SUMMARY REPORT

on

EVALUATION CAPABILITIES FOR TRANSIENT PRESSURE TRANSDUCERS

to

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by

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ACKNOWLEDGMENT

This program of establishing a transducer evaluation capability at Battelle Memorial Institute was initiated under the monitorship of Mr. Henry Burlage of the NASA Office of Advanced Research and Technology. At roughly midpoint in the program, Mr. Burlage was succeeded by Mr. Jack Suddreth, and under his guidance, Dr. Marshall Burrows of the Lewis Research Center was appointed technical monitor of the program. The cooperation and guidance of these three have been greatly appreciated.

During the course of the program several Battelle professional staff members have taken part, including R. E. Robinson, J. L. Harp, K. O. Stein, R. E. Mesloh, and Dr. C. Y. Liu. The background, skills, and contributions of each are gratefully acknowledged.

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EVALUATION CAPABILITIES FOR
TRANSIENT PRESSURE TRANSDUCERS

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Battelle has recently conducted a program for NASA aimed at making available to the scientific community the transducer evaluation facilities and techniques developed over the past several years by Princeton University under NASA sponsorship. It is of particular concern to NASA that these skills and laboratory capabilities be used effectively in the various research and development programs under Government sponsorship.

The Princeton work is well summarized in a recent paper by J. P. Layton, et al,[1] which describes both the test equipment used and some of the results of recent transducer evaluations.

The Princeton equipment has now been moved to Battelle and placed in a special laboratory with other instrumentation useful for pressure measurement in rocket combustion chambers. Although measurements of this type are of particular interest to NASA, the skills that have been developed, as well as the laboratory facilities, are applicable to many transducers developed for other applications where dynamic pressures of appreciable amplitude must be measured.

The demands imposed on pressure transducers are becoming continually more stringent. This is particularly true in the measurement of combustion pressures in rocket motors during severe pressure transients such as those

(1) Jones, H. B., Jr., R. C. Knauer, J. P. Layton, and J. P. Thomas, "Transient Pressure Measurements in Liquid Propellant Rocket Thrust Chambers", Instrument Society of America Transactions, Vol. 4, No. 2, pp 116-132 (April 1965).

encountered in startup, unstable burning, and shutdown. Accurate observation and analysis of these combustion pressure transients requires:

- That the pressure transducers withstand the complex and severe environmental exposure at least long enough to obtain a suitable record.
- That they generate a signal responsive to the pressure transients of concern to the investigator.
- That there be a pre-established correlation between the pressure imposed on the transducer system and the signal generated by the system.

TRANSDUCER EVALUATION SKILLS

A concerted attempt was made by Battelle personnel to assimilate the capabilities of the Princeton staff for evaluating transducers. Several staff members spent time at the Forrestal Research Center of Princeton University to observe their techniques in using, handling, and evaluating transducers. The observations covered physical testing in the laboratory, the use of general instrumentation and special devices as needed, and the interpretation of raw test results. This study was considered essential for establishing the capabilities at Battelle. The Princeton staff had developed these unique skills over the past four years while working closely both with several transducer manufacturers and with rocket motor operators who use transducers in the measurement of transient combustion pressures.

TRANSDUCER EVALUATION FACILITIES AVAILABLE

The complete evaluation of dynamic pressure transducers requires the use of specialized equipment. As a part of this program, Battelle has established a separate laboratory for transducer evaluation as shown in Figure I. The NASA-supplied equipment in this laboratory includes a static pressure calibration bench, a coolant flow test bench, a sinusoidal pressure generator, a shock tube,

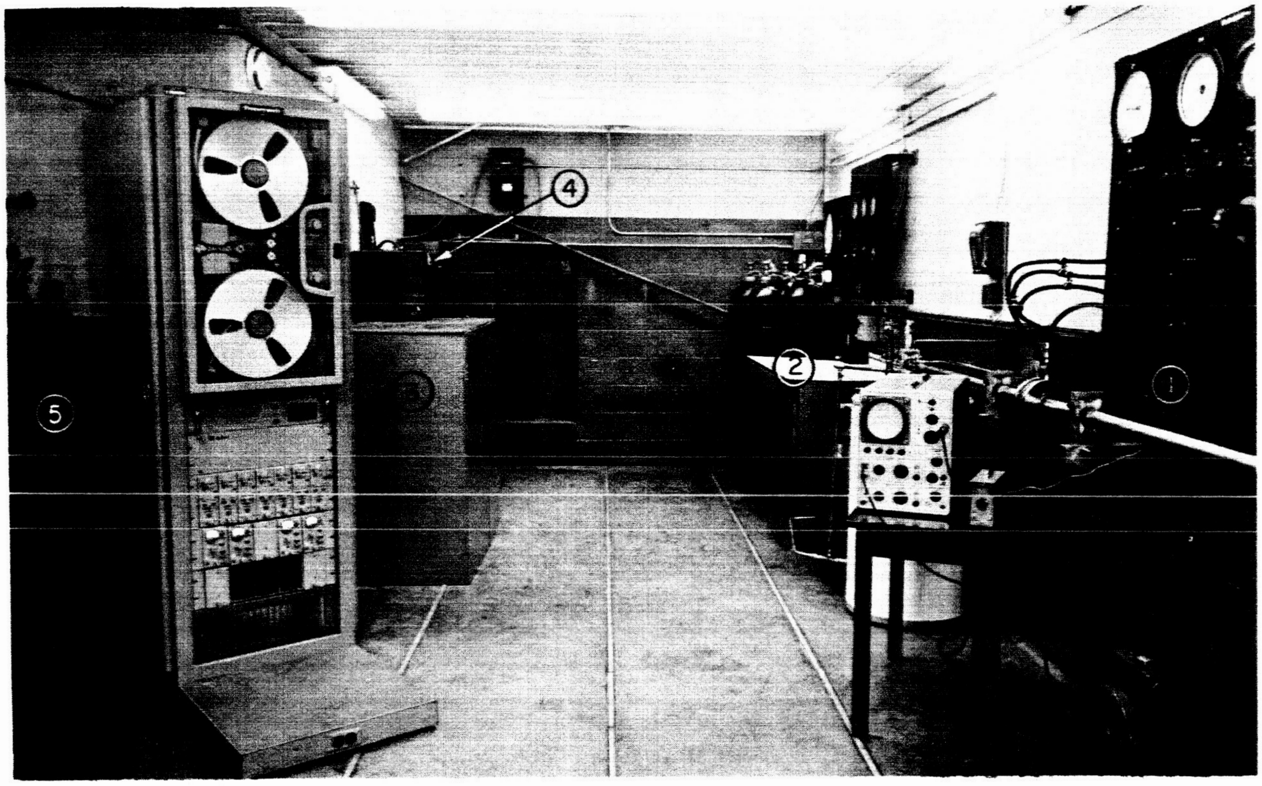

FIGURE I

TRANSDUCER EVALUATION LABORATORY

1. Shock tube and control panel
2. Static pressure and coolant flow calibration bench
3. Sinusoidal pressure generator enclosure
4. Sinusoidal pressure generator controller
5. Helium supply manifold

and some accessory equipment such as constant-voltage supplies, charge amplifiers, flow meter, and gas-supply systems.

Static Pressure Calibration

The static pressure calibration bench setup is suitable for accurate determination of pressure response including hysteresis, linearity, reproducibility, and response to changes in equilibrium temperature. Many transducers have dynamic cooling systems, either open cycle in which a liquid or gas coolant is exhausted into the pressure-source chamber or closed cycle in which a liquid coolant is circulated through the transducer. The static calibration bench is suitable for determining the effects of temperature, pressure, and flow rate of the coolant on the pressure response of the transducer.

The static pressure calibration range extends to 2000 psi, a Heise test gage being used as a working calibration standard. A Grove pushbutton gas-pressure regulator permits small incremental changes in pressure without overshoot. Although the laboratory gage is assumed to have an accuracy of only 0.25 percent, supporting calibration equipment (Ruska dead-weight testers) is accurate to 0.04 percent with traceability to the National Bureau of Standards maintained.

Coolant Flow Calibration

In many transducers the dynamic cooling system is critical to the performance of the instrument. A closed water-supply system is so assembled that distilled water can be forced through a transducer at various pressure levels. Working pressures to 1600 psi can be provided. A turbine-type flowmeter is used to measure liquid flow rates in the range 0.1 to 1.0 gal/min (0.014 to 0.14 lb/sec).

This coolant flow system is normally used in conjunction with a static pressure calibration, as the effects of coolant system operating parameters on the pressure readout are often significant. The static pressure and coolant flow calibration equipment is shown in Figure II.

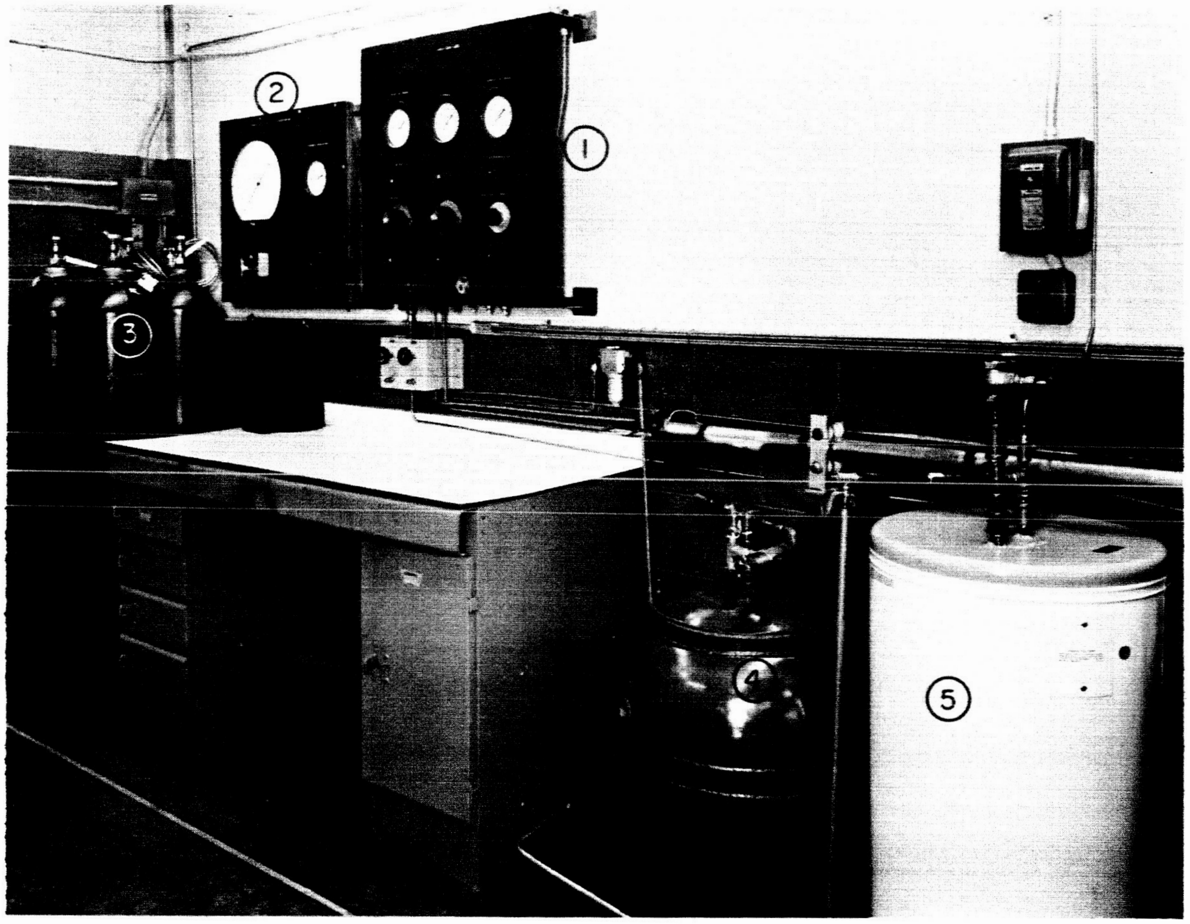

FIGURE II

STATIC PRESSURE AND COOLANT FLOW CALIBRATION BENCH

1. Flow calibration panel

2. Static pressure panel

3. Nitrogen supply

4. High-pressure water supply

5. Distilled water storage and receiver

Sinusoidal Pressure Generator

Driving a transducer with sinusoidal pressure pulses covering a range of frequencies permits direct comparison of the amplitude and phase of its output with the output of a known or standard transducer. A pneumatic sinusoidal pressure generator (SPG) has been developed as shown in Figure III. This device operates by feeding high-pressure helium into a small chamber, the outlet of which is through a choked orifice that is intermittently opened and closed. As can be seen in Figure III, this pulsing is provided by a rotating disk with a series of holes near the rim. A variable-speed motor drive for this disk controls the frequency.

The usual chamber pressure averages 250 psi with peak-to-peak pressure oscillations varying from 150 psi at 1000 cps to 12 psi at 10,000 cps. The output of a monitor transducer (Kistler 601) known to have linear dynamic response in this frequency range is compared on a dual-beam oscilloscope with the test transducer and the two traces are photographed. Direct comparison of amplitude and phase can be made from such photographs.

Although the equipment is normally operated between 1000 and 10,000 cps, the operating frequency can be extended to 30 cps at the low end and to 18,000 cps at the high end with some reduction in reproducibility and accuracy of sinusoidal wave form. This device is able to accommodate transducers which inject a coolant as well as transducers which are connected to the pressurized chamber with a restricting flow passage. In either case, the effects of the transducer on the pressure-time pattern generated within the SPG must be considered. Fortunately, the reference transducer in the SPG chamber does respond to the altered pressure pulse so that a true representation of the actual pressure pulse is provided.

Shock Tube

A shock tube technique has been developed at Princeton and elsewhere for dynamic response analysis of transducers. With suitable choice of pressure levels, gases, and geometry, a discrete pressure rise of 1000 psi can be imposed on the transducer within one microsecond, followed by a constant-pressure period

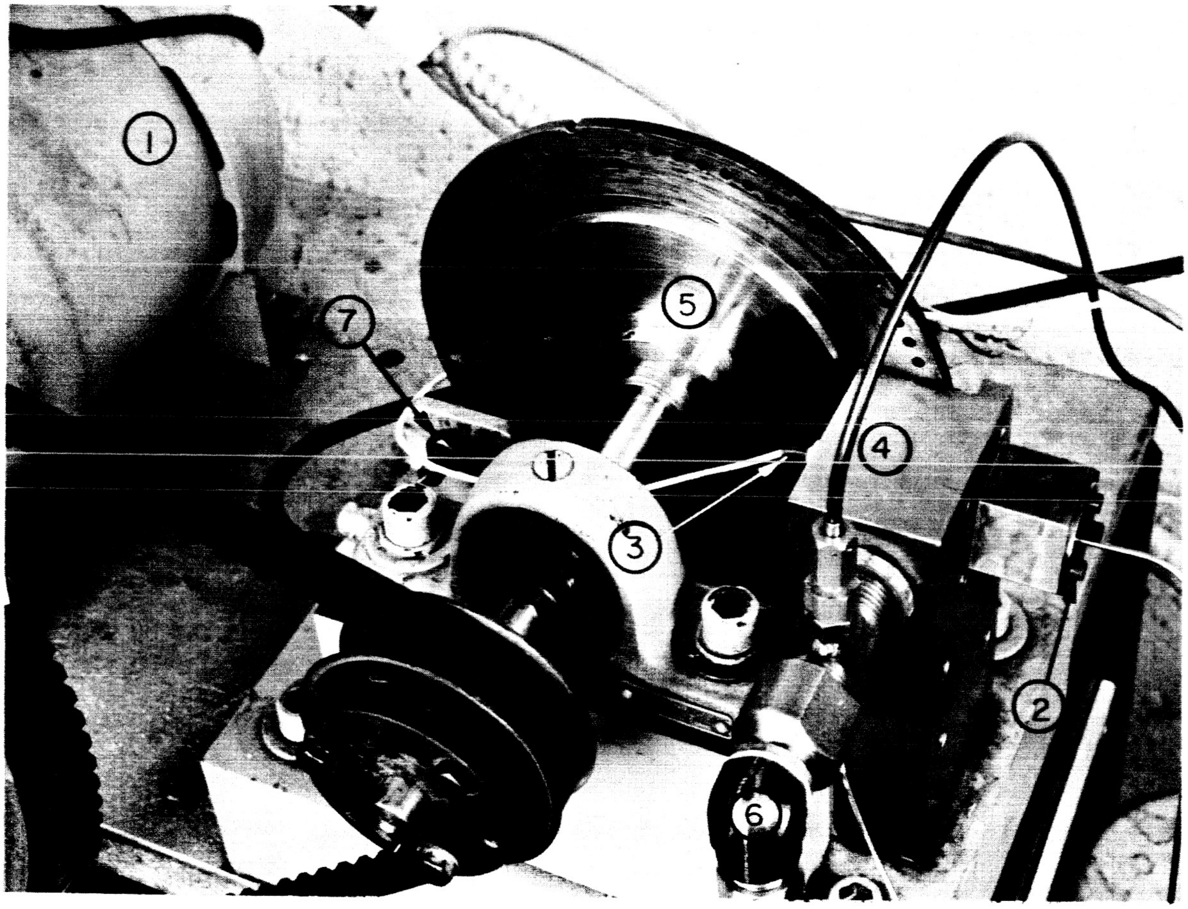

FIGURE III

SINUSOIDAL PRESSURE GENERATOR

1. Variable-speed drive motor
2. Transducer under test
3. Reference Kistler transducer
4. Pressure chamber
5. Rotating disk with multiple exit ports
6. Helium supply line
7. Revolution counter

lasting about 4 milliseconds. The pressure pulse is sufficient to "ring" or drive the transducer into oscillation. The succeeding steady-pressure period is long enough for observation of the decay rate of this oscillation.

The transducer response to this shock is displayed on an oscilloscope and photographed. This record of signal amplitude versus time is then transposed onto input cards and fed into a digital computer. The computer calculates response amplitude versus frequency and phase angle versus frequency for the transducer. The natural frequency for zero phase angle can then be determined by comparison with mathematically derived relations should this be desired.

Figure IV shows the shock tube and control panel installed in the laboratory. The burst diaphragm, located in the midpoint flange, is broken by a small increment in driver pressure, and the shock is driven toward the near end of the tube where the transducer is located. The oscilloscope is shown with the camera removed.

Other Facilities Available

Additional test facilities have been made by Battelle to support the transducer evaluation equipment supplied by NASA. The more pertinent of these include vibration equipment, rocket test facilities, and high-speed signal recording and data analysis instrumentation.

In many rocket motor applications, high-intensity vibrations are transmitted through the structure during operation, and these may or may not include the same frequency as those being observed in the combustion chamber. The sensitivity of the transducer to structure-applied vibrations during use is, therefore, of importance. Electromagnetic vibrators (shakers) are available with which the transducer can be vibrated along any axis while a static pressure calibration is obtained. With a transducer weight of 1/10 lb, the available vibration equipment will provide vibrations of 100 g over a frequency range from 100 to 20,000 cps. Although more severe vibrations may be encountered in some rocket motor applications, this type of vibration analysis will demonstrate the

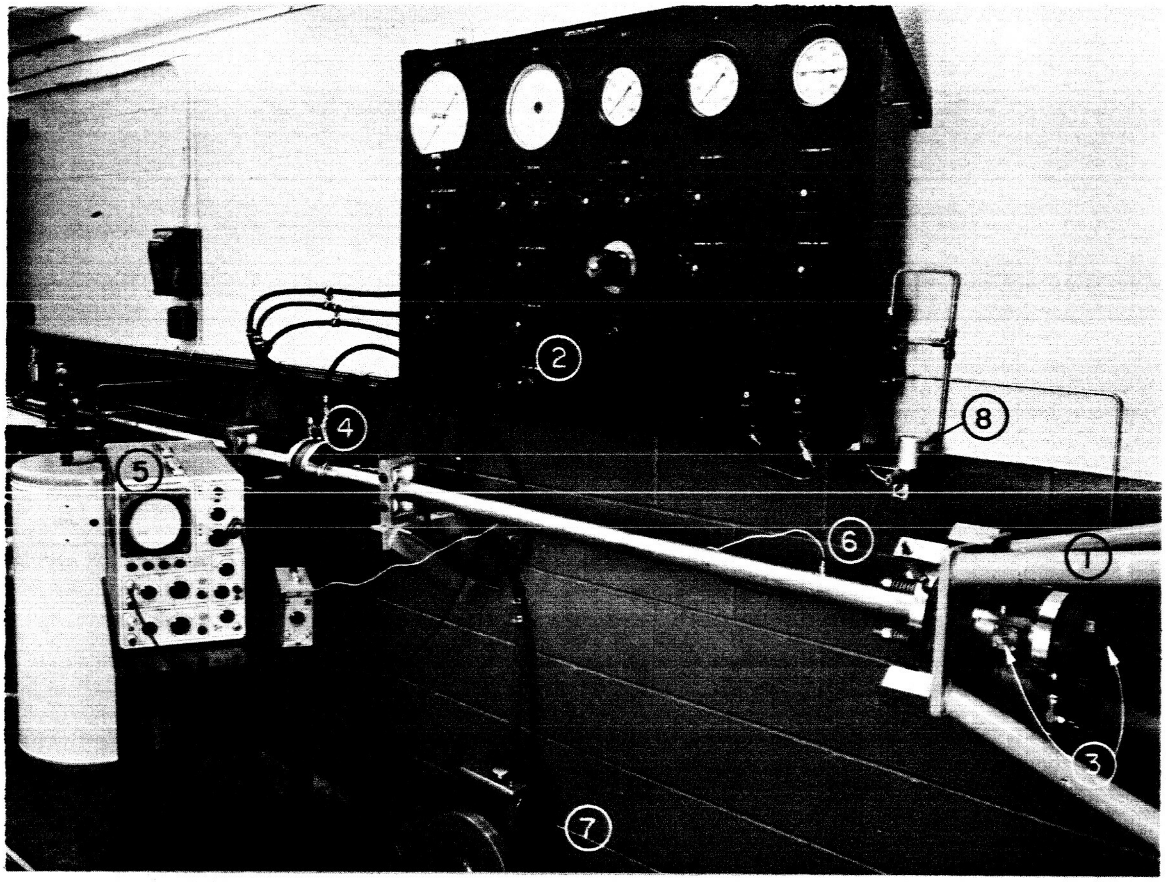

FIGURE IV

SHOCK TUBE

1. Structural support

2. Control panel

3. Alternative test transducer locations

4. Diaphragm-containing flange

5. Readout oscilloscope

6. Triggering pressure transducer

7. Vacuum pump

8. Solenoid to initiate gas flow to transducer under test

vibration sensitivity of the transducer which must be considered in many applications.

A Battelle rocket motor has been modified in conjunction with another current program(2) to provide a severe thermal exposure for transducers. This small water-cooled laboratory rocket motor imposes a high convective heat flux with combustion products concurrently with imposition of a high aerodynamic shear stress, but without an appreciable pressure pulsation amplitude. In order to provide this environment, the rectangular throat of the gaseous fueled hydrogen-oxygen motor has been extended into a parallel-walled channel. The transducer is mounted in one wall and therefore it can be exposed to an essentially uniform throat environment. The opposing wall is instrumented to constitute a heat-flux calorimeter. With this arrangement, the convective heat flux can be varied at will by changing the combustion stoichiometry and pressure, while the heat flux being imposed by the combustion gas stream is continuously and directly monitored. Although no discrete pressure oscillations are deliberately or knowingly generated in this motor, the usual "noise" from sonic flow of combustion products is encountered. Figure V shows this rocket motor assembly being utilized for the evaluation of a pressure transducer being developed for combustion instability studies. Cold-wall heat-flux values in excess of 25 Btu per (in.^{2})(sec) have been obtained with this facility with a continuous exposure duration of about one minute. Simultaneous recording of radiant heat flux from the exposed face of the transducer is also possible through a window in the calorimeter wall.

Multi-channel magnetic tape recorders, high-speed recording potentiometers, and oscillographs are available for recording the direct signal from the transducer and any tailored signal provided by other support equipment. Other instrumentation and supporting facilities for transducer studies are also available at Battelle.

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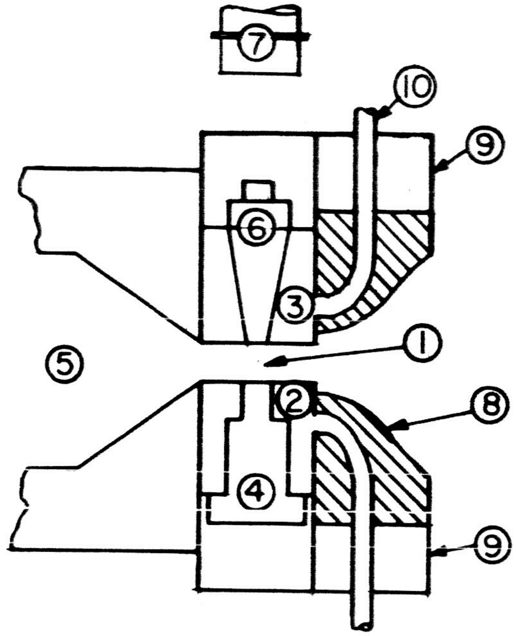
(2) NASA 8-11933, "Design, Development, and Fabrication of an Experimental, High-Temperature, High-Frequency-Response Pressure Transducer for Combustion Instability Studies".

Photograph



Sectional Schematic

FIGURE V

HIGH HEAT-FLUX EXPOSURE ASSEMBLY ON ROCKET MOTOR

1. Rectangular nozzle throat extension
2. Water-cooled transducer nozzle block
3. Water-cooled window block, alsc a calorimeter
4. Pressure transducer
5. Combustion chamber
6. Quartz window
7. Radiation pyrometer, "Rayotube"
8. Refractory ceramic potting material
9. Brass retaining body
10. Cooling water lines to nozzle blocks
11. Ignition wire for rocket combustion

IMPROVEMENTS NEEDED IN EVALUATION CAPABILITIES

In the course of this program discussions were conducted with many individuals who are concerned with the development, manufacture, and use of pressure transducers. In these discussions, special attention was directed toward the required characteristics and the evaluation of transducers suitable for the measurement of the transient pressures which occur during combustion instability in liquid-propellant rocket motors.

Four areas were identified where improvements were sorely needed. These were:

(1) The ability to impose appropriate vibrations through the transducer housing.
(2) The ability to provide controlled and reproducible exposure at high heat-flux levels.
(3) The ability to make dynamic pressure calibrations and to perform life testing at both high amplitudes and high frequencies.
(4) The availability of an accurately characterized unstable combustion environment for exposure evaluations.

Externally Applied Vibrations

The vibration level encountered in some rocket motor structures apparently reaches very high intensity. Estimates of intensity appreciably above 1000 g have been made. These vibrations may or may not be coupled to the combustion instabilities, and they may be received by the transducer in a direction either along or across the transducer axis. With suitable equipment, undesirable resonance or vibration of transducer components over a wide range of frequencies can be identified either as an output signal or by visual observation of external components with a stroboscopic light source.

As noted previously, Battelle has made available electromagnetic vibrators which can impose an acceleration magnitude of 100 g over a frequency range of from 100 to 20,000 cycles per second. Although these laboratory vibrations are about an order of magnitude less severe than might be encountered in motor applications, these can demonstrate the sensitivity of an instrument to the vibrational equipment.

Extended Steady-State Heat Flux

An available exposure facility providing continuous, reproducible, and controllable convective heat flux was described earlier in this report. The 25 Btu per (in.^{2})(sec) capacity of the present equipment roughly matches the heat flux encountered in conventional liquid-fueled motors. Combustion pressures appreciably above 1000 psi, as are now being considered in both laboratory and flight motors, make an evaluation facility desirable with a heat-flux capability of at least 50 Btu per (in.^{2})(sec). Current transducer development programs being conducted by Battelle and others will require such an evaluation facility to determine and to demonstrate the heat-flux capability of new transducers.

Although the rocket motors presently in use at Battelle are limited in heat-flux capacity to about 25 Btu per (in.^{2})(sec), there appear to be no insurmountable obstacles in using the same approach to obtain a steady-state convective heat flux of 50 or 60 Btu per (in.^{2})(sec). The imposition of a convective heat flux with a gas stream which is near equilibrium is generally preferred, although for some instruments, an appreciable contribution by radiation or surface chemical effects might be acceptable.

Oscillating Pressure Generators

The SPG currently available, and others used by various laboratories, have severe pressure amplitude and frequency limitations. The amplitude currently available with the Battelle SPG is lower than the average imposed pressure by a factor of 20 when operation is at about 10,000 cps. In some rocket combustion oscillations, the pressure amplitude becomes equal to the average pressure. Any appreciable increase in amplitude will permit better evaluations of the dynamic response and, incidentally, provide a more realistic environment when the fatigue life of the transducer is considered.

As presently installed, the SPG uses room-temperature helium as the working gas. Heating the gas would increase the pressure amplitude because of the corresponding increase in sonic velocity. The use of hydrogen would improve the pressure amplitude available with the SPG, especially at frequencies below 10,000 cps. The use of hydrogen would also reduce gas consumption costs. One or both of these approaches may be required for special applications or when pressure amplitudes must be pushed to the highest possible level. When the transducer design is compatible with the use of a liquid as the pressure-application fluid, the pressure amplitude could easily be increased to any desired value.

Another improvement in laboratory pressure generators which would materially assist those making transducer evaluations would be to use a gas hot enough that an appreciable heat flux could be applied simultaneously with the oscillating pressure. The advantage of such a procedure over the use of an oscillating rocket motor directly is that the frequency and pressure level can be independently controlled, and the combined environment can be more accurately characterized for calibration purposes.

Although limited to about 5 psi pressure amplitude at the upper frequency limit of 18,000 cps, the present SPG is a valuable diagnostic calibration device. Until improved equipment is available, it is uniquely suited to provide controlled, reproducible, and well-monitored pressure pulsations.

Oscillating Rocket Facility

A widely needed facility for the evaluation and demonstration of transducers is an unstable rocket engine. In most cases the transducer developer has to rely on customers who are users of his product to supply performance data obtained in the integrated exposure environment. In general, these data are not obtained in known and reproducible environments, as the motor firing conditions are governed or set to satisfy demands not directly related to transducer evaluation. The availability of a rocket facility providing a severely oscillating combustion environment which was both well characterized and reproducible would be very useful in the development and evaluation of pressure transducers.

SUMMARY

The measurement of transient pressures in rocket combustion chambers imposes severe performance requirements on pressure transducers, especially during severe combustion instabilities. Technical and experimental capabilities have been established for the appropriate evaluation and diagnosis of dynamic pressure transducers intended for this application. The laboratory environmental conditions currently available are summarized below. This laboratory is now ready at Battelle for use in transducer studies required by the technical community.

Static Gas Pressure Calibration to 2000 psi

Gas Coolant, Helium or Hydrogen

Flow rate as required
Helium pressures to 6000 psi

Liquid Coolant, Distilled Water

0.1 to 1 gal/min flowmeter
Pressures to 1600 psi

Oscillating Gas Pressures (Sinusoidal) at Ambient Temperatures

250 psi average pressure usually used
30 to 18,000 cps
12 psi amplitude at 10,000 cps
Gas bleed systems accommodated

Discrete Pressure Step (Shock Tube)

1000 psi rise in about 1 microsecond
4 millisecond dwell time
Gas bleed systems accommodated

Vibrations Applied Externally

100 g accelerations to a 1/10-lb transducer
100 to 20,000 cps

Convective Heat Flux, Rocket Motor

25 Btu per (in.^{2})(sec) maximum
High shear in nozzle throat exposure
Steady state or variable with time
Hydrogen-oxygen fueled with variable stoichiometry.