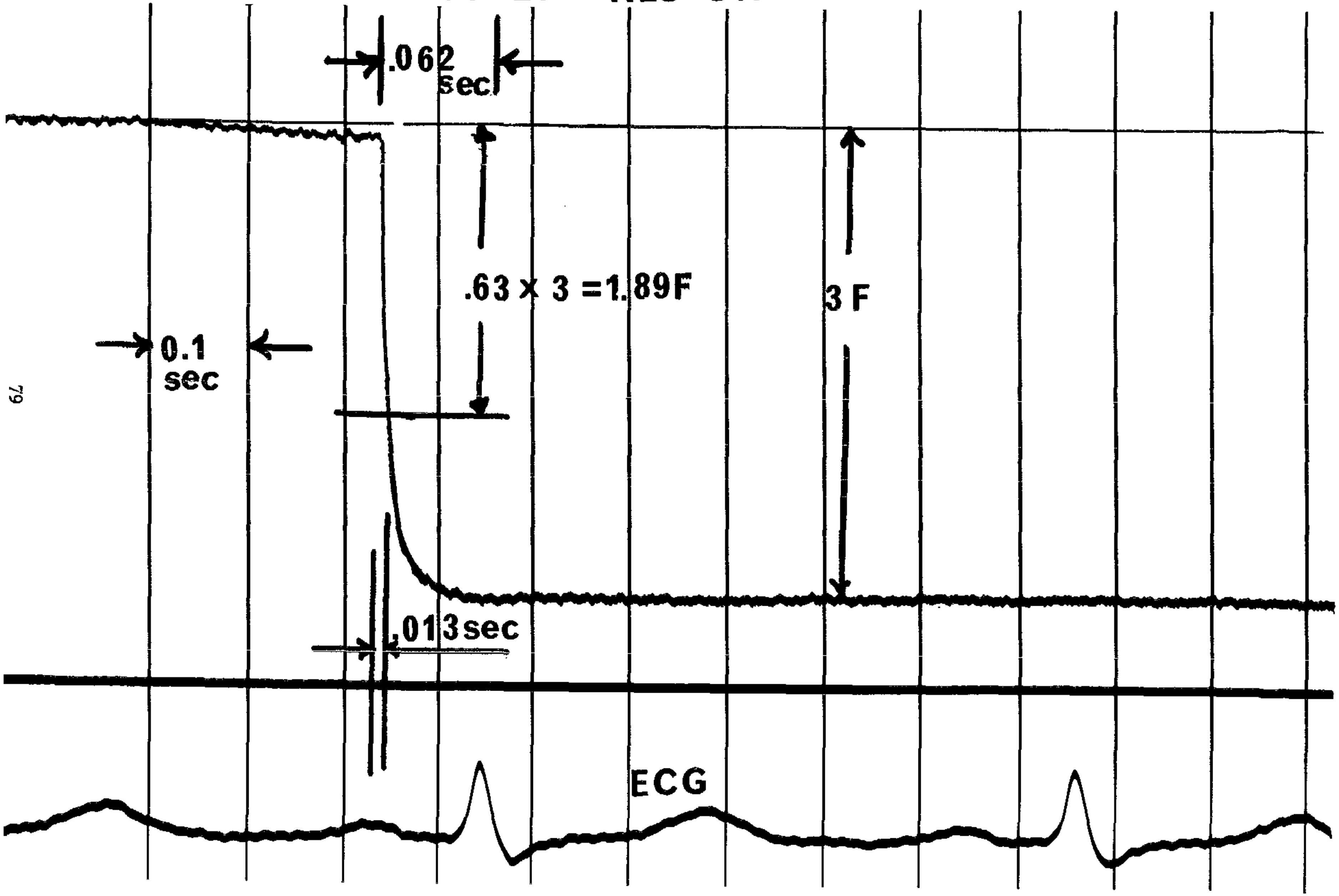
Drag: $F_{Drag} = 2\pi a l \tau(a)$

For an outer annulus diameter (2b) of 0.250 inch, an inner annulus diameter (2a) of 0.125 inch and a flow rate 0.00327 in^3/sec a drag force of 0.00112 pounds (500 mg) is produced on a 10" sting, the flow Reynolds number is 6.73.

Preliminary test data indicates that a 200 mg weight on the beam in the plane of the sting will produce an output signal of approximately 20 mv, since the read-out is in the micro-volt range three significant figures can be easily obtained. To date, only preliminary calibration has been made with the device.

This work is being done in conjunction with the Hemotology and Thrombosis Laboratory of the V.A. Hospital, East Orange, New Jersey.

FIG. 1 SYSTEM RESPONSE



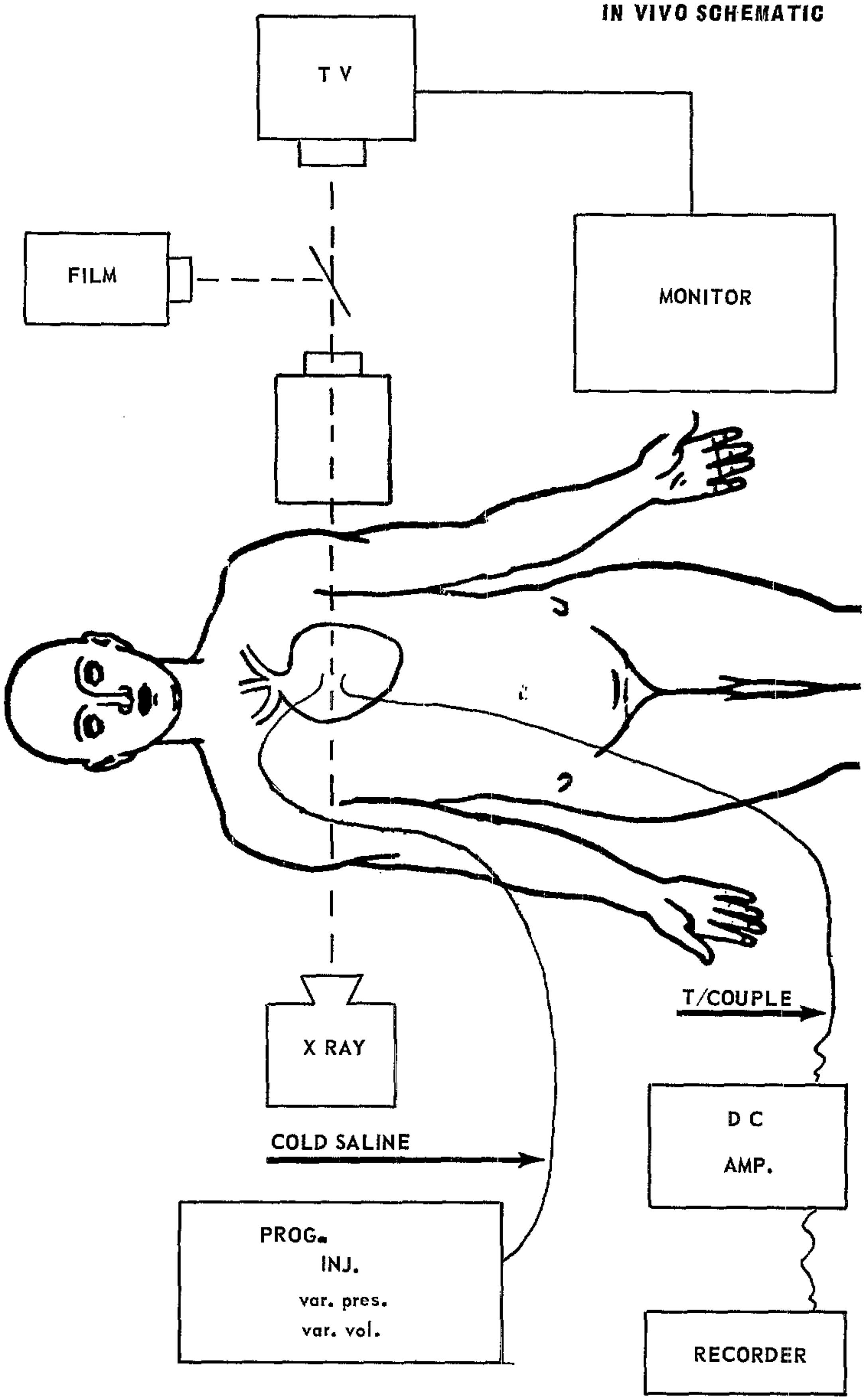
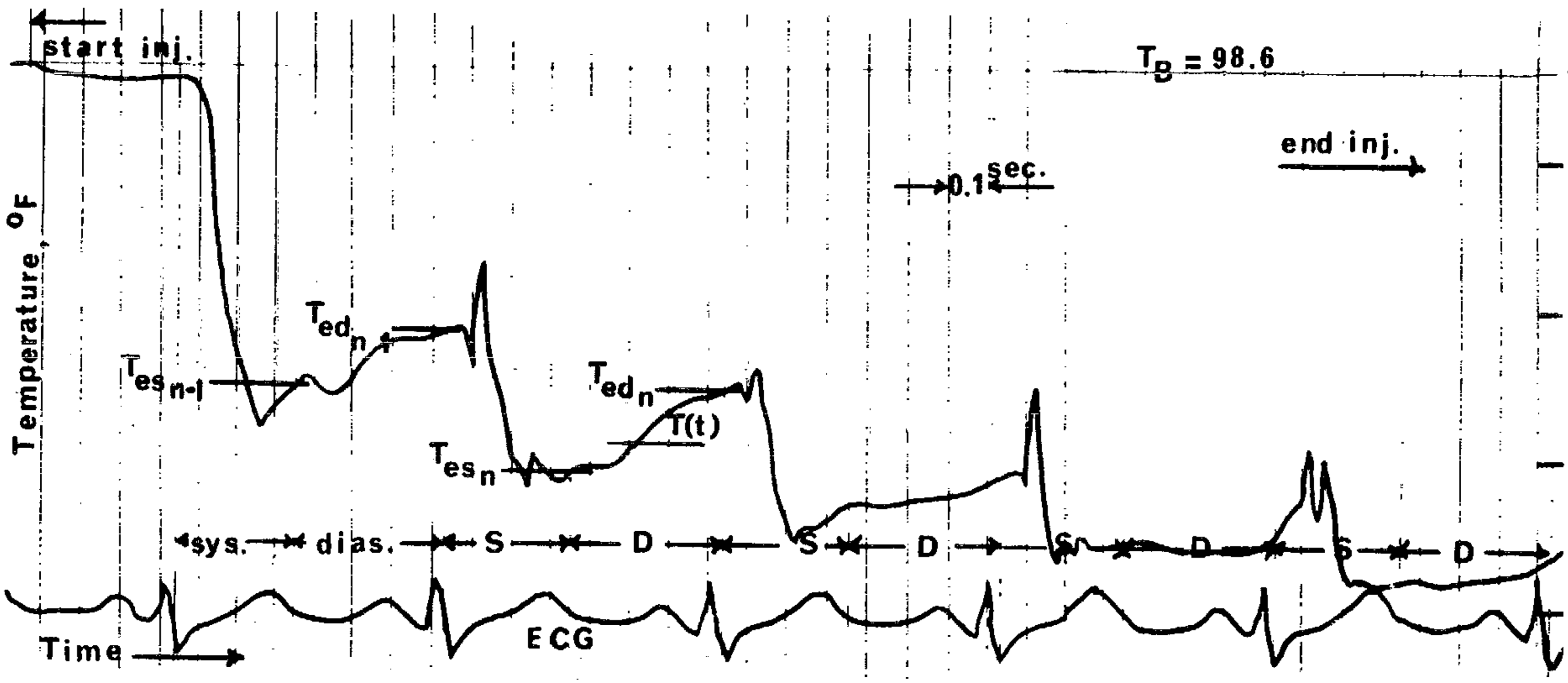

IN VIVO SCHEMATIC
T V
FILM
MONITOR
T/COUPLE
X RAY
COLD SALINE
D C
AMP.
PROG.
INJ.
var. pres.
var. vol.
RECORDER

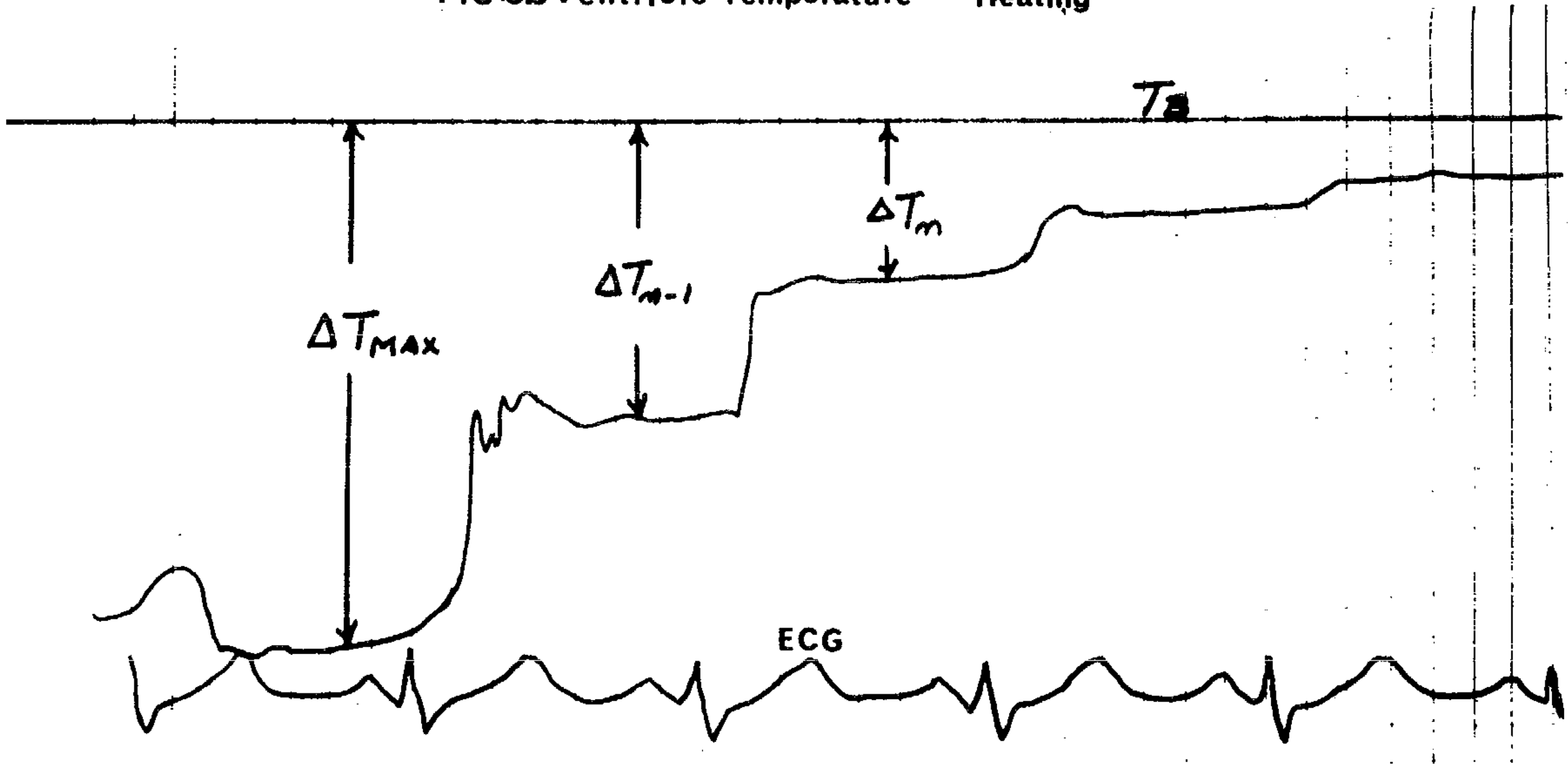
FIGURE 2



VENTRICLE TEMPERATURE — Cooling

FIG. 3a

FIG 3b Ventricle Temperature Heating



$$EVD = V_{inj} \ (T_B - T_{inj}) \ / \ T_{max} \qquad (1)$$

$$EVD = SV \ / \ (1-k) \qquad (2)$$

$$k = \frac{\Delta \ T_n}{\Delta \ T_{n+1}}$$

$$ESV = EDV - SV \qquad (3)$$

$$V(t) = ESV_n \ (T_B - T_{ES,n}) \ / \ (\ T_B \quad T(t) \qquad (4)$$

$$EDV_n = \frac{IV_{DIA} \ (T_{ED,n} - T_{inj})}{k \ T_{ES,n-1} + (1-k) \quad T_B - T_{ED,n}} \qquad (5)$$

$$ESV_n = k \ EDV_n \qquad (6)$$

FIGURE 4

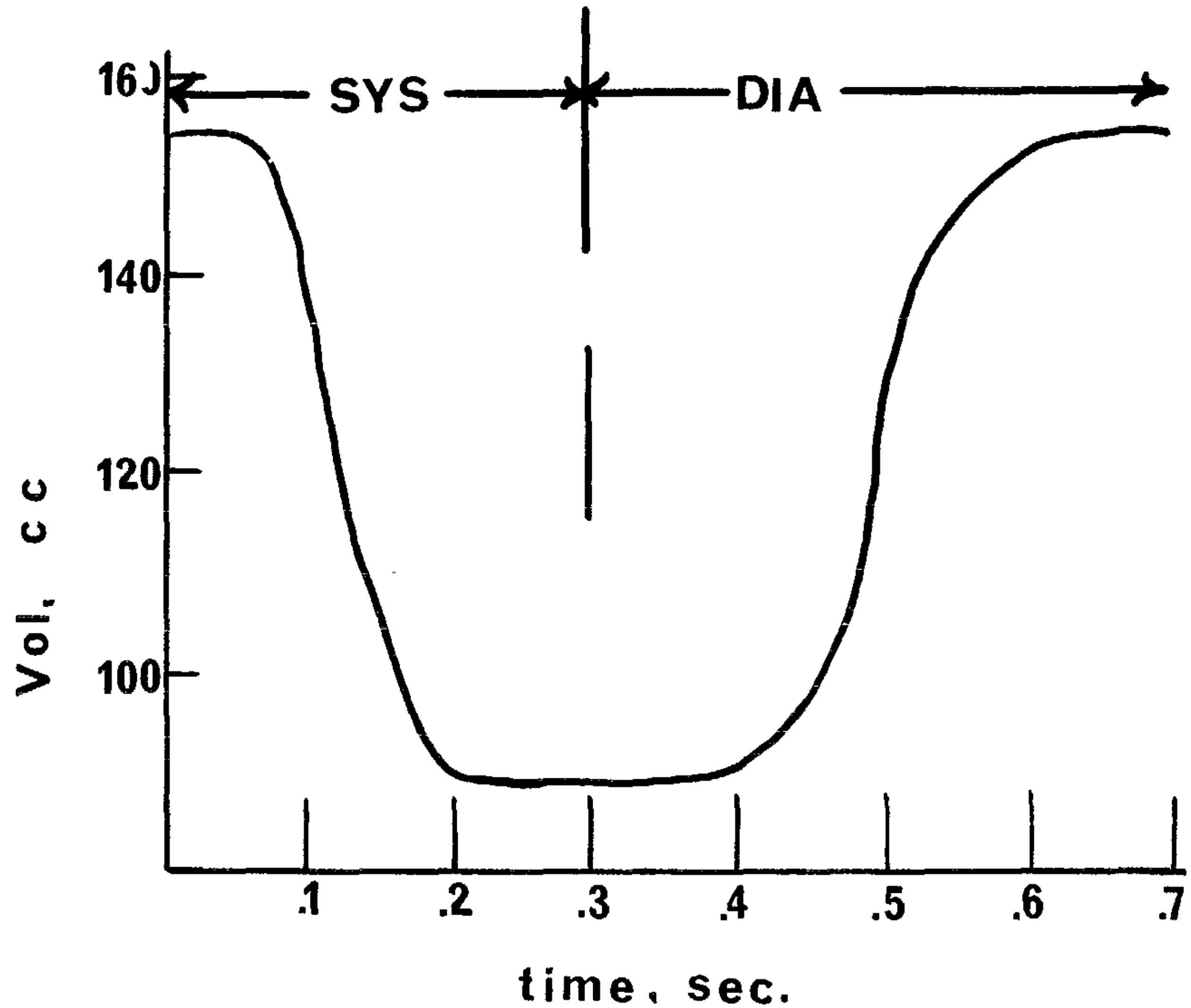


FIG.5a Ventricular Volume, cc

LV WORK DIAGRAM

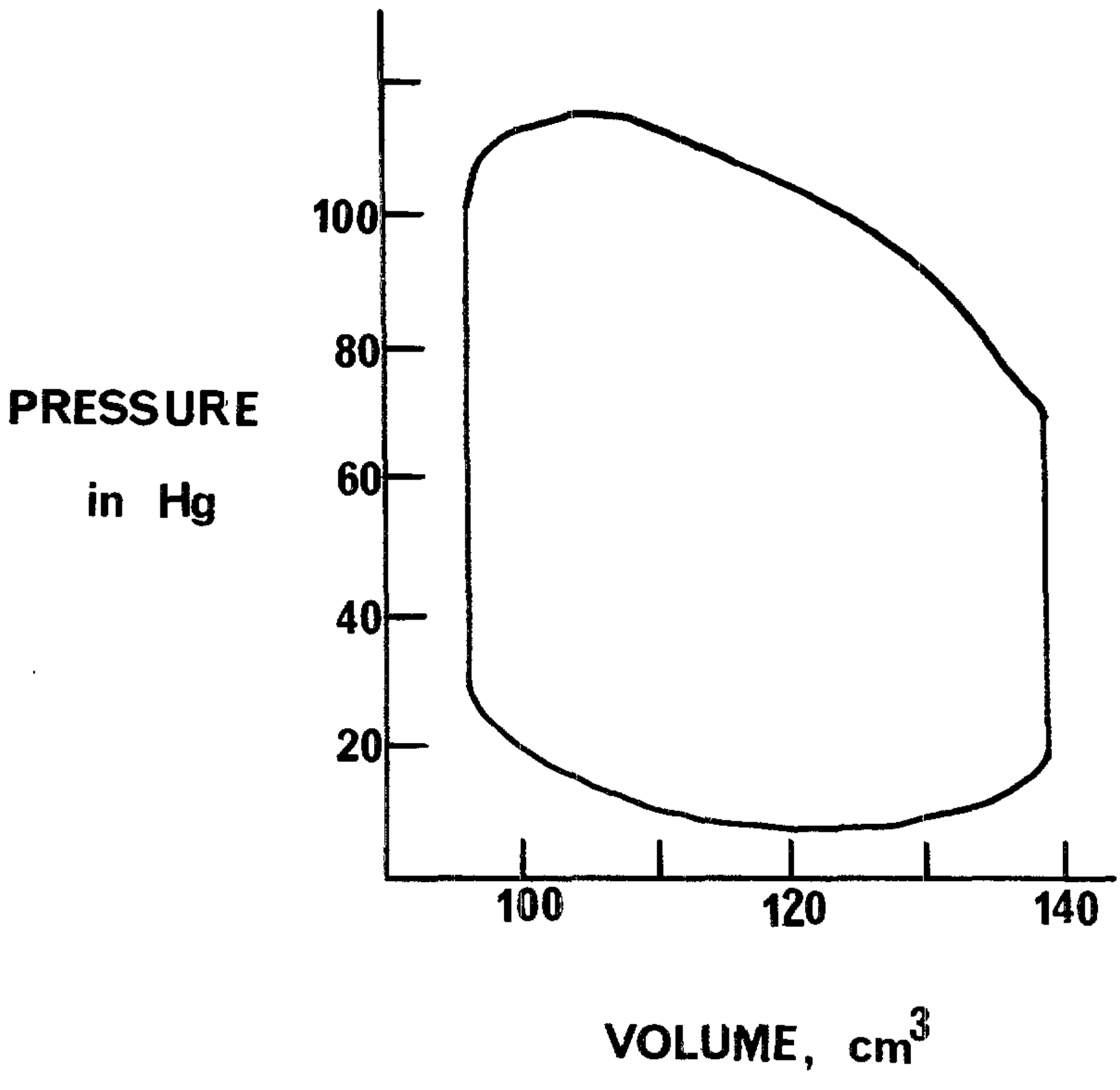


FIG 5b

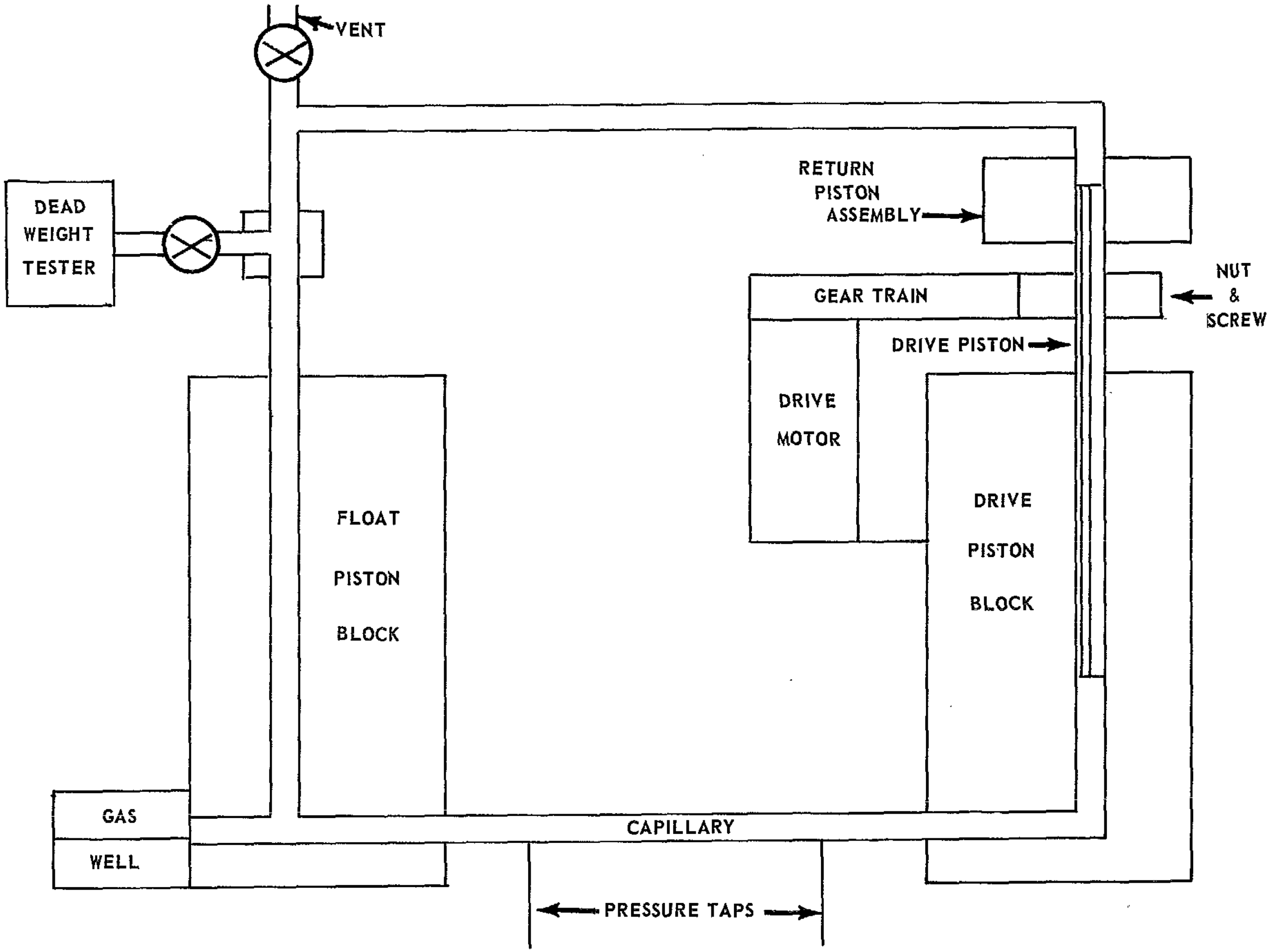

VENT
DEAD WEIGHT TESTER
RETURN PISTON ASSEMBLY
GEAR TRAIN
NUT & SCREW
DRIVE PISTON
DRIVE MOTOR
FLOAT PISTON BLOCK
DRIVE PISTON BLOCK
GAS
WELL
CAPILLARY
PRESSURE TAPS

FIGURE 6 A

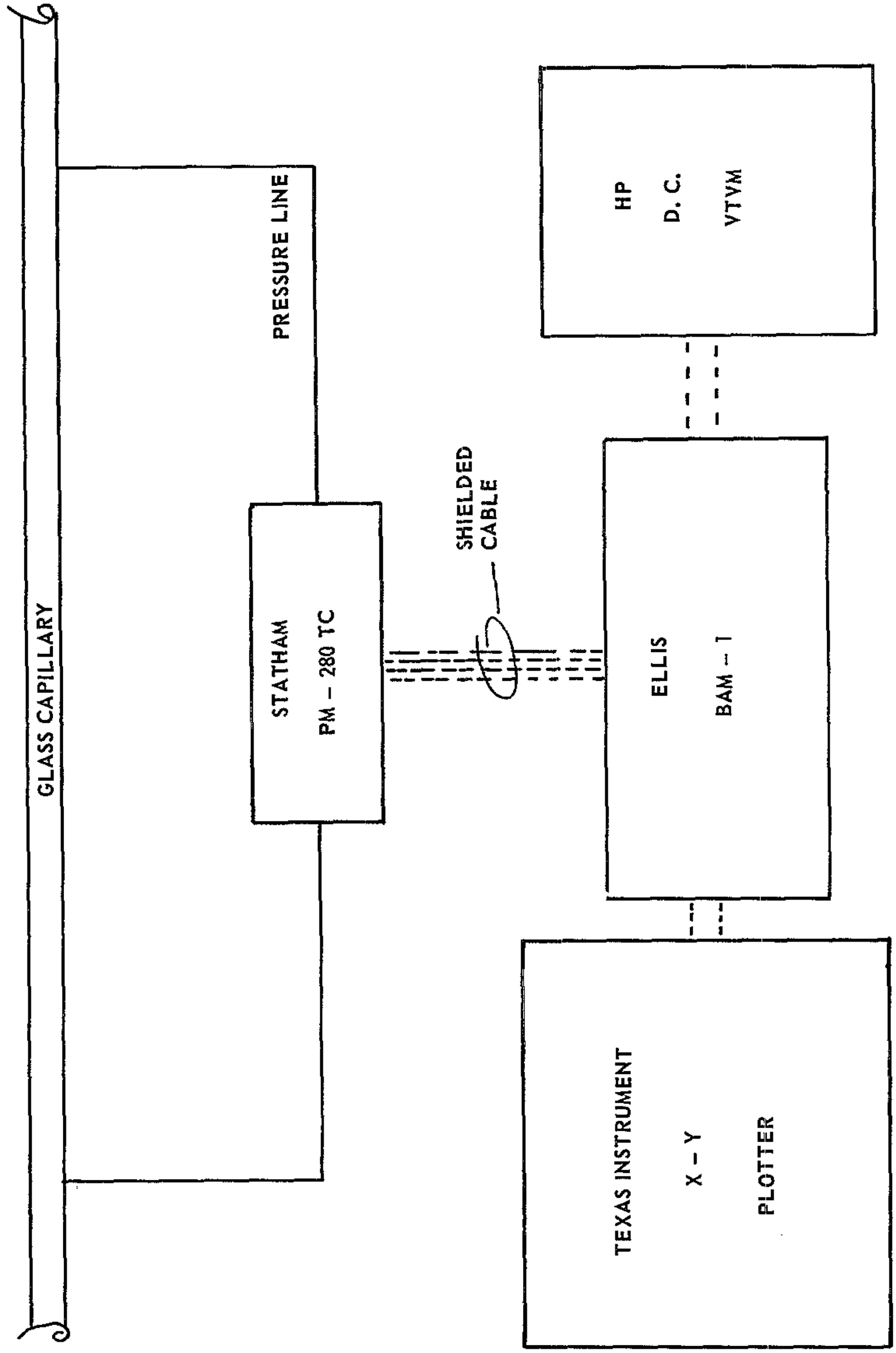

GLASS CAPILLARY
PRESSURE LINE
STATHAM
PM – 280 TC
SHIELDED
CABLE
ELLIS
BAM – 1
HP
D. C.
VTVM
TEXAS INSTRUMENT
X – Y
PLOTTER

FIGURE 6 B

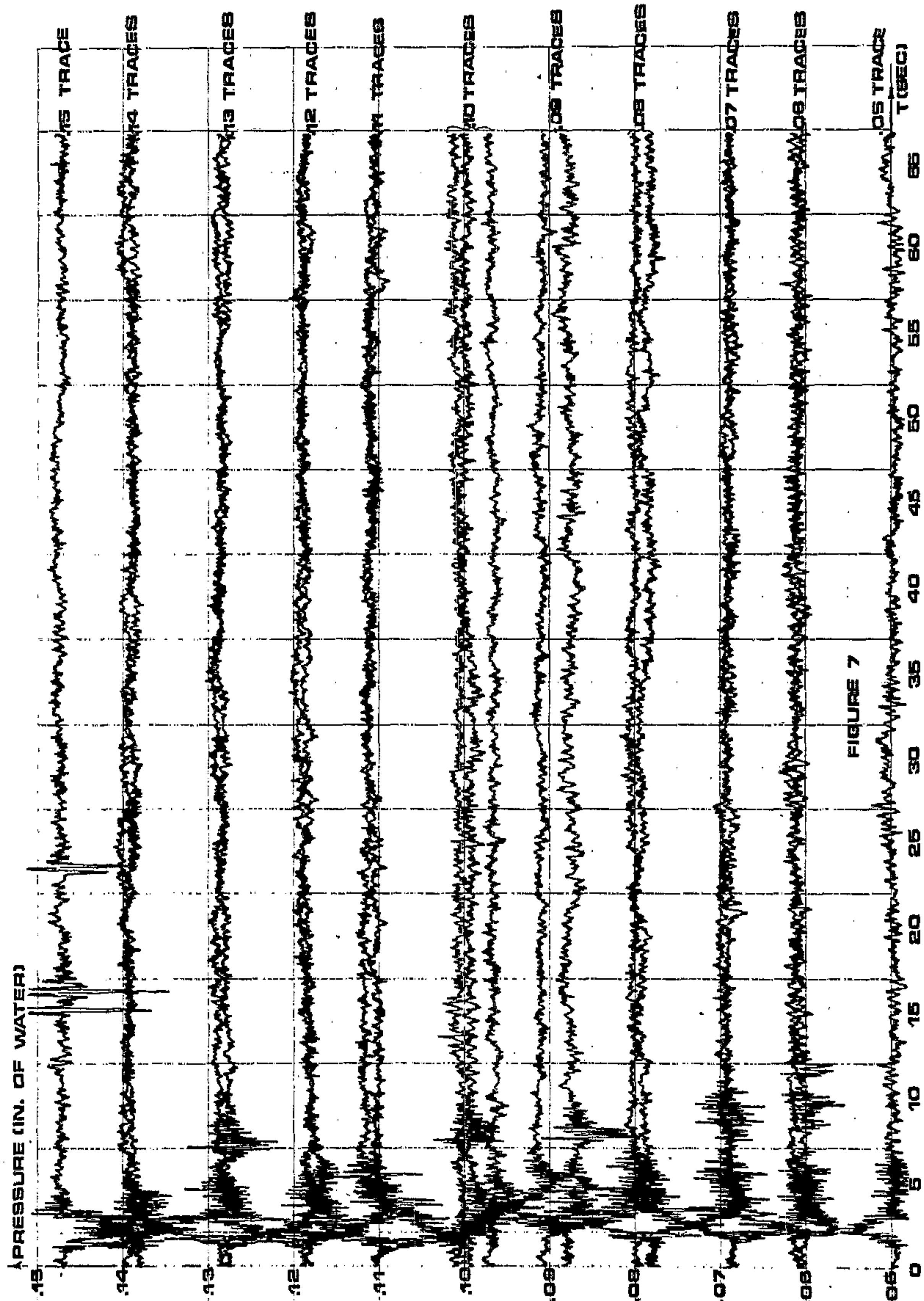

PRESSURE (IN. OF WATER)
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
0
5
10
15
20
25
30
35
40
45
50
55
60
65
T (SEC)
.15 TRACE
.14 TRACES
.13 TRACES
.12 TRACES
.11 TRACES
.10 TRACES
.09 TRACES
.08 TRACES
.07 TRACES
.06 TRACES
.05 TRACE

FIGURE 7

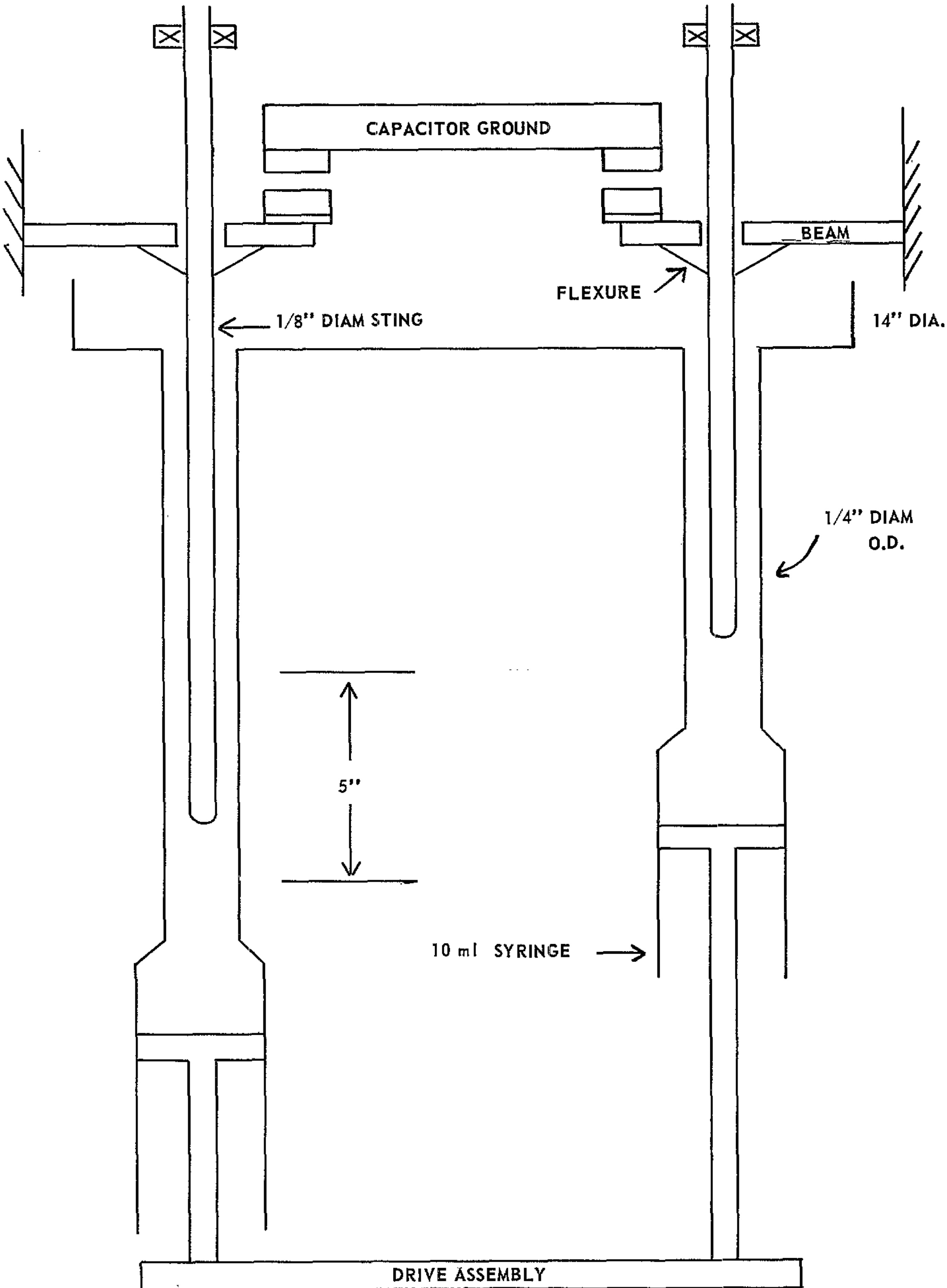

CAPACITOR GROUND
BEAM
FLEXURE
1/8" DIAM STING
14" DIA.
1/4" DIAM O.D.
5"
10 ml SYRINGE
DRIVE ASSEMBLY

FIGURE 8

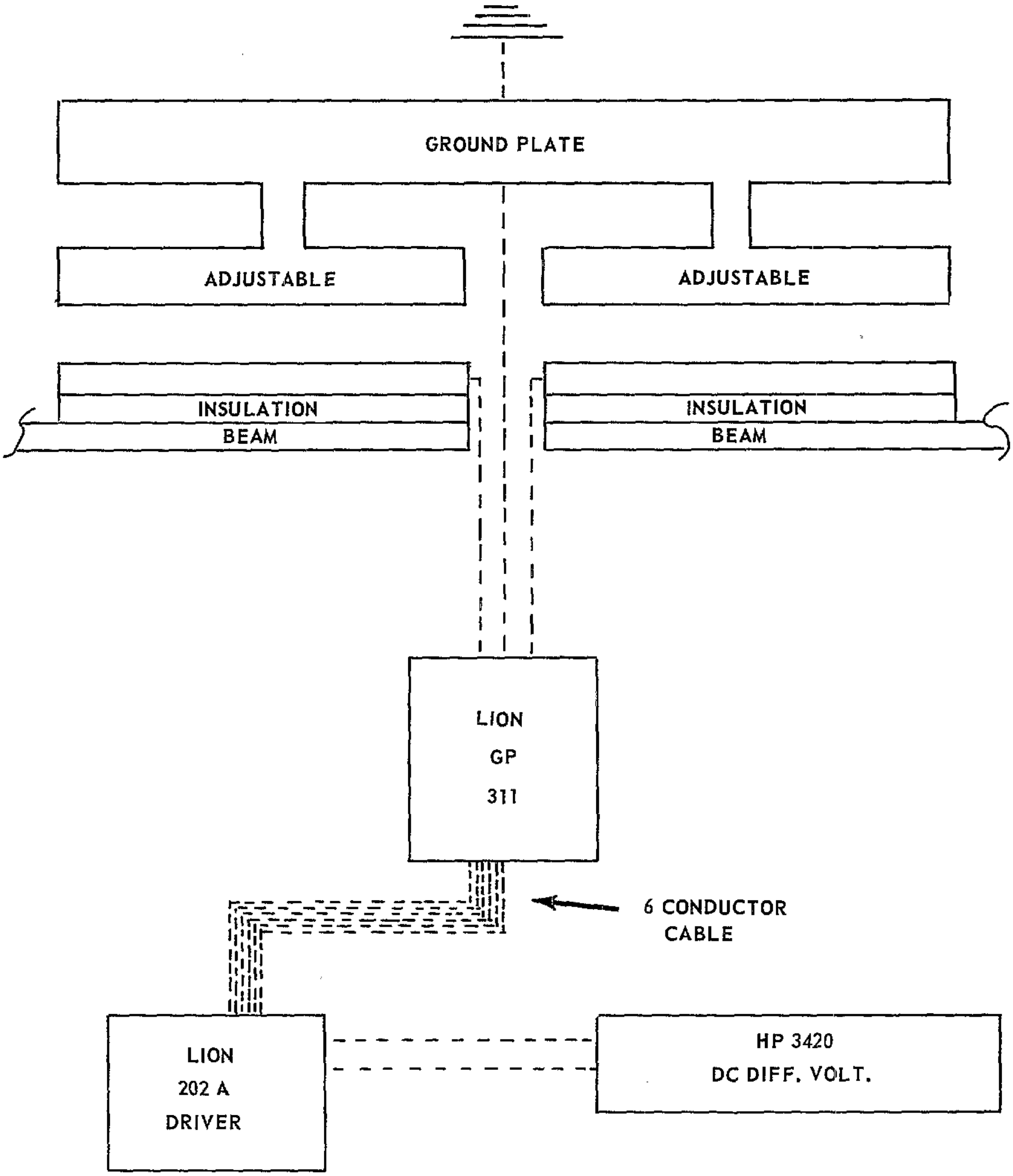

GROUND PLATE
ADJUSTABLE
ADJUSTABLE
INSULATION
BEAM
INSULATION
BEAM
LION
GP
311
6 CONDUCTOR
CABLE
LION
202 A
DRIVER
HP 3420
DC DIFF. VOLT.

FIGURE 9

THE RESPONSE OF TRANSDUCERS TO THEIR ENVIRONMENT

THE PROBLEM OF SIGNAL AND NOISE

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The target for a measurement engineer is valid, noise-free data emerging from a measuring system. The problem of data validity has been discussed elsewhere (references 1, 2). This paper is devoted to the problem of how transducers respond to their environment, and to the deliberate design of measuring systems so that only the desired response to the desired environmental aspect is achieved. Since every link in the measuring chain is capable of producing three entirely different noise levels, the problem of their specific identification at any instant in any test situation becomes important. The emphasis here is on the documentation of these noise levels. The methods presented here permit documented presence of noise to identify specific problems which require solution. Documented absence of noise guarantees the data, regardless of how unexplainable these data appear to be.

INTRODUCTION

All transducers respond in all ways in which they can to all aspects of the environment. These responses are lawful, and represent normally respectable physical or chemical energy-converting transducing responses. The SIGNAL, in every case, is defined as the DESIRED RESPONSE TO THE DESIRED ASPECT OF THE ENVIRONMENT. The other three combinations are undesired, and will therefore be defined as NOISE. It is important to recognize that this definition of noise embodies BOTH environmental excitation factors and transducer response factors. Unless these concepts are kept clearly separate, no methodical approach to the study of the problem of signals and noise is possible. Table I identifies the definitions.

The purpose of this paper is to establish a systematic methodology for the determination and documentation of the presence or absence of these noise levels on any given test set-up at any time, before, during, or after the test. The discussion is limited to those cases where the information to be obtained (often called the MEASURAND) is ORIGINALLY in analog form.

Corollaries of the method developed here are:

1. The method is general and applicable to all links in all measuring systems in all disciplines.

2. There are three different environment-response combinations classed as noise levels in every link in the measurement chain. Thus there are always three different targets for noise suppression -- and hitting the wrong target bull's eye does not help matters any.

Certain methods of noise suppression are guaranteed to solve certain of these environment-response combinations while equally guaranteed not to solve others. With three distinct sets of problems it is necessary to evolve distinct methods of noise suppression generally applicable in all disciplines.

3. An immediate implication is that those transducing processes designated as NOISE in one test may well be SIGNAL in another. Many instances of valuable patents based on the OPPOSITE of what disturbed an investigator, are on record (ref. 1).

Even time can be an undesired, environmental factor such as when it produces zero shifts, zero-drifts, or calibration changes in a measuring system -- and yet when time is to be measured we deliberately design transducers the outputs of which change in a predictable manner with the passage of time (clocks). Time, in the frame of reference of this paper, is just another environmental factor which may or may not affect system performance. The methods used to suppress the effects of time are the same which are used to suppress the effects of other undesired environmental factors.

Noise levels are transducing processes gone wrong, and can be rehabilitated for useful service as the occasion demands.

TABLE I: SIGNAL AND NOISE

ENVIRONMENTAL ASPECT	RESPONSE	
	DESIRED	UNDESIRED
DESIRED	SIGNAL is the desired response to the desired aspect of the environment	NOISE-1 is the undesired response to the desired aspect of the environment
UNDESIRED	NOISE-2 is the desired response, but to the undesired aspect of the environment	NOISE-3 is the undesired response to the undesired aspect of the environment

ENVIRONMENT-RESPONSE INTERACTIONS IN TRANSDUCERS

THE ENVIRONMENT OF A TRANSDUCER

For purposes of this paper, the environment to which a transducer is exposed includes the entire world as distinct from the transducer itself (*). The "entire world" in turn, is subdivided into:

1. That aspect (or factor) in the environment to which the transducer should respond--i.e., the desired aspect of the environment such as temperature for thermocouples or resistance thermometers.

It is sometimes necessary to be more specific about the environment--such as the surface temperature at point "A" and NOT the temperature of the surrounding gases or other solids. A differential pressure transducer is supposed to respond to the differential pressure across its input ports independently of the common pressure level (line pressure or the "common mode"), and directional transducers such as load cells are to respond to excitations in one direction to the exclusion of excitations in transverse directions.

2. The undesired aspect, namely everything else such as magnetic fields, mechanical-strain fields, vibrations, etc., to which the transducer is also exposed.

Note that the undesired aspect may be of the same physical quantity as the desired aspect! Thus, typical undesired aspects in ALL differential measurements are common mode levels, and in ALL directional measurements are transverse excitations.

*The word TRANSDUCER is used here to denote any component in a measuring system which processes BOTH information and energy. The definition includes not only such devices as thermocouples and piezoelectric accelerometers, but also telemetry oscillators, amplifiers, recorders--even cables!
In short, every link in a measuring system which transmits information and energy is a transducer BY DEFINITION.

RESPONSES OF A TRANSDUCER

The response of any member of a group depends on

1. Environmental factors of the present.
2. Type of connection to that environment.
3. Accumulated past history--past environmental factors.
4. Genetic make-up.
5. The location of the individual within the group structure.

Transducers (*), which are component members of the organizational structure known as the measuring SYSTEM, behave no differently in these respects, from any other members of any other group.

Present Environmental Factors

The purpose of this paper is to investigate the role of present environmental factors in eliciting transducer responses. The other four factors govern the potential ability of the transducer or measuring system to respond to these environmental factors. In other words, the measurement engineer can operate within these four areas, which are under his control, to design measuring systems which respond in specific and controllable ways to present environmental factors which are NOT under his control!

The deliberate design of measuring systems to obtain valid, noise-free data is treated elsewhere. This paper treats only the methods of determining what problems exist in any specific test and to document the present or absence of noise levels--i.e., the ability of the system to respond to or to suppress certain environmental factors. A brief survey of what is involved in each of the four areas is, however, given below for the sake of completeness.

Type of Connection to That Environment

The calibration certificate for every transducer, embodying its total performance data, depends on the boundary conditions at the connections of the transducer to other transducer-links in the measuring chain. This dependence of calibration data on boundary conditions has been called the GOLDEN CALF EFFECT because calibration certificates obtained for transducers under one set of boundary conditions do not apply to any other set (refs. 1, 2).

Accumulated Past History

This factor, called "initial condition," "total integrated experience," or simply "history" is a much-neglected factor in evaluating the response of transducers to their environment. The response of any transducer today is governed by its total past history, usually divided into three of many chains of events:

Chemical history: material composition and any changes in composition due to chemical reaction, curing, oxidation, corrosion, alloy migration, etc.

Thermal history: heat treatment, quenching, cooling rates, heating rates, cure cycles, time-at-temperature, levels of temperature,etc.

Mechanical history: cold work, strain cycling, sequence of levels on cycling, rates of applied strain, strain levels, etc.

It is recognized that other past event sequences such as any nuclear history, pressure history, etc., may also influence material properties and system structure and hence transducer behavior.

It is well known, for example, that certain alloy formulations combined with specific heat treatments and cold work cycles produce alloys which permit the construction of transducers for which the spring constant, or resonant frequency, or resistance change is independent of some environmental factor such as temperature-- self-temperature-compensated main springs in watches, tuning forks and bonded-resistance-strain-gages, respectively, for example.

Genetic Make-up

The construction of any transducer embodies the distribution of materials in some oranized manner. In general, the components of a transducer represent combinations of power-dissipating or energy-storing action which in turn may be in the form of potential energy storage (as a level) or kinetic energy storage (as a rate--rate of change or rate of accumulation). The make-up of a transducer as an organized arrangement of these components in lumped-parameter or distributed-parameter model form, with linear or non-linear inter-relationships, governs the response of that transducer. Thus frequency response, transient response, input-output relationships, etc., are also determined by this "genetic inheritance" of the transducer.

The Location of the Individual Within the Group Structure

Overall performance of a measuring system can be expressed as the result of the multiplication of a series of matrices each belonging to a component in this chain. Since matrix multiplication is a non-commutative process, the sequence of operations in a measuring system may not be interchanged without altering performance.

Operations involved in measuring systems are those related to: information transmission or information conversion; energy transmission and energy conversion.

The relative order of operations within a measuring system drastically affects the system's ability to separate SIGNALS (as defined above) from NOISE (as defined above) and to assure satisfactory signal/noise ratio at the output (ref. 1).

THE TRANSDUCER AND ITS ENVIRONMENT

The response elicited from a transducer by its environment can always be divided into two parts:

The Self-Generating Response

Requires only a single energy input to produce an energy output. Typical members of the family of transducers in which this is the desired response are thermocouples, piezo-electric devices, electro-magnetic field probes, magnetic-tape heads, mechanical levers and gears. One of the most important properties of all responses of this type is that only energy, but NOT information can be converted in them. If the information enters in analog form it must leave in analog form; if it enters PAM it must leave PAM, etc.

The Non-Self-Generating Response

Requires two energy inputs to produce a single energy output. Examples of members of the family of transducers in which this is the desired response are galvanometers, resistance strain gages, resistance-thermometers, LVDT's, capacitive transducers and photoelastic specimens. All impedance-based responses belong to this family, whether the impedance change is mechanical, electrical, magnetic, thermal, optical, etc. The energy input containing the quantity to be observed is called the MAJOR INPUT. The second input energy is called the MINOR INPUT and is also known as the supply, the carrier input and the biasing input.

It is convenient to look at impedance changes as an example of LATENT INFORMATION--information which is not in the form of an energy component, and hence cannot be directly transmitted. Thus a resistance change is not an energy component. The only way resistance can be measured is to apply a voltage and measure a current or vice versa.

The operation of these non-self-generating responses is best visualized as follows:

> The MAJOR INPUT containing the desired signal, produces latent information within the transducer, usually in the form of an impedance change. This latent information is then CARRIED through to the output on some property, or pattern of properties, of some wave shape of one of the energy components at the MINOR INPUT. (See ref. 1 for information-carrying methods.)

One vitally important property of all members of this family of responses is that only in non-self-generating responses can information be converted! But this information-conversion can be carried out only if the minor input wave shape is other than a constant level (DC). Thus only when information is carried on some property or pattern of properties of sine waves, pulses, etc., can information be converted. This property is extremely important when information conversion is to be used for noise-suppression.

It can easily be visualized that non-self-generating responses can be undesired, such as changes in cable resistance or capacitance for any transducer, whether a thermocouple or a resistance-thermometer (to cite desired self-generating and non-self-generating responses).

Non-self-generating responses can be one (or a combination) of three different kinds:
- Power dissipating, such as resistive, in electrical devices.
- Potential energy storing, such as capacitive.
- Kinetic energy storing, such as inductive.

Thus the RESISTANCE CHANGE in a resistance thermometer is the desired, non-self-generating response. There may also be changes in the sensor-specimen CAPACITANCE--since temperature affects both the dielectric constant and the thickness of whatever adhesive holds the sensor in place, for example. Any geometric distortions of the sensor grid or changes in the magnetic permeability of the medium in and around the coil of wire which forms the resistance thermometer, will produce a change in INDUCTANCE. The measuring system here must be capable of responding to resistance changes only as opposed to capacitive or inductive responses.

Thus in non-self-generating transducers it becomes important to specify exactly which of the three major kinds of responses is desired.

The UNDESIRED RESPONSE section of Table I, then, will include those two of the three which are to be suppressed.

Note that the desired response to the desired environmental factor, even when successfully isolated, will still be a function of the frequency-and-amplitude content of the desired environmental factor. The problems of the effects of frequency and amplitude on the magnitudes and phase angles of the various transducer performance coefficients have been discussed in ref. 1 and are not a subject of this paper.

Corollary

Every transducer responds in both self-generating and non-self-generating ways to all factors in the environment. The general arrangement of responses of a transducer to its environment is shown in Fig. 1, indicating the four information-transmission paths between the environment and every transducer. One of these paths will correspond to the SIGNAL and the other three will be the three NOISE responses identified in Table I. It is the measurement engineer's job to enhance the desired response to the desired environmental factor and to suppress all other responses.

METHODS OF NOISE SUPPRESSION

There are only three basic methods of suppressing those transducer responses defined as noise levels in Table I, in measuring systems for which the original input is in analog form. The methods are briefly described below:

Cancel by Subtraction

> Expose two sensors.
> To the same environment at the same time.
> If they respond the same way

subtract their outputs. Since the difference between two quantities cannot be measured independently of the level of the difference (the common mode), a certain residual quantity will always be present. This residual quantity is the level divided by the common mode rejection ratio of the subtractor, at the frequency and amplitude of that level.

Minimize by Division

Reduce the amplitude of the interference with respect to that of the signal. If the signal and the noise are caused by different physical quantities, isolation and shielding may be used.

If the interference and the signal are the same physical quantity but differ in certain characteristics, filters may be used; frequency-or-amplitude selective filters are examples, as are particle-size-selective filters such as sieves.

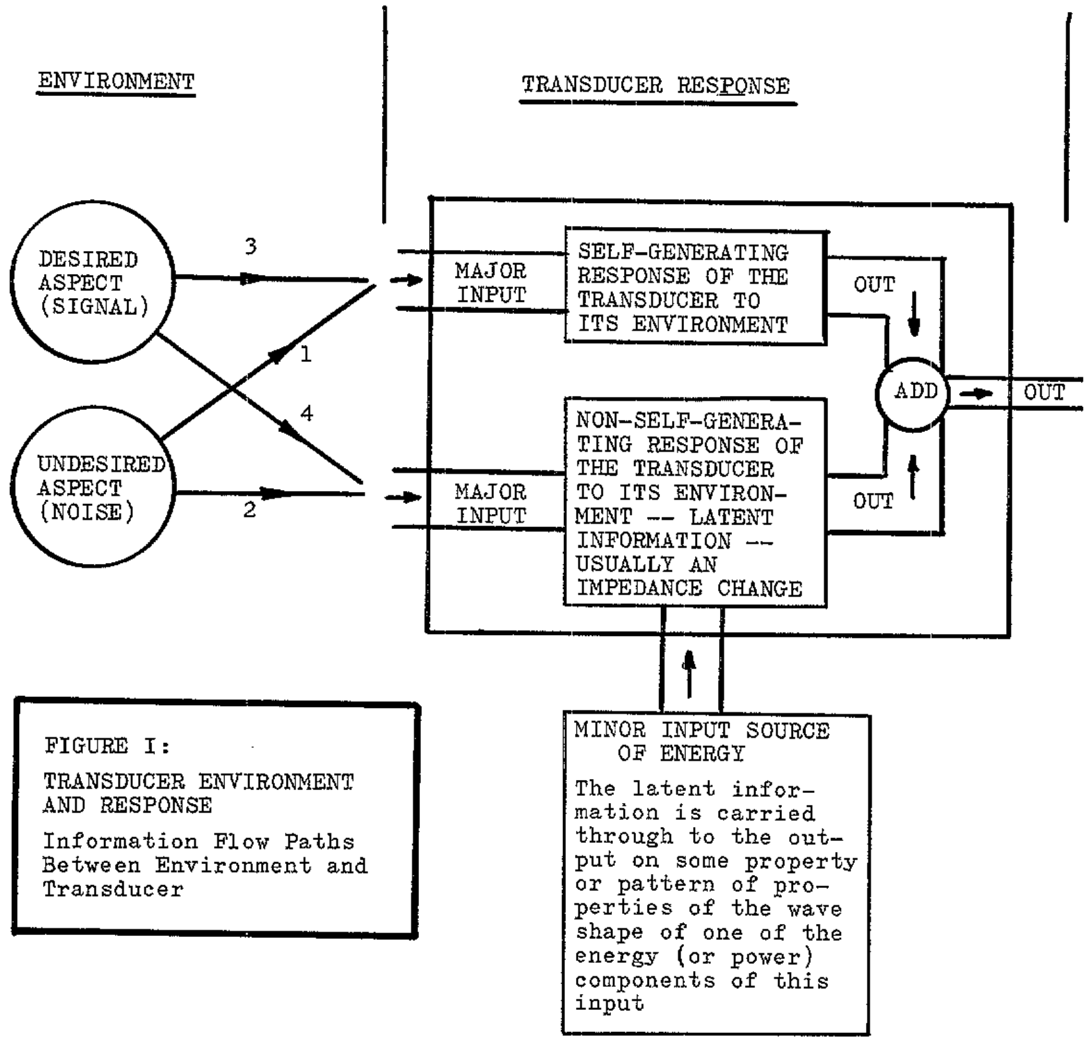


FIGURE I:

TRANSDUCER ENVIRONMENT AND RESPONSE

Information Flow Paths Between Environment and Transducer

If the noise and the signal are the same physical quantity and exhibit no separable characteristics, then special arrangements of component transducers in the measuring system must be used to minimize the effect of the noise. The four-terminal resistor, driven shield, and guarded amplifier principles are examples of this approach.

Information Conversion

For (and ONLY for) non-self-generating responses, information may be converted from the original analog to some other form. The self-generating response remains analog. The two responses have thus been separated both along the time and frequency domains. Non-DC minor input wave shapes are necessary for this separation. Usual wave forms for that purpose are sine waves and pulse trains.

Comments

Note that these three methods work in the three areas identified in Figure I:

Cancellation by subtraction works at the output of the transducer, permitting spurious responses to occur and relying on the subtractive cancellation of like effects in two separate transducers.

Minimizing by division operates with the environment, preventing it from producing appreciable responses in the transducer in the first place.

Information conversion operates on the responses within the transducer, separating the self-generating from the non-self-generating.

Each method is capable of certain performance criteria and limited in its scope. Used jointly, these methods can yield valid, noise-free data in a deliberate manner -- by design. This, after all, is the target of measurement engineering.

EXAMPLES: TEMPERATURE MEASUREMENT IN A MAGNETIC FIELD

There are two possible operating conditions:

1. the self-generating response is to be enhanced
2. the non-self-generating response is to be enchanced.

One example of each of these two cases will be given to illustrate the problems and to identify some approaches to their solution. It is to be recalled that the purpose of this paper is not to study in depth the methods for noise suppression, but primarily to develop methods for determining and documenting each of the three possible noise levels in every transducer in a measuring system. Hence discussions of noise suppression below is specific to the examples cited. A general discussion applicable to all components of all measuring systems will be found in Ref. 1.

The design of a measuring system and the selection of the individual components and their relative arrangement is heavily dictated by the environment in which the system must operate. Thus it is important to gain an appreciation for the many ways in which any one transducer can respond to its environment, and of the means available for controlling (enhancing or suppressing) these responses.

Thermocouple as Temperature-Sensing Transducer

Desired response: self-generating (voltage)
Undesired response: non-self-generating (impedance changes)
Desired environmental factor: temperature
Undesired environmental factor: magnetic field.

Desired Response to Desired Environmental Factor

The thermoelectric effect is one of voltage generation along homogeneous electrical conductors in temperature gradients. Thermocouples take advantage of this effect by maximizing the differential voltage-generating ability of materials of different history, electrically connected. This differential history is most often one of different chemical composition, but heat treatment, and cold work are known to produce differential thermoelectric properties even in materials of identical chemical composition! and very minor changes in chemical composition in any material may produce drastic changes in its thermoelectric behavior! (Ref. 1)

Desired Response to the Undesired Environmental Factor

Time-varying magnetic flux lines cutting the area of the single loop of conductor which is the "thermocouple", may induce voltages into its circuit. This desired (self-generating response but to the wrong part of the environment, can be treated by two of the three basic ways of suppressing noise: a magnetic shield exemplifying minimizing the noise level by division; and twisting the thermocouple conductors, exemplifying cancellation by subtraction to the extent that magnetic-field gradients and twisting geometry permit.

Undesired Response to the Desired Environmental Factor

Changes in the resistance of the electric conductors of which the thermocouple is made, will occur as the direct result of the temperature environment. These non-self-generating responses are undesired in a thermocouple. Their suppression can be achieved only by one of the three available noise-suppression methods: minimizing by division by means of special arrangements of the parts of the measuring system. The components of the measuring system are so arranged that the null-balance operating mode is used. A resistor through which there is no current can not produce a voltage-drop. Hence thermocouple-conductor resistance or resistance changes do not affect the data. It must be remembered that the no-current condition obtains ONLY when the system is at static balance, a condition unlikely when time-varying temperatures are measured. Under those conditions the system is always hunting for balance but is never AT balance, hence the electrical resistance of the conductors will always have some effect on the data.

Undesired Response to the Undesired Environmental Factor

Changes in magnetic field strength will produce changes in electrical resistance of the conductors of which the thermocouple is made. This magneto-resistive effect can be minimized by the same technique as the noise level identified in item (c) above, or by the selection of thermocouple materials which are very little magnetoresistive. Note that magnetic fields also produce mechanical strains in the conductors if these are subject to magneto-strictive effects, and that, for example Chromel-P - Alumel thermocouples are not only magnetic, but also piezoelectric, so that these dynamic strains may themselves generate voltages in the thermocouple.

Resistance-Thermometer as Temperature-Sensor

Desired response: non-self-generating (resistance change).
Undesired response: non-self-generating (capacitance or inductance change); self-generating (voltage generation).
Desired environmental factor: temperature.
Undesired environmental factor: magnetic fields.

Desired Response to Desired Environmental Factor

The resistance-temperature coefficient of a homogeneous material is the basis of the resistance thermometer. It, in common with the thermoelectric coefficient of a material, is a precariously balanced property, dramatically a function of exact chemical composition, mechanical and thermal history, and in magnetic materials, also of past history of magnetic-field exposures. Any change in chemical composition, heat treatment, cold work or remnant megnetization will therefore affect the resistance temperature coefficient.

Desired Response to the Undesired Environmental Factor

Time-varying magnetic fields may produce magnetoresistive responses in the resistance-thermometer, if the sensor material is subject to the effect. Such resistance changes can only be controlled by either selecting a magnetoresistively insensitive sensor material, or by magnetically shielding the sensor material. One method guaranteed NOT to supress these responses is information conversion (also known as modulation or a non-DC carrier system).

Undesired Response to the Desired Environmental Factor
SELF-GENERATING responses caused by temperature can be elicited from every resistance thermometer, because somewhere or other there must be a pair of thermocouples where material-property-discontinuities exist between sensor material and lead wires. If these thermocouple junctions are in a temperature gradient, or if they have different thermal time-constants because of different amounts of solder-mass on them or because of differential local heat transfer coefficients, then their outputs will not cancel. In general, the two lead-sensor junctions must be made between lead materials which have been drawn through different dies at different times, and hence probably have different mechanical and chemical histories, and hence may have different thermoelectric properties themselves.

Self-generating responses can be suppressed by the three general methods discussed in detail in Ref. 1:

Cancel like effects by subtraction, to the degree that the voltages generated by the two thermocouples are indeed the same.

Minimize the effects by division, such as by provided thermal lagging, isolation or shielding of the two junctions.

Information conversion by measuring the sensor resistance change with a non-DC wave shape minor imput. This method is always capable of separating self-generating from non-self-generating responses, either in the time domain or the frequency domain.

NON-SELF-GENERATING responses such as capacitive and inductive changes in the resistance thermometer circuit may be created by mechanisms discussed in another section above. They can be suppressed best by the correct selection of the minor input wave shape, as also discussed above. Under certain conditions the effects can be minimized by division through the use of special arrangements of the components in the measuring system.

Undesired Response to the Undesired Environmental Factor
Time-varying magnetic flux lines cutting the area of the loop(s) of conductor which form the thermocouple, may induce voltages in the sensing circuit. This self-generating response is POLARIZED, and thus the terminals of any impedance-based device exposed to magnetic fields MUST BE KEPT SEPARATELY IDENTIFIED -- because it is possible, and highly practical, to subtract like effects picked up by two sensors. Such means are highly useful when non-inductively wound sensors are either not available and not practical. It is possible to mount two sensors side by side and to connect them in series-subtracting for self-generating responses, while they are in series-adding for non-self-generating responses' In bridge circuits it is possible to place sensors, exposed to the same magnetic field environment in adjacent bridge arms, subtracting BOTH the self-generating and non-self-generating responses. In adjacent bridge arms, non-self-generating responses are ALWAYS subtractive whereas self-generating responses may be added or subtracted depending on the polority of connection of the sensors in the bridge arms. These techniques illustrate an example of the cancel-by-subtraction principle of noise suppression. The magnetic field could also be minimized by shielding the sensor. Finally, the third method of information conversion can be used, as identified for the self-generating response in item above.

Summary

The two examples above have been selected to identify the basic method of noise-hunting developed in the Unified Approach to the Design of Measuring Systems (Ref. 1).

1. The first step is to identify the nature of the problems in any given situation.
2. The second step is to select suitable noise-suppression methods from among the three general principles available, usually applied in combination.
3. The third step is to document the resulting three responses which are classified as NOISE (Table I) at any time during, before, or after the test. It is only the first and third steps which are the subject of this paper.

It should be noted that the question of whether the effects discussed in the examples above are large or small is not important here -- the fact is that they are present, and that any measuring system design aimed at producing valid, noise-free data must either:

1. Incorporate methods of determining whether the effects are small enough to be called negligible when compared to the signal, at ANY TIME before, during or after the test.
2. Be designed so as not to respond to the expected level of the undesired responses by proper operation in the five areas which determine the response of a transducer to its environment.

The first target is the better, since DESIGN is one thing, and DOCUMENTED PROOF OF ABSENCE OF NOISE is another and preferable method.

The examples cited, were specific. The approach identified in Table I and Figure I, on which the examples were based, is general and suitable for all transducers used in measurements in any discipline.

Note
It should be noted that both thermocouples and resistance thermometers, can only indicate their own temperature, even under the most ideal

conditions of non-existence of any of the noise levels discussed above. Whether the sensor temperature is related to the temperature of interest, is a heat-transfer design problem, some aspects of which are treated in Ref. 1, among others. This question is not discussed in this paper.

THE DOCUMENTATION OF NOISE LEVEL

The aim of the measurement engineer is to design measuring systems which yield valid, noise-free data without affecting the behavior of the process being observed. It is therefore desirable to document the three major types of noise identified in Table I. This documentation may serve one of two purposes:

1. It may identify problems requiring treatment.
2. It may prove that noise levels were successfully suppressed to yield acceptable signal/noise ratios. The data, however inexplicable they seem, are DATA and do represent the phenomenon to be investigated, and must therefore be interpreted.

BASIC PHILOSOPHY

The basic philosophy of noise level documentation is as follows:

1. Produce a condition where a known level of output is expected from the measuring system, and where any deviation from this level which exists, is diagnostic of a specific problem -- i.e. identifies one of the three undesired channels of communication as shown in Table I and Figure I.

   This step in noise documentation identifies any additive noise levels, usually called zero shift, zero drift, unbalance, pick-up, etc. These are usually the most significant problems in any measuring system.

2. Produce a condition where a known increment in output is expected. If that increment is not achieved, then multiplying noise levels have been identified, usually known as gain changes, transfer ratio change, sensitivity change or calibration change.

   It is important to note that these checks do not, in general, calibrate the system; they only check for noise levels. A true calibration must simulate the boundary conditions across the first interface -- that between the process being observed and the input sensor to the measuring system. This simulation is generally not possible, especially in non-electrical-input systems (Ref. 2). Since that portion of the measuring system can not normally be calibrated, it must be designed to yield data within a specified validity tolerance of a specified target (Ref. 2).

3. Design the measuring system in such a way that checks (1) and (2) above, can be carried out easily at any time before, during, and after the test -- or, if sequential operation is not possible, parallel operation of check-channels must be planned.

   It is necessary to have a target of which checks should be performed, so that those that can not be performed in any specific situation are identified as potential trouble spots which must be investigated separately. It must be emphasized that there is no general ANSWER to the problem of noise documentation -- only a general approach: that this is necessary. Sometimes extreme ingenuity has been shown by investigators on specific projects, and a collection of many of these approaches is embodied in Ref. 1.

With a clear understanding of how the environment can influence the response of every transducer in a measuring system, the measurement engineer can plan to document undesired communication channels most likely to be the worst offenders in any given situation. It is seldom possible to document ALL possible spurious responses of a measuring system -- but it is always possible to TRY, and hence to know how close to the targets established above, one has hit.

Producing a Known Output Level

The known output level most commonly selected as noise-check reference is the level corresponding the the initial operating point of the transducer under consideration. Operating points can be divided into three general classes:

1. Zero output for zero input
This operating point implies a balanced system or transducer. It is an extremely common operating point for which numerous examples could be cited.

2. Finite output for zero input (zero output for finite input)
This operating point implies an initially unbalanced system or transducer. Typical examples of such operation are:

a. Zero-suppression, such as the suppression of the weight of the tank in which a liquid is contained, when only variations in liquid content are to be observed. (Zero output for finite input unbalanced condition).

b. Biasing the output into the linear range of the transducer transfer characteristics, such as the function of the biasing oscillator in magnetic tape recording. (Finite output for zero input unbalance condition.)

c. Use of the output LEVEL to determine the input SIGN (or phase) such as in standard AM communications systems such as radio detectors using the carrier-present or unbalance method of phase detection of a modulated signal. (Finite output for zero input unbalance condition.)

d. The inability to produce truly zero inputs, such as temperature, often necessitates the operation around a non-zero input reference. (Finite input for zero output unbalance condition.)

e. The inability to produce truly zero outputs, such as for a resistance sensor in a single-ended constant-current circuit. (Finite output for zero input condition.)

3. Finite output for finite input
This operating point would obtain if the sensor in example 2-e above were a resistance thermometer. This condition is not usual but entirely possible.

The principle of noise checking is that the input(s) (is)(are) returned to reference conditions, or to the value(s) which produce(s) zero output, if at all possible. The deviation of any quantity from zero is usually easier to observe than its deviation from a non-zero level, hence production of conditions where zero output is expected are preferable to finite-output expectations. Return to reference conditions is necessary for non-linear systems, which may be linear only incrementally around the original reference.

The production of known outputs infers the production of known inputs. These are discussed in the next section.

Producing Zero Inputs or Reference Inputs

The success of a noise documentation program hinges upon the measurement engineer's ability to produce zero or reference inputs to the various links in the measurement-system-chain.

Special Note for Differential Quantities
When the difference between two levels is to be observed, the simulation of zero-difference (zero input) must always be made at the average level at which that difference exists during operating or reference conditions. Thus, differential pressure transducers should be checked with line-pressure applied to both input ports, producing zero-differential conditions at the average level of the pressures being subtracted (approximately). The same statement would be true of differential temperature sensors, differential voltage amplifiers, and so on.

The zero-difference must be produced at the common mode level so that documentation of the presence or absence of common-mode effects can be made. These effects are so serious and so prevalent that the importance of this special note can not be over-emphasized! The common mode levels selected for these checks should span the range of values encountered in service, which is automatically done when these checks are repeated periodically throughout a test run.

The Use of Standard Techniques
Depending on the physical/chemical quantities being observed, the production of zero inputs or reference inputs requires more or less ingenuity and pre-test planning. Some typical examples will be cited here for a few specific cases; others are collected in Ref. 1.

1. Pressure level: The production of reference pressure level can be achieved by means of a solenoid-operated pneumatic or hydraulic switch which connects the pressure transducer input port to a reference pressure (such as atmosphere) during the test.
2. Differential pressure: Zero differential pressure across the two input ports of a pressure transducer can be achieved by switching both input ports (with solenoid-actuated pneumatic/hydraulic switches for example) to the same pressure, usually one of the two pressure levels to which the ΔP-device is exposed.
3. Force or Load: By means of a jack, the load can be lifted off the load cell (or the load cell lowered so that the load is allowed to rest on an alternate fixed support) so that a zero-load condition exists on the load cell.
4. Voltage: A short-circuit (which does not act as an inductive loop or as an antenna) is a common zero-voltage check.
5. Differential voltage: A short-circuit across the differentially coupled input terminals of an amplifier, but DURING the application of the common mode voltage (i.e., during test conditions.)
6. Current: An open circuit (which is not also a stray capacitance in an electric field) often serves as a zero-current check.

The Use of a Separate Check Channel
In many instances it is not possible to produce a reference condition DURING a test run on the measuring transducer -- such as the application of a known pressure level to the diaphragm of a flush-mounted pressure sensor in an engine or a structure. It may be necessary, then, to use the concept of a check-channel to document the output from a similar transducer in the same environment as the measuring sensor except NOT exposed to the desired aspect of the environment (in this case -- pressure).

Figure II illustrates the principle applied to the measurement of pressure on the inner surface of a shroud in a gas-turbine compressor where ambient temperature, acceleration and magnetic environments were quite hostile. The check-channel output is used NOT to CORRECT the data from the measuring transducer, but only to indicate that the data are likely to be noise-free in the measuring channel when the check-channel output is acceptably low -- i.e. within signal/noise ratio target.

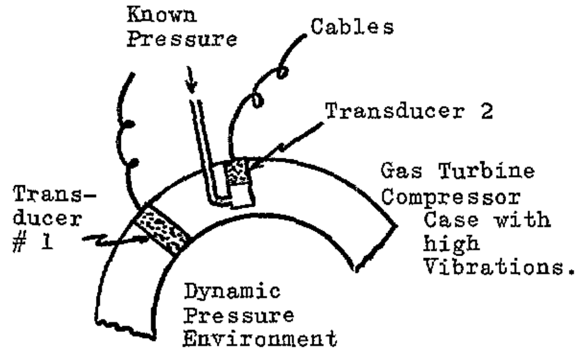
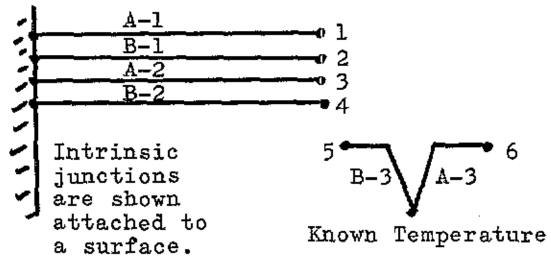


ILLUSTRATION OF ONE METHOD OF PRODUCING CONDITIONS WHERE ZERO OUTPUT IS EXPECTED AND WHERE A KNOWN OUTPUT IS EXPECTED.

FIGURE II



SIMPLE ARRANGEMENT FOR DETERMINING PRESENCE OR ABSENCE OF CERTAIN NOISE LEVELS IN A THERMOCOUPLE-BASED TEMPERATURE MEASURING SYSTEM

FIGURE III

The reason why data correction from check channels is seldom possible is that:

1. The two sensors may not be exposed to the same environment at the same time -- a point to remember even in strain-gage active-dummy gage compensation when transient temperatures and differential thermal time-constants prevent the GAGE GRIDS from being at the same temperature at the same time.

2. The two sensors may not respond the same way, a problem especially severe under dynamic conditions. Frequency-response characteristics for magnitude and phase must be identical for the two channels in response to the UNDESIRED environmental aspect -- for which transducers just are not calibrated or designed! -- in order for subtractive cancellation to be applicable. Two miniature, flush-diaphragm pressure transducers just will not have the same characteristics when used as accelerometers in an acceleration-suppression subtractive-cancellation scheme unless the manufacturer has specifically designed them for that purpose. It is the difference in PHASE ANGLE of the responses which is the most severe problem, and the least studied one.

Thus on two counts the application of the cancel-by-subtraction principle of noise suppression may fail. The principle that like sensors in like environments will respond approximately the same, however, is more likely to be applicable than the assumption that they are in identical environments responding identically. It is this "more likely" principle which is advocated in the check-channel method. The INVESTMENT (not waste, as some supervisors would say) of a check channel to validate a data channel, is recommended. This is in essence the use of a spy to spy on a spy, an accepted technique for data validation in systems other than those devoted to measurements.

All measuring systems are spy-systems since it is their purpose to obtain information about other systems without their presence resulting in a detectable change in behavior of the system being observed.

The Use of Special Techniques

Sometimes, by no stretch of the imagination, can a specific reference be achieved for the quantity to be observed, during a test run. An example would be the problem of producing a reference-temperature condition for a temperature sensor embedded in an internal combustion engine or mounted on a surface within a nuclear device. The production of zero-acceleration (or velocity or displacement) in a vibrating object during a test would also be difficult, especially since the stopping of a vibration exciter may also eliminate the magnetic fields which may be the most important undesired environmental aspect--and it would be difficult to stop an engine in flight merely to produce a reference condition for a noise check.

It is necessary, in such cases, to exercise some ingenuity in producing a channel in which responses to the desired aspects of the environment should not exist. For thermocouples, the four-wire thermocouple is such a device. Two checks are provided to answer the following questions: (Fig III)
a. Is this junction the only emf-contributing junction in the measuring system? Are there other junctions injection temperature-induced voltages?
b. Is this junction the only voltage-contributing portion of the system or are there ground-loops, magnetically induced signals, charges collected in ceramic insulation at high temperature, voltages due to electrolytic action, etc.?

These checks involve the connection of terminals 1 and 3 to the measuring system input, and subsequently the terminals 2 and 4. If the system output is other than zero, one of these problems has been identified. If the output is zero, a documentation has been made that at this time those problems did NOT exist.

Two checks are provided to answer the question:

c. Does thermocouple resistance or change in resistance with ambient temperature, magnetic fields, mechanical strains, etc., affect the data.

This check involves connecting 2 to 5 and reading across 4 and 6; then connecting 1 to 6 and reading across 3 and 5. In each case, the known temperature should be indicated; if not, then problem (c) has been identified, in the absence of (a) and (b). A possibility for piezo-electric devices is the use of a complete transducer but made from unpolarized ceramic material, and hence not expected to respond to acceleration (if the transducer would be an accelerometer, where the material polarized.) In this case the responses to some environmental aspects would be lost, but other would be identifiably recorded.

A simple test for connecting cables is to run a cable into and out of the environment to which the cable is not supposed to respond; terminate the cable at one end with a fixed impedance simulating transducer output impedance and observe outputs at the other end. A subsequent step would be to feed the cable at one end from a voltage generator also simulating the impedance level of the transducer normally attached to that end of the cab le, and to observe the outputs from the measuring system. Technically this check is the production of an input for which a known output is expected, which forms the topic of a subsequent section. The examples cited above are discussed in more detail in Ref. 1.

An extreme case of investigator ingenuity in producing a known temperature level for a thermocouple on a turbine blade under operating conditions is cited in Ref. 1. The investigator hollowed out a portion of the blade, poured molten lead into the cavity and embedded a thermocouple into the lead. When, during engine acceleration the local temperature passed through the melting point of lead--an accepted standard temperature level--the latent heat of fusion of the lead caused a plateau at that temperature to appear in the record. This ingenious rotating standard documented noise-free operation of a thermocouple circuit with sliprings, involving over a dozen different materials in electrical contact.

DOCUMENTATION METHODS FOR ADDITIVE NOISE LEVELS

The methodology of individually identifying the information flowing along the Paths 1, 2, 3, and 4 shown in Fig. I is the heart of the noise documentation method in the Unified Approach to the Design of Measuring Systems (Ref. 1).

For Non-Self Generating Responses

Table II illustrates the procedure for isolating sequentially each of the three information-flow paths shown in Fig. I. Path 4 is desired, the other three are undesired. Table II and the discussion below are specific for the case when balance (zero output for zero input) is the initial operating condition. The preceding sections permit generalization of the method to other cases.

Path 1: No Major Input, No Minor Input
To isolate Path 1, remove the minor input and return the major input to its reference value (see previous sections for general discussion). This operating condition for the transducer results in the suppression of paths 2 and 4 (no minor input to carry the latent information in the non-self-generating response through to the output) and Path 3 (no major input). Path 1 has been isolated, and its effects must now be suppressed until they are within the specified signal/noise ratio. If cancellation by subtraction and minimizing by division fail, information conversion is in principle, guaranteed to solve the problem (a modulating carrier of some kind as minor input).

Path 2: No Major Input, Minor Input On
Path 1 having been brought under satisfactory control, the application of whatever the minor input is for the transducer being investigated, will now actuate Path 2. Paths 3 and 4 are still suppressed--no major input. The transducer output now evidences any impedance changes (latent information) from the undesired aspects of the environment which exist in the transducer. Such effects as initial bridge unbalance, resistance-temperature effects in strain gages, residual humidity-induced "edge effects" in photoelastic models, etc. are identified. At the same time, however, any self-generating "ripple" present in the minor input will also be observed at the transducer output. Minor-input energy sources must be checked separately for the presence of such undesired outputs.

Only cancellation by subtraction and minimizing by division methods can be used to suppress Path 2. Information conversion cannot possibly separate resistance-changes due to strain from those due to temperature. As identified in an earlier section, the correct wave shape selected for the minor input can separate capacitive responses (potential energy storing) from resistive responses (power dissipating) in a sensor, so that the problem of cable capacitance effects in resistance transducers can be treated by specifying certain characteristics for the minor input.

Path 3: Major Input On, Minor Input Off
Paths 1 and 2 having been suppressed to the desired signal/noise ratio target, the application of the desired aspect of the environment, coupled with the removal of the minor input

supply will now reveal Path 3--the undesired response to the desired environmental aspect. For impact tests using bonded-resistance strain sensors, the displacement wave which accompanies the strain-creating force wave, moves the gage grid in ambient magnetic fields (the earth's if nothing else), extremely rapidly even though by only a small distance. The induced voltages will typically be several hundred microvolts and will have the appearance of traveling strain waves, because they are created by the displacement-wave companion of the force wave. This example is just one of many which could be cited, of phenomena the presence or absence of which can be documented by this technique at this stage of the documentation procedure. Thermoelectric potentials generated in resistance thermometers would be another example, and so on. The desired environmental aspect created undesired responses is a serious problem for all non-self-generating devices.

Information conversion, as a method, is guaranteed to suppress Path 3 type noise levels. Whether the hardware can be built or bought is not a topic for discussion here.

Path 4: Major Input On, Minor Input On

Paths 1, 2, and 3 having been individually investigated and suppressed to permissible levels, Path 4 now represents noise-free data, to the extent that other factors (validity, frequency-and-amplitude-response effects, etc.) have been satisfactorily considered.

Special Techniques When Minor Inputs Cannot Be Removed

If it is not possible to turn the Minor Input off, it may be possible to invert its polarity, thus inverting the polarity of the output from the non-self-generating-response-portion of the transducer. If the total transducer output is not simply changed in polarity when this operation is carried out, then the difference between the outputs when the minor input is polarized in each of the two ways, represents twice the effect of Path 1. Path 3, however, can NOT be checked by this method unless the desired environmental aspect can be reproduced exactly for both minor input polarizations. Some minor inputs (such as light intensity sources) cannot be polarized, and this technique can then not be used. In non-linear systems, the response for polarity-reversal conditions may not be a simple polarity reversal, such as for a diode, for example.

If the minor input can neither be removed nor inverted, it may be possible to alter its amplitude. A reduction of the minor input by a factor of 2, for example, should reduce transducer output by 2. Any lack in directly-proportional reduction is diagnostic of one of two possible conditions:

a. Non-linear transducer and/or measuring system.
b. Self-generating responses remaining constant as the effect of the non-self-generating response is reduced, hence their sum does not reduce proportionately to the minor input reduction.

System or transducer linearity characteristics are considered under the topic of the effect of frequency and amplitude of the desired environmental aspect of the magnitude and phase of the transducer characteristics, and are not a subject of this paper (ref. 1).

For Self-Generating Responses As Desired Responses

For this case, Path 3 in Fig. I is the desired path, and the output of the self-generating-response portion is actually the minor input for the non-self-generating response.

TABLE II

NOISE LEVEL DOCUMENTATION WHEN THE NON-SELF-GENERATING RESPONSE IS THE DESIRED RESPONSE

PATH	MAJOR INPUT	MINOR INPUT	TYPE OF RESPONSE	FROM ENVIRONMENTAL ASPECT	INDICATED ACTION
1	OFF	OFF	Self-generating	UNDESIRED	Any noise-suppression method. Information conversion guaranteed.
2	OFF	ON	Non-self-generating +	UNDESIRED	Information conversion will not work, unless problem is to separate power-dissipating from energy-storing responses
			Self-generating	Minor Input	
3	ON	OFF	Self-generating	DESIRED	Any method. Information conversion will work.
4	ON	ON	None	Valid, noise-free data	

The above sequence of tests should be run either sequentially or with a number of parallel check channels. Path numbers refer to Figure I.

In a thermocouple, for example, it is the thermal emf developed which is the minor input to the resistance of the leads of the thermocouple. The total output is the self-generating (open-circuit) response of the thermocouple less the voltage lost in the leads by any current flow.

For piezoelectric devices the internal capacitance (non-self-generating response) is charged from the self-generating response across the piezoelectric element itself.

Since a transducer for which the self-generating response is the desired response does not have an externally supplied, controllable, specifiable minor input:
a. Information conversion can NOT be used as a noise suppression method; only minimizing by division and cancellation by subtraction are available methods.
b. The minor input can not be turned off, since that automatically involves removal of the major input as well. Hence Paths 2 and 4 can not be checked by the general method outlined in the preceding section for non-self-generating sensors.

In general, the non-self-generating responses do not create additive noise levels for the transducers considered here, but only multiplicative noise levels (gain changes, calibration changes, transfer ratio changes) and these are discussed in a later section. One general method of minimizing the effects of impedances in self-generating transducers is to make one of the two energy components (or power components) at the minor input arbitrarily small. Thus:
a. A resistor can contribute no voltage if there is no current through it. Hence null-balance (zero-current) voltage read-out from a thermocouple makes the read-out independent of lead resistance.
b. A capacitor can not generate a charge if there is no voltage across it. Hence the zero-drive, short-circuit, charge-amplifier principle for piezoelectric devices, and the driven-shield principle for cable capacitance minimization.

In this paper, only basic principles are discussed. The listing of large numbers of specific examples has been done elsewhere (Ref. 1). The literature shows a great amount of ingenuity on the part of many investigators in all disciplines, to achieve the broad aims set forth here. Only a few examples have been cited, but the reader should not feel that these methods are restricted to these few examples. They apply to all measurements in all disciplines.

DOCUMENTATION METHODS FOR MULTIPLICATIVE NOISE LEVELS

The chek on transducer or system calibration, sensitivity, gain, transfer ratio, etc., is usually achieved by producing an input variation which should result in a known output increment. This aim can be achieved in one of at least three ways:
a. Apply at the measuring system input a known amount of the quantity to be measured--pressure applied to a pressure transducer, for example--and observe system response. This is the most desirable manner of producing known input increments, but it is not always possible. If it is not possible in the actual measuring transducer, it may be possible in the check channel (if one is used) as illustrated in Fig. II for pressure measurement. The question of whether or not the presence of the leads of a thermocouple affect the transfer ratio of the system was already answered in the "Special Techniques" section above. The question of whether or not a thermocouple in a chemically active environment has changed calibration can NOT be answered even by a normal Standards Laboratory calibration!!! (refs. 1, 2.)
b. If the input sensor is non-self-generating, operating on impedance changes, artificially produce an impedance change corresponding to a known equivalent amount of the quantity to be measured. The shunt-resistance calibration of resistance sensors is a standard method using this principle.
c. Produce or inject an equivalent voltage (in electrical systems) at the earliest stage in the measuring system where such a voltage would normally appear. The simulating voltage source should duplicate the output impedance of the transducer which it simulates.

SEQUENCE OF NOISE DOCUMENTATION

Noise documentation should start at the read-out instrument and progress back towards the input transducer, if the method is to be of any use at all in permitting the diagnosis of specific problems. Built into the measuring system should be checks, identified in Fig. IV, which permit the sequential disconnection of each link of the measuring chain (where every cable is also a transducer-link processing and possibly altering information and energy').

Example for Resistance-Bridge Device

Figure V illustrates a typical set-up for resistance-bridge sensors in which the various switches can be actuated by a cycle-timer periodically during a test run. The returning of the Major Input to its operating point is not shown here, and hence information Path 2 (Fig.I) is not documentated here; but the requirements for its documentation, if desired, are now clear.

Step 1: Switch 1 to Position f
The observed output should be zero; if it is not, then one of the following problems has been isolated:

Common mode rejection problems in any differentially coupled amplifier following the bridge transducer. Any zero-shifts or drifts in the entire measuring system following the bridge.

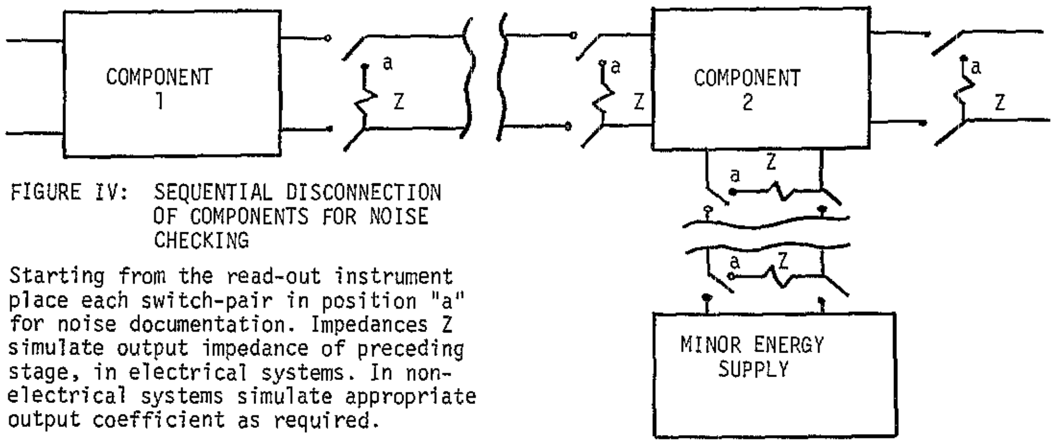
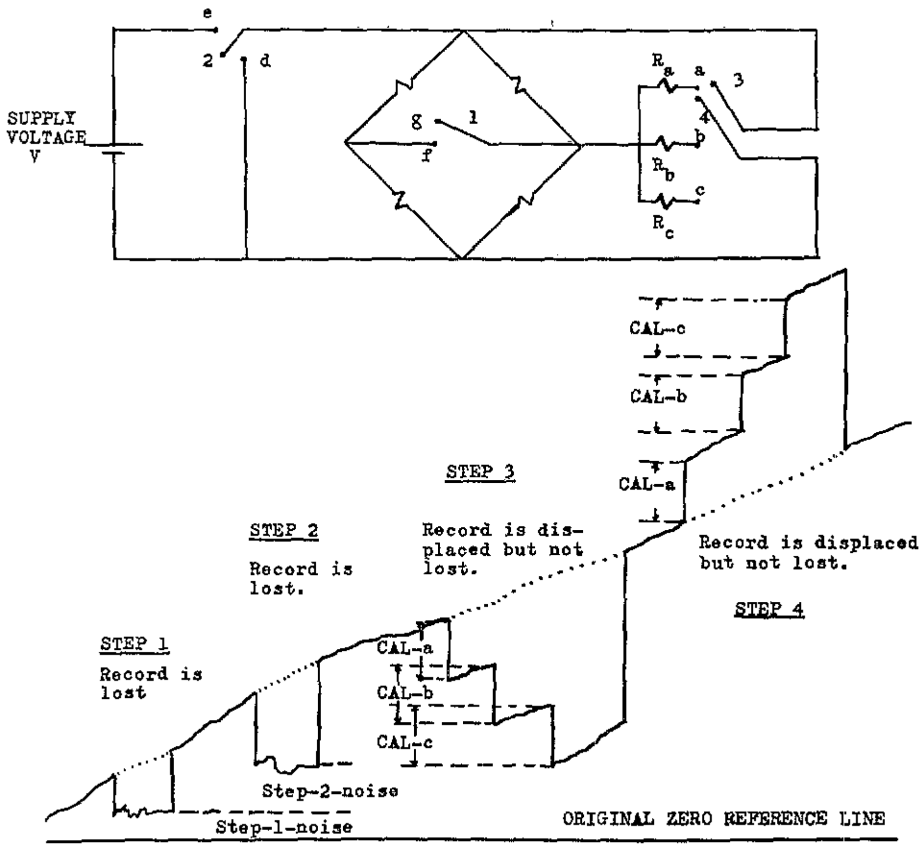


FIGURE IV: SEQUENTIAL DISCONNECTION OF COMPONENTS FOR NOISE CHECKING

Starting from the read-out instrument place each switch-pair in position "a" for noise documentation. Impedances Z simulate output impedance of preceding stage, in electrical systems. In non-electrical systems simulate appropriate output coefficient as required.



SIMPLE SEQUENTIAL SWITCHING SYSTEM FOR RECORDING PRESENCE/ABSENCE OF NOISE LEVEL, AND SYSTEM CALIBRATION AND LINEARITY AT THE OPERATING POINT.

FIGURE V

Step 2: Switch 2 to Position d
Switch 1 is returned to g. The Minor Input to the non-self-generating response (desired here) has been turned off. The output should be zero; if it is not, then the following problems have been identified:

Self-generating responses within the bridge circuit such as magnetic pick-up, electric field effects, thermocouple voltages, etc., even those created by the desired environmental aspect.

Step 3: Switch 3 Cycles Through a-b-c-off
Resistors R_a, R_b, R_c are precision shunt-calibration resistors which produce known equivalent resistance changes in the bridge curcuit--i.e., incremental outputs which can be related back to equivalent and known inputs. If these predictable outputs do not occur then a change in system calibration has been documented.

The output increments appear superimposed on the signal being recorded and are shown as Cal-a, Cal-b, and Cal-c on the record. There are other simulation techniques where the output increments appear about the original balance point (Bridge-Series Method). Switch 1 has been set back to Position e prior to the operation identified above.

Step 4: Switch 4 Cycles Through a-b-c-off
The same shunt calibration resistors as used in Step 3 are now used to produce changes in output level equal in magnitude as those in Step 3 but opposite in sign.

The significance of Steps 3 and 4 is that a calibration and linearity check have been performed AROUND THE OPERATING POINT and in both positive and negative directions.

Whether a linearity check around the instantaneous operating point or the original operating point is desired depends on test conditions. The bridge-series method would perform these checks around the original operating point (zero, for example).

Step 5: Turn Desired Environmental Aspect Off
If this operation is possible, with switches in positions 2-e, 1-g, 3 and 4 off, this condition documents Information Channel 2 (Fig. I), namely the non-self-generating responses created by the undesired portions of the environment, such as resistance-temperature, resistance-magnetic-field, etc., effects in the bridge.

With these five steps documenting ABSENCE of responses or ABSENCE of changes in responses, the recorded data can be guaranteed as free from additive or multiplicative noise levels, except for the fact that Steps 3 and 4 are SIMULATED calibration checks and do not check the resistance sensor itself, nor the first process-sensor interface, nor has the ability of the environment to elicit non-resistive impedance changes in the sensors been checked. In other words, it is KNOWN that the ultimate target has not been hit by these three factors, and any doubts can now be concentrated into those areas.

CONCLUSION

The aim of a measurement engineer is to elicit valid, noise-free data from measuring systems--data that represent the process being investigated without interfering with either the process or the data. Measurement Engineering, as a discipline, assumes that the properties of systems used to measure physical and chemical quantities are a respectable goal for study in and of themselves. The material for study includes the laws of physics, mathematics, and system behavior as they are involved in making a measurement.

It is the attempt of the Unified Approach to the Engineering of Measuring Systems to apply general methods and basic principles towards the achievement of the goals of a measurement engineer. This paper summarizes those methods and principles which pertain to the separation of the desired system response to the desired environmental aspect, from all other responses to all other environmental factors. Specific applications have been shown, and the general philosophy of establishing a target and planning system operation so that the closeness of target-hitting can be determined, had been emphasized.

REFERENCES

1. Stein, P. K., Measurement Engineering, Vol. I, 5th Edition, 1969, Stein Engineering Services, Inc., Phoenix, Arizona.

2. Stein, P. K., Traceability - The Golden Calf, Measurements & Data, Vol. 2, No. 4, July-August 1968, pp. 97-105

TRANSDUCERS - TREND OF THE ART SURVEY
By W. G. James, W-PAFB, Ohio

INTRODUCTION

During the morning session of the Sixth Transducer Workshop, a questionnaire was distributed among the attendees to assess attitudes and judgements of this group of experts regarding state-of-the-art and trends in transducer technology. This paper reports the responses received to that questionnaire. The questionnaire was purposely kept extremely short in order to encourage and facilitate the response. All replies on this survey are anonymous; the actual responses received will be kept by the author for approximately six months after publication of the minutes of the above Transducer Workshop in the event additional questions and interests are expressed in specific responses.

BACKGROUND OF THE WORKSHOP AND NATURE OF THE GROUP

Transducer Workshops have been held approximately every two years beginning in February 1960. These workshops are attended by transducer users, government agencies, university researchers, and consultants; manufacturers of transducers are specifically excluded from attendance and open discussion of both good and bad experience with specific transducers is encouraged.

These workshops are sponsored by the Transducer Committee of the Telemetry Working Group which is one of nine working groups which comprise the Inter-range Instrumentation Group (IRIG). The IRIG consists of technical representatives from the nine national and service test ranges plus various support and associate agencies. The IRIG was established by the Range Commander's Council to exchange information, coordinate technical matters for the ranges, to facilitate joint planning, and to improve the knowledge and use of range instrumentation.

The Transducer Workshop was held at the facilities of NASA, Langley Research Center. It is estimated from the attendance register that approximately half of the attendees were from this facility; it is therefore presumed that approximately half of the responses tabulated on this questionnaire were from this facility.

TABULATION OF RESPONSES

A copy of the actual questionnaire used is attached for reference. In tabulating the responses, the questions have been regrouped by area of common interest. In the following discussion, the actual questions will be identified by * and responses are tabulated and reported with as little interpretation as possible by the author. Author comments or interpretations are indicated under the heading "Remarks". Questions are grouped and the responses are tabulated by the following categories:

A. Nature of the Responding Group.
B. Company Viewpoint Regarding Transducers
C. State-of-the-Art, Problems, and Trends.
D. Social and Political Questions.

A. NATURE OF THE RESPONDING GROUP:

* Question 9: "Would you describe your present job duties as:

Technician	(1)
Engineer	(18)
Eng. Mgmt	(8)
Other	(1)

* Question 8a: Years since BS Degree? (1-35) years
  Remarks: See Table 1

* Question 8b: Advanced Degrees:

BS Only	(10)
BS + Addl Courses	(9)
MS	(4)
MS + Addl Stdy	(3)
PhD	(0)

Remarks: At least three attendees are known to have PhD Degree.

* Question 10a: Gross Salary: $(8-20),000

* Question 10b: Growth Potential, Present Position

Nil	(2)
Poor	(5)
Fair	(20)
Excellent	(1)

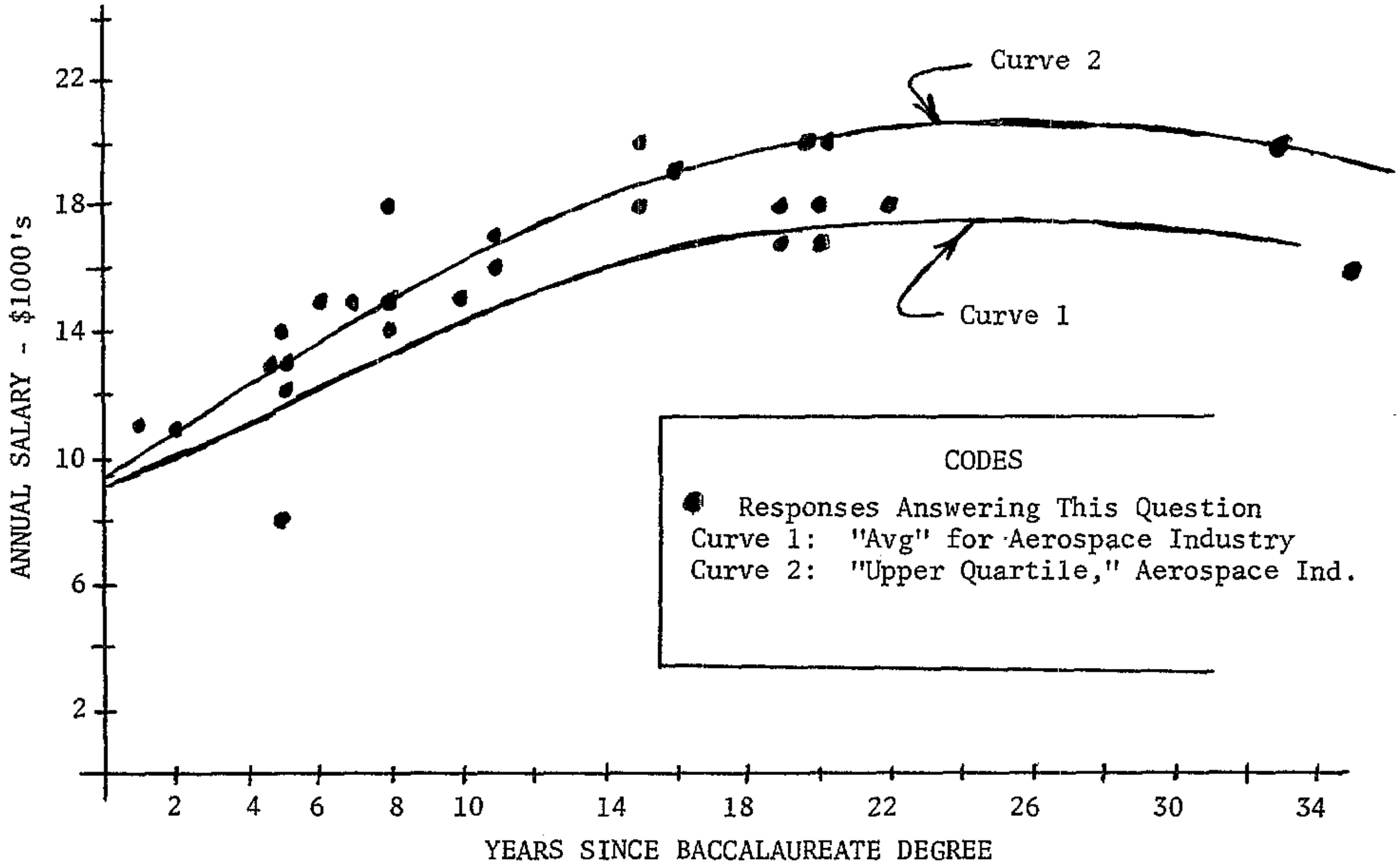
*Question 6: Present Pay for Present Job:

Low	(2)
About Right	(22)
High	(4)

Remarks: Several comments were noted indicating responder is under-utilized.

*Question 10c: Membership in Professional Societies

None	(10)
One	(12)
Two	(4)
Three	(2)



B. COMPANY VIEW OF INSTRUMENTATION:

* Question 5 "Within your Company, is instrumentation viewed:

(18) As a primary and essential function
(8) As a necessary function but not primary
(1) As a necessary evil
(1) As an unnecessary but unavoidable evil

C. STATE OF THE ART AND TRENDS:

* Question 1 "List up to 5 transducer characterics (parameters:

Most useful and important (92)
Least useful and unimportant (15)

Remarks: Several responses interpreted this question as meaning parameters such as pressure, temperature, etc.; this interpretation is nearly impossible to answer and these answers are not tabulated. The question was intended to mean parameters such as scale factor, linearity, resolution, etc.; these responses are grouped as follows reflecting the author's judgement of similarity. A listing of specific responses is included in Appendix 2.

Most Useful:
- Frequency Response (12)
- Size (Mass, Wt, etc.) (9)
- Sensitivity (9)
- Environmental Specs (Mostly Temperature) (8)
- Environmental Effects (7)
- Repeatability (7)
- Hysteresis (5)
- Linearity (5)
- Long Term Stability (4)

Least Useful and Unimportant:
- "None are Important" (2)
- Color, Flavor (2 each)
- Linearity (2)
- Temperature Effects (2)
- {Readout, Threshold, Resolution, Long Term Drift, Warm up time} (1 each)

Additional Remarks: It is noted that "linearity", "Stability (Long Term)", and "Environmental Specs and Effects" are included on both lists. It is presumed by the author that these are considered important data by all responders; the stability, linearity, and environmental sensitivity of the transducer is, however, unimportant to test situations which allow post test data reduction (and calibration and correction) while being important to real time operational system applications for transducers. This presumption was mentioned by the author during the open discussion time and no disagreement was evident.

* Question 2, "Major transducer areas and breakthroughs needed:

Remarks: A summary of responses follows, grouped by category in the author's judgement; specific responses are listed in Appendix 3.

- Dynamic Calibration Techniques (7)
- Improved Accuracy (2)
- Miniducers with Integrated Signal Conditioning Suitable for rugged environments (2)
- Other responses mentioned only once (10)

* Question 4, "Indicate areas of technology and/or new transducing techniques which are on the verge of providing breakthroughs in instrumentation:

Remarks: Practically no concensus was evident to the author. A summary of responses follows, grouped by category in the author's judgement; specific responses are listed in Appendix 3.

- Solid State Sensors (2)
- Lasers (2)
- Integrated Amps inside transducer case (2)
- Other responses mentioned only once (11)

* Question 3 "Regarding the New ISA Transducer Compendium:
  a. Do you have personal access to it? Yes (16); No (10)
  b. Do you use it: Often (0) Occasionally (10); Seldom (6)
  c. Remarks: Favorable (5)
     Constructive Recommendations (4)
     Negative (1)

Remarks: During discussion, the following information was presented. The "Transducer Compendium" was originally published by the Instrument Society of America in 1963. This publication was prepared in a 10 x 14 inch format which would not fit on standard bookshelves and the information compiled on transducers available was not organized in a form suitable for rapid searching. Further publication of this compendium was suspended during the time period when the Transducer Information Center at Battelle Memorial Institute was in operation. In the fall of 1968, the Transducer Compendium format was revised and the ISA published Part I of the second edition which covers the measurement of pressure, level, and flow. Part II will be published in 1969 which will cover the measurement of motion, dimension, force, torque, and sound. Part III will be published in 1970, which will cover the measurement of temperature, chemical composition, physical properties, humidity, moisture, and nuclear radiation. Each part will then be revised sequentially on a four year cycle. The second edition of the Compendium is organized for rapid scanning and is prepared in a size which will fit on standard bookshelves. Copies of the ISA Transducer Compendium may be ordered from the Instrument Society of America, 530 William Penn Place, Pittsburgh, Pennsylvania 15219.

D. SOCIAL AND POLITICAL QUESTIONS:

* Question 7 "If work week shortened to 30 hours:
  a. Could you do same work you now do in 40 hours?
     Yes (8), No (13), No Answer (7)
  b. Would you prefer:
     (4) 3 Days at 10 hours each
     (19) 4 Days at 7.5 hours each
     (1) 5 Days at 6 hours each

* Question 11 "Are you active in church and community?
  (3) Totally Inactive - Don't Monitor
  (4) Inactive but Monitor and Discuss
  (16) Moderately Active
  (6) Very Active
  (0) Crusader
  (0) Other: ______________________________

* Question 12 "Is the Engineer or Scientist responsible for the social or political consequences of his work:
  (16) Must feel a strong responsibility even though generally beyond his control.
  (6) Knowledge and know-how are the primary objectives of science and engineering--how this is used or mis-used is irrelevant.
  (0) Should not work on technology of destruction, war, etc.
  (2) No opinion or undecided

Remarks:

(1) Answer 3 ("Should...destruction, war, etc.) had one four letter comment indicating strong disagreement with this answer.

(2) In addition to the responses tabulated above, 3 responses were made indicating a mixture of answers 1 and 2; further, one response indicated the engineer or scientist should be trained to have stronger influence over the social and political consequences of his work.

GENERAL REMARKS:

After reporting and discussing the results of this questionnaire, a lively interest was noted among the group in attendance. The attendees indicated a willingness to cooperate with one or two additional iterations of the questionnaire refining the results of this effort. Due to this interest and subsequent encouragement, it is intended to proceed with this technique to assess the attitudes and judgements of this group of transducer experts.

APPENDIX I - Questionnaire Used

OPTIONAL QUESTIONNAIRE

All replies are anonymous

1. List up to 5 transducer characteristics (parameters):

Most Useful and Important		Least Useful and Unimportant	
	________		________
	________		________
	________		________
	________		________
	________		________

2. Major transducer problem areas and breakthroughs needed: ________

3. Regarding the New ISA Transducer Compendium:
   a. Do you have personal access to it? ________
   b. Do you use it: Often ____ Occasionally ____ Seldom ____
   c. Remarks: ________

4. Indicate areas of technology and/or new transducing techniques which are on the verge of providing breakthroughs in instrumentation: ________

5. Within your Company, is instrumentation viewed:
   ____ As a primary and essential function
   ____ As a necessary function but not primary
   ____ As a necessary evil
   ____ As an unnecessary but unavoidable evil

6. Your pay for the job you do is: ____ Low, ____ About Right, ____ High

7. If work week shortened to 30 hours:
   a. Could you do same work you now do in 40 hours? ________
   b. Would you prefer: ____ 3 Days at 10 hours each
      ____ 4 Days at 7.5 hours each
      ____ 5 Days at 6 hours each

8. a. Number of years since Baccalaureate Degree? ____ Years
   b. Please indicate Advanced Degrees and/or graduate study: ________

9. Would you describe your present job duties as:
   ____ Technician, ____ Engineer, ____ Eng. Management, ____ Other.

10. a. Approximate Annual Salary (Gross): $,000
    b. Growth Potential - Present Position:
    ____ Nil, ____ Poor, ____ Fair, ____ Excellent
    c. Membership in Professional Societies: ________

11. Are you active in church and community?

_____ Totally Inactive - Don't Monitor
_____ Inactive but Monitor and Discuss
_____ Moderately Active
_____ Very Active
_____ Crusader
_____ Other: ____

12. Is the Engineer or Scientist responsible for the social or political consequences of his work?

_____ Must feel a strong responsibility even though generally beyond his control.
_____ Knowledge and know-how are the primary objectives of science and and engineering--how this is used or mis-used is irrelevant.
_____ Should not work on technology of destruction, war, etc.
_____ No opinion or undecided

APPENDIX II

Responses to Question 1

Transducer characteristics (parameters) considered most useful and important:

Friction
Sensitivity
Stability
Zero Value
Repeatability
Rise Time
Temperature
Physical size
Hystereses + Lin
Temp. coef or Sens
Repeatability
High Frequency Response
Rugged
Repeatability
Over-range Capability
Input characteristics
Output characteristics

Size
Frequency Response
Power
Accuracy
Hysteresis
Size-compatibility
Sensitivity
(Size,Meas,Etc) Little interference with meas.
Accuracy over entire meas range

Sensitivity
Repeatability
Physical Size
Time constant
Broad spectrum of environmental conditions
Reliability
Sensitivity to environmental effects
Operating range
Environmental Effects
Physical characteristics
Dependability
Performance in adverse environments

Hysteresis
Repeatability
Sensitivity
Accuracy
Temperature response
Resonate Frequency
Frequency Range
Sensitivity
Repeatability
Durability (Life)
High Sensitivity
Low Cost
Hysteresis
Temp. Stability
Sensitivity
Transfer characteristics
Amplitude & Frequency effects on magnitude & phase of each of these characteristics
Accuracy
Environmental Specs
Sensitivity
Precision
Drift rate
Accuracy
Response

Power required
Generally this depends on what you are trying to do with the transducer
Range
Response Time
Dynamic range
Hysteresis

Dynamic response
Total accuracy
Long term stability
Power Requirements
Overall accuracy
Minimum effect on test cond.
simplicity

Reliability

Resonant freq.
Temp. Response
Size
Stability
Temp. coeff.
Response time (transient)
Radiation Effects (pulsed)
Physical Size
Linearity
Dynamic Response

Availability of reliable performance information
Linearity
Sensitivity
Range
Linearity
Response time
Hi Temp. characteristics
Resonant freq.
Repeatability
Size

Transducer characteristics (parameters) considered least useful and unimportant:

Color
Temp coef of zero output
Hysteresis
Thermal sensitivity
Long term drift
Impedance
Color
It has been my experience that every known parameter must be defined to permit proper selection for various applications
Nuclear Reaction
Threshold

Flavor
Linearity
Warm up time
Linearity
Readout
Chrome Plating
None are important
Ambiguous specifications
Resolution

APPENDIX III

Responses to Questions 2 and 4

Question 2: Major transducer problem areas and breakthroughs needed:

- Sterilizable accelerometers, gyros, etc.
- Sinusoidal Pressure Generator
- Dynamic characteristics, Dynamic calibrations, Good sinusoidal pressure generators
- Dynamic Pressure calibration
- Better solid state and thin film devices
- Determination of input characteristics of non-electrical-input transducers
- Miniature transducers with int. crt. ampl., Signal conditioning integrated- suitable for use in rugged environments.
- High temperature transient generator (<1ms risetime)
- Sensor readout capability compatible with digital accuracies
- Dynamic testing
- Major problem area of small open loop transducers is that of long term drift
- Performance in adverse environments - Particularly in wide temp ranges
- Inexpensive ($10 in quantity) D.C. amplifier for low level (<1mvdc) signals
- Adequate sinusoidal pressure standard for testing
- A really good mass flow meter, Improved methods of recording and analyzing dynamic data
- Humidity, Measurements, Angular Acceleration-Low Ratio $20°/sec^2$
- Radiation effects - methods of hardening

Question 4: Transducer technology on verge of providing breakthroughs needed:

- Probably fluid amplifiers, Computer-controlled analysis, solid-state mini circuits
- Integral amplifiers inside transducer cases, sub-min A-D converters
- Optical computing, Real time spectrum analysis, "mini"-computers
- Fire detection for on-board spacecraft
- Low airspeed for airplane installations
- Integrated ckt. signal conditioning in/on miniature transducers
- Solid state transduction devices are expected to provide the next transducer generation
- Lasers
- Hi-G wide freq. band damped accelerometers
- SS Sensors Lasers, Nuclear Magnetic Resonance

REMARKS AND ANSWERS FROM

SESSION III, "GENERAL

MEASUREMENT PROBLEM AREAS"

Chairman James presented the results of a poll taken of all participants on transducer applications, problem areas, impending breakthroughs, and nature of the participants' jobs.

A discussion ensued on how to check for a "bad" thermocouple. Prof. Stein's paper on "Noise Levels" was viewed as mapping out a procedure for indicating how and when a transducer was misbehaving. However, Stein commented that AERD (British) work reveals the impossibility of calibrating a used thermocouple or checking for contamination. The advisability of establishing a service life for transducers was also discussed.

In response to a question on why miniducers are not more widely available, it was generally agreed that, while some types of transducers have already been miniaturized (e.g., piezoelectric gauges) the marketing of miniducers might be highly desirable.

Prof. Jacobs, who spoke on "Transducer Instrumentation Used in Bio-Engineering Measurement", was asked whether pressure difference measurements in the heart would be valuable in determining flow data. He responded by pointing out that the chief drawback to this is that the walls (in the heart, etc.) are not rigid. A discussion followed on types of sterilization of transducers.

The definition of accuracy as applied to a transducer was not readily agreed upon by all participants, although the poll taken indicated the importance of accuracy. It was pointed out that an ISA Standard (SP 37.1) was available, which had definitions for transducer technology, and that this document was available from ISA, 530 Wm. Penn Place, Pittsburgh, Pa. Workshop Chairman Lederer also mentioned the "Dynamic Calibration Guide" for pressure transducers established by the USASI B88 Committee.

The meeting ended with a discussion on resonances in measuring systems.

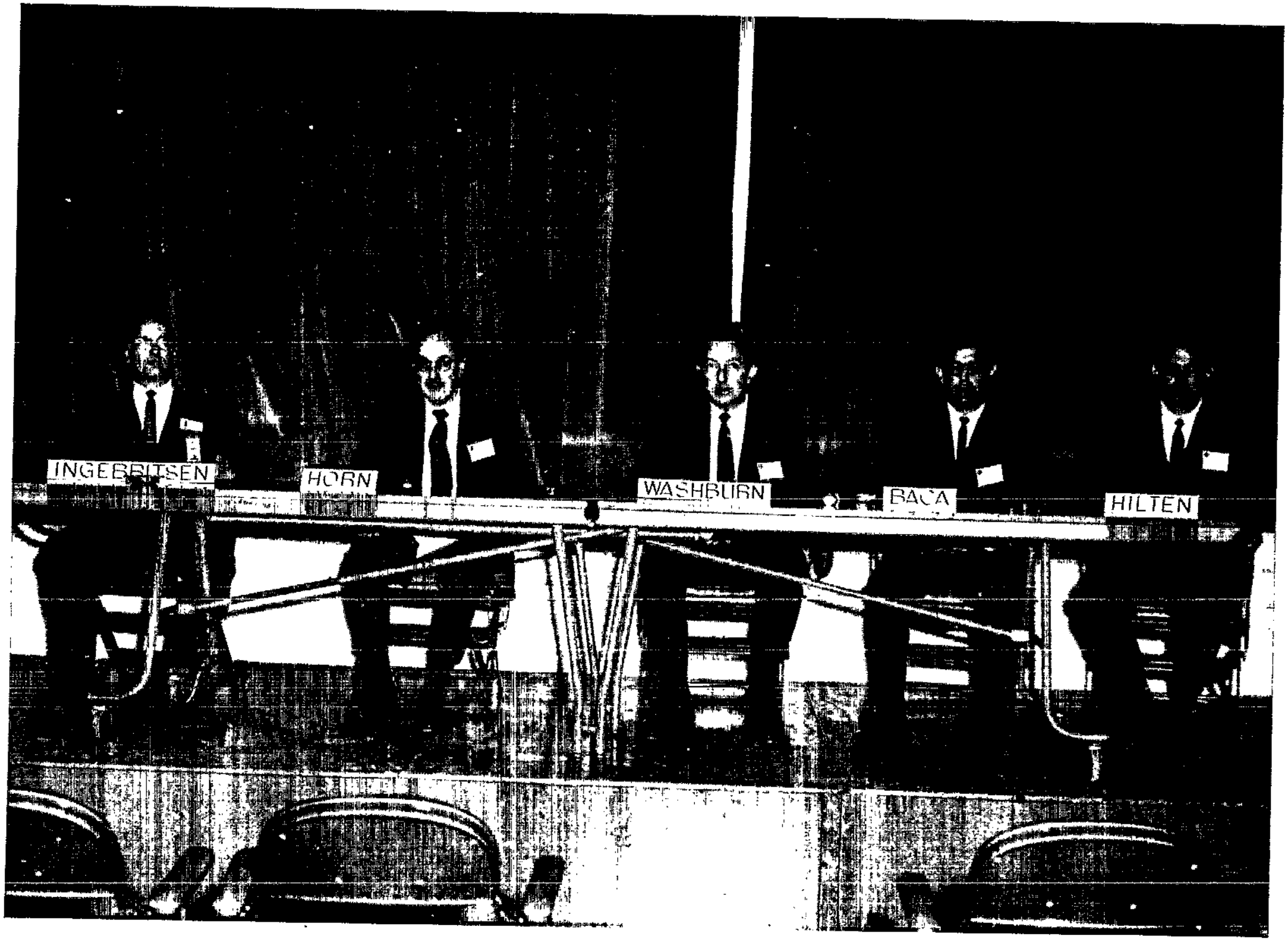
SESSION IV

Measurement of Force and Acceleration

Chairman: Leon Horn, National Bureau of Standards

Recorder: John Hilten, National Bureau of Standards

Panelists: O. Ingebritsen, NASA Langley Research Center
R. Naylor, Defense Research Establishment, Canada
B. Washburn, Los Alamos Scientific Laboratory
J. Baca, AF Special Weapons Center



Panel Session IV "Measurement of Force and Acceleration"
O. Ingebritsen; L. Horn, Chairman; B. Washburn; J. Baca; J. S. Hilten, Recorder.

VIBRATION MEASUREMENTS AT CRYOGENIC TEMPERATURES AND HIGH ACCELERATION LEVELS*

B. W. Washburn
Staff Member
University of California
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

ABSTRACT

Application considerations of the wide band acceleration instrumentation for the Rover Ground Test Facility dual liquid hydrogen turbopump system are described. The study of structural and flow induced vibrations required information bandwidths up to 50 kHz. Transducer environments varied from 530 to 114 degrees Rankine with complex acceleration levels up to 2,000 g's pk-pk. Elementary analyses in support of transducer selection and transducer mounting considerations are presented. The need for knowing the total transducer and mounting environment is emphasized.

INTRODUCTION

The Los Alamos Scientific Laboratory Rover nuclear rocket ground testing facility in Nevada utilizes high speed turbopumps, developed by Rocketdyne, to supply liquid hydrogen propellant to the reactor under test. One configuration consisted of two turbopumps arranged such that they could be operated in single or dual (parallel) mode to furnish flow rates up to 350 pounds per second of liquid hydrogen at 1,500 psig. Each turbine was rated at 25,000 horsepower and 34,000 rpm. A general view of the turbopump system is shown in Figure 1. The turbine energy source is hydrogen gas produced in a bootstrap operation of the turbopump by a hot water-to-liquid hydrogen heat exchanger.

The Los Alamos Scientific Laboratory has utilized several circuit configurations and bandwidths in making vibration measurements on this turbomachinery. Routine vibration measurements on the pump, turbine, and duct components had 1,000 Hz bandwidth, the frequency range of interest for structural and rotational speed-connected components. Channels extending to 50 kHz have been utilized to define the vibration spectral environment to which the sensors on the 1,000 Hz channels are subjected and to study flow induced vibrations.

BASIC MEASUREMENT PROBLEMS

Los Alamos Scientific Laboratory instrumentation and testing experience on smaller, single turbopump systems earlier in the Rover program had indicated the presence of relatively large amplitude acceleration components at frequencies

*Work performed under the auspices of the United States Atomic Energy Commission

above the 1,000 Hz limit of interest to the designers. The larger, higher power systems have shown a more severe environment in this respect. The higher power systems have acceleration components above 1,000 Hz which are of the order of 40 db greater in level than the components below 1,000 Hz. Actual levels of 1,000 to 2,000 g's pk-pk at frequencies above 1,000 Hz were commonly present in the system. The existence of large amplitude, high frequency components gives rise to mechanical and electrical problems in making the lower frequency measurements. The transducer and mount must linearly follow the complex composite vibration motion. These environmental conditions can subject a one ounce assembly to peak forces of the order of 40 to 70 pounds making necessary a very rigid installation of the transducer to insure mechanical linearity. High frequency components present may excite transducer and mount resonances.

When primary measurement interest is in components at the lower end of the spectrum, the electrical output of the transducer must be transformed linearly with good signal-to-noise ratio until the higher frequency components can be removed. Separation and processing of only the desired frequency components permits use of signal transmission, amplification, recording, reproducing, and analysis systems having less dynamic range and poorer noise performance than would be required to handle the entire spectral range of the composite signal. From the data system point of view, it is desirable to perform the spectral separation as close to the signal source as possible.

The pump and ducting measurements were made at locations where the transducer temperatures are around 114 to 140 degrees Rankine. The entire pump and piping system were chilled down with liquid hydrogen prior to turbopump operation. As a result, the temperature of the accelerometers has essentially stabilized at the beginning of the data taking interval. Compatible material properties at these low temperatures are essential to maintaining the necessary rigid sensor installation. Transducer installations and check-out were done at room temperature conditions since the chilled system was not accessible for such routine work.

SELECTION OF COMPONENTS

Transducer

The various piezoelectric accelerometer designs were examined and judgements were made concerning the expectations for each to perform in the environment. A single-ended compression design, quartz element accelerometer was selected. Units of this particular design had previously undergone limited testing in the laboratory at 38 degrees Rankine (LH_2) and had been used on three earlier and smaller LH_2 pumping systems by Los Alamos Scientific Laboratory. A one ounce unit having a mounted first resonance over 33 kHz was selected for use up to 10 kHz and a similar unit weighing 0.3 ounce and having a first resonance above 75 kHz was selected for higher frequency measurements.

An approximate design analysis was performed on the candidate transducer to estimate its performance at the low temperatures and high "g" levels. The transducer center post and quartz stack stress-elongation characteristics are illustrated in Figure 2. Calculations for room temperature conditions gave a maximum range of ± 2460 g's pk which compares favorably with the manufacturers rating of 1,000 pk g's sinusoidal for 1% distortion and 2,000 pk g's shock. A 2,000 pk g shock will stress the center post to about 80% of the calculated limit. The room temperature static condition or "operating point" gives about 160 micro-inch of center post elongation and a sensitivity of the center post-mass assembly of the order of 15 g's per micro-inch of elongation. Stating these results in another way, this sensitivity means that for every micro-inch of center post or base deformation due to extraneous causes, the range to distortion or clipping may be reduced by 15 g's.

At a temperature of 140 degrees Rankine the tension on the center post will be greater than that at room temperature since the post shrinks faster than the quartz stack. The center post static stress and strain are increased by some 45% at the lower temperature while the yield stress is approximately doubled and the overall length of the assembly has decreased by about 2.5%. Figure 2 compares the low temperature characteristics and operating points with those at room temperature. The stress in the quartz stack, to a first approximation, will be dependent upon the strain in the center post. As the dependent variable, the quartz stress-compression characteristic at the lower temperature is shown appropriately shifted on the axis of abscissas with respect to the room temperature characteristic. The quartz stack is always under compression unless the center post breaks; reduction otherwise of the center post tension stress to zero results in increased compression stress on the quartz stack. Thus the transducer range may be approximately doubled at 140°R although the static strain has been increased by only 45%. The sensitivity will be reduced by about 2.5% at the lower temperature due to the variation in Young's modulus with temperature.

The selected transducers had a 303 stainless steel base which may or may not undergo a permanent dimensional change at cryogenic temperatures, around LN_2, due to crystal transformation. A 100% transformation results in approximately 4% increase in dimension. The transformation, if it occurs, is usually around 5 to 10% thus making the dimension increase of the order of 0.2 to 0.4%. Transducers were temperature cycled between room temperature and LN_2 prior to use to insure stabilized dimensions.

Transducer Mounting

Figure 3 shows a typical accelerometer mounting. All mountings were directly in flanges or cases and utilized a standard commercial insulated mounting stud. The stud material was 416 stainless and the insulation was epoxy and fiberglass. Careful attention to mounting details seems advisable in order to achieve linear transmission of the complex accelerations from the pump to the transducer sensing element. It is of interest to examine the performance of a mounting which has a transmission or transfer characteristic similar to that shown in Figure 4. We approximate this characteristic by the following expression for analysis:

$$X = x + ax^2 + bx^3 \qquad (1)$$

In general this characteristic, which will produce second and third-order modulation of the input, will not be symmetrical about the origin and the coefficient a will not be zero. The coefficient b is negative for this characteristic. For purposes of illustration we assume a grossly oversimplified representation of the complex input function as follows:

$$x = x_1 \sin\omega_1 t + x_2 \sin\omega_2 t + x_3 \sin\omega_3 t \qquad (2)$$

It is necessary to include three frequencies in the input function in order to obtain all the types of combinations which may be produced in the output. Using equation (2) as the input function and solving equation (1) shows that the output contains twenty-nine new frequency components in addition to erroneous components at the three input frequencies. Table I gives the frequencies and amplitudes of the distortion components present in the output. If the input consisted of only two frequency components instead of three, the output would contain eleven new frequencies in addition to the two input frequencies. If the input consists of many frequencies, non-linearities in the transmission of the mounting will produce a very complex spectrum at the transducer.

In the present case we are concerned with the effects of the presence of high level, high frequency components while trying to measure low level, low frequency components. We assume, for analysis, that the ω_1 component is of primary measurement interest and ω_2, ω_3, etc., components are the disturbing high level, higher frequency components. The second-order modulation components contain d.c. terms with amplitudes as follows:

$$\frac{a}{2}\left(x_1^2 + x_2^2 + x_3^2\right)$$

The crystal-amplifier circuit will not normally reproduce a steady d.c. signal; however, this term is of interest in as much as the abrupt build-up or decay of a large amplitude component such as x_2 or x_3 will produce an electrical output having the appearance of a shock. When the measurement channel has less bandwidth than will reproduce the ω_2 or ω_3 components, only the shock-like response will be indicated. This erroneous indication will have a steep leading edge and will decay according to the circuit time constant.

The third-order modulation components contain erroneous terms which have the same frequencies as the input function and amplitudes as follows:

$$\omega_1 \ ; \ \frac{3b}{2}\left(\frac{x_1^3}{2} + x_1 x_2^2 + x_1 x_3^2\right)$$

$$\omega_2 \ ; \ \frac{3b}{2}\left(\frac{x_2^3}{2} + x_1^2 x_2 + x_2 x_3^2\right)$$

$$\omega_3 \; ; \; \frac{3b}{2}\left(\frac{x_3^3}{2} + x_1^2 x_3 + x_2^2 x_3\right)$$

It is of interest to examine the magnitude of such errors under the approximate conditions of our application. We assume, for purposes of simplicity and illustration of the case at hand, a low amplitude component, ω_1, of primary measurement interest in the presence of a much larger amplitude, higher frequency component of lesser or no measurement interest at ω_2:

$$x_1 \ll x_2 ; \; \omega_1 \ll \omega_2$$

If the non-linearity of the transfer characteristic is such as to produce ten percent third harmonic of ω_2, and if $x_2 = 100x_1$, the component at ω_1 will appear to be only 40% of its true amplitude due to combination of the true component with the distortion component. While the component at ω_2 experiences 10% third harmonic distortion, the lower amplitude component at ω_1 will experience only 10^{-3}% third harmonic in the assumed transfer process. Thus the direct distortion of the component of interest, ω_1, is negligible while the extraneous component or error at ω_1 due to the presence of ω_2 is of large amplitude. If this non-linearity produces only 1% third harmonic of ω_2 and $x_2 = 100x_1$, the component at ω_1 will appear to be 94% of its true value. This type of consideration shows the necessity for linear transmission of the motion from the pump to the transducing element and the need to consider the effects of components present although such components may not be of data interest. Knowledge of the distortion and distortion components is helpful in the data assessment and qualitative evaluation processes.

The following mounting tolerances were design objectives: 1.) Perpendicularity of stud hole to accelerometer mating surface within 15 minutes of arc, 2.) Flatness of mounting/mating surface within ±0.0005 inch, 3.) Mating surface finish equal to or less than 16 microinch RMS, and 4.) Class 3 threads.

The mounting involved three different stainless steels as follows: pump case, 310; stud, 416; and accelerometer base, 303. Analyses indicated that loosening of the mountings was a possibility at the low temperatures due to mechanical tolerances and dimensional changes in these three materials. The uncertainty in the calculations is due to nominal tolerances on threads and surfaces and the inability to accurately calculate the tension in the small mounting studs.

These marginal expectations for the standard insulated mounting stud led to the fabrication of a few non-insulated, 303 stainless studs having thread tolerances which would give tighter fits in the pump and in the accelerometer bases. These were used on a few pump runs and the measurement performance was compared with data obtained with the standard insulated studs. Qualitative performance of the complex waveforms was the same with both materials.

The dynamic forces are alternately transmitted by the thread surfaces and by the surfaced faces and bosses. Tolerances and finishes on these surfaces along with cleanliness of the surfaces are important. While the spring-mass system of the accelerometer makes the electrical output proportional to acceleration, displacement as a function of time is the driving or input parameter which must be accurately followed by the mount-transducer assembly. As noted earlier, a transfer characteristic which introduces ten percent third harmonic of the large amplitude, high frequency component results in significant error in the smaller amplitude component being measured. In the application under consideration a ten percent distortion of the large amplitude components is of the order of seven to ten micro-inch (pk). Surface imperfections and foreign matter such as lint and dirt on the surfaces may easily be deformed by these amounts when subjected to dynamic forces of the order of 70 pounds.

In mounting the transducer it seems advisable to keep in mind that the actual mounting of the transducer is really the final mechanical assembly step of the unit and as such this operation should be carried out with somewhat the same care used in building the transducer. All surfaces and threads were thoroughly cleaned with alcohol and dried prior to assembly. Mounting torque was 18 to 25 inch-pounds. Spacers of several thicknesses for use on mounting studs were fabricated from invar; however, these were not utilized since the range of mounting torque values was sufficient to provide acceptable electrical connector positioning. Invar was chosen for its low coefficient of thermal expansion as compared to that of the other materials involved.

Cables

Standard low noise, teflon insulated Microdot cables were used with a silicone compound seal at all connectors. Cables were not fastened to the turbopump system at the transducer end due to mechanical details of the pump case insulation. Instead, a short length of heat shrink tubing was applied over the connector and cable at the transducer.

Amplification

A voltage system was used. This choice was influenced by 1.) the need to transform linearly the complex transducer output signal while eliminating the large amplitude frequency components above the frequency range of interest and 2.) the transducer charge sensitivity and capacitance variations at low temperatures.

The amplifier, like the accelerometer-mount system, must be capable of linear amplitude transformation over the range of complex signal amplitudes expected from the accelerometer if the entire spectrum is to be measured or amplified. The amplification problem may be simplified when the data of interest can be confined to a portion of the spectrum. Such interests in this particular application were limited to frequencies below 1,000 Hz where acceleration levels were expected to be less than 100 g's (pk-pk). Measurement requirements below 1,000 Hz utilized Dynamics Instrumentation a.c. amplifiers, Model 6163, with third order low-pass filters in the input to reject components above 1,000 Hz. Thus the amplifier transformed only those signal components of data interest plus the portion of the higher frequency, high amplitude components which the input filter did not reject. Channels were scaled by considering the amplitudes of both the components of interest and the attenuated high frequency components.

Channels having greater than 1,000 Hz bandwidth utilized a cathode follower driving a fourth order, active low-pass filter. The filter rejected components above the frequencies of interest, matched the cathode follower output, and drove the long cables running to the data acquisition system. The particular commercial cathode follower available in the system had adequate dynamic range to linearly transform the complex composite signal when loaded with a high impedance but was inadequate for driving cable capacitance at the large amplitudes and high frequencies.

All voltage amplifiers and filters were located in the turbopump area such that the transducers typically drove fifteen feet of the Microdot cable and the amplifier inputs. The voltage sensitivity of the transducer driving the cable and amplifier will decrease with temperature. The change in sensitivity was estimated as follows:

$$E_1 = q/C_t \text{ at temperature } T_1$$

where:

E_1 = voltage sensitivity - in pk volts/pk g

q = charge sensitivity - in pk cmb/pk g

C_t = transducer capacitance plus nominal external capacitance which makes voltage sensitivity independent of temperature - in farads

at temperature T_2: $$E_2 = \frac{q + \delta_q}{C_t + \delta_c}$$

where:

δ_q = change in charge sensitivity with temperature

δ_c = change in capacitance with temperature

Since C_t made the voltage sensitivity independent of temperature, we may write

$$E_2 \cong \frac{q}{C_t}$$

and

$$\frac{\delta_q}{\delta_c} = \frac{q}{C_t}$$

We add the external cable and amplifier input capacitance, C_c

$$E_1' = \frac{q}{C_t + C_c}$$

and

$$E_2' = \frac{q + \delta_q}{C_t + C_c + \delta_c}$$

The change in voltage sensitivity due to temperature may be written as:

$$\Delta E = E_1' - E_2'$$

and

$$\frac{\Delta E}{E_1'} = \frac{\delta_c C_c}{C_t(C_t + C_c + \delta_c)}$$

(δ_c is negative when $T_2 < T_1$).

For the application under consideration the voltage sensitivity decrease at 114 degrees Rankine was expected to be of the order of 3 to 4% of the room temperature value. This adds to the decrease due to Young's modulus for a total sensitivity decrease of the order of 6% between room temperature and 114 degrees Rankine.

All signals are FM recorded on magnetic tape for post-test reproduction and analyses.

Calibration, Set-up, and Check-out

Procedures were evolved to insure channel integrity with minimum handling of the elements. Laboratory calibration was performed at relatively low "g" levels and room temperature with cable and amplifier combination. Initial installation, pre-test and post-test check-outs were performed using series voltage insertion without breaking connections or removing the transducers. Mounting torques were checked before and after a test without loosening to prevent foreign matter from accidentally entering the mounting. Exposed cables were visually inspected for mechanical damage and checked for noise generation by manually flexing while observing the amplifier output on an oscilloscope. Pre and post-test checks were made for proper circuit isolation. Removal of circuits, cables, mounts, etc., is not considered as routine. This was done only for major system mechanical work or when a component was definitely proven defective.

EXPERIENCE

With one year of operational test experience there was one transducer failure (crystal stack insulator fractured during post-test warm up from cryogenic temperatures) and two mounting stud insulation bond failures which occurred in post-test periods. The only known cable problems have been damage inflicted during routine work on the system. Cables are in conduit except for about a one foot length at the transducer end.

Transducers mounted on scored and unfinished mating surfaces consistently produced clipped or distorted waveforms in this system. Similar behaviour has been noted when mounting threads were dirty.

Establishing ranges for these channels was a problem. As the pumps, turbines, and inlet ducting were replaced during the course of the development tests, the system resonant frequencies shifted to a degree but the changes in resonance amplitudes were most dramatic. Amplitude changes by factors of two to ten were not uncommon. Also, transducer locations varied on the different pumps and turbines used.

Transducer torques have been checked with the system cold and no significant loss from the room temperature value has been observed.

Vibration levels and frequencies were plotted on the pump map for correlation with pump flow, discharge pressure, and speed. See Figure 5. Components below 1,000 Hz usually correlate with speed while those above 1,000 Hz correlate with liquid hydrogen flow rate. While it is difficult to generalize, some predominant components and typical levels are given in Table II.

This is by no means all resonances or components observed as tests on the system have shown over twenty resonances below 1,000 Hz.

High "Q" responses have been observed at the turbine case between 12,600 and 20,000 Hz. Levels between 600 and 2030 g's pk-pk have been recorded. The only correlation at present for these flow noises is turbine speed. These components are of interest since some stages of the turbine have blade resonance modes in this region.

SUMMARY

High level vibrations and cryogenic temperature environments necessitate care in measurement component selection, installation, and signal processing. Spectrum conditioning of the complex composite vibration signal prior to amplification is necessary to remove large amplitude, high frequency flow excited components when measuring low amplitude, low frequency structural, and speed connected components.

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TABLE I

GENERATED DISTORTION COMPONENTS

Response distortion terms are of the form:

2nd order: A cos Bt

3rd order: A sin Bt

Order of Distortion	Component Coefficients B	A
2nd	d.c.	$\frac{a}{2}(x_1^2 + x_2^2 + x_3^2)$
	$2\omega_1$	$-\frac{a}{2} x_1^2$
	$2\omega_2$	$-\frac{a}{2} x_2^2$
	$2\omega_3$	$-\frac{a}{2} x_3^2$
	$(\omega_1 - \omega_2)$	$a(x_1 x_2)$
	$(\omega_1 + \omega_2)$	$-a(x_1 x_2)$
	$(\omega_2 - \omega_3)$	$a(x_2 x_3)$
	$(\omega_2 + \omega_3)$	$-a(x_2 x_3)$
	$(\omega_1 - \omega_3)$	$a(x_1 x_3)$
	$(\omega_1 + \omega_3)$	$-a(x_1 x_3)$
3rd	ω_1	$\frac{3b}{2}(\frac{x_1^3}{2} + x_1 x_2^2 + x_1 x_3^2)$
	ω_2	$\frac{3b}{2}(\frac{x_2^3}{2} + x_1^2 x_2 + x_2 x_3^2)$
	ω_3	$\frac{3b}{2}(\frac{x_3^3}{2} + x_1^2 x_3 + x_2^2 x_3)$
	$(2\omega_1 + \omega_2)$	$-\frac{3b}{4} x_1^2 x_2$
	$(2\omega_1 - \omega_2)$	$\frac{3b}{4} x_1^2 x_2$
	$(2\omega_1 + \omega_3)$	$-\frac{3b}{4} x_1^2 x_3$

<u>TABLE I</u> (con't)

Order of Distortion	Component Coefficients B	A
3rd	$(2\omega_1-\omega_3)$	$\frac{3b}{4}\, x_1^2 x_3$
	$(2\omega_2+\omega_1)$	$-\frac{3b}{4}\, x_1 x_2^2$
	$(2\omega_2-\omega_1)$	$\frac{3b}{4}\, x_1 x_3^2$
	$(2\omega_2+\omega_3)$	$-\frac{3b}{4}\, x_2^2 x_3$
	$(2\omega_2-\omega_3)$	$\frac{3b}{4}\, x_2^2 x_3$
	$(2\omega_3+\omega_1)$	$-\frac{3b}{4}\, x_1 x_3^2$
	$(2\omega_3-\omega_1)$	$\frac{3b}{4}\, x_1 x_3^2$
	$(2\omega_3+\omega_2)$	$-\frac{3b}{4}\, x_2 x_3^2$
	$(2\omega_3-\omega_2)$	$\frac{3b}{4}\, x_2 x_3^2$
	$3\omega_1$	$-\frac{b}{4}\, x_1^3$
	$3\omega_2$	$-\frac{b}{4}\, x_2^3$
	$3\omega_3$	$-\frac{b}{4}\, x_3^3$
	$(\omega_1+\omega_2-\omega_3)$	$\frac{3b}{2}\, x_1 x_2 x_3$
	$(\omega_1-\omega_2+\omega_3)$	$\frac{3b}{2}\, x_1 x_2 x_3$
	$(\omega_1+\omega_2+\omega_3)$	$-\frac{3b}{2}\, x_1 x_2 x_3$
	$(\omega_1-\omega_2-\omega_3)$	$-\frac{3b}{2}\, x_1 x_2 x_3$

TABLE II

FREQUENCY (Hz)	TYPICAL RANGE (g's pk-pk)
250	1-7
525-535	5-60
1000	50-270
1141	16-130
1600	75-780
4000	120-420
6300	70-1260
8000	200-1075

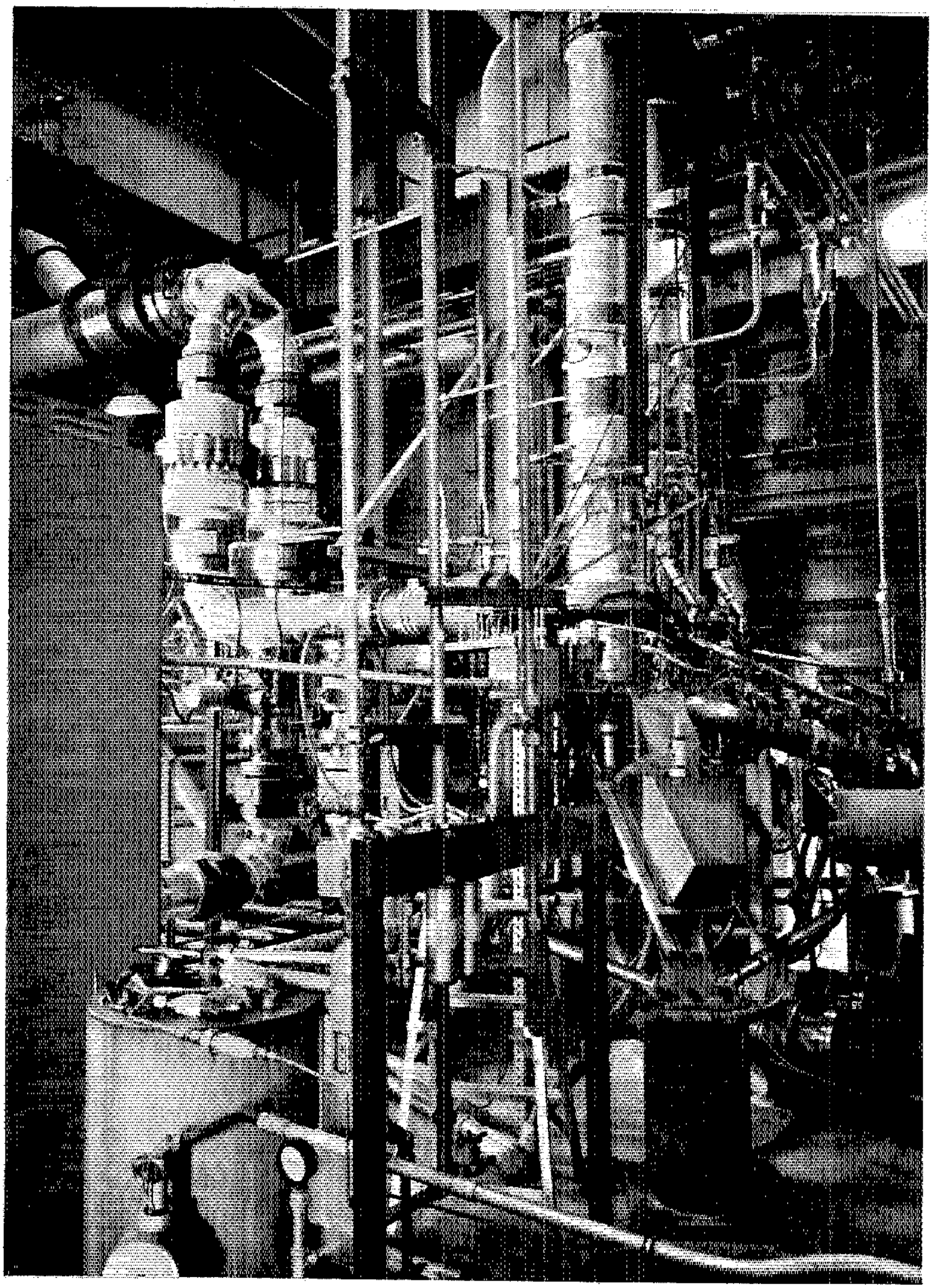


FIGURE 1. TURBOPUMP SYSTEM

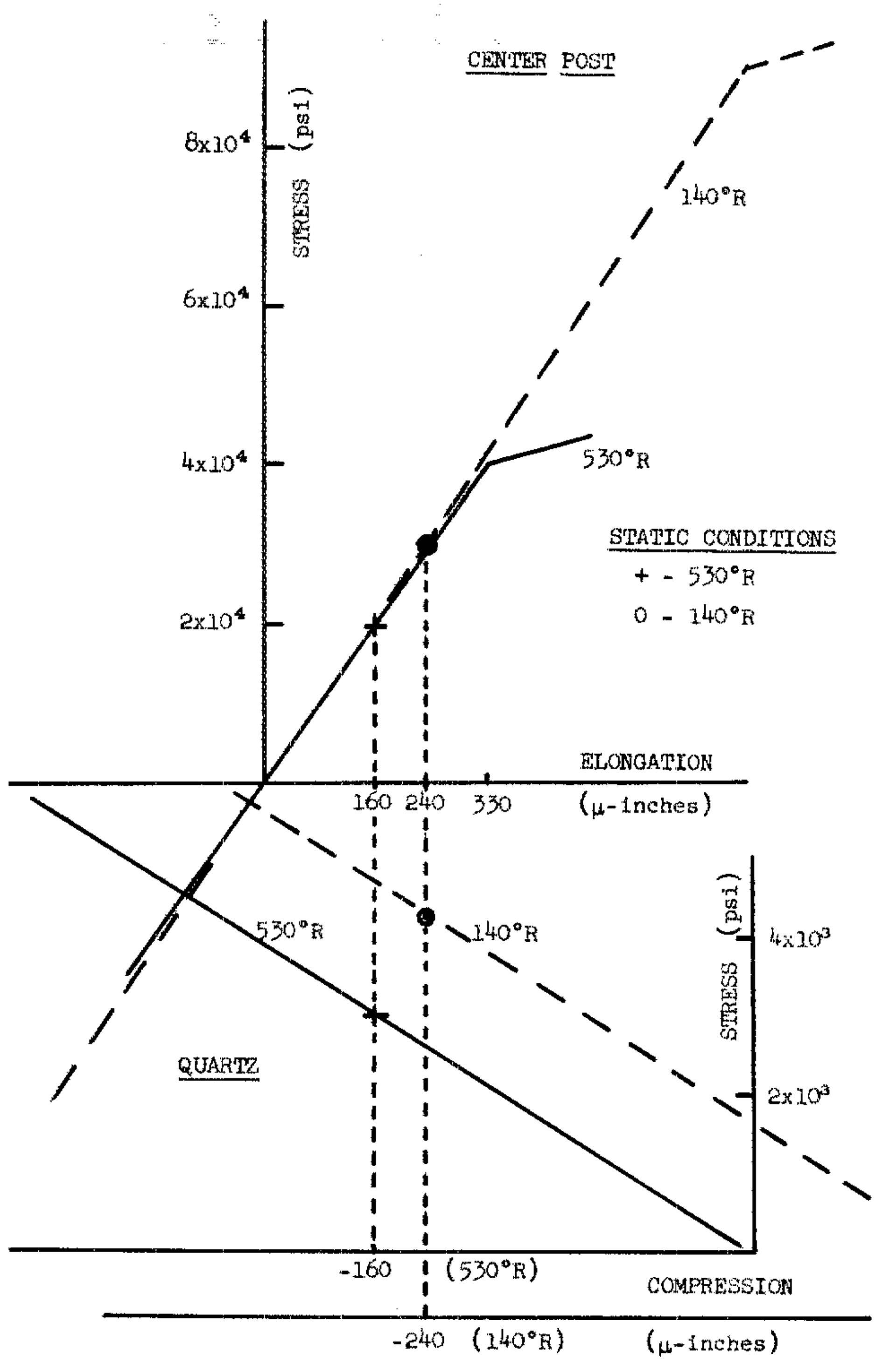


FIGURE 2.

STRESS-ELONGATION RELATIONSHIPS

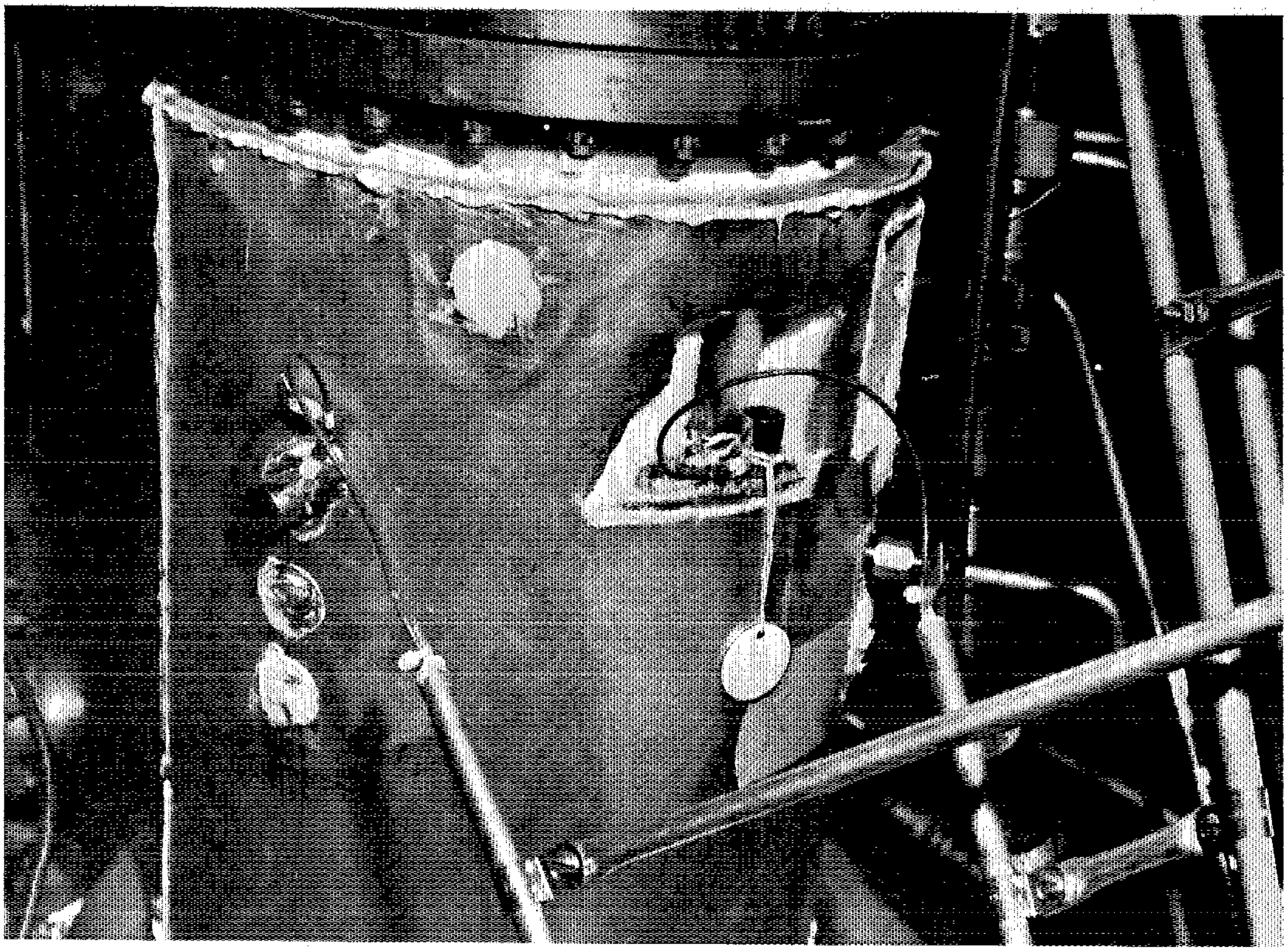


FIGURE 3. TYPICAL ACCELEROMETER INSTALLATION

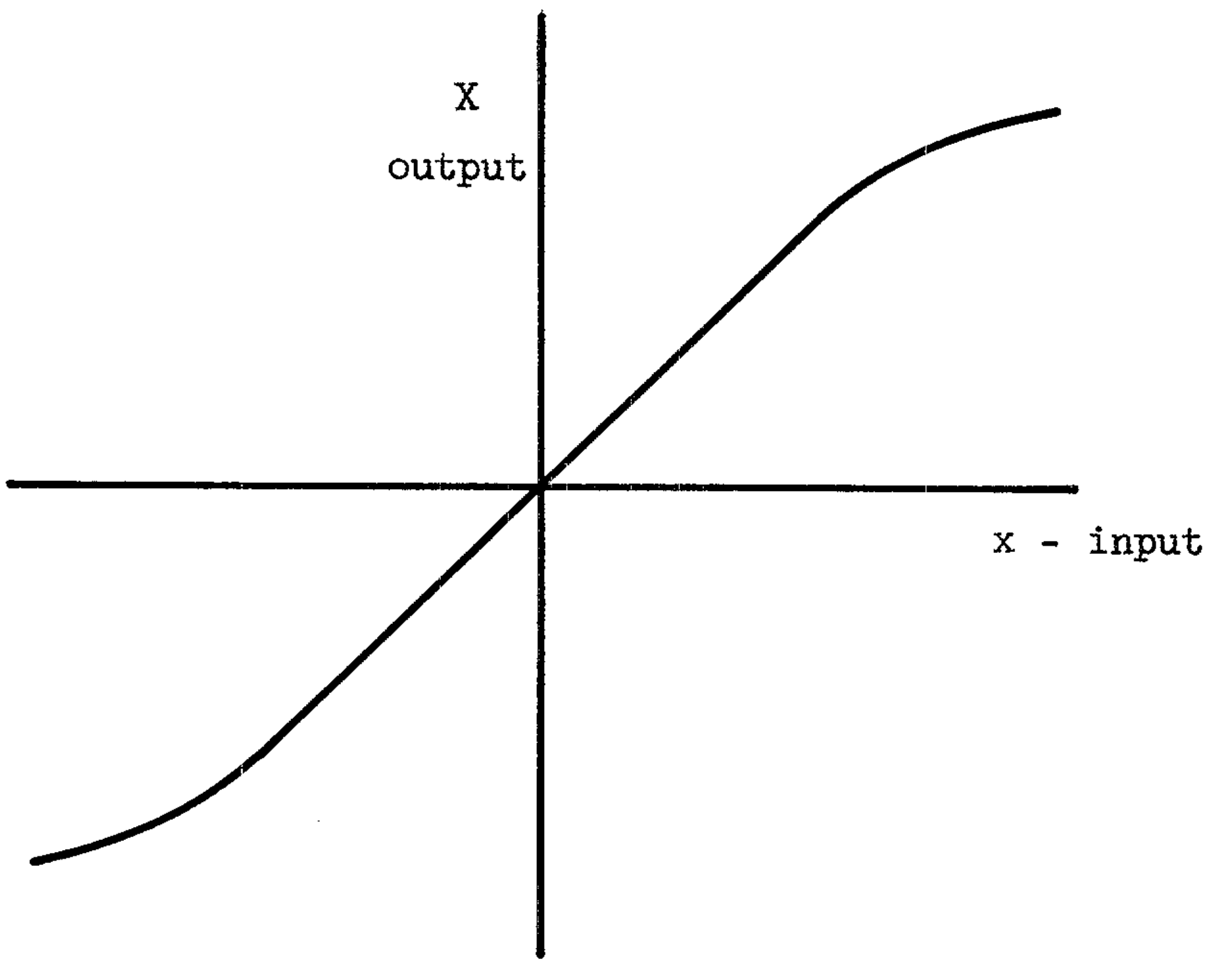
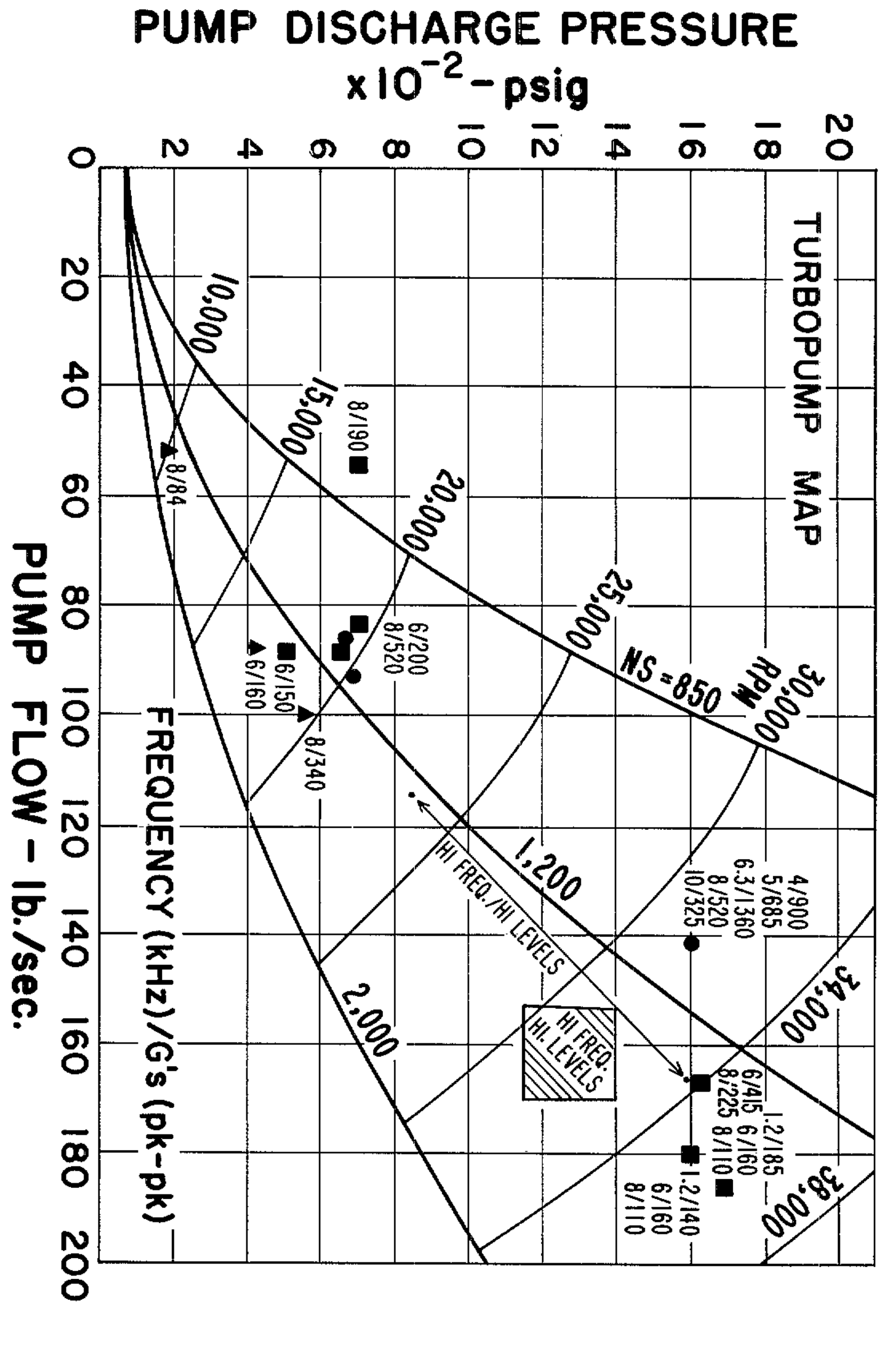


FIGURE 4.

TRANSFER CHARACTERISTIC


PUMP DISCHARGE PRESSURE
x10^-2 - psig
TURBOPUMP MAP
PUMP FLOW - lb./sec.
FREQUENCY (kHz)/G's (pk-pk)
10,000
15,000
20,000
25,000
30,000
RPM
34,000
38,000
NS=850
1,200
2,000
HI FREQ./HI LEVELS
HI FREQ.
HI. LEVELS
8/190
8/84
6/200
8/520
6/150
6/160
8/340
4/900
5/685
6.3/1360
8/520
10/325
1.2/185
6/160
8/110
6/415
8/225
1.2/140
6/160
8/110

DYNAMIC RESPONSE ANALYSIS OF SHOCK INSTRUMENTATION SYSTEM

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1. ABSTRACT

Selected instrumentation systems used by AFSWC in the "High Explosive Simulation Technique" tests are evaluated from their response to static, sinusoidal and transient inputs. Transfer functions are calculated from the transient data and the gain and phase response information obtained from the transfer function is compared to empirical data. The results of the study will be used in the future as a basis for a data correction study and as a guide in establishing procedures for future dynamic calibration.

2. OBJECTIVES

2.1 The objectives of this study were to:

A. Determine the dynamic performance of shock instrumentation.

B. Demonstrate the feasibility of obtaining valid transfer functions from transient data.

C. Develop procedures for dynamic calibration of future systems.

3. INTRODUCTION

AFSWC is involved in studying soil motion due to a simulated nuclear blast which employs high explosives to generate a shock wave. The instrumentation used to obtain data is embeded in the structure under test or in the soil surrounding the structure. Some of the transducers are placed months before the test. They must therefore survive a moist and highly corrosive environment as well as withstanding the high shock conditions. However, data acquired in a recent test indicates that some of the information may have been distorted by the dynamic limitations of the measurement systems. This distortion and its source are the underlying reasons for this report and for a proposed indepth analysis of the total system.

Although several types of measurement systems are used in HEST tests, only three were selected for evaluation. The systems selected were those designed to produce information which is descriptive of shock wave pressure, velocity and acceleration. Each of these systems can be depicted by a block diagram configuration such as is illustrated in Figures 1 and 2.

The overall study of these systems involves two contractors and an inhouse testing program. A contract was awarded to IIT Research Institute (IITRI) for a study of the soil to transducer interaction. Their report will contain soil to transducer transfer functions derived analytically and recommendations for tests of existing and future systems. The other contract was awarded to Agbabian-Jacobsen Associates (AJA). Its purpose was to support the AFSWC inhouse analysis of the three systems mentioned earlier. AJA will provide AFSWC with a literature search of techniques for dynamic calibration of instrumentation systems; an analysis of the test procedures and results of the inhouse testing program; a recommendation of procedures for future dynamic calibration, and a documentation of the entire program. The inhouse effort was primarily directed towards conducting the necessary tests, obtaining valid transfer functions and using the transfer functions to establish data correction procedures.

4. TRANSFER FUNCTION EVALUATION

In obtaining transfer functions, two main approaches were utilized. The first is the classical approach of applying a sinusoidal signal to the input of the system under test and then measuring the system amplitude and phase response as the input frequency is varied. For many electrical systems this method is adequate. However, for many mechanical systems, the difficulties involved in generating high frequency input signals make the method insufficient.

The second approach was to apply a known transient signal (e.g. step, pulse, etc.) to the input of the system under test and then measure the resulting system response. Although some difficulties may arise in accurately measuring such a transient input, it is more often than not mechanically feasible to generate it. Thus, going on the assumption that the input and output can be measured, it is possible to obtain the intervening transfer function.

The transfer function approach to dynamic analysis of physical systems cannot be applied indiscriminately. There are certain limitations as to its usefulness. The primary restriction is that the system under consideration be linear. A system that is not linear may be analyzed by utilizing describing functions, by breaking the system into piecewise linear segments, or by utilizing a computer aided parameter optimization scheme. Also, before a single input - single output transfer function can be used, it must be ascertained that the system is not multi-input-multi-output nor does it have cross coupling effects present.

5. DERIVATION OF THE TRANSFER FUNCTION FROM THE TRANSIENT RESPONSE

Since the method of applying a sinusoidal input to the system in order to determine the transfer function is self explanatory and easy to use, it will not be explained in this section. The method of transient response evaluation is, however, more difficult to apply and will thus be the subject of the proceeding discussion.

Several methods are available for evaluating a system transfer function from the transient input and transient output. One of the more lucrative methods to use would be a computer-aided parameter identification scheme. Several unavoidable problems made it unfeasible to use the digital computer. Thus, a method was sought which would allow Laplace transformations to be used in conjunction with an "at the desk" method of calculating the transfer functions. The following section is a discussion of such a method.

5.1 Slope Method of Laplace Transforms (Reference #1)

In the Slope Method of Laplace transforms the time function to be transformed is approximated by a series of straight line segments as shown in Figure 3. (Obviously, the larger the number of segments drawn, the more accurate the approximation, but, subsequently, the larger the number of calculations involved.) Once the segments are drawn, each individual slope and time coordinate for the point of intersection with the previous line segment are measured. The straight line approximations are then broken up into the components as shown in Figure 3.

Each component in Figure 3 is thus a ramp of known slope and delay. (The delay corresponds to the time coordinate.) The Laplace transform of a delayed ramp is given (Ref. #1) by

$$\mathcal{L}\left\{\begin{matrix}\text{Delayed}\\ \text{Ramp}\\ \text{Function}\end{matrix}\right\} = \frac{A_i}{S^2}\, e^{-St_D} \qquad (2)$$

where A is the slope and t_D is the delay time. By applying the principle of superposition to linear systems, the transform of the function given in Figure 2 is the summation of the Laplace transforms of the components shown in Figure 3.

$$\mathcal{L}\left\{ f\ (t) \right\} = \sum \frac{A_i}{S^2}\, e^{-St_{Di}} \qquad (3)$$

Given Equation (3) as the output of the system of interest, it is possible to derive the describing transfer function simply by operating upon the system input. The operation consists of defining the input in the Laplace domain and then dividing it into the system output, i.e. Equation (3). The result is the familiar output divided by input relationship which is used to define a transfer function. To obtain the phase and frequency response of the system, it is only a matter of substituting jw for s in the transfer function and then calculating the resultant complex quantity as w(w=2πf) is varied through the frequency range of interest.

6. TESTS

Now that a method of analyzing transient data has been selected, we can turn our attention to the techniques used to obtain the data necessary to calculate the required transfer functions. The first step in the testing program was to decide what loading conditions would be used and what other constraints would be placed on the system. The information derived from these tests was therefore assumed valid only for the conditions under which the system was tested.

6.1 Record-Reproduce System

The first series of tests were conducted on the record-reproduce system shown in Figure 4. The VCO, discriminator and filter can be chosen for a desired bandwidth. For this test, a 16KHz center frequency $\pm$ 1KHz bandwidth VCO was used and the low pass output filter was chosen at 1 KHz.

Two series of signals were applied to the system and recorded on magnetic tape. The first series of signals were step pulses from a Data Pulse Generator Model 101. The amplitude of the pulser was chosen such that the system remained in its linear range of operation. Sinusoidal signals were then applied (H. P. Signal Generator Model 241A) again fixing the amplitude for linear operation. The tape was sent to AFSWC's Data Reduction group for playback.

Figure 5 shows a step input after it is passed through a 1KHz, seven pole Bessel filter and is digitized at a rate of 10 K SPS. Due to the low sampling rate, the curve is already a series of straight lines segments. Using these segments, to approximate the response, the transform technique described previously was used to calculate the Laplace transform of the signal. The input is taken to be a perfect step so its transform is $\frac{A}{S}$. Dividing the transform of the output by the transform of the input, we obtain the system transfer function.

$$G_R(s) = \frac{1}{8.5S}\left[1 + 5e^{-.1S} + 9e^{-.2S} - 7e^{-.5S} - 8e^{-.6S} - 5e^{-.7S} - e^{-.8S}\right]$$

By substituting jw for S and calculating the transfer function for various values of w, we obtain the frequency characteristics of the system. Figures 6 and 7 show the gain and phase response obtained from the transfer function compared to the theoretical data of the Bessel seven pole filter. The gain response obtained experimentally from the sinusoidal test is also plotted in Figure 6. It appears that the response of the Record-Reproduce System is approximately the response of the Bessel filter.

6.2 Pressure Tests

Several types of pressure gages were used in HEST V. However, since the Norwood pressure gage Model 111 was used for most measurements, it was chosen for evaluation. This gage is of the four active leg strain-gage type with a range of 500 psi.

The static calibrations were performed several times from 0 to 500 psi and back again using a dead weight tester. The output of the gage was recorded on a digital voltmeter and a stable electronic power supply was used for the excitation voltage. The gage was also calibrated using compressed air controlled by a variable pressure regulator. Pressures were read on a pre-calibrated "Heise" Bourdon type, pressure gage. The output was read on a digital voltmeter and a six volt dry cell battery provided the excitation. The outputs of both calibrations gave consistent results.

For dynamic calibration, an input pressure step was applied by an AFSWC version of the Dynamic Pressure Transducer Calibrator, D-142, designed by the Metrology Engineering Center, Naval Plant Representative in Pomona, California (reference 2 and 3). The apparatus (refer to Figure 8) employs a dropping mass to rapidly open a poppet valve thereby producing a fast rising pressure step.

The calibrator can be used in two modes. In mode 1, a high pressure pulse with a rise time of about 100 micro seconds can be generated. This mode provides a capability for calibration of low and intermediate frequency transducers and provides an excellent means of determining creep effects in high frequency transducers. In the second mode, a shock wave adapter tube is utilized such that the calibrator has the characteristics of a shock tube. In this mode, the calibrator is capable of generating a step pressure pulse with a rise time (10 - 90%) of about 10 micro seconds.

One disadvantage of the calibrator is that the input signal, which cannot be monitored as a pulse, is applied to the gage under test. A common method of overcoming this problem is to determine the characteristics of the calibrator by using a transducer whose characteristics are known and whose response is much better than the response of the gage under test. The reference gage selected for this series of tests was a modified

Susquehanna Instruments pressure gage, model ST4. Sufficient tests on the calibrator were performed to establish the signature of the input waveform in both modes 1 and 2. Figures 9 and 10 show the pulse output of the D-142 calibrator when nitrogen is used as the gas media. A pulse of about 2 micro seconds rise time can be generated when helium is used as the media.

For the purposes of this study, the principle value of the shock tube configuration is excitation and identification of the main resonant frequency of the transducer under test. Figure 11 shows the ringing frequency of a Norwood Pressure transducer Model 111 due to a shock wave. Photographs taken at faster sweep speeds show the ringing frequency to be approximately 30 KHz and the overshoot to be approximately 50%. This data along with the rate of dampening is sufficient information to plot an approximate frequency response of the transducer. It should be noted that more exact methods exist to measure the ringing frequency of a transducer. The ringing signal can be recorded on a transient data recorder and later played continuously into a spectrum analyzer or the signal could be recorded on a wide band tape recorder and its spectrum determined by data reduction techniques.

6.3 Acceleration

Two CEC Model No. 4-202-0001 and two Statham Model A-69-TC accelerometers were subjected to dynamic calibration tests. Static calibrations were performed in a Schaevitz, type M2A Rotary Exciter (centrifuge), with runs in both directions at various bridge excitations. The power supply and bridge balance were provided by a B & F Instruments Model 24-AM-25 Signal Conditioner. Read out employed a Hewlett Packard Model 2010-B "Dymec" Data acquisition system.

Dynamic calibration consisted of frequency response testing of the bare accelerometer at several g levels from 50 Hz to 2.5 KHz on an Unholtz-Dickie Model 100 shaker. Using the same shaker, tests were also performed on the accelerometer-amplifier combination with the amplifier sitting on a workbench. Figure 12 shows the results of the tests performed on a Statham gage.

An attempt was made to obtain the frequency characteristics from transient data. Single pulse, shock input tests were performed using a Monterey Research Model No. 2424 "Impac" drop test machine. However, one of the pitfalls of using transient signals to obtain frequency response was encountered in the analysis of these tests. Namely, the input transient signal was not fast enough to excite the higher frequencies of the system. Transient inputs with a faster risetime were later applied with a HYGE impac machine, but the data from these tests contained too much noise after the pulse to attempt a manual calculation of the transfer function.

6.4 Velocity

The velocity gages evaluated were Sparton Southwest, Models 601V and 601H. Only the 601V was tested in this program. The velocity gage (refer to Figure 12) is basically an integrating accelerometer with a pendulous mass suspended in a highly viscous fluid. The gage is designed so that the mass is damped by the viscous characteristics of the fluid and also by the restriction of the fluid flow within the mass-fluid housing. The displacement of the mass is sensed by a variable reluctance transformer, which produces an output proportional to velocity.

Two series of tests were performed on this gage. The first test is a "1g turnover" test which basically consists of placing the gage in a horizontal position, so that the spring exerts a downward force on the pendulum. A powerful magnet is used to pull the pendulum to its uppermost position. When the magnet is removed, the force of gravity and the one gravity force of the spring act on the pendulum to give it a two gravity acceleration in a downward direction. The output is recorded on a CEC Type 5-124 Recording Oscillograph. Since the velocity is known as a function of time, and the output signal is known as a function of time, the output voltage can be related to velocity.

The second series of tests utilized the Monterey Research Model No. 2424 "Impac" drop test machine. The velocity gage was dropped from various heights to give it an impact of acceleration each time the table decelerated to a stop. The output of the gage was fed through 1000 feet of Times cable to the CEC Model 118 discrimination and its output was recorded on magnet tape. See Figures 2 and 4 for the system configuration. A crystal accelerometer mounted on the drop table was chosen as the reference gage.

Figure 14 shows the outputs of the velocity gage and reference accelerometer after they are recorded on magnetic tape and later reduced. The ramp functions that appear on the velocity trace are due to the one g acceleration of the table before and after the impact. When the velocity data is corrected for the one g fall, a step signal with a 9.5 ms risetime is obtained. The integral of the reference accelerometer signal is a step velocity signal with a risetime of approximately 2ms. Using the equation:

$$t_r^2 \text{ (observed)} = t_r^2 \text{ (input)} + t_r^2 \text{ (system)} \qquad (2)$$

we find that the risetime of the system is 9.3 ms. Using the approximation

$$fc = \frac{0.35}{t_r} \qquad (3)$$

we obtain the frequency at the half power point to be approximately 38 Hz.

The above method for determining the frequency response of a system is not exact and phase response information can not be obtained by using it, but it has the advantage of being fast and easy to use. More accurate results were obtained by calculating a Laplace transform for the system. This was accomplished by Laplace transforming the velocity and acceleration outputs and integrating the acceleration function by dividing by "S" in the Laplace domain. The transfer function for the entire system is obtained by dividing the velocity transform by the integrated acceleration transform:

$$G_v(S)=\frac{\frac{S}{32.2}\left[-3.82e^{-.003S}+1.59e^{-.0065S}+0.965e^{-.0011S}+0.265e^{-.0019S}\right]}{\left[-65-560e^{-0.001S}+1247e^{-.002S}-622e^{-.003S}\right]} \quad (4)$$

Substituting "jw" for "S" in equation (4) the gain and phase angle can be calculated as a function of w. Figure 15 shows the results of these calculations.

For these tests, a low pass filter whose response is also plotted in Figure 15 was added to the output of the CEC System D demodulator. As can be seen from the Figure the frequency at the half power point is equal to 34 Hz. The velocity systems follows the response of this filter to about 100 Hz after which it rolls off at a faster rate. The faster roll off is due to the fact that the input velocity step has a 2ms rise-time which corresponds to a 175Hz bandwidth and also to the fact that the demodulator has an internal 500 Hz filter. The phase response also follows the response of the filter at low frequencies. Figure 16 shows an example of actual data that has been corrected.

Future work in this area will include removing the external filter from the demodulator output and applying a faster pulse to the velocity gage. There is then the possibility that the frequency response will then be limited by the design of the demodulator and its internal filter. A task is in progress to allow FM recording of the velocity gage output before it is demodulated. Demodulation will be performed by the computer to increase the system bandwidth and to reduce noise. A velocity sled is also under development and will later be used for evaluation of velocity gages.

6.5 AFSWC Gage Amplifier

Approximately one half of the gages for which AFSWC is responsible use a dc operational amplifier package that was developed at AFSWC specifically for shock environments. The amplifier is designed to be located at the gage installation to amplify the output signal of the gage and to increase the signal-to-noise ratio before it is transmitted through the signal cable to the instrumentation vans. Some of the primary advantages provided by the amplifier package are listed below.

1. Isolation of input lines to the gage

2. Low output impedance (less than 1 ohm) with high output ($\pm$2.5 volts)

3. Power regulation at the gage

4. Shunt step calibration of the gage

5. Differential input

Another advantage of the amplifier is that the frequency response can be set to be compatable with the transducer with which it is mated. For most applications the bandwidth was set at 1 KHz.

The tests conducted on the amplifier included static, sinusoidal steady state, and step signals. Figure 17 shows the amplitude response of a typical gage.

6.6 Cable Test

The instrumentation cable tested was the Times Wire and Cable Company's #M1-31099, "Low Noise, 3 Pair, Instrument Cable." Each of the three pairs is shielded with aluminum - mylar tape and provided with a drain wire for shield grounding. The conductor insulation and outer pocket are a polyvinyl chloride copolyme.

Several 1000 ft. lengths of cable were tested using a Wavetek Model 111 signal generator. A sinusoidal signal was applied to the cable and the frequency was varied from 100 Hz to 100 KHz. Several terminations of the cable were tried. Below approximately 10 KHz the voltage amplitude loss was approximately the computed "I^2R" loss of the cable. Above 10 KHz, reflected waves began to act constructively and resulted in an apparent gain as shown in Figure 18. An output versus input voltage phase lag also appears at about 10KHz and increases rapidly to about 130 degrees at 100 KHz.

When the cable was terminated with the input impedance (250K) of a voltage controlled oscillator, the sinusoidal tests indicated that an impedance mismatch was present. The square wave tests confirm that the VCO does not provide a proper impedance match to the cable. The manufacture of the cable confirmed our observation. When terminated in an open circuit, 1000 ft. of the cable is approximately a quarter wavelength at a frequency of about 125 KHz.

SUMMARY

This paper represents the first of a series of efforts by AFSWC to determine the dynamic characteristics of shock instrumentation systems. The feasibility of obtaining transfer functions and correcting actual test data was demonstrated. As a side benefit, possible problem areas were discovered.

Future work in this area will consist of developing the hardware necessary to obtain valid data specifying the computer software necessary to perform transformation and correct data, and expanding this type of analysis to other types of systems such as Electromagnetic Pulse (EMP) Systems.

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INSTRUMENTATION SYSTEM FOR BRIDGE TYPE TRANSDUCERS

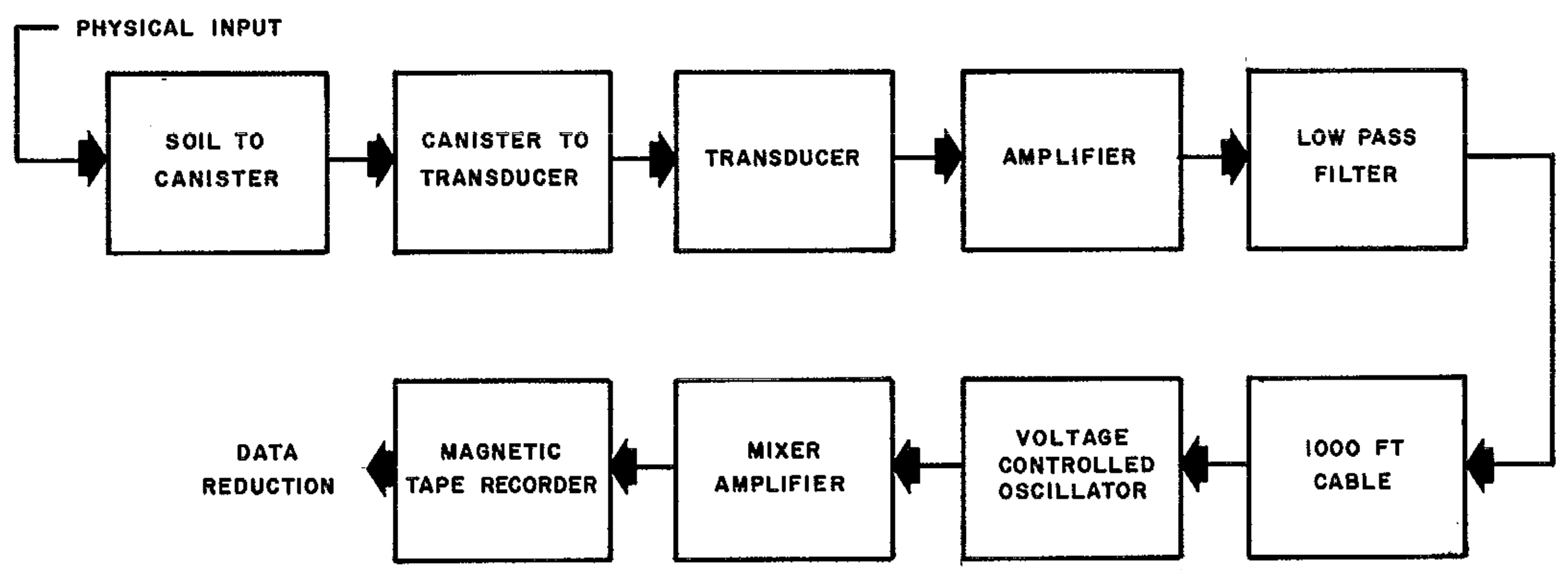


FIGURE I

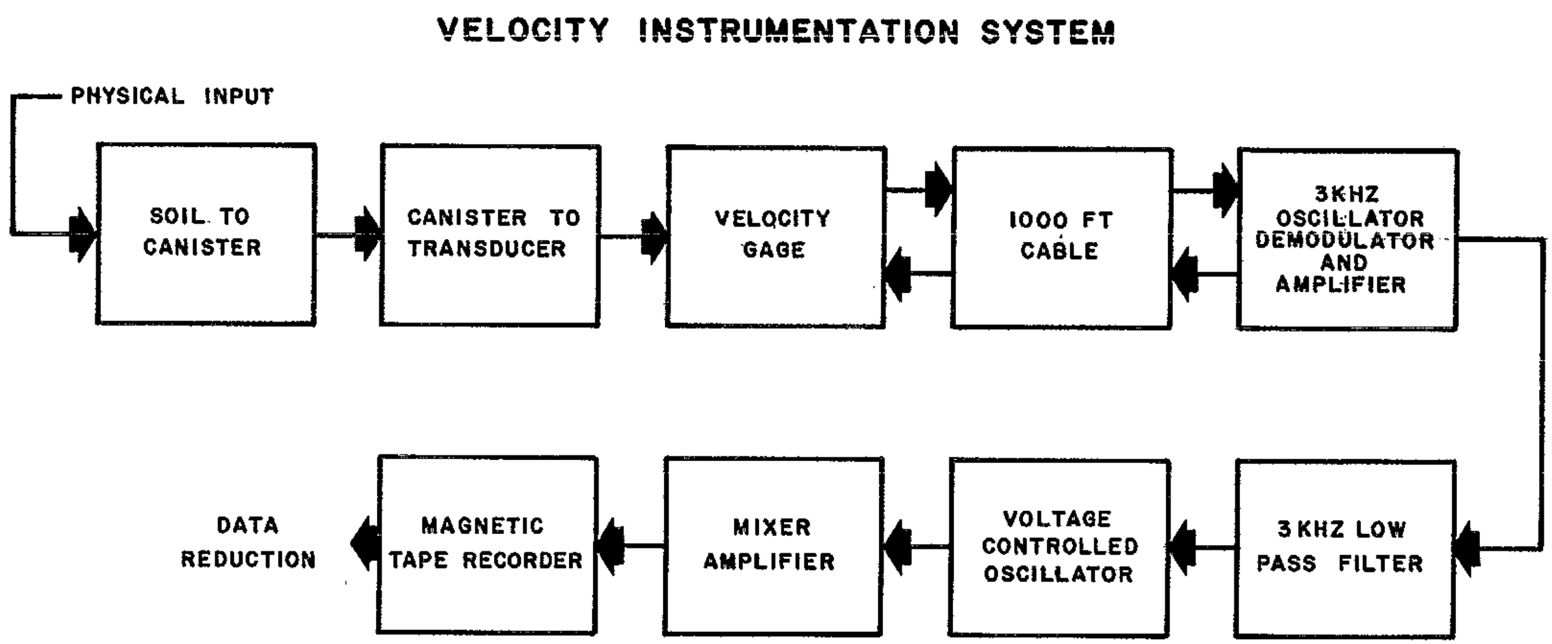
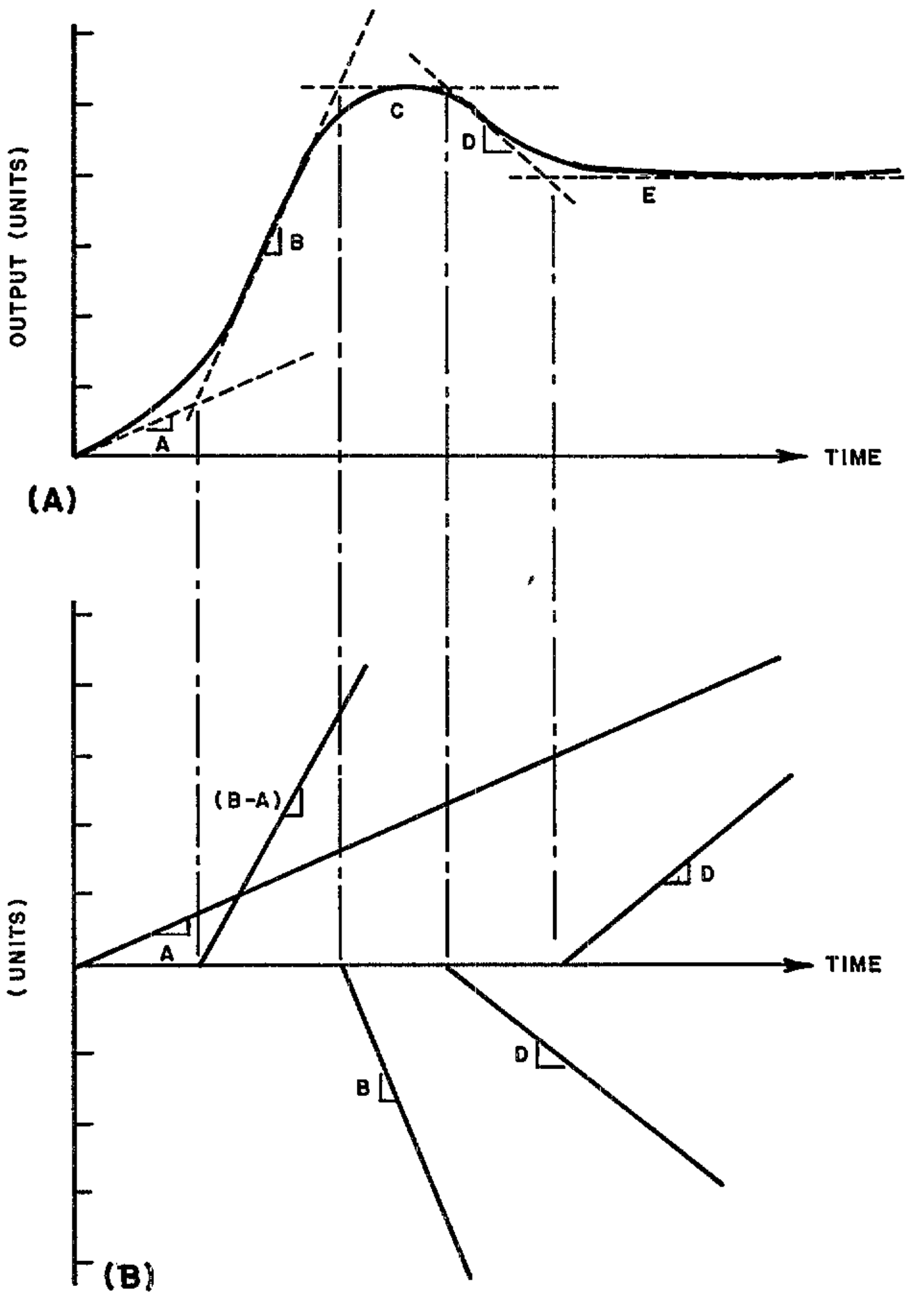

VELOCITY INSTRUMENTATION SYSTEM
PHYSICAL INPUT
SOIL TO CANISTER
CANISTER TO TRANSDUCER
VELOCITY GAGE
1000 FT CABLE
3KHZ OSCILLATOR DEMODULATOR AND AMPLIFIER
3 KHZ LOW PASS FILTER
VOLTAGE CONTROLLED OSCILLATOR
MIXER AMPLIFIER
MAGNETIC TAPE RECORDER
DATA REDUCTION

FIGURE 2

SLOPE METHOD OF LAPLACE TRANSFORM



A. STRAIGHT LINE APPROXIMATION TO SIGNAL
B. COMPONENTS OF APPROXIMATION

FIGURE 3

RECORD - REPRODUCE SYSTEM

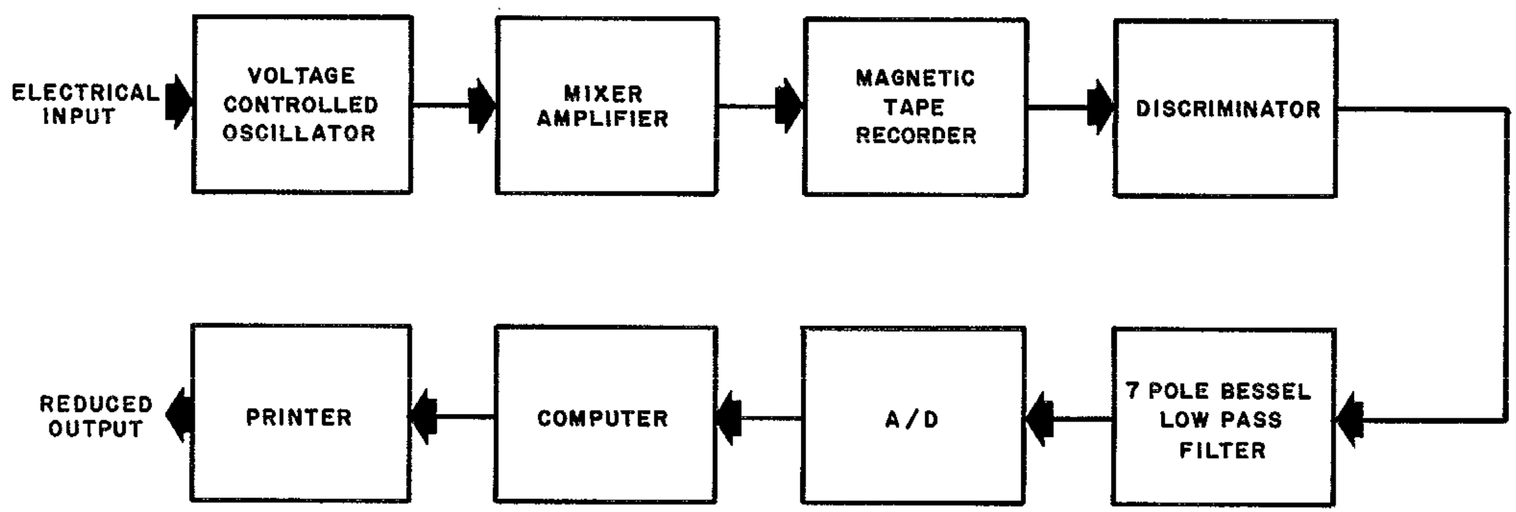


FIGURE 4

RESPONSE OF 1KHZ RECORD-REPRODUCE SYSTEM TO A STEP INPUT

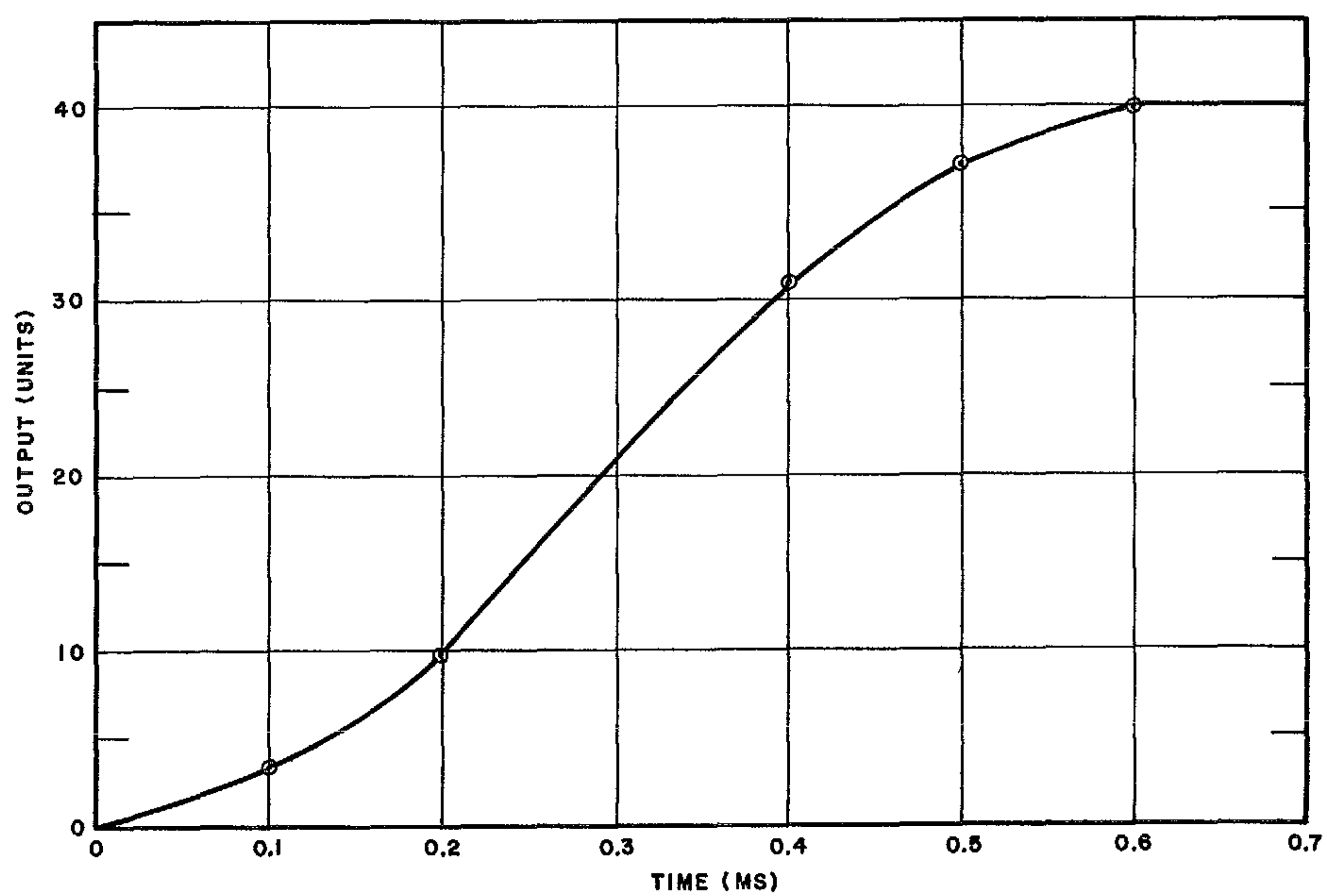


FIGURE 5

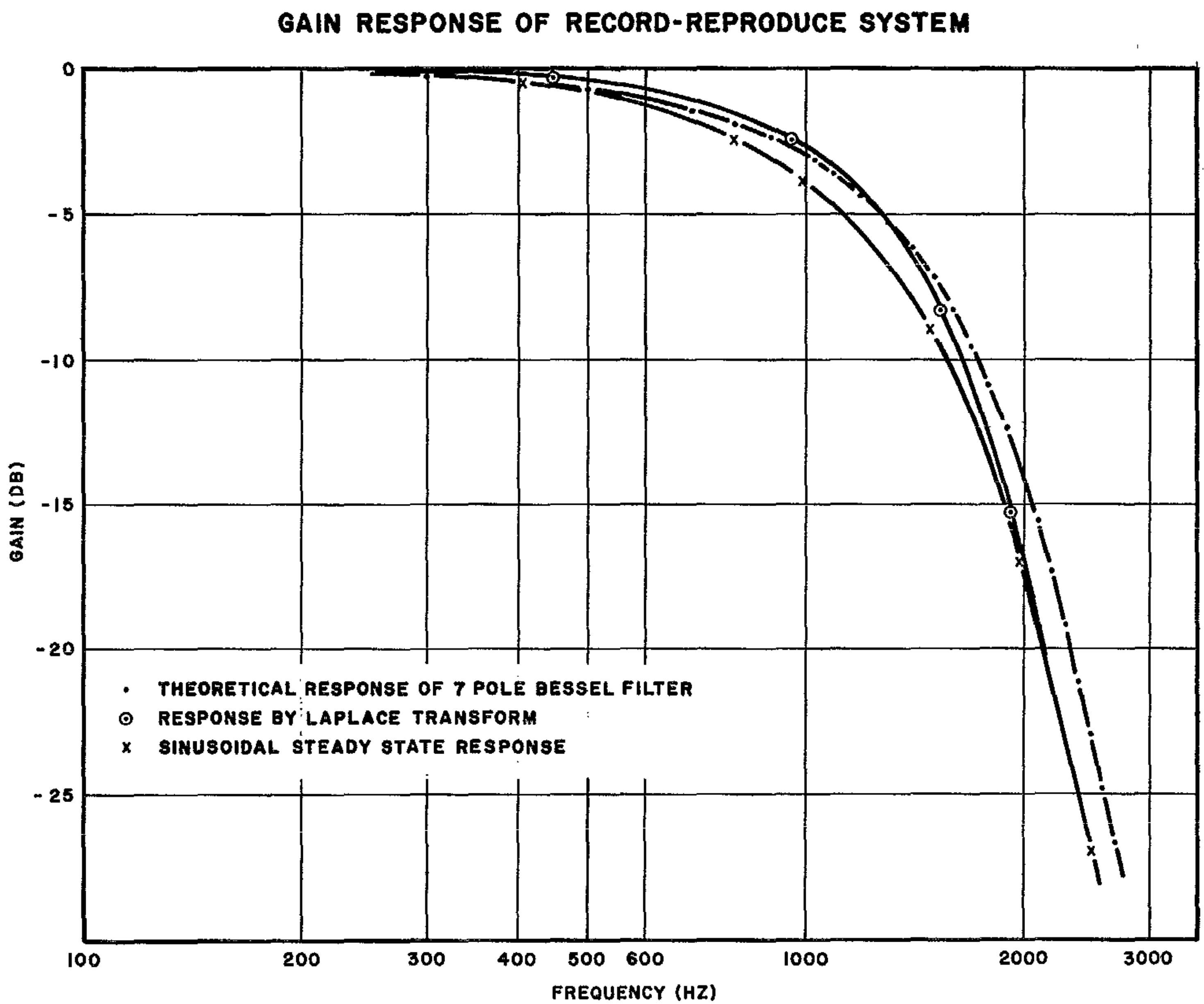

GAIN RESPONSE OF RECORD-REPRODUCE SYSTEM
GAIN (DB)
0
-5
-10
-15
-20
-25
• THEORETICAL RESPONSE OF 7 POLE BESSEL FILTER
⊙ RESPONSE BY LAPLACE TRANSFORM
x SINUSOIDAL STEADY STATE RESPONSE
100
200
300
400
500
600
1000
2000
3000
FREQUENCY (HZ)

FIGURE 6

PHASE RESPONSE OF RECORD REPRODUCE SYSTEM

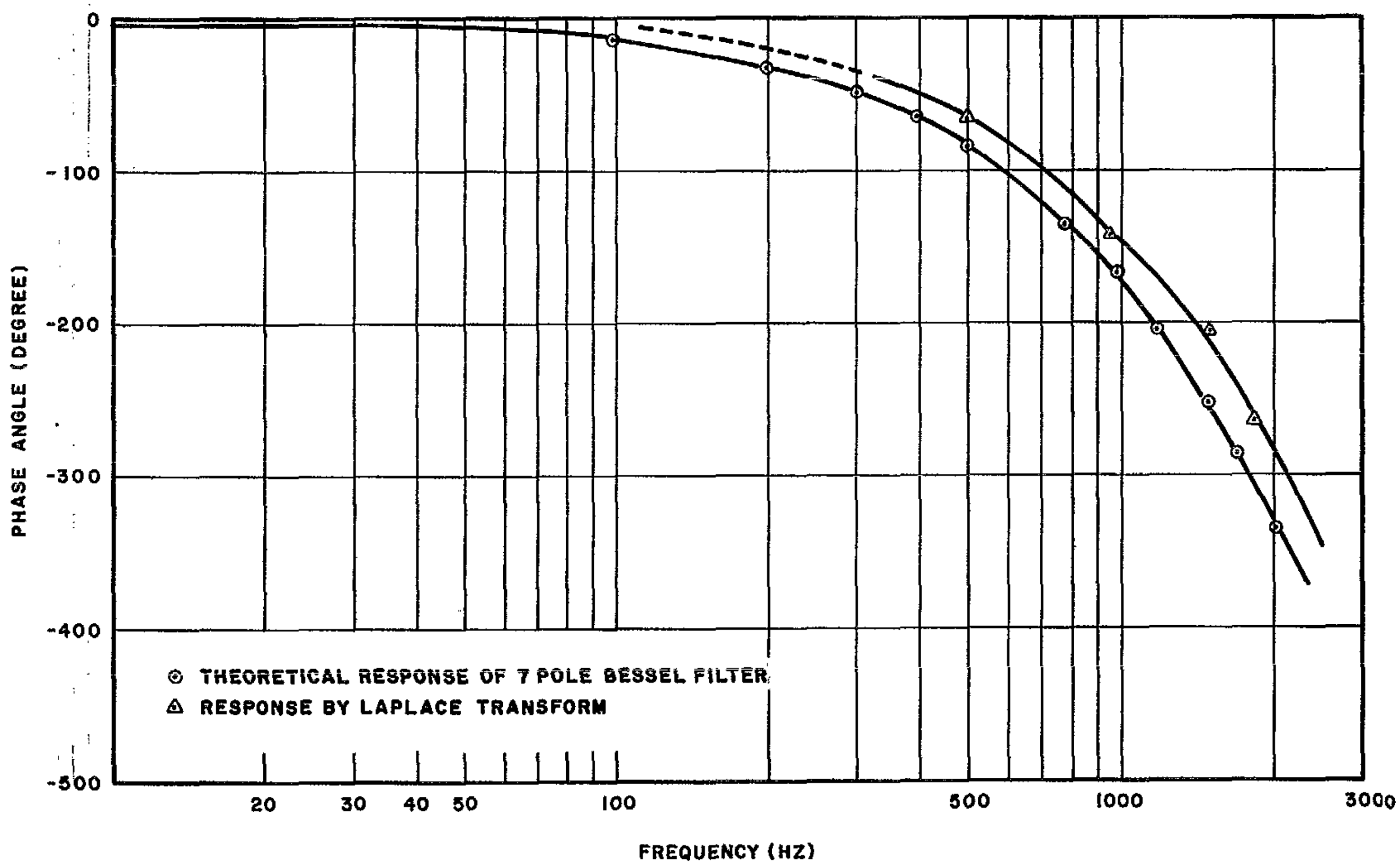
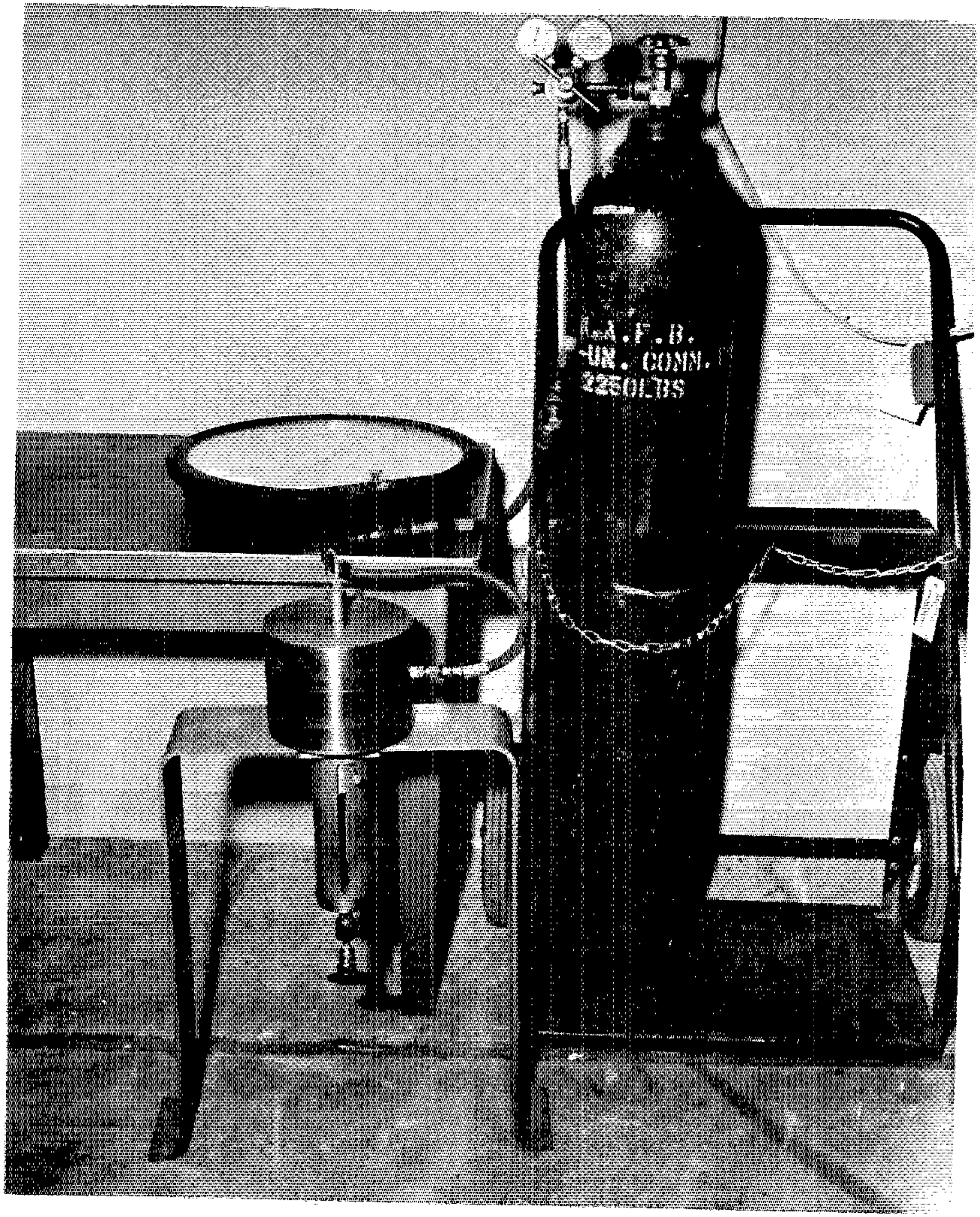


FIGURE 7



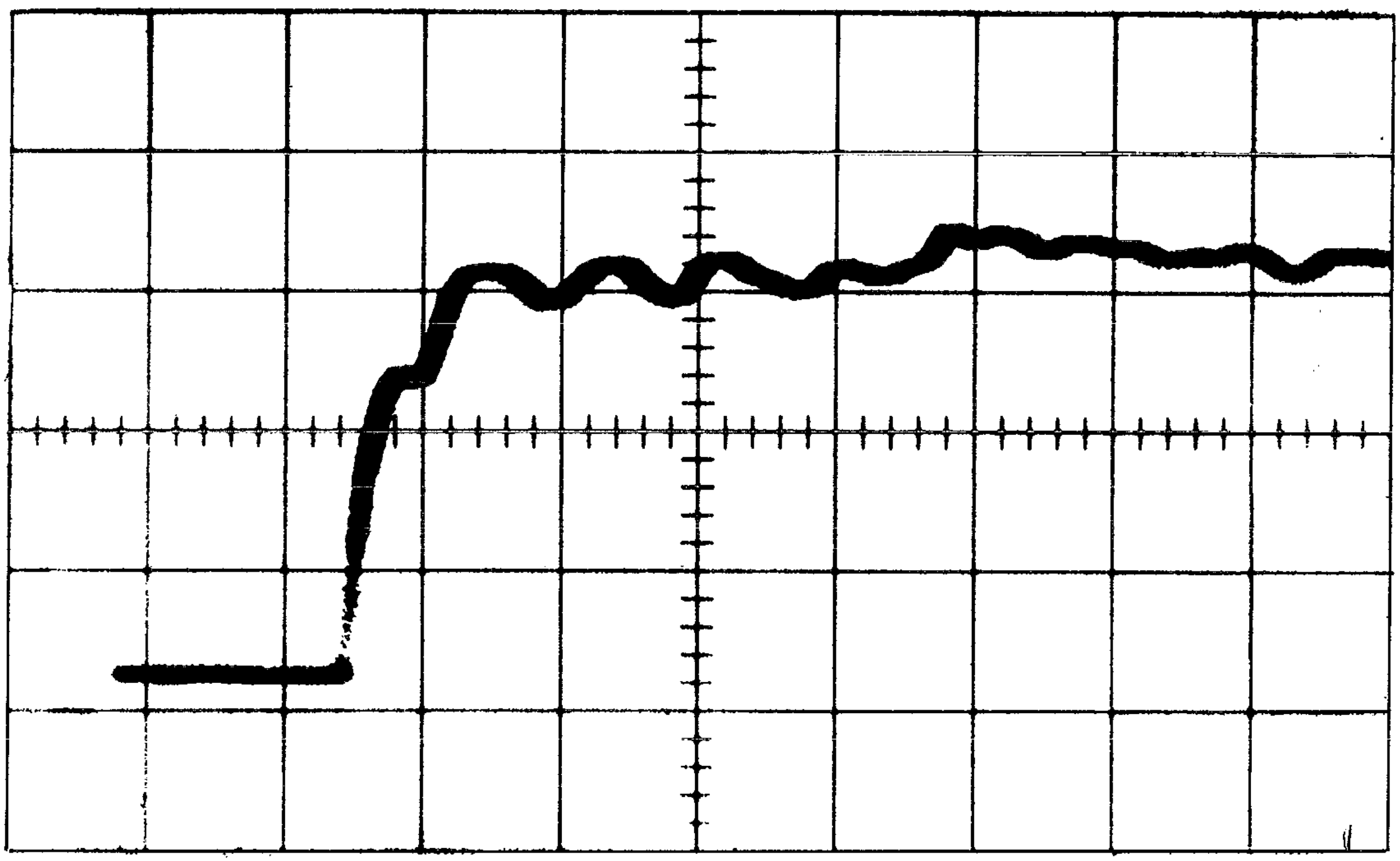


FIG. 9 RESPONSE OF ST4 TO D-142 MODE 2 INPUT (10us / cm)

RESPONSE OF HEST V PRESSURE SYSTEM TO
MODE I STEP PULSE FROM THE D-142 CALIBRATOR

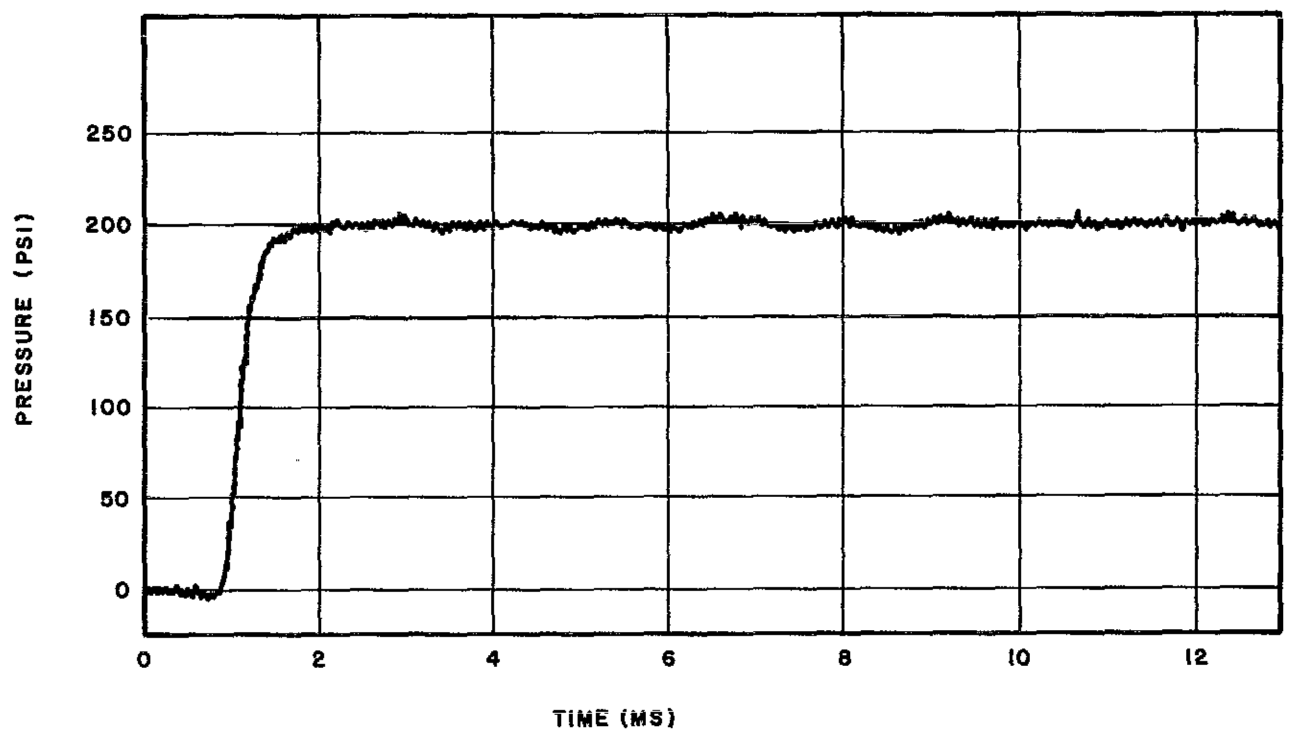
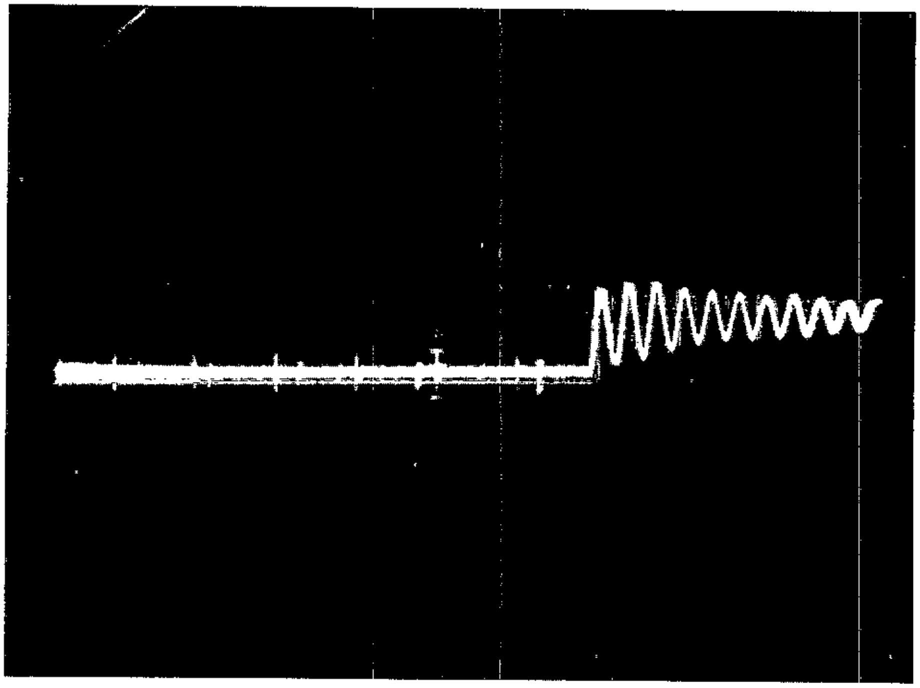


FIGURE 10



Response of Norwood Gageto -

Response of Norwood Gage to Step Input
(100 us/cm)

FIGURE 11

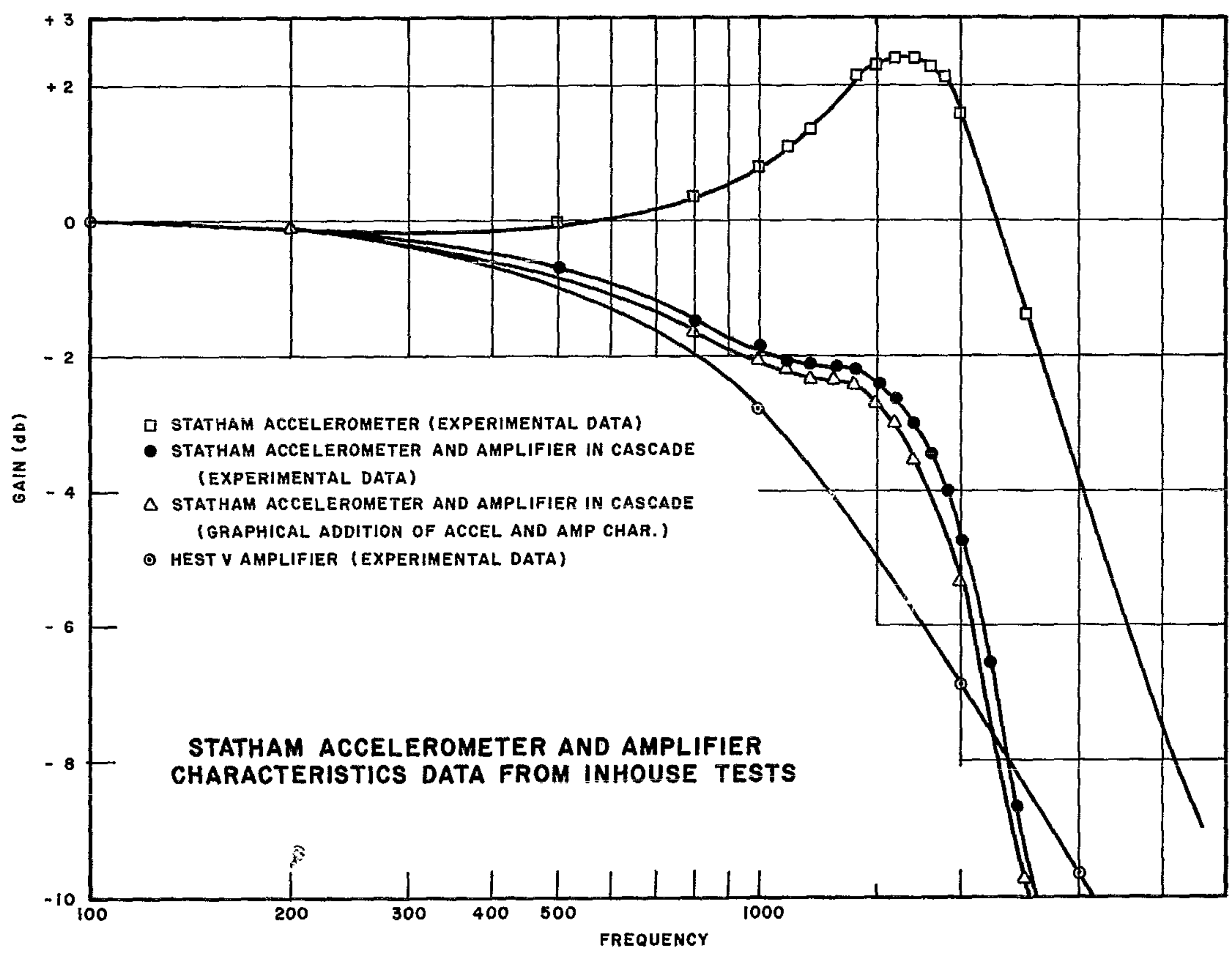

+ 3
+ 2
0
- 2
- 4
- 6
- 8
-10
GAIN (db)
100
200
300
400
500
1000
FREQUENCY
□ STATHAM ACCELEROMETER (EXPERIMENTAL DATA)
● STATHAM ACCELEROMETER AND AMPLIFIER IN CASCADE (EXPERIMENTAL DATA)
△ STATHAM ACCELEROMETER AND AMPLIFIER IN CASCADE (GRAPHICAL ADDITION OF ACCEL AND AMP CHAR.)
⊙ HEST V AMPLIFIER (EXPERIMENTAL DATA)
STATHAM ACCELEROMETER AND AMPLIFIER CHARACTERISTICS DATA FROM INHOUSE TESTS

FIGURE 12

VELOCITY GAGE (VERTICAL MODEL)

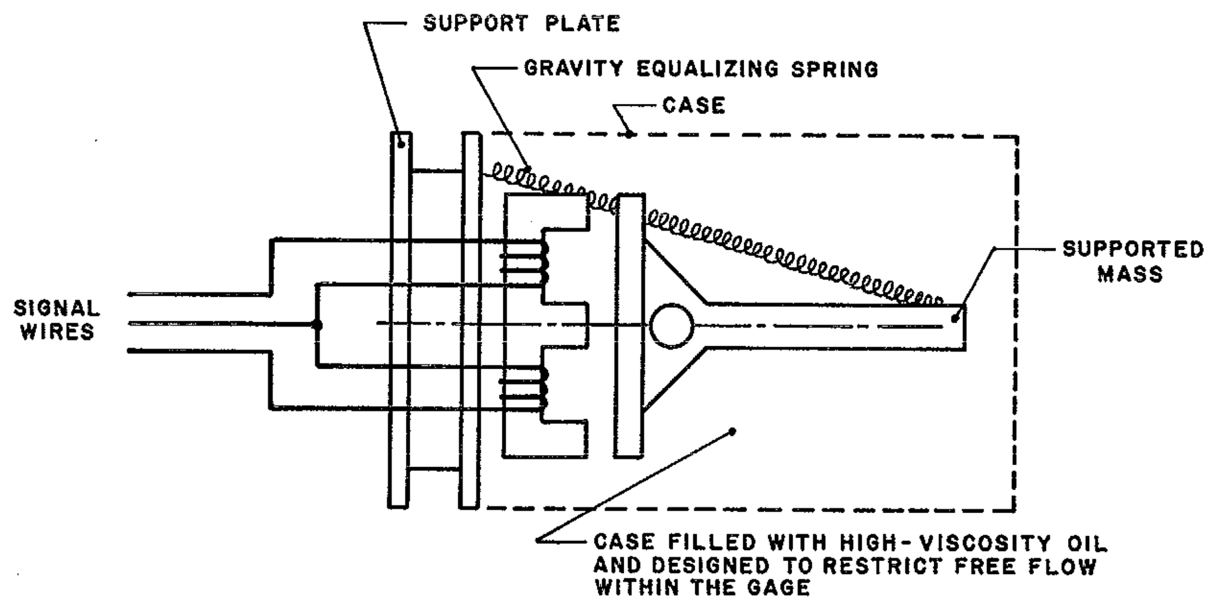


FIGURE 13

VELOCITY RESPONSE TO NON-IDEAL STEP INPUT

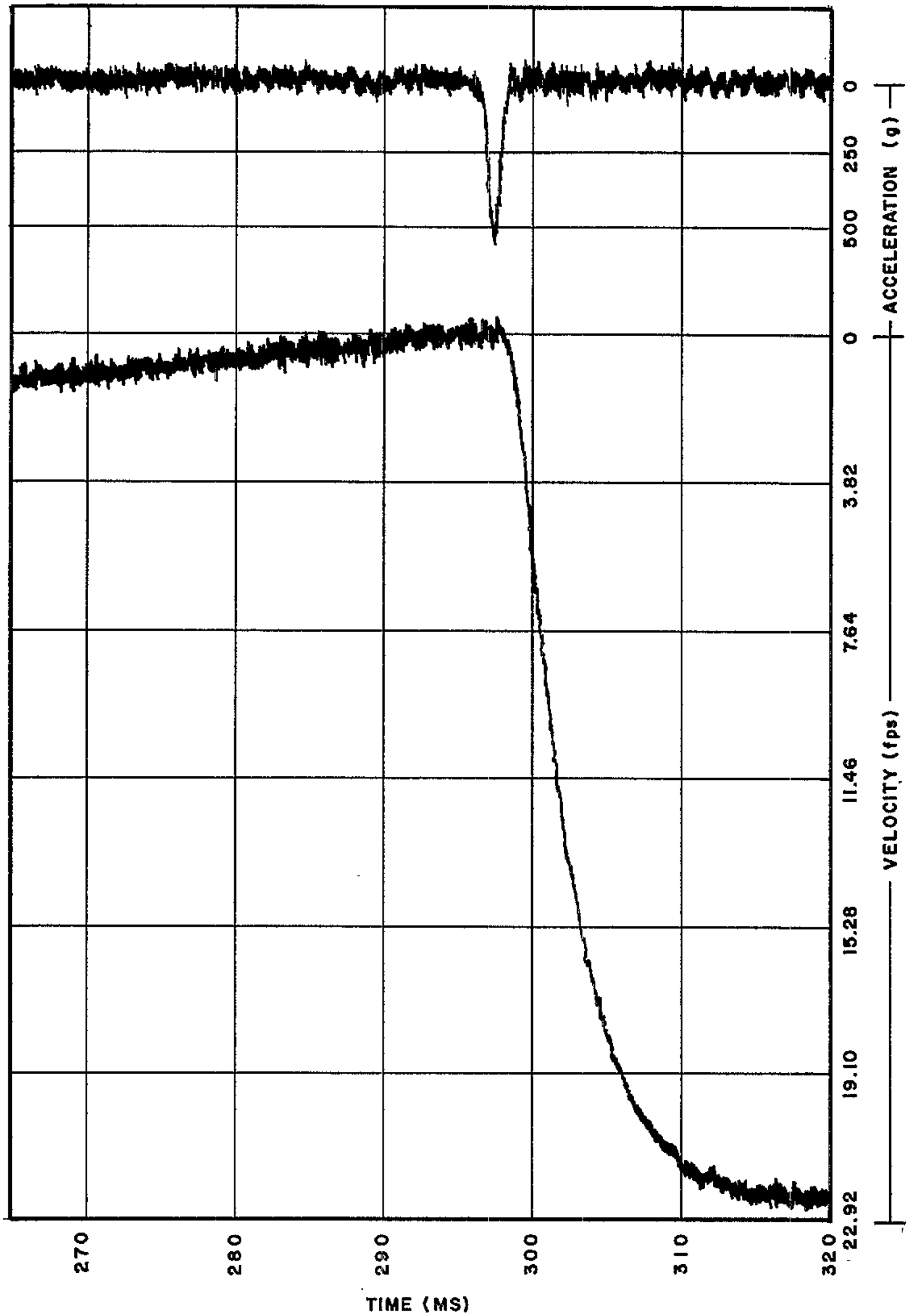


FIGURE 14

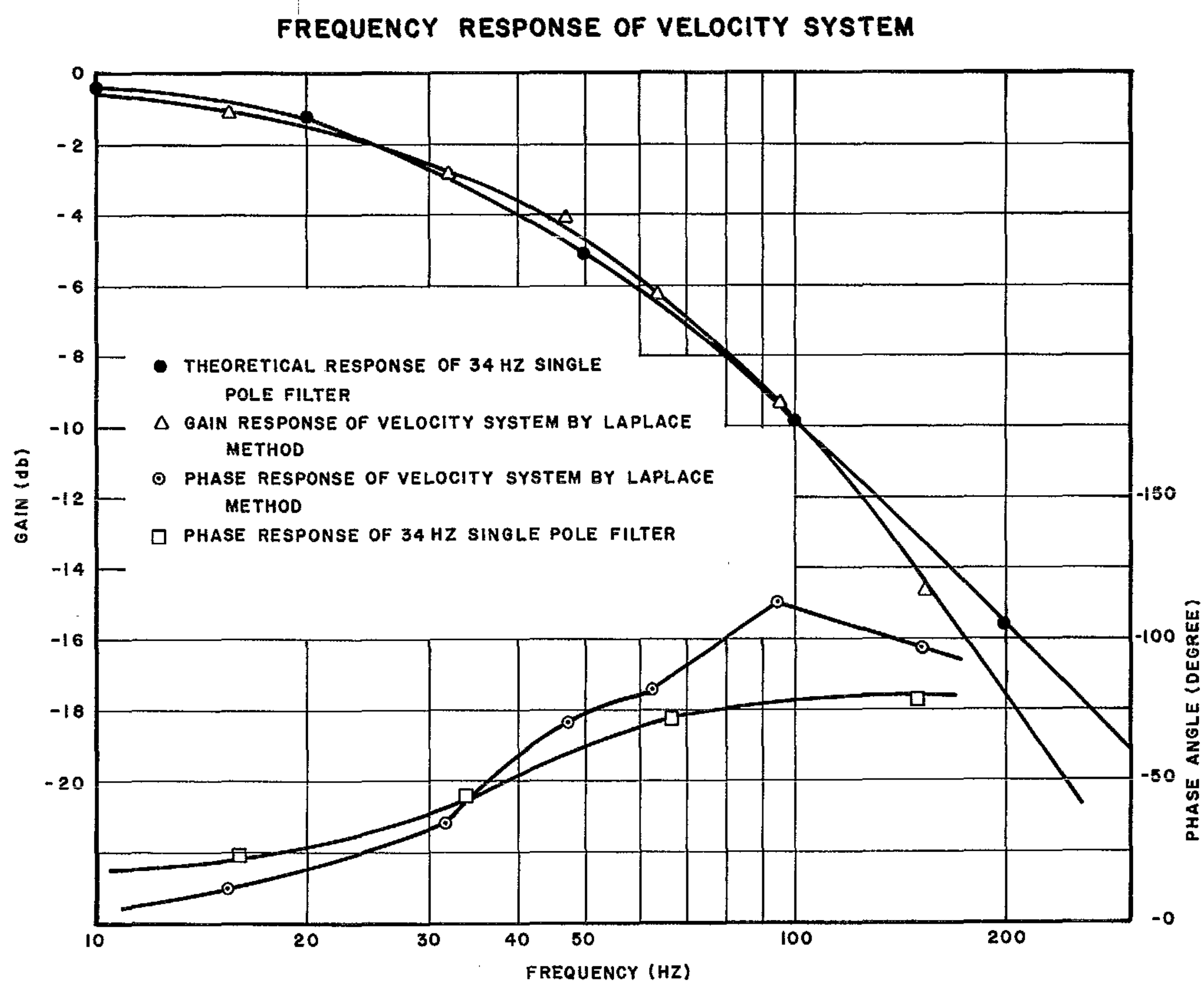

FREQUENCY RESPONSE OF VELOCITY SYSTEM
GAIN (db)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
THEORETICAL RESPONSE OF 34 HZ SINGLE POLE FILTER
GAIN RESPONSE OF VELOCITY SYSTEM BY LAPLACE METHOD
PHASE RESPONSE OF VELOCITY SYSTEM BY LAPLACE METHOD
PHASE RESPONSE OF 34 HZ SINGLE POLE FILTER
-150
-100
-50
-0
PHASE ANGLE (DEGREE)
10
20
30
40
50
100
200
FREQUENCY (HZ)

FIGURE 15

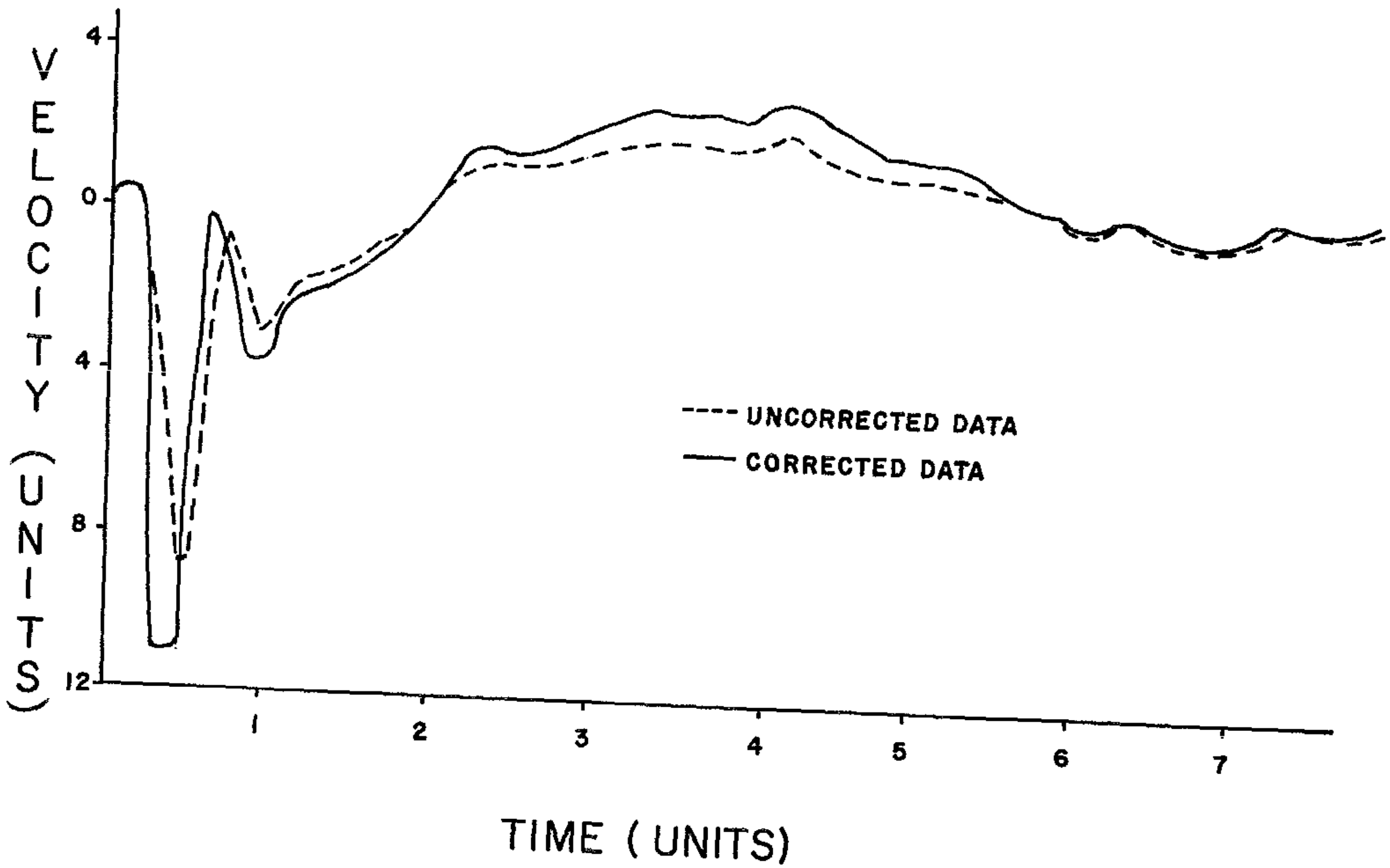

VELOCITY (UNITS)
4
0
4
8
12
1
2
3
4
5
6
7
TIME (UNITS)
UNCORRECTED DATA
CORRECTED DATA

FIGURE 16

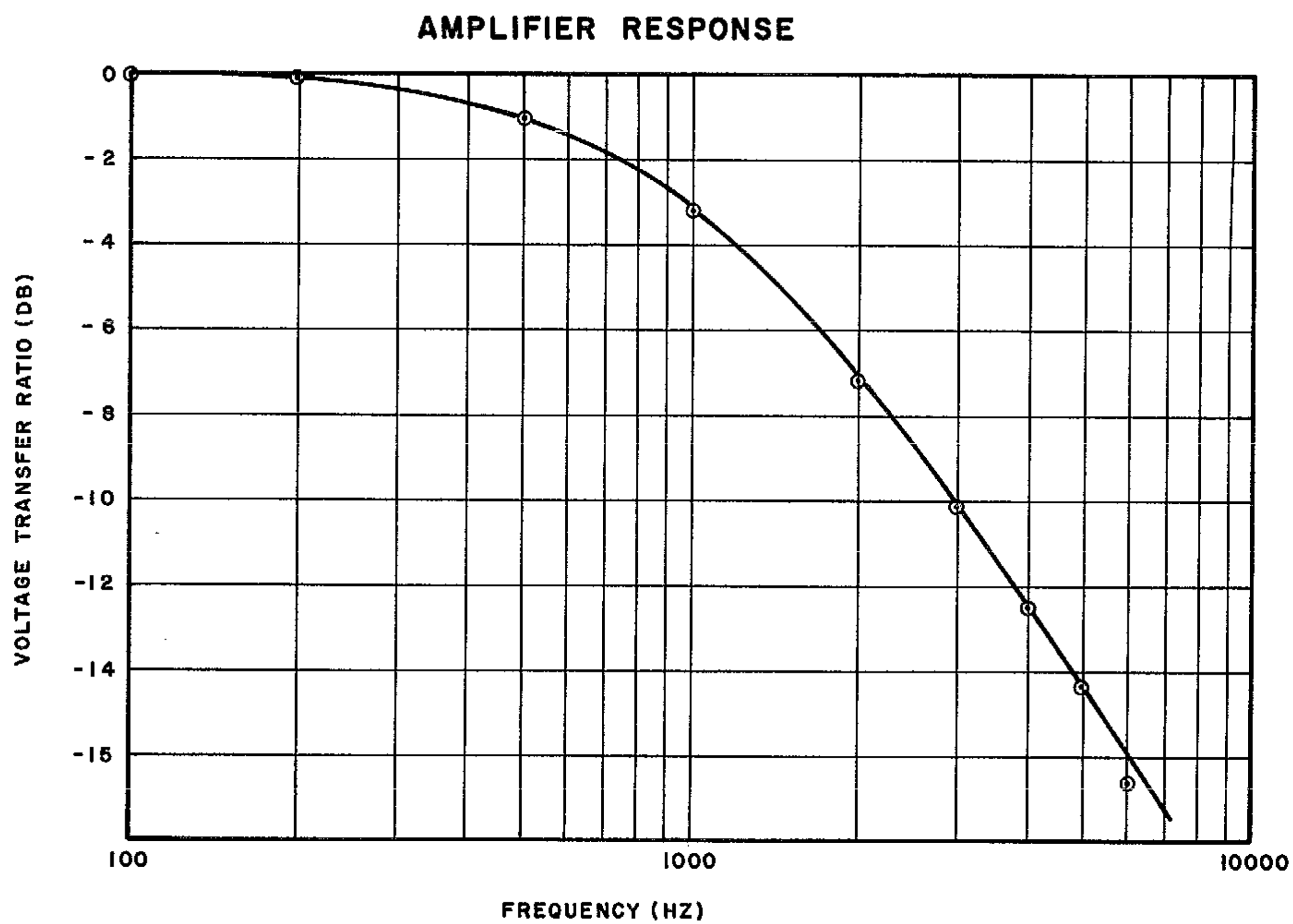

AMPLIFIER RESPONSE
0
-2
-4
-6
-8
-10
-12
-14
-15
VOLTAGE TRANSFER RATIO (DB)
100
1000
10000
FREQUENCY (HZ)

FIGURE 17

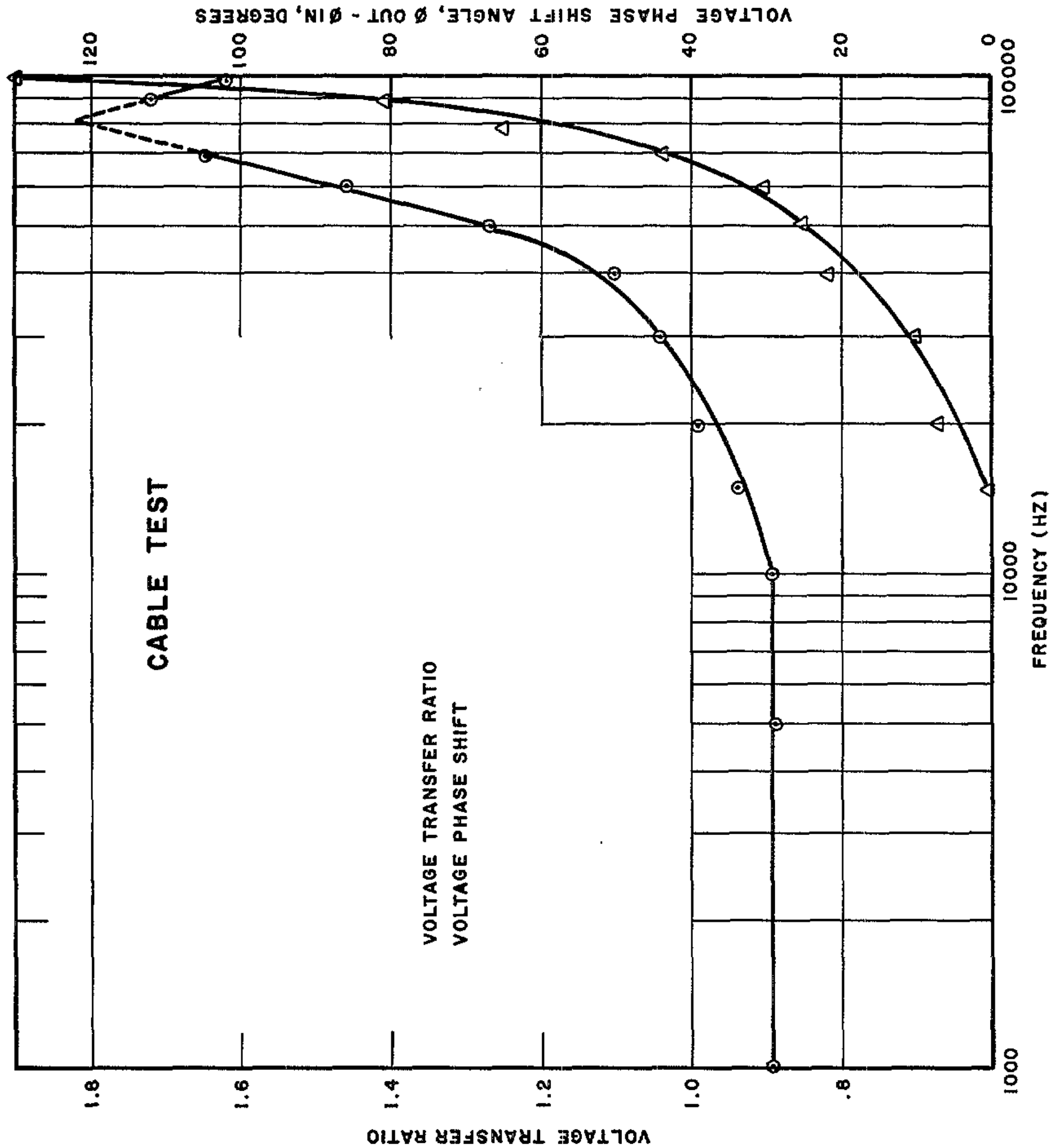

CABLE TEST
VOLTAGE TRANSFER RATIO
VOLTAGE PHASE SHIFT
VOLTAGE PHASE SHIFT ANGLE, Ø OUT - ØIN, DEGREES
120
100
80
60
40
20
0
VOLTAGE TRANSFER RATIO
1.8
1.6
1.4
1.2
1.0
.8
FREQUENCY (HZ)
1000
10000
100000

FIGURE 18

SUMMARY OF QUESTIONS, ANSWERS AND COMMENTS

SESSION IV "MEASUREMENT OF FORCE AND ACCELERATION"

In Baca's paper he had indicated a low frequency cut off of 34 Hz. Horn pointed out that in some tests that he was familiar with for another application that soil resonance occurred between 20-40 Hz in soil varying from sandy to normal; he wondered if the 34 Hz cut off was not unduly low. Baca allowed that this might be the case and pointed out that the instrumentation design was based on earlier predictions. Baca also indicated that they were attempting to use data beyond 34 Hz by correcting it but also pointed out that in amplifying the signal the noise was also boosted. He pointed out that there is a limit as to how far out in frequency you can correct before the noise swamps you. James asked if they had run a sample case to see how far out in frequency they could go and still reconstruct a valid signal. Baca said that it was hard to simulate a test because of the irregular and unpredictable nature of soil such as rocks and water. Baca was also asked what explosives were used and he indicated that primer cord was used.

Horn asked Naylor to describe the low cost amplifier for which he had drawn a schematic in an earlier session. Naylor said that they had been paying about $150 for their amplifiers when they decided to try their hand at building their own (they were eventually to build about 60 of them). The heart of the device is a $5 operational amplifier; the gain of the strain gage amplifier is about 5000 at 15 kHz and 100 at 50 kHz. They use cable lengths up to 4000 feet and one of the features of the amplifier is good common mode rejection.

Horn then asked Naylor to describe the work he has been doing on blast testing of gas turbine engines. Naylor said they obtained some CF 100 Interceptor aircraft and tied one of them down for the tests. They took a 17 inch shock tube and fired it into the inlet and the gas turbine ran faster; they then decided to fire the shock tube into the exhaust end. This was done by firing the shock tube into the tail of a T-shaped arrangement that directed part of the gases upstream and part into the exhaust. At first the combustion flames burned brighter and then the compressor stalled and the flames went out apparently for lack of oxygen. The same test with a high engine speed showed little effect. The instrumentation used was as follows: a thermistor bead was adopted for high wind velocity measurements at the inlet (constant temperature type, 50 ms time constant); iron constantine thermocouples were used in the exhaust (100 ms time constant); Bytrex strain gage pressure transducers were used near the middle of the engine where the temperature was about 150°C; Suffield made piezoelectrics were used where it was cooler; water cooled transducer mounts for pressure transducers were used where it was hotter (the exhaust gases were about 700°C); accelerometers were mounted on the engine to sense vibration and the output was integrated to get velocity. All told about 40 channels of instrumentation were used.

Horn raised the question as to whether it is really desirable to combine the transducer and electronics in one package. He pointed out that this requires expertise in materials, solid state physics, electronics as well as instrumentation; he also noted that a combination package probably would not be significantly cheaper. Metz mentioned that in oceanographic applications where distances as great as

30,000 feet may be encountered, that transducer, amplifier and A to D converter are packaged together; he added that this was not a "miniducer" but a rather large package with a heavy housing. Lederer suggested that there would be a considerable advantage to the transducer package having the standard telemetry system output of 0 to 5 volts; strain gages, for instance, have outputs now that vary from 0-10 mV to 0-500 mV. In addition the package might contain an active filter as well as an A to D converter. In the case of crystal pickups, built in field effect transistor followers ought to be very desirable. Ingebritsen asked how information like this could get back to the manufacturer and Lederer cited the ISA as a good medium. Horn pointed out that the manufacturer's reps are eager to hear user wants if there is a market. James suggested that some flexibility would be desirable - enabling for instance an engineer to use the walls of a piece of aerospace equipment as the container for the transducer too. Lynch put in a plug for the two part system noting that this allows for changing the range of both the transducer and the amplifier. This also allows the amplifier to be used for a variety of systems. He did point out however that the Piezetron allows one to use low level lines which is a considerable advantage. Finley also cited good experience with the Piezetron and noted that it contains a mode for checking; he also pointed out that the fixed sensitivity of the instrument removes a potential pitfall. An audience comment suggested that one solution to the range problem would be the use of external components to change the range. Another audience comment arguing for separate systems cited how a single amplifier and multiplexer could be used for a number of transducers. He also pointed out that the state of the art makes amplifiers more susceptible to critical environments than transducers. Naylor divided the problem into two parts, (1) piezoelectrics, where the Piezetron does effect a big difference and (2) strain gages, where impedance is no problem; in the strain gages even 500 mV output is too low to help much except in an improvement in signal to noise ratio. He would like the ability to calibrate piezoelectrics directly and perhaps multi-wire systems for strain gages so that shunt calibration can be carried out. Ingebritsen felt that the telemetry VCO should be a voltmeter, with a variable range, limiting and perhaps with an input filter such that it would carry the burden of handling the signal and not the transducer. Curry pointed out that the transducer plus amplifier versus the transducer package argument really depends upon the application. Lathrop now arguing for the integrated package cited difficulties Sandia has had with RF. This problem has been more prevalent in strain gages and thermocouples despite the fact they had comparatively short leads (3-10 feet). Kirshman indicated they also had RF problems but Metz said although their cable lengths were sometimes as long as 100 feet, they only rarely had the problem. Lederer suggested that a rugged integrated transducer might have many uses in industrial applications where there is much mechanical and electrical noise. Lynch observed that a high voltage at the source requires you to have high current to drive the lines where you have long cable lengths. Lathrop pointed out to Ingebritsen that there are new VCO's on the market that are in the millivolt range. Ingebritsen again suggested that the burden has often been put on the transducer rather than the VCO. Horn said that if the manufacturer makes the whole system then he can tailor it to the specific needs. Hilten suggested that the connectors and lead cable could use some attention because at the present rate the connector is going to be bigger than the transducer.