CASE FILE COPY

RESEARCH REPORT

FOURTH QUARTERLY REPORT

on

NONCONTACTING DEVICE TO INDICATE DEFLECTION OF TURBOPUMP INTERNAL ROTATING PARTS
(Contract NAS 8-26903)

to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER

Battelle
Columbus Laboratories

FOURTH QUARTERLY REPORT

on

NONCONTACTING DEVICE TO INDICATE DEFLECTION OF TURBOPUMP INTERNAL ROTATING PARTS

(Contract NAS 8-26903)

to

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER

March 15, 1972

by

D. B. Hamilton, D. R. Grieser, A. M. Plummer,
Dale Ensminger, and E. J. Saccocio

BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

NONCONTACTING DEVICE TO INDICATE DEFLECTION
OF TURBOPUMP INTERNAL ROTATING PARTS
(Contract NAS 8-26903)

by

D. B. Hamilton, D. R. Grieser, A. M. Plummer,
Dale Ensminger, and E. J. Saccocio

SUMMARY

Phase II (Development) was concluded for the ultrasonic Doppler device and the light-pipe-reflectance device. An ultrasonic Doppler breadboard system was assembled which accurately measured runout in the J-2 LOX pump impeller during operation. The transducer was mounted on the outside of the pump volute using a C-clamp. It was not found necessary to smooth the volute surface. Vibration was measured by conducting the ultrasonic wave through the volute housing and through the fluid in the volute to the impeller surface.

The impeller vibration was also measured accurately using the light-pipe probe mounted in an elastomeric-gland fitting in the pump case. The sensor was not found to be unduly sensitive to reflectance. A special epoxy resin developed for cryogenic applications was forced into the end of the fiber-optic probe to retain the fibers. Subsequently, the probe suffered no damage after simultaneous exposure to 2150 psi and 77 F.

Preliminary flash X-radiographs were taken of the turbine wheel and the shaft-bearing-seal assembly, using a 2-megavolt X-ray unit at McMinnville, Oregon. Reasonable resolution and contrast was obtained; however, further optimization of procedures and processing is necessary. The Phase II (Development) efforts for the flash X-ray technique will be completed as soon as arrangements can be made to conduct further development using the flash-X-ray unit at the National Bureau of Standards.

A fast-neutron detector was fabricated and sensitivity was measured. The results determined during this Phase I (Feasibility) study demonstrated that the technique is feasible for integrated-time measurements requiring, perhaps, 240 revolutions to obtain sufficient exposure at 35,000 rpm.

Phase III (Experimental Verification) plans are given in the Appendix.

INTRODUCTION

The purpose of this program is to develop techniques to measure vibrations and displacements in internal components of future LOX and LH_2 turbopump prototypes during operation. The techniques are to be such that substantial modification of the pumps will not be required. The program is to result in breadboard techniques which have been developed to the point that the required measurements can be made. Optimization of the techniques for manufacture is not included in the program.

The measurements of interest include shaft vibration, axial and radial motion of the wheel and impeller, blade clearance and vibration of seal components. The vibration magnitudes of interest cover the range of perhaps 2.5 micron (0.1 mil) to 0.5 mm (20 mils).

The program is a three-phase effort: feasibility, development, and experimental verification. Phase I (Feasibility) was concluded at the end of the first quarter, with the following three techniques selected for Phase II (Development).

(1) Ultrasonic Doppler device

(2) Flash X-ray

(3) Light-pipe reflectance.

Subsequently, a fast-neutron device was conceived and authorization was received to perform a Phase I (Feasibility) study for it. This study has just been completed. Phase II has been completed for the ultrasonic Doppler device and the light-pipe-reflectance technique. With respect to the flash X-ray technique, we are awaiting approval to use the NBS 2-megavolt unit; therefore, Phase II (development of the flash-X-ray technique) is still under way.

The Phase I and Phase II results are reported below. In addition, plans recommended for conducting Phase III (Experimental Verification) are submitted in the Appendix.

ULTRASONIC DOPPLER DEVICE

Background

Ultrasonic waves are capable of penetrating most engineering materials to considerable depths and they do this at low energy levels. In addition, they are capable of being guided through curved paths. They are sensitive to abrupt changes in acoustic impedance and for this reason they have been used to measure thickness of materials, to measure distances to target areas, and to locate defects in materials.

Methods of generating, detecting, and processing ultrasonic data are numerous. Several of these have been evaluated during Phase I as possible means of measuring the deflection of turbopump internal rotating parts such as shafts.

During the first quarter, we concluded that ultrasonic Doppler devices appeared feasible. However, their utility should be dependent on the actual geometry of the turbopump involved. During the second quarter, examination of drawings representative of a variety of turbopump designs convinced us that ultrasonic Doppler techniques are definitely applicable to turbopumps, although not all of the desired measurements are likely to be possible. Measurements in the turbine sections will be difficult, if not impossible. In particular, measurements of turbine-blade vibration or clearance, turbine-wheel vibration, or turbine shaft movement may not be feasible. However, measurements of impeller or diffuser vibration or other movement in the pump sections appear to be feasible. The attractive feature of ultrasonic Doppler measurements is that, if the source and receiver are rigidly fixed to the pump case, very little modification of the pump is needed.

During the third quarter, we showed experimentally the feasibility of the Doppler method using laboratory equipment and devices. In addition, our measurements showed that the acoustic transmission properties of the housing of the J-2 turbopump are favorable to the ultrasonic method. A breadboard ultrasonic Doppler system for measuring vibration amplitudes was assembled and evaluation of the system using the J-2 turbopump was conducted during the fourth quarter of the project.

An additional benefit to be derived from the ultrasonic method is that at the same time that it is monitoring vibrations in a local section, it can be used passively to detect anomalous behavior in other parts of the turbopump.

Ultrasonic research activity during the fourth quarter is summarized in detail in the following paragraphs.

The Doppler Effect

When the distance that a sound wave travels between a source and a receiver varies during the time of travel, the number of wave-fronts arriving at the receiver within a given period of time differs from the number of wave-fronts emitted during a similar period of time. The pitch of the wave detected by the receiver is either higher or lower than the pitch of the emitted wave depending upon whether the travel distance is decreasing or increasing, respectively, during the time of travel. The change in pitch is called a Doppler effect and the difference between the transmitted and received frequencies is called Doppler frequency. The change in path length may be caused by relative motion between the source, the receiver, and reflecting surfaces along the path of the sound beam.

When the sound source and the receiver are located side-by-side in a stationary position (monostatic arrangement) so that they may be considered as though they occupied the same position, the Doppler frequency caused by a single reflecting surface moving parallel to the path of the sound beam is

$$f_D = \frac{-2v}{c} f_o \quad , \qquad (1)$$

where

v = the velocity of the reflecting surface

c = the velocity of sound in the medium in which the reflecting surface is located

f_o = the frequency of the emitted wave, or carrier frequency.

The velocity v is a function of time, and for a vibrating surface it depends upon the nature of the vibration. In the case of a sinusoidal vibration parallel to the direction of beam travel, Equation (1) may be rewritten as follows

$$f_D = \frac{-2V\cos\omega t}{c} f_o \tag{1a}$$

$$= \frac{-2\xi\omega\cos\omega t}{c} f_o \quad ,$$

where

V = maximum velocity

ω = angular frequency ($=2\pi f_v$)

f_v = the frequency of vibration

ξ = the maximum amplitude of vibration.

A positive or negative f_D indicates, respectively, that the received signal has increased or decreased from the carrier frequency. If the Doppler variation for which Equation (1a) is applicable were extracted by comparing the received signal with the carrier frequency, the observed frequency amplitude would vary between zero and the maximum value regardless of the direction of motion of the reflecting surface. A plot of the magnitude f_D through a full cycle of vibration would be a full-wave rectified wave. If the received wave is compared with another constant frequency (intermediate frequency) which differs from the carrier frequency by an amount greater than the magnitude of f_D, the difference, or beat frequency, will not pass through zero. A plot of the magnitude of the difference between the frequency of the received signal and the intermediate frequency is of the form

$$A = B + C\cos\omega t \tag{2}$$

and $C\cos\omega t$ is a true representation of the implied f_D given by Equation (1a).

Since the only variables in Equations (1) and (1a) are those corresponding to velocity of vibration and the dependent variable f_D, Equation (1) may be rewritten

$$f_D = kv \quad , \tag{3}$$

where

k = a constant .

Thus, a plot of f_D derived from Equation (2) represents a plot of v. Since

$$v = d\xi/dt \tag{4}$$

then

$$\xi = \int v \, dt \quad . \tag{5}$$

For a purely sinusoidal vibration at a known constant frequency, the curve of f_D can be calibrated directly in terms of displacement.

These principles are applied in the ultrasonic system developed for measuring vibrations of rotating parts in turbopumps.

Influence of Ultrasonic Wave Propagation Characteristics on Effectiveness of the Doppler Method

It is important in the application of the ultrasonic Doppler method to provide for the impingement of the ultrasonic energy upon the surface to be measured and for the return of at least a portion of the reflected energy to the receiver. A consideration of ultrasonic wave propagation characteristics will aid in the selection of probe locations and orientations or modifications in turbopump designs to aid the effectiveness of the ultrasonic method.

Ultrasonic waves can be made to travel in directional beams in homogenous media. The directionality of the beams depends upon the ratio of the cross-sectional dimensions of the source to the wavelength (except in the special case of wave guides in which the boundaries of the guides limit the spreading of the beam).

Ultrasonic waves obey the same laws of reflection and refraction that apply to other types of wave motion, for example Snell's law of reflection and refraction. The angle of reflection from a boundary between two media is equal to the angle of incidence. The angle of refraction at a boundary between two media is determined by the following equation

$$\frac{c_1}{c_2} = \frac{\sin \theta_1}{\sin \theta_2} \quad , \qquad (6)$$

where

c_1 = the velocity of sound in the medium of the incident wave

c_2 = the velocity of sound in the second medium

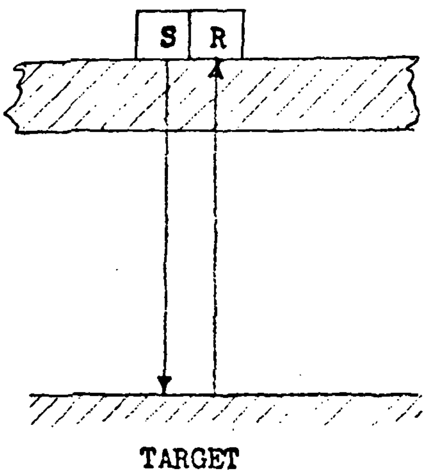
θ_1 = the angle of incidence

θ_2 = the angle of refraction.

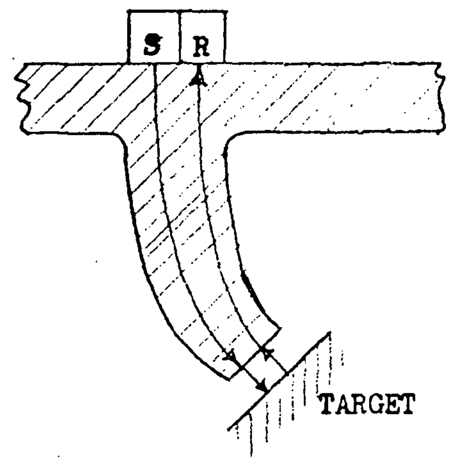
Figure 1 shows schematically how the principles described previously can be applied to detect and measure vibrations of a remote surface.

The schemes shown in Figures 1a and 1b have been demonstrated experimentally during Phase II. Since the primary consideration is to direct an incident beam onto the desired surface and to direct a portion of the incident energy to the receiver, the other arrangements are given for design purposes only. Obviously, Figures 1b, 1c, and 1d are simplified.

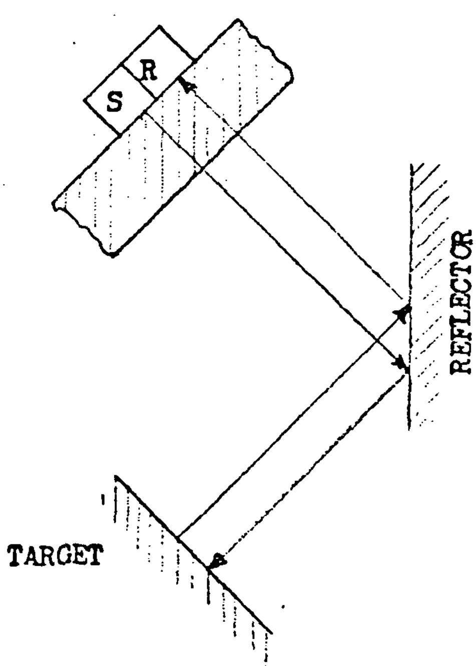
A knowledge of the exact path of the ultrasonic beam is important to the proper installation and calibration of the ultrasonic Doppler system. By applying the simple principles described previously in this section, the turbopump designer could provide a slight boss on the exterior of a pump housing which would identify a location for the ultrasonic transducers. These bosses would imply that the ultrasonic beam has an unobstructed path to and from the surface of interest. Air pockets, packings, and similar asperities in the path of the beam interfere with the transmission of ultrasound and could render the method ineffective.



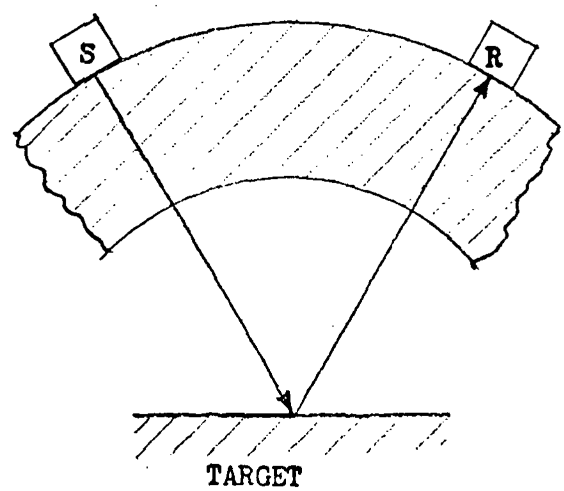
a. Direct Path



b. Wave Guide



c. Intermediate Reflector



d. Bistatic arrangement for use where operation at normal incidence is not possible.

FIGURE 1. ARRANGEMENTS OF SOURCE S AND RECEIVER R THAT CAN BE APPLIED TO DETECT AND MEASURE VIBRATIONS OF A REMOTE SURFACE

Low frequencies are less directional than are high frequencies. They also suffer less attenuation. In some areas this might be an advantage, for instance in the turbine region. However, lower frequencies would be less sensitive to low amplitudes of vibration. If they are too low, they are more sensitive to normal displacements such as the movement of impeller blades or turbine buckets. These possibilities must be considered in the design of low frequency systems.

Reflection and Transmission at a Boundary Between Two Media

The intensity of the energy reflected from and transmitted across a boundary between two media also are important to the effectiveness of the ultrasonic Doppler method. The transducers used in the system developed during the present research program are sensitive to ultrasonic pressure.

At normal incidence, the equations for determining the pressures of the reflected wave and the transmitted wave relative to the pressure of the incident wave are

$$\frac{p_R}{p_i} = \frac{Z_2 - Z_1}{Z_1 + Z_2} , \qquad (7)$$

and

$$\frac{p_T}{p_i} = \frac{2Z_2}{Z_1 + Z_2} , \qquad (8)$$

where

p_R = the acoustic pressure of the reflected wave

p_T = the acoustic pressure of the transmitted wave

p_i = the acoustic pressure of the incident wave

Z_1 = the complex acoustical impedance of the medium containing the incident wave

Z_2 = the complex acoustical impedance of the medium containing the transmitted wave.

The values of Z_1 and Z_2 depend upon the location of the point within the wave at which the impedance is measured. If the two media are effectively semi-infinite, i.e., no standing waves are possible, Z_1 and Z_2 in Equations (7) and (8) may be replaced by their corresponding characteristic acoustical impedances $\rho_1 c_1$ and $\rho_2 c_2$. On the other hand, for the special case of a wave at normal incidence on a thin section one-half wavelength thick, no reflection occurs and the wave is transmitted through the section suffering only those losses associated with the internal damping properties of the section. If the section is a quarter-wavelength thick, the wave is completely reflected.

The ultrasonic properties of the cryogenic materials LOX and LH_2 are similar to those of typical liquids at room temperatures. The important characteristics are tabulated as follows.

TABLE 1. ACOUSTICAL PROPERTIES OF LOX AND LH_2

Liquid	Temperature, C	ρ g/cm^3	c 10^5 cm/sec	ρc 10^5 g/cm^2-sec
LOX	-183.6	1.143	0.911	1.042
	-210	1.272	1.130	1.437
LH_2	-252.7	0.355	1.127	0.400
Fresh Water	20	0.998	1.483	1.48

The acoustical properties of aluminum alloys at cryogenic temperatures are not available. However, a reasonably good estimate, at least for the purpose of evaluating the effectiveness of the ultrasonic Doppler system for measuring vibrations of remote surfaces, can be obtained by using room-temperature data. A typical value of ρc for aluminum alloys is 1.75×10^6 g/cm^2-sec. From Equations (7) and (8), typical ratios of p_R/p_i and p_T/p_i at an aluminum/liquid interface are as shown in Table 2.

TABLE 2. REFLECTION AND TRANSMISSION OF ULTRASONIC ENERGY AT AN ALUMINUM/LIQUID BOUNDARY

Liquid	Temperature, C	p_R/p_i	p_T/p_i
LOX	-183.6	-0.8875	0.1125
	-210	-0.848	0.152
LH_2	-252.7	-0.955	0.0447
Fresh Water	20	-0.844	0.156

Values for fresh water at 20 C are included in Tables 1 and 2 for purposes of comparison. Transmission of ultrasonic energy from aluminum into water has often proven to be sufficient for the detection of reflecting surfaces located in the water. The energy transfer properties of both LOX and LH_2 appears to be more than adequate for the use of the ultrasonic Doppler measurement technique.

<u>Advantages of the Doppler Method Over Other Ultrasonic Methods</u>

In a system having complex acoustic paths such as those existing on a turbopump, an ultrasonic beam encounters many reflecting surfaces which may reflect more energy to an ultrasonic receiver than would be expected from the surfaces of interest. Although these surfaces probably are stationary, signals reflected from them would obscure the desired signals and make an accurate measurement impossible.

The Doppler method is inherently a type of correlation technique in which motion signals are separated from static signals. Only those signals within a narrow range of the carrier frequency can enter the detector system through the narrow bandpass input filter. By virtue of the means of processing the signal, only those signals which modulate the carrier (or the i-f) are eventually displayed unless the processing system develops excessive internal noise. Thus, the Doppler method provides an effective means of measuring vibrations at remote locations within an inherently noisy environment. At high frequencies, the ultrasonic beam is directional. The most important requirement is that an acoustic path be provided for transmission of the waves to the target area and for the return of the reflections to the receiving transducer.

Apparatus Developed for Measuring Vibrations by the Doppler Method

Electronic Circuitry

Figure 2 is a block diagram of the electronic circuitry required for the displacement measuring device based upon the ultrasonic Doppler principle.

In referring to Figure 2, the power supply, R.F. Oscillator 1 and amplifier are the driving source for the transmitting transducer. A laboratory-model CW power oscillator was used for this purpose during Phase II of the present research program.

The transmitting transducer is a piezoelectric plate. A narrow bandpass type of transducer is preferred for this function; however, during Phase II, we were able to show that good results are possible using either a broad-band or a narrow-band transducer. A narrow-band transducer with feedback control of frequency is recommended.

If the side branch consisting of low-pass filter, amplifier, and detector, is used, the receiving transducer should have sufficiently broad-band response to provide a flat response over the range of the low-pass filter. If the side-branch is not used, the transducer can have a band-pass characteristic similar to that of the band-pass filter that follows it. The band-pass of the receiver should slightly exceed the maximum frequency modulation anticipated. For example, if the maximum amplitude to be measured is 0.32 mm (0.0125 inch), 0.64 mm (0.025 inch) total displacement, in LH_2 at -252.7 C, the maximum Doppler frequency obtained for a shaft rotation of 36,000 rpm and a carrier frequency of 5 MHz is 10,650 Hz. The bandpass of the filter and transducer should be at least 4,989,000 to 5,011,000 Hz.

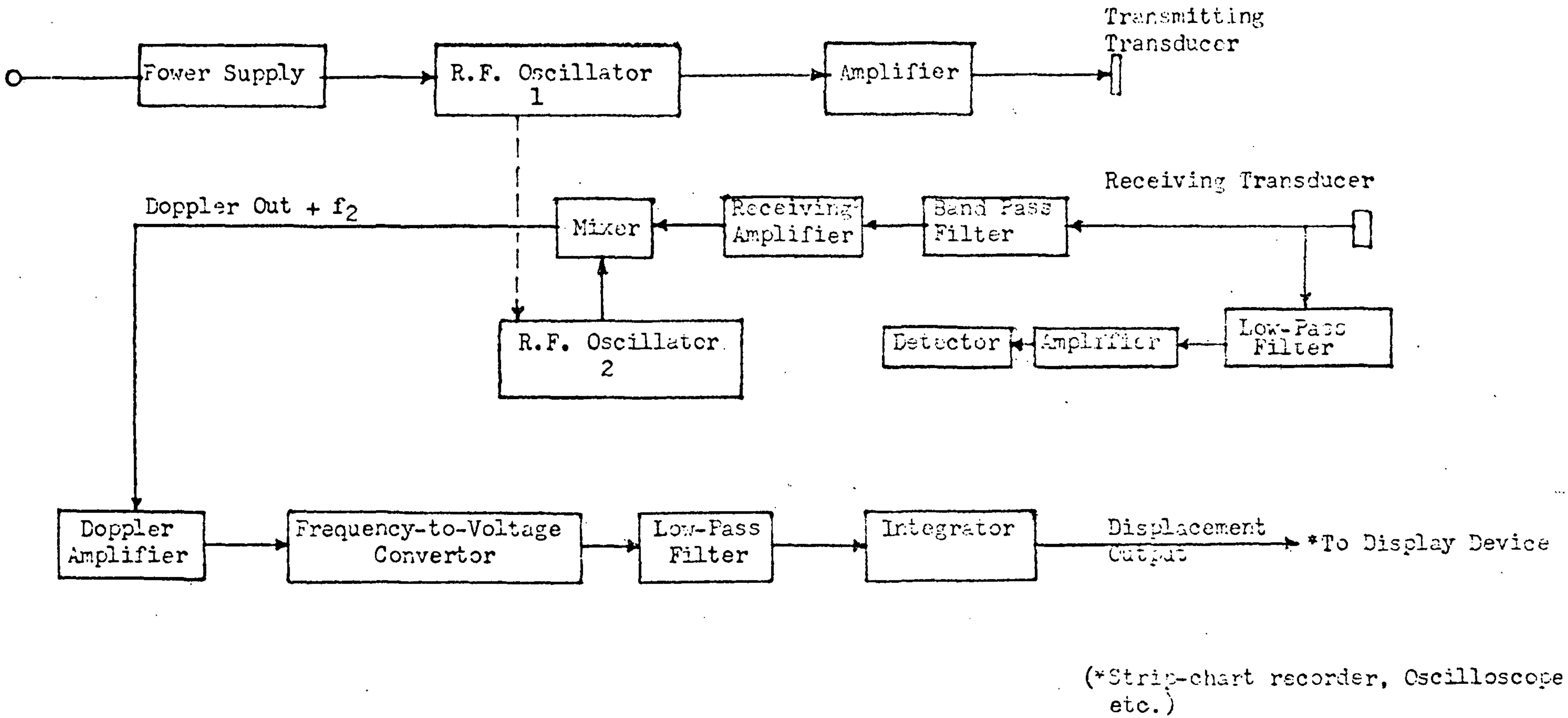


FIGURE 2. BLOCK DIAGRAM OF ULTRASONIC DOPPLER DEVICE

The receiving amplifier amplifies the received signal to a level suitable for operation in the mixer. An intermediate frequency is also produced in the mixer to provide a biasing frequency for the FM or Doppler signal. The i-f is necessary to prevent full-wave rectification of the Doppler signal in the frequency-to-voltage convertor, which has no other means of determining whether the Doppler frequency represents a shift above or below the carrier frequency. The i-f is the difference between the carrier frequency and the output frequency of R.F. Oscillator 2, and this difference is held constant at a level exceeding the maximum Doppler shift. The mixer extracts both the i-f and the Doppler frequency. These components are amplified as needed in the Doppler Amplifier and fed into the Frequency-to-Voltage Convertor.

The output of the Frequency-to-Voltage Convertor is a voltage signal corresponding to the frequency swing of the input signal. It contains two components; the i-f component at the intermediate frequency and the modulation component at the vibration frequency. The i-f is removed by the low-pass filter. The output from the filter is a voltage signal having an amplitude corresponding to the velocity of vibration and a frequency corresponding to the frequency of vibration. The Integrator converts the velocity signal to an amplitude signal. The Integrator is not essential if the vibration is sinusoidal.

The receiver circuit including the Band-Pass Filter, Amplifier, R.F. Oscillator 2, Mixer, and Doppler Amplifier were incorporated in a commerically available device: a Hammerlund HQ100A receiver (amplifier, heterodyne oscillator, mixer, filter).

A constant-frequency difference between Oscillators 1 and 2 was maintained manually by taking advantage of the characteristics of the equipment. The transmitting transducer was tuned to resonance (5 MHz). The Hammerlund receiver has an intermediate frequency of 455kHz and a band-pass filter which permits a swing of approximately 3000 Hz to either side of 455 kHz.

Only the tunable r-f amplifier, local oscillator (heterodyne oscillator) and the i-f amplifier circuits of the Hammerlund receiver were used. The output signal was taken from the secondary winding of the last i-f transformer. The audio detector tube was removed from its socket. The signal from the i-f amplifier in the HQ100A receiver was fed to the input of the GR1142-A discriminator.

The Frequency-to-Voltage Convertor was supplied by a General Radio frequency meter and discriminator, Type GR1142-A.

The output of the Frequency-to-Voltage Convertor (GR1142-A) was fed into a tunable filter, Type GR1232-A. This filter removed the i-f signal and presented the Doppler signal to the display device, which was a Tektronix oscilloscope. A Tektronix (Type 565) oscilloscope was used generally for displaying the output signal.

Function of the Supplementary Circuit

The extra circuit consisting of low-pass filter, amplifier, and detector is optional. This circuit utilizes the same receiving transducer that is used for the Doppler measurements to provide passive sonic monitoring of the operation of the turbopump. Obvious anomalous operation of the turbopump would produce corresponding signals which might be detected early enough that catastrophic failure could be prevented. The amplifier could be a relatively inexpensive unit with band-pass characteristics extending through the audible range and into the low ultrasonic range. The cutoff frequency of the filter also could be a low ultrasonic frequency.

Transducers

Experiments during Phase II have shown that certain precautions are necessary in the design and use of ultrasonic transducers for applying the Doppler principle to the measurement of vibrations in the moving elements of turbopumps. Perhaps the best combination of transmitter and receiver would consist of a narrow-bandwidth transmitter and a broad-bandwidth receiver. Our experiments have proven that this is not a rigid requirement, however. The philosophy of using a narrow-bandwidth transmitter is that such transducers are easily adapted for controlling the frequency of the power oscillator and thus maintaining the frequency and amplitude of the transmitted (carrier) signal at reasonably constant levels. On the other hand, a broad-band transmitter provides less loss of signal amplitude with drift in frequency when manually adjusted oscillators are used.

The transmitter and receiver may be assembled in a common, compact housing thus comprising a dual-element probe. Operation in this manner is called monostatic. The primary precaution to be observed in designing a dual-element probe is to prevent both electrical and acoustical cross-talk. If cross-talk occurs, the magnitude of the cross-talk signal is so much greater than is the signal from the vibrating surface that the Doppler signal is completely overcome.

Cross-talk was prevented during the experimental work on Phase II with dual element probes by completely encapsulating each element separately in its own electrically conductive housing. The two units were then mounted together in a common housing in which they were acoustically isolated.

Dual-element probes are available commercially for measuring thicknesses by pulse-echo (pitch-catch) means. For such measurements, cross-talk presents no problem. Experiments using one of these commercial probes during Phase II showed excessive cross-talk for Doppler measurements. However, excellent results were obtained when only one of the elements was used as a transmitter and a second small, commercial probe was used as a receiver. No acoustical or electrical cross-talk was possible with these probes because they were completely shielded electrically and they were acoustically isolated.

In some situations, it may be possible to transmit the incident wave from one location, but the angle of incidence in the vibrating surface may be such that it is necessary to detect the reflected wave at another location. This arrangement of a separate transmitter and receiver is called a bistatic arrangement. Such an arrangement increases the versatility of the ultrasonic Doppler method. Transducers for bistatic arrangements are immune to cross-talk if they are properly shielded.

Broad-band transducers are recommended for the receiver with the center-frequency equal to that of the carrier frequency. The output signal is then a reasonably good reproduction of the received signal, being able to follow the frequency modulation. Broad-band transducers are obtained by backing the piezoelectric element with a damping material.

The extremely sensitive receiving transducers are neither necessary nor desirable. The ultrasonic transmission characteristics of the materials used in the J-2 turbopump housing are good. Transducers having very high sensitivities were evaluated during Phase II and were found to contribute excessive noise to the measuring system. Rubbing the electrical leads or the housings of the electrical components to which the electrical leads were attached generated acoustical noises that were detected by the transducers and were transmitted through the electrical system as noise. The transducers shown in Figure 3 are typical of the high-sensitivity transducers that were evaluated during Phase II. Since the transducers are not highly damped, their bandwidth is relatively narrow. Potting the transducers with acoustically absorbent material after assembly would lower the sensitivity and increase the bandwidth of the transducers.

The piezoelectric elements used in the transducers shown in Figure 3 are lead-zirconate-titanate discs, resonant at 5 MHz.

No externally induced noise was encountered for less-sensitive transducers. In fact, excellent results were obtained when one-half section of a 1.3 cm (1/2 inch) diameter 5 MHz dual-element probe was used as a transmitter and a separate 0.64 cm (1/4 inch) omnidirectional 5 MHz probe was used as the receiver. Thus, it would appear that miniature, button-type transducers in which each element may be as small as 0.64 cm (1/4 inch) in diameter or 0.64 cm (1/4 inch) square would be adequate for the turbopump application. The beam spread of a 0.64 cm (1/4 inch) diameter, 5 MHz beam in aluminum is approximately 22 degrees. It is approximately 5 degrees in typical liquids. If greater directionality is required and if no liquid or solid structure is available which is suitable for use as a wave guide, collimation can be improved by increasing the area of the radiating surface.

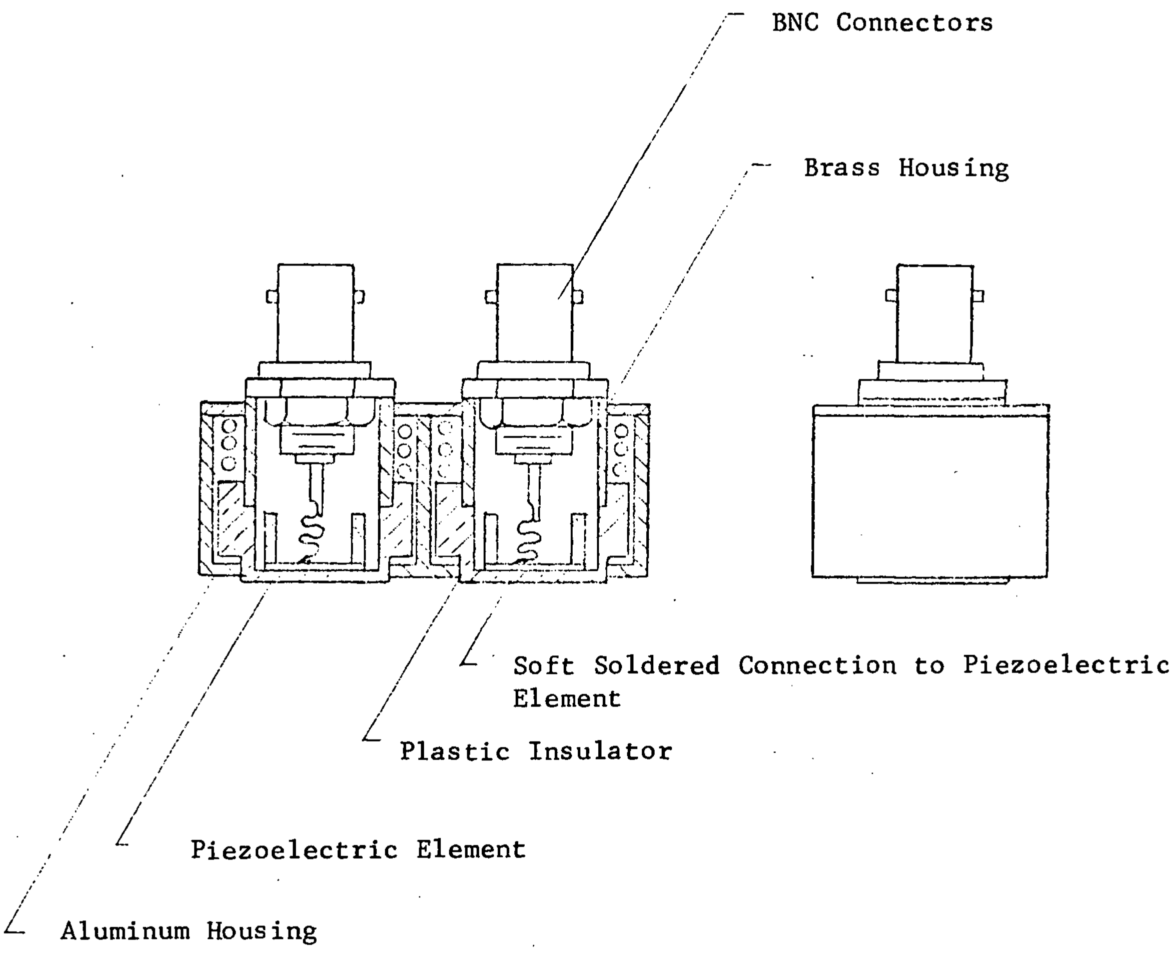


FIGURE 3. HIGH-SENSITIVITY TRANSDUCERS FOR USE IN MEASURING VIBRATIONS BY THE ULTRASONIC DOPPLER METHOD (MONOSTATIC ARRANGEMENT)

The beam spread of a round piston-type source is given by

$$\sin \theta/2 = 1.2\lambda/D \quad , \tag{9}$$

where

θ = the angle of beam spread

λ = the wavelength of sound in the transmitting medium

D = the diameter of the radiating surface.

For square transducers

$$\sin \theta/2 = \lambda/b \quad , \tag{10}$$

where

b = the length of one side.

Miniature button-type transducers of a construction shown schematically in Figure 4 are recommended for use in measuring vibrations in regions of a turbopump for pumping cryogenic materials. The monostatic arrangement is used when the probe can be located so that the transmitted wave approaches the reflecting surface at normal incidence. (A modification of the transducers of Figure 4 consists of concentric piezoelectric plates in which the outer, larger area plate is the transmitter and the smaller, center plate is the receiver. The two elements must be electrically and acoustically isolated.) Bistatic arrangements (transmitter and receiver separated) are used when reflections do not return to the area of the transmitter.

Coupling Transducers to the Turbopump

The acoustical impedance of air is very low compared with the impedance of solids. For this reason nearly 100 percent of the energy of an ultrasonic wave incident on an air/metal or metal/air interface is reflected from the interface with little or no transmission across the interface.

There are special techniques for improving the impedance match between gases and solids. For example, coupling across a half-wave air gap

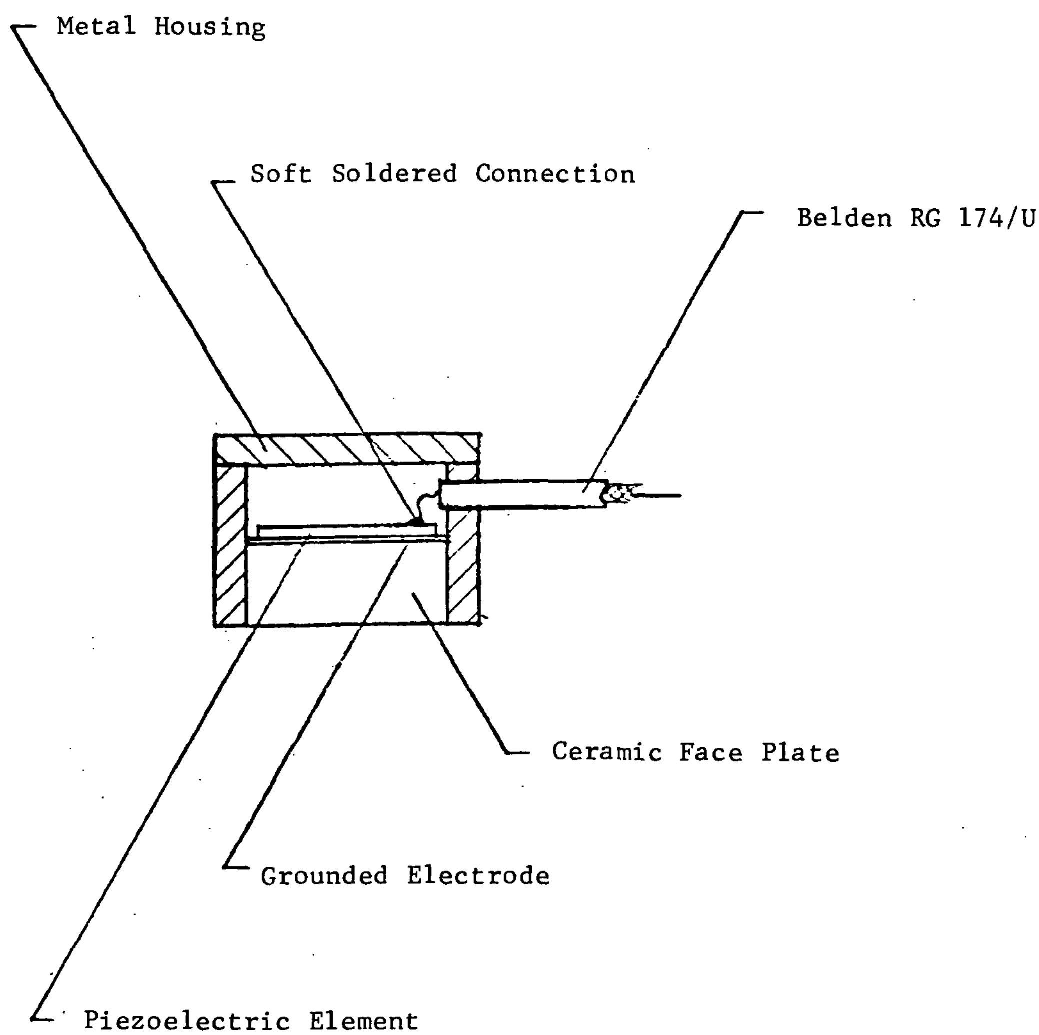


FIGURE 4. ENLARGED SCHEMATIC VIEW OF MINIATURE ULTRASONIC TRANSDUCER RECOMMENDED FOR USE IN MEASURING VIBRATIONS IN PUMP SECTION OF TURBOPUMP

takes advantage of the distributed, complex impedance of the gap to obtain a match. The extremely close tolerances required at 5 MHz makes such coupling impractical for the turbopump application. At lower frequencies, good coupling into gases is accomplished by increasing the radiating surface by attaching small energizing elements to diaphragms of relatively large area (i.e., relative to the cross-section of the energizing element). This method is not adaptable to the pump section but, conceivably, it could be applied in the turbine-section. In the turbine gases, a frequency of 100 KHz would produce wavelengths of approximately 3 mm (0.12 inch). A displacement of 0.025 mm (0.001 inch) would produce a Doppler shift of 57 Hz.

Research on the ultrasonic Doppler method has been restricted to the pump section during the present research program.

Transducers used in the experimental research of Phase II have been coupled to the test apparatus by means of lubricating oil. Other oils or greases, such as silicone stopcock grease, are also suitable couplants. For permanent installations, the transducers may be bonded to the test apparatus. Several epoxy materials are suitable for this purpose. The mating surfaces must be free of grease and dirt and the epoxy must be free of gas bubbles to insure a good bond over the entire radiating surface.

When measurements are made at cryogenic temperatures, compensation must be made for the fact that typical piezoelectric elements used in high-frequency ultrasonic transducers are ceramic elements. Differences in thermal expansion could result in damage to the elements. Methods of preventing such damage could include provisions designed into the transducer for locally heating the transducer, using a grease that does not solidify at cryogenic temperatures (if such exists), or attaching a short transmission line to the transducer or to the housing of the pump so that the end to which the transducer is attached can be warmed without effectively heating the cryogenic material inside the pump.

Experimental Measurements With Ultrasonic Doppler Method

During Phase II of the current research program, experiments have been conducted to verify the effectiveness of the proposed ultrasonic Doppler method. Transducers having various operating characteristics were fabricated and evaluated initially using a simple laboratory device consisting of an aluminum block and an eccentric as shown in Figure 5. Transducers similar to the design of Figure 3 were clamped to the aluminum plate. The eccentrics were rotated at the rate of approximately 27 rev/sec. The circuitry shown in Figure 2, minus the side branch and the integrator, was supplied by the Hammerlund 100A (5 MHz amplifier, heterodyne oscillator, mixer, and filter), Frequency-to-Voltage Convertor (GR1142-A), and tunable filter (GR1232-A).

Measurements were made using eccentricities ranging from 0.125 mm (0.005 inch) to 0.63 mm (0.025 inch). Figure 6 shows two oscilloscope traces obtained from two different eccentricities. The eccentricity used to produce Figure 6a is 0.32 mm (0.0125 inch) and that for Figure 6b is 0.63 mm (0.025 inch).

Figure 7 shows the transducers (mounted on a J-2 turbopump) that were used to obtain the traces shown in Figure 6. A number of attempts to measure the displacements of reflecting surfaces attached to the impellers of the pump were unsuccessful when the transducers were mounted in the positions shown in Figure 7. The problem was traced to the fact that the vane, which it had been hoped could be used as a transmission line, was not aligned with the reflecting surface in such a manner that energy would be reflected to the receiver. After this conclusion had been reached, a new area was located which would provide access to the reflecting surface.

The transducers shown in Figure 3 were too large to fit into the available space in the second location. Therefore, two miniature probes consisting of one-half section of a Branson 5 MHz, 1.3 mm (1/2-inch) diameter probe used as a receiver were substituted for the larger transducers. (The two elements of the Branson dual-element probe are not electrically isolated so that a separate probe was necessary to prevent excessive cross talk.) Coupling was achieved through the rough cast surface of the turbopump housing.

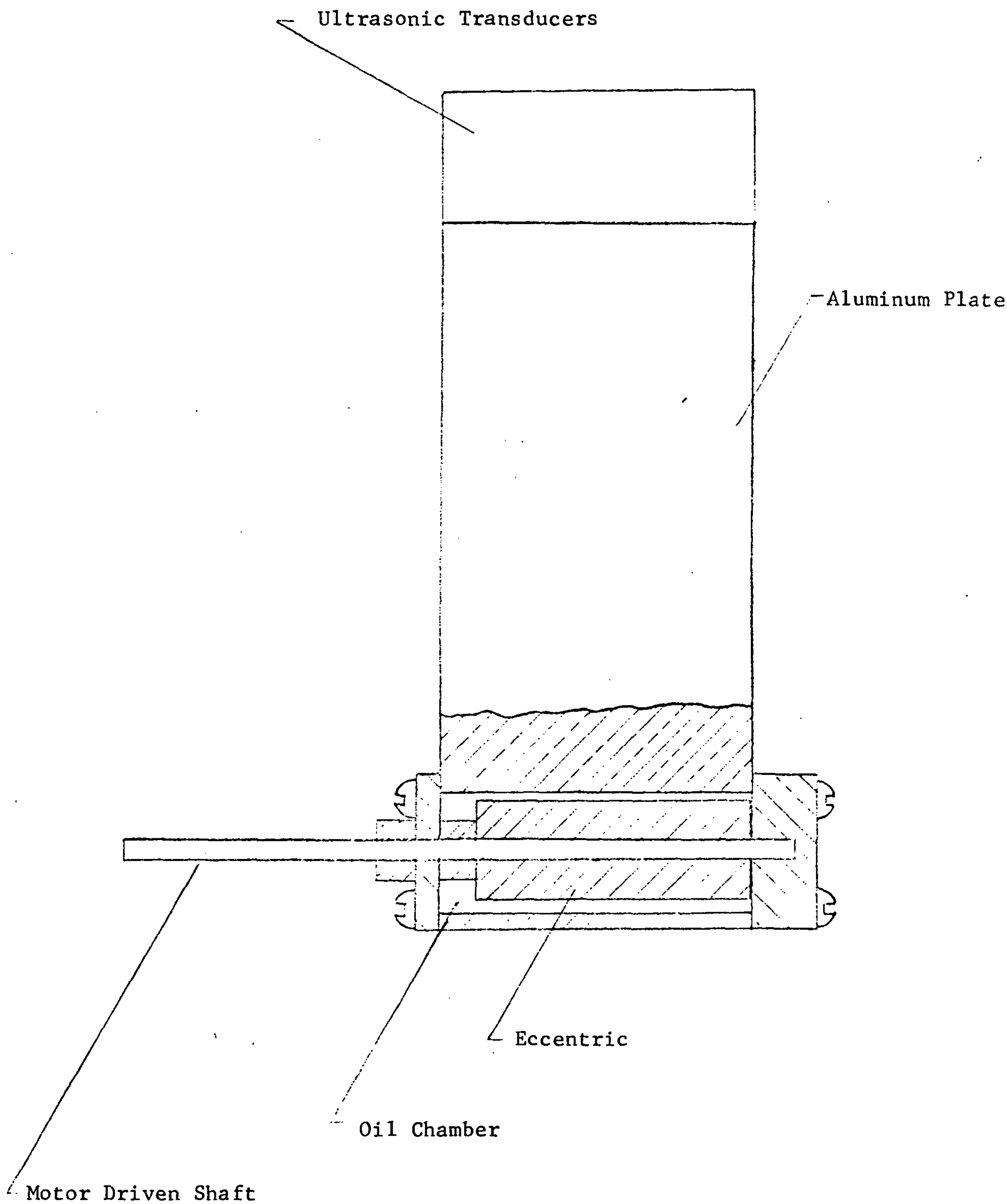
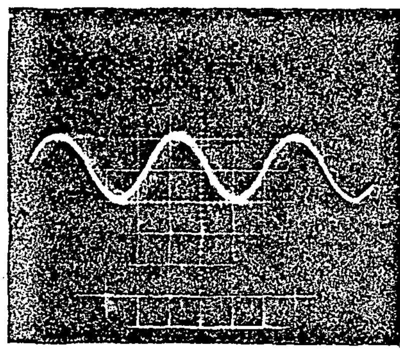
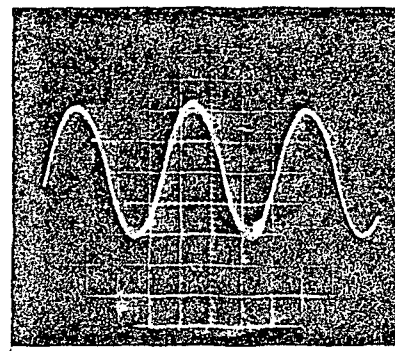


FIGURE 5. LABORATORY APPARATUS FOR EVALUATING ULTRASONIC DOPPLER METHOD OF MEASURING VIBRATORY DISPLACEMENTS OF ROTATING PARTS



a. With an Eccentricity of 0.0125 Inch



b. With an Eccentricity of 0.025 Inch

FIGURE 6. ULTRASONIC DOPPLER SIGNALS RECEIVED FROM THE ECCENTRICS OF FIGURE 5 ROTATING AT 27 REV/SEC

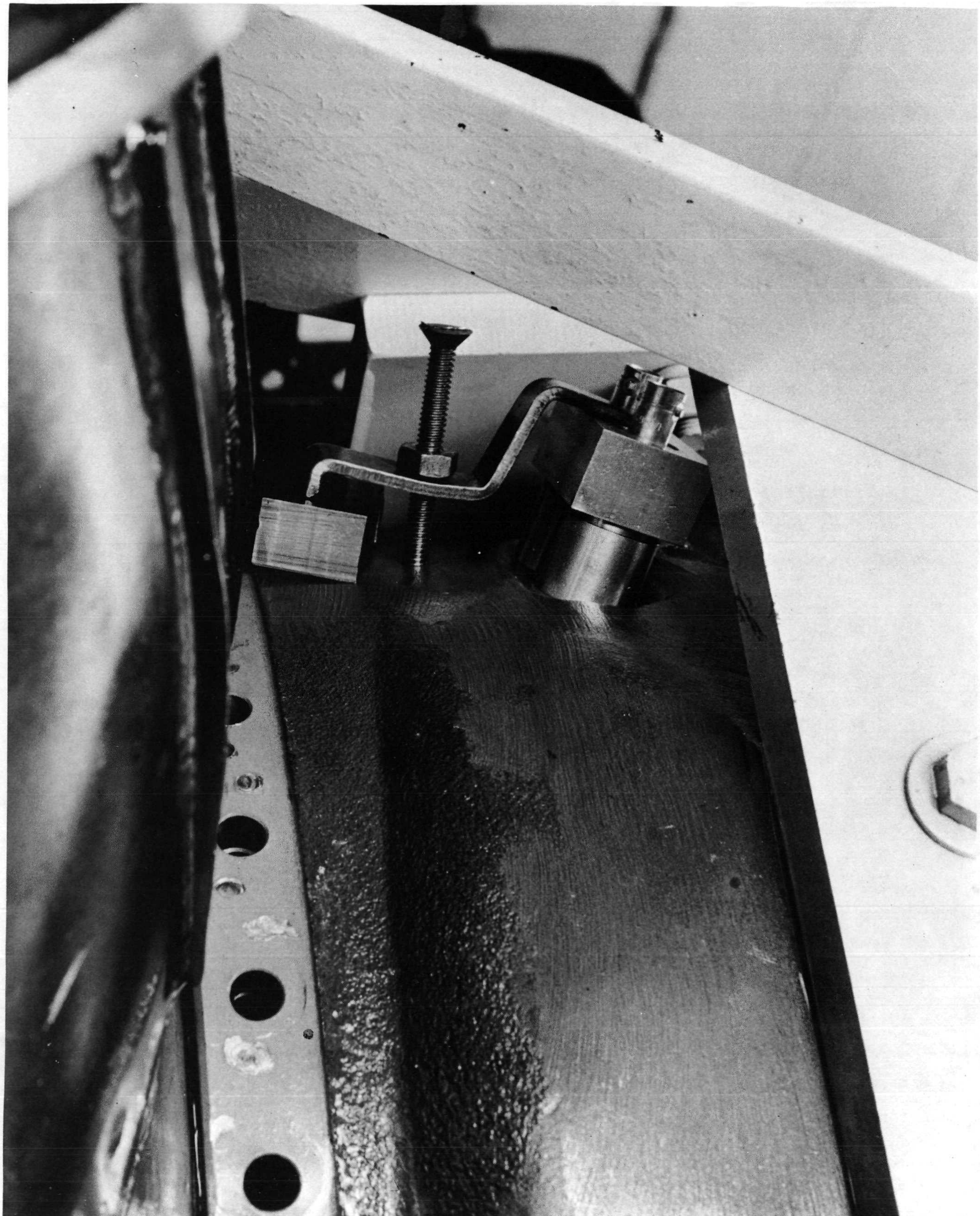


FIGURE 7. TRANSDUCERS OF FIGURE 3 MOUNTED ON THE J-2 TURBOPUMP

Transmission was conducted through the wall and through a considerable distance in the oil used inside the turbopump. In spite of the rough surface and the fact that the miniature probes were less sensitive than were the larger transducers, the sensitivity was more than adequate. Figure 8 is an oscilloscope trace obtained with the miniature transducers.

The only problem encountered in the experiments involving the miniature transducers was associated with using an oil couplant on a vertical, rough surface. The oil drained from the surfaces fairly rapidly. This is not considered to be a significant problem in that it can be corrected easily by (1) using grease instead of oil, or (2) bonding the transducers to the surface.

The ultrasonic Doppler technique for measuring the amplitudes of vibration of rotating parts has been proven to be feasible to our satisfaction during the experimental research conducted during Phase II. A few questions remain to be answered during Phase III regarding the ability of the transducers to withstand vibration, means of coupling to cryogenic systems without damaging the transducers, and ability of the method to measure vibrations at 35,000 rpm. We believe that careful consideration of materials properties of the transducers and couplants, and acoustical characteristics of the turbopump will result in a useable system which requires little or no modification of the pump design.

Conclusions and Recommendations

Our investigation of the ultrasonic Doppler technique has proceeded far enough that we believe we can justify making certain recommendations toward implementing the method on a turbopump. Our research to date has proven that, if an ultrasonic beam can be directed to a reflecting, regular surface and the reflected energy can be directed to a receiving transducer whether the receiver and transmitter are arranged monostatically or bistatically, the vibrations can be measured by Doppler methods. Our primary recommendation is that the turbopump manufacturer identify areas in the pump section where the transducers should be mounted. These areas would indicate that an acoustic

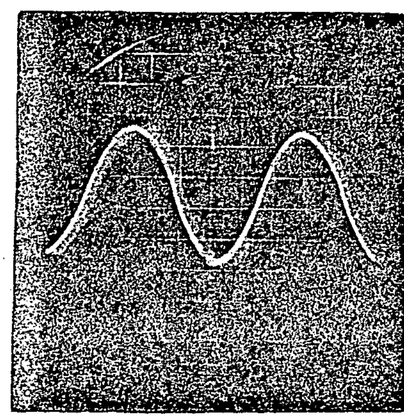


FIGURE 8. ULTRASONIC DOPPLER SIGNAL OBTAINED FROM RELECTING SURFACES BONDED TO THE IMPELLER OF THE J-2 TURBOPUMP SIMULATING A VIBRATION AT 37 Hz AND A TOTAL DISPLACEMENT OF 1/8 INCH

path to possibly vibrating surfaces is available. The principles discussed early in this report should be used as a guide for determining these locations.

The same elements are used in manufacturing ultrasonic transducers that are used in many accelerometers. Their ruggedness is a function of the design. Transducers should be designed to withstand the vibratory accelerations of the turbopump test. The vibrations of the housing should not induce unwanted signals in the system. The leads should be capable of withstanding the same accelerations. The coupling between transducer and turbopump should not be affected by the vibration to which the machine is subjected. Electrical leads should be capable of withstanding the cryogenic temperatures, or should be protected from them. The transducers should be designed to withstand temperature variations, or there should be a provision for heating them locally to prevent damage to the elements.

Transmitting and receiving elements should be isolated completely--both electrically and acoustically.

More complete recommendations are expected to result from the Phase III study.

OPTICAL LIGHT-PIPE REFLECTANCE DEVICE

During the first and second quarters, a variety of optical devices was evaluated. All of the methods considered required modification of a pump to the extent necessary to provide a window of some sort to admit light into and out of the pump. The most attractive method involved a commercially available unit which senses displacement by measuring reflected light intensity from the vibrating surface. Light is admitted into the surface through a flexible fiberoptic bundle, which serves as the window. Although this technique requires greater pump modification than the ultrasonic, the fast neutron and the flash X-ray techniques, it is simpler and more flexible in its application than the currently used inductance transducers. The light-pipe reflectance technique was, therefore, advanced to Phase II partly as a backup effort to the more exotic techniques also being developed in Phase II.

During the first three quarters of the program, experiments were performed which verified the manufacturer's claims regarding sensitivity and speed capability. During the fourth quarter, the fiber-optic probe was mounted in the J-2 LOX turbopump which was assembled on a test stand at Battelle-Columbus. Measurements of pump impeller runout were made during slow-speed operation of the pump filled with kerosene or oil. In addition, the general effects of high pressure and cryogenic temperature on the fiber-optic probe were investigated.

Runout Measurement

The J-2 turbopump modification to incorporate the light-reflectance probe was commissioned during this report period. The probe was inserted into the exit stream region of the pump through an elastomer-sealed pressure fitting. The fitting was located so that the probe looked at the lower flange of the centrifugal impeller. Figure 9 shows the probe mounted in the pump.

A cyclically varying signal was obtained with kerosene in the pump when the shaft was turned by hand. When the shaft was rotated at 1070 rpm with the drive motor, the cyclic signal was completely obscured by a random signal. This indication of bubble entrainment was confirmed by the observation of bubbles through the transparent lid and hoses on the pump. Further confirmation came when the kerosene was drained from the pump so that the probe operated in air. A repetitive, cyclic signal was obtained with almost no random noise.

The upper trace in Figure 10 was obtained with the kerosene drained and with the shaft driven at 1070 rpm. The slowly varying cyclic signal indicates a runout of 0.079 mm (3.1 mils) with an uncertainty of $\pm$0.005 mm (0.2 mil). A precision dial gage with the shaft rotated stepwise by hand gave a value of 0.074 mm (2.9 mil) with an uncertainty of $\pm$0.008 mm (0.3 mil). the maximum and minimum radii matched in circumferential location between the two measurement methods further confirmed the optical measurement. These results demonstrate that this optical technique has the potential for high precision. The higher frequency information obtained in the scope trace was unexpected.

It was suspected that variations in surface reflectance around the periphery of the impeller resulted in the repetitive high-frequency components

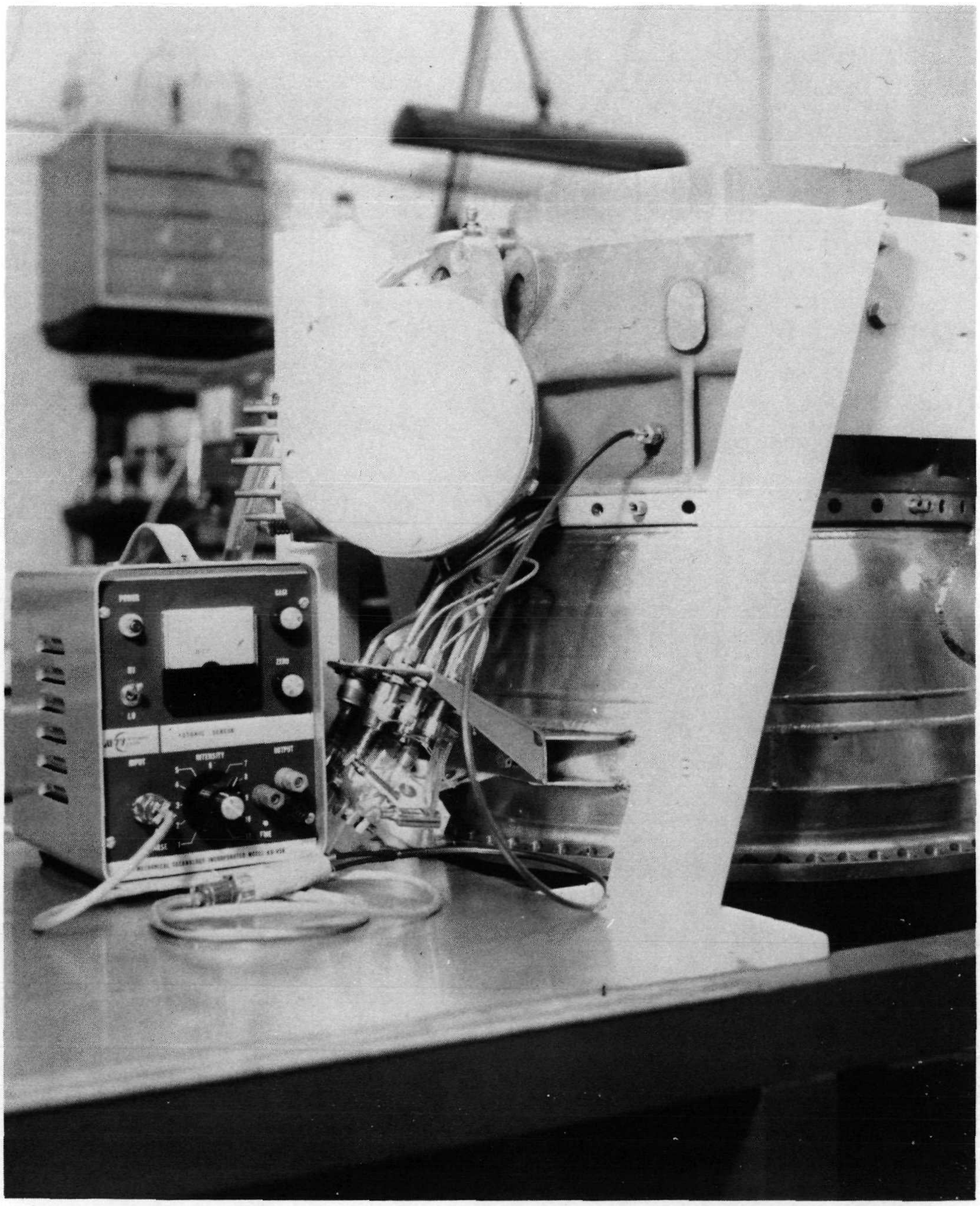


FIGURE 9. LIGHT-PIPE-REFLECTANCE PROBE MOUNTED IN TURBOPUMP AND INSTRUMENTATION

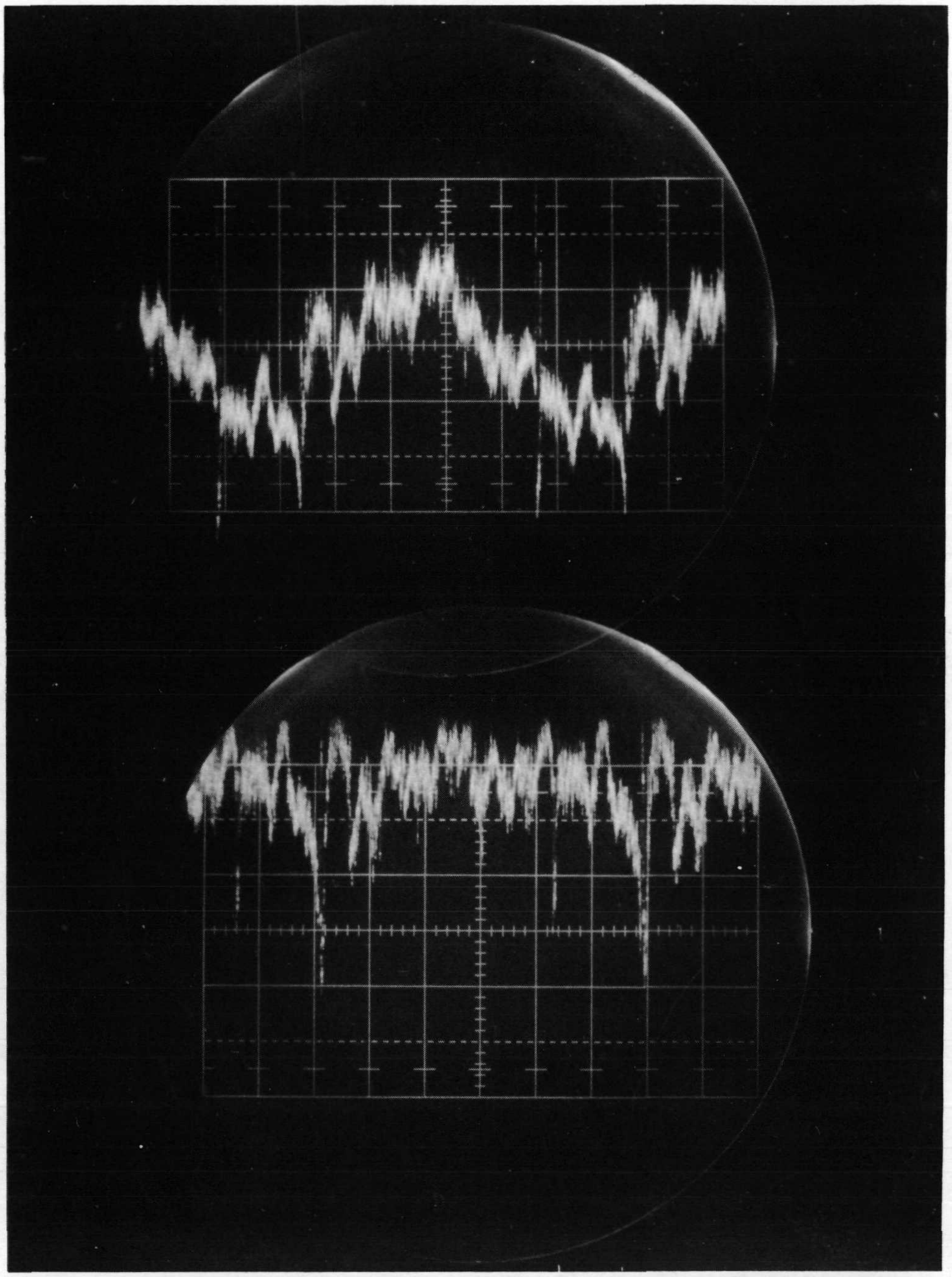


FIGURE 10. OSCILLOSCOPE TRACES OF OUTPUT FROM LIGHT-PIPE-REFLECTANCE UNIT

of the signal. This was confirmed by withdrawing the probe sufficiently far from the surface that the sensitivity to the gap was virtually nullified. The lower trace in Figure 10 shows that under this condition, while the effect of runout on the signal is gone, the probe indicates that the reflectance does indeed vary in a very complex manner around the periphery of the impeller. The correspondence of the high-frequency variation between the upper and lower traces shows that surface reflectance variation can be a problem but that high-precision measurements should be possible in the presence of such variance by suitably designed duplex probe arrangements.

An effort was made to reduce these reflectance variations by careful vapor-blasting of the surface of the impeller periphery. After replacing the impeller in the pump and filling the pump with degassed vacuum oil, the replicate traces shown in Figure 11 were obtained. The absence of extensive high frequency hash demonstrates the efficiency of careful surface preparation for reducing reflectance variations. Therefore, it should be possible in some applications of the probe to obtain high precision without resorting to reflectance compensation techniques.

The two single traces shown in Figure 11 were obtained about 100 revolutions apart. The exact duplication of signal between these and the many other traces recorded with the degassed oil in the pump show that the optical probe can be used in flowing liquid if bubble entrainment and cavitation is absent.

Cryogenic and High-Pressure Endurance

Endurance testing of a probe tip under helium pressure and at liquid-nitrogen temperatures has been conducted using the system shown in Figure 12. Connected to a helium tank is a pressure gage, a needle valve, high-pressure tubing to another needle valve, a high-pressure "T", and finally the pressurization chamber for the probe.

The pressurization tubing is arranged so that the test chamber can be lowered into a medium-sized cryogenic dewar. The photograph shown in Figure 12 was taken shortly after completion of a run with liquid nitrogen cooling. The dewar has been removed but the frost on the test chamber indicates that it has not yet warmed back to room temperature.

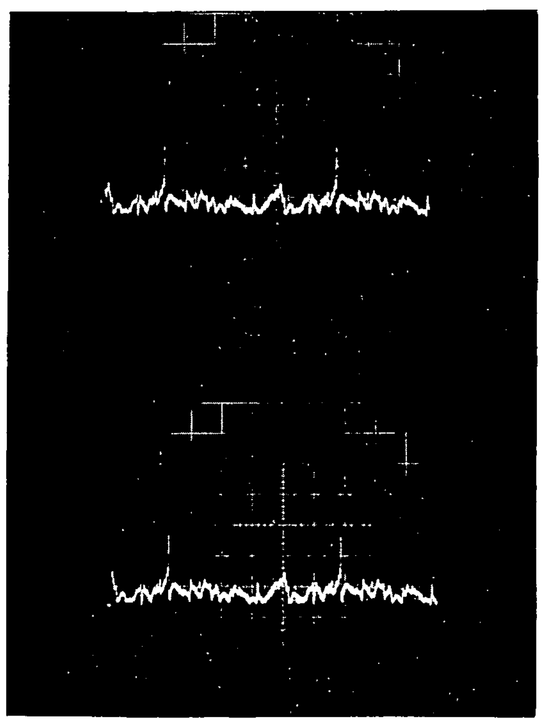


FIGURE 11. REPLICATE OSCILLOSCOPE TRACES OF OUTPUT FROM LIGHT-REFLECTANCE UNIT

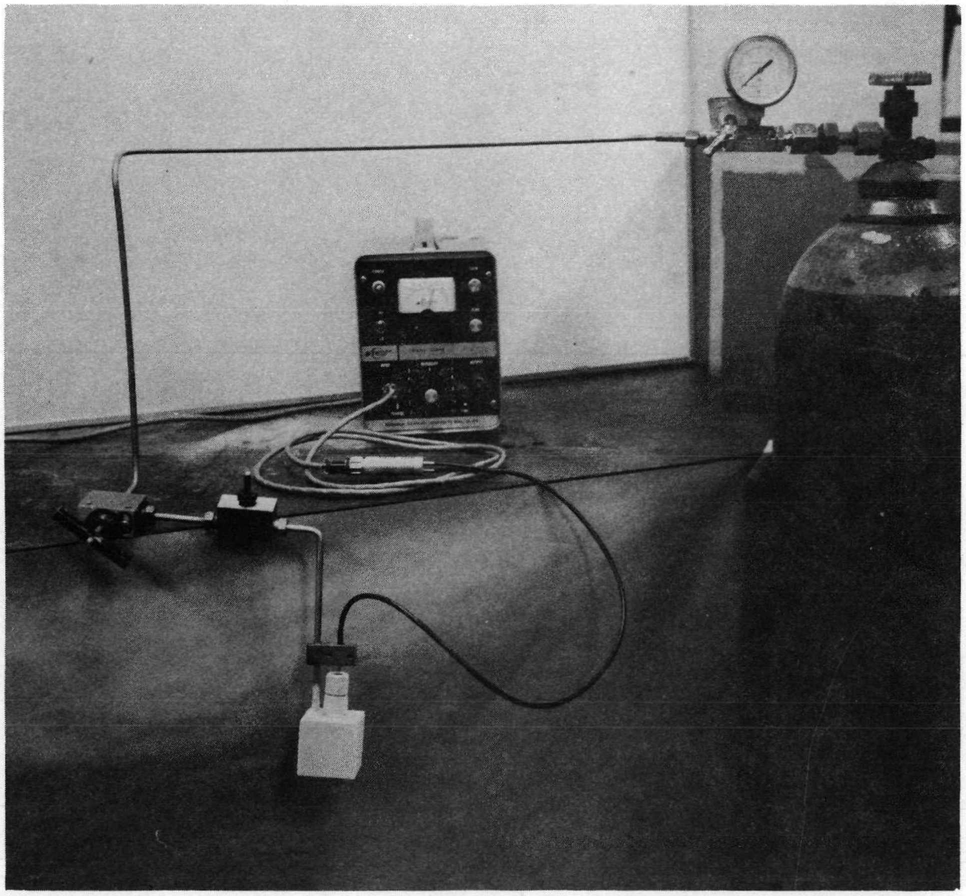


FIGURE 12. SYSTEM FOR TESTING EFFECT OF PRESSURE ON REFLECTANCE PROBE

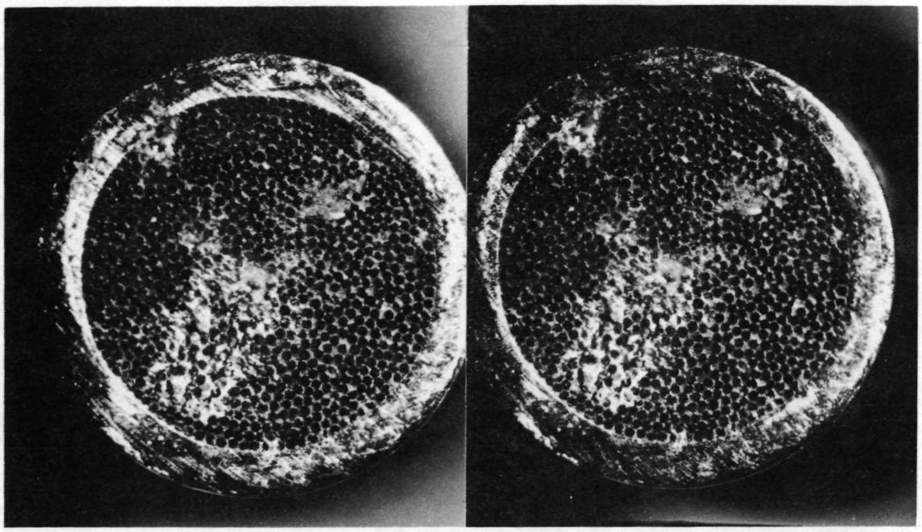
At the beginning of a pressure test, the probe is adjusted so that when the high-pressure Conax fitting is tightened, the probe is spaced from the bottom of the pressure chamber so as to be operating in the middle of its high sensitivity range. Operation of the reflectance probe system during pressure evaluation has shown that there is no noticeable effect on the optical performance of either cryogenic temperatures or pressurization to about 2200 psig.

The probe showed no signs of breakdown when first subjected to helium pressures of 2200 psig and then to liquid nitrogen immersion, each applied separately. When cooling and pressurization were combined, the probe leaked slightly.

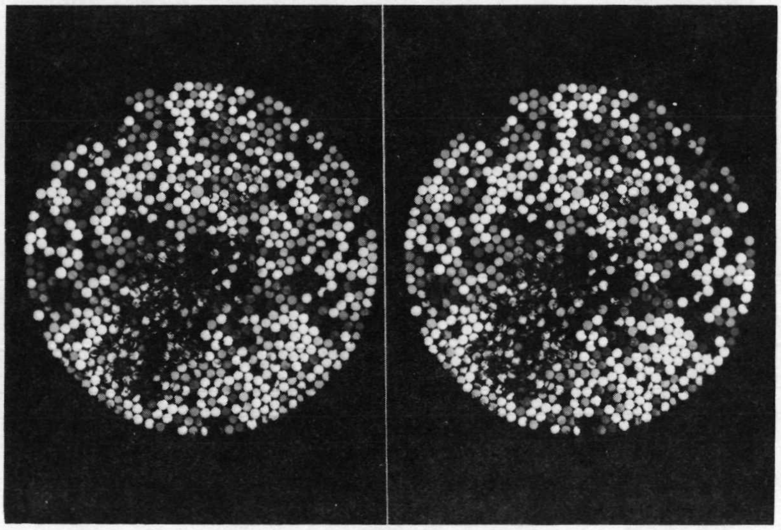
Examination after disassembly revealed that some dozens of the 600 glass fibers of the bundle had been forced several fiber diameters back into the tip. Stereo enlargements of the probe tip under two lighting conditions are shown in Figure 13. The tip area stretching from the center to the edge at the 7 o'clock position suffered the most extensive extrusion. This area had been roughened by slight contact with the rotating impeller during optical evaluations made earlier in the program and may, therefore, have been weakened.

The probe tip was repaired by forcing Armstong A-31 epoxy adhesive (an adhesive developed for cryogenic applications) into the probe surface using 1000 psi of helium pressure. The probe was removed from the pressure chamber, wiped free of excess adhesive, and baked at 165 F overnight in order to thoroughly cure the adhesive. The tip was then ground and lapped to remove the previously damaged surface and return it to a planar condition. The pressurization was repeated at room temperature and then at liquid nitrogen temperature. There was no sign of leakage this time when the pressure reached the maximum of 2150 psig, even at 77 K. The probe tip was examined subsequently and showed no sign of change. Whether or not the probe will withstand 7000 psi will be determined in Phase III.

The optical signal was carefully monitored as the pressure was raised in steps. The data indicate a linear change in gap as a direct function of pressure. The gap opened up by 280 microinches at room temperature with a pressure increase of 2150 psig. at 77 K, the change in gap was 110 microinches.



a. Reflected Light



b. Transmitted Light

FIGURE 13. STEREOPHOTOGRAPHIC PAIRS OF OPTICAL SENSOR PROBE TIP FOLLOWING HIGH PRESSURE CYROGENIC EXPOSURE

Since these changes were reversible, they indicate a mechanical flexing within the system as a function of pressure. If the flexing is assumed to take place in a length equivalent to the internal length of probe, then the equivalent modulus of rigidity is 13 x 10^6 psi and 32 x 10^6 psi at room temperature and 77 K, respectively. These are values that would be expected for glass at these temperatures. The observed gap enlargement may, therefore, result from compression of the glass fiber in the probe. Since this deflection is reversible and is predictable, it can be taken into account when measuring in a high-pressure pump.

Conclusions and Recommendations

The Phase II evaluation of the optical light/reflectance technique has been completed. A number of conclusions based on the literature and on the evaluations made during the current program can be stated

- Vibration amplitudes of 3 to 100 mils can be measured with a sensitivity of $\pm$1 percent of full range.
- Vibrational frequencies up to 100 kHz can be measured readily.
- Uniform surface reflectance is desirable in high precision measurements but compensation methods can be employed to circumvent such problems.
- Currently available probes are capable of at least 2150 psig at 77 K.
- Custom made probes should be capable of enduring 900 F at pressures of about 200 psig.
- Conax pressure fittings with Teflon glands are suitable for 2150 psig at temperatures down to 77 K.
- Wall penetration of at least 1/10-inch diameter is required for a probe.
- The optical technique becomes inoperable in the presence of gas entrainment or cavitation.

FLASH X-RAY TECHNIQUE

Field-emission equipment is available commercially which can supply a high-energy pulse of X-rays of about 20 nanoseconds' duration. Units are available which produce X-ray energies up to 2 megavolts.

During the first quarter, experiments with BCL's 300 kilovolt flash X-ray apparatus demonstrated the feasibility of using pulsed X-rays to observe position (and, therefore, deflection) of components within a housing where the thickness of heavy metal sections was not great. During the second quarter, application of the 300 kilovolt apparatus to actual J-2 pump components demonstrated that further development would require the use of a 2-megavolt unit. During the past quarter, portions of the J-2 pump were taken to McMinnville, Oregon, and flash X-radiographs were taken using a 2-megavolt X-ray unit. The portions radiographed were the turbine wheel assembly (Figure 14) and the shaft-bearing-seal assembly (Figure 16).

Initially, we found that we were unable to obtain sufficient contrast with the apparatus. The energy (2 megavolts) of the X-rays is so high that very few were absorbed to expose the photographic film being used. To increase exposure, a phosphor plate was placed behind the film. Backscattered radiation from the plate then provided greater exposure; however, the use of backscattering tends to reduce resolution.

Figure 15 shows a radiograph of the turbine wheel assembly, consisting of two wheels, two sets of rotatable blades, and a set of stationary blades separating the rotatable blades. The radiograph was, of course, taken with the assembly stationary. In Figure 15, the wheel axis is vertical, and the outer diameter of the wheels is at the left. The bright area at the bottom is a piece of lead, so brightness represents absorption. The X-rays were essentially passed through the wheels parallel to the plane of the wheels.

One of the items of interest is the position of the labyrinth seals on the wheels surrounding it. At the upper left of Figure 15, the single-convolution labyrinth seal on the upper wheel is clearly visible. As expected, the honeycomb material around it on the outside is nearly transparent to X-rays.

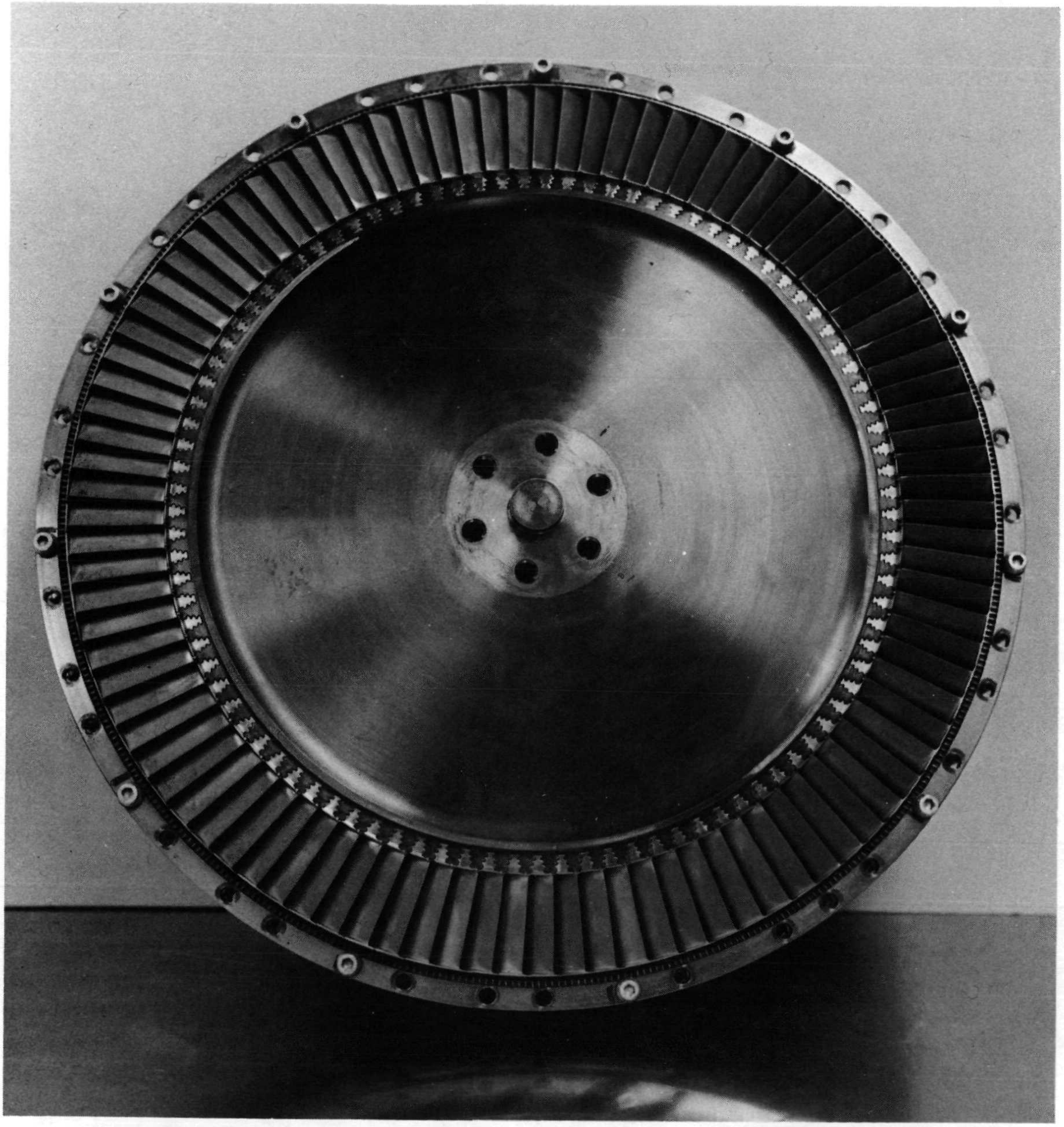


FIGURE 14. PHOTOGRAPH OF TURBINE WHEEL ASSEMBLY

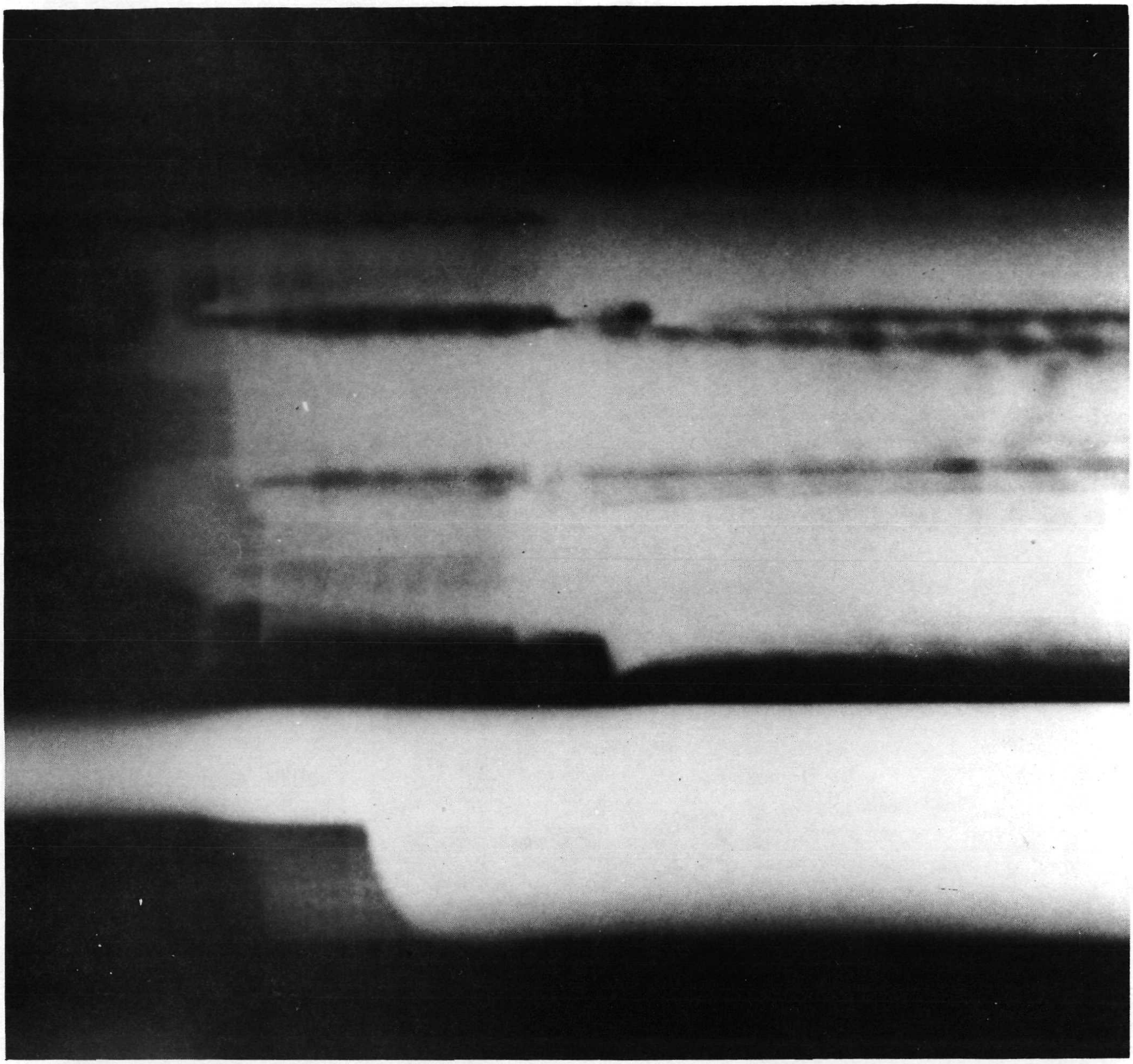


FIGURE 15. FLASH X-RADIOGRAPH OF TURBINE WHEEL ASSEMBLY

- Bright areas represent absorption; dark areas represent transmission.
- Exposure obtained with 2-megavolt X-rays.
- Wheel axis vertical.
- Bright area at bottom of photograph represents a lead block.

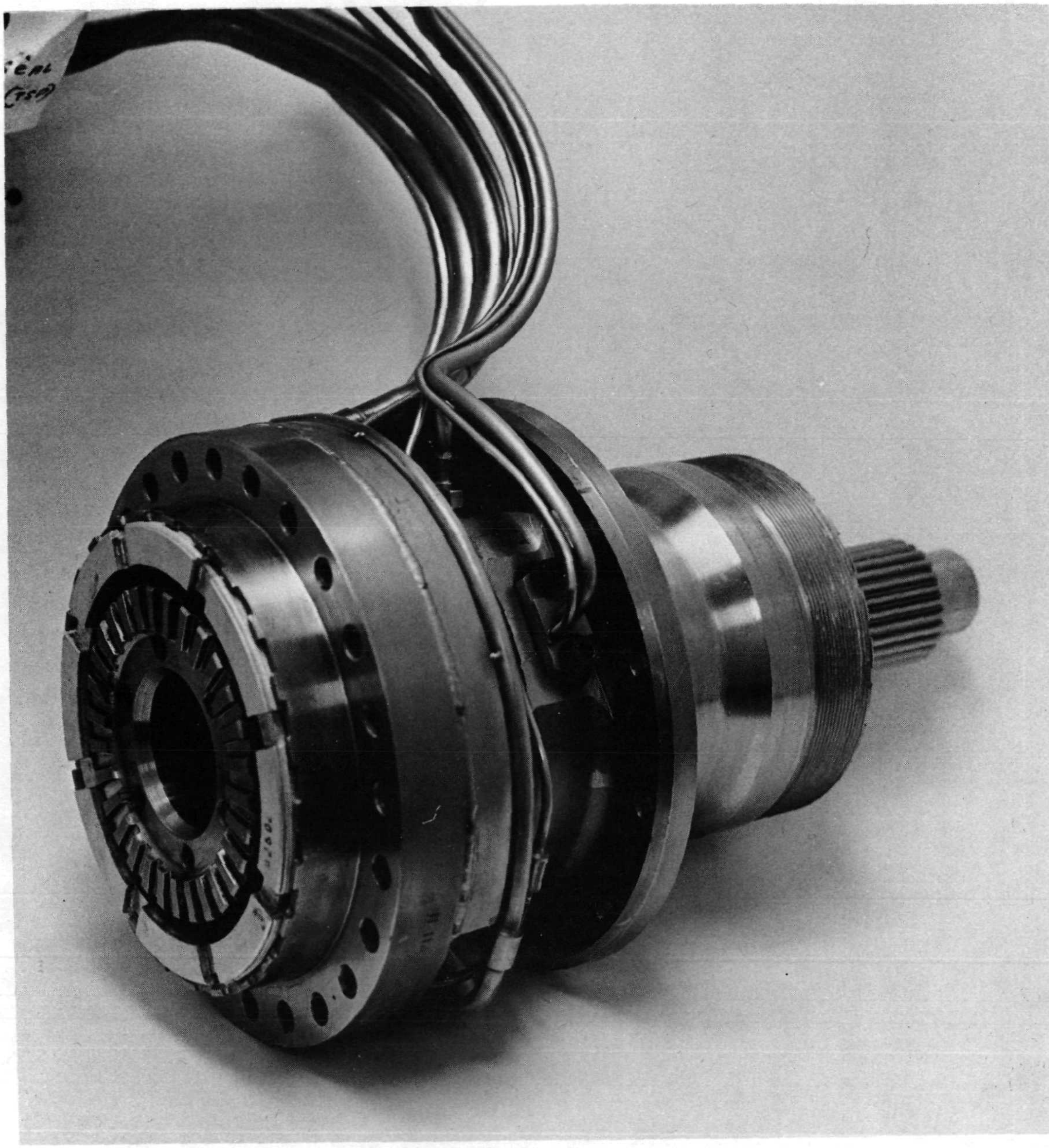


FIGURE 16. PHOTOGRAPH OF SHAFT-BEARING-SEAL ASSEMBLY

The fuzziness of some of the edges of the turbine blades is undoubtedly due to at least four things: backscattering from the phosphor plate, scattering in the metal components themselves, imperfect alignment of the X-ray beam with the plane of the wheels, and the finite size of the X-ray source.

We were initially puzzled that the relative dimensions of the bottom wheel in the radiograph in Figure 15 did not seem to agree with a cross-sectional drawing of the pump. In addition, the single-convolution labyrinth seal on the bottom wheel is obscured, whereas its counterpart is clearly visible on the top wheel. It seemed almost as if the bottom wheel were upside down. Now, several months later, we have found the explanation. The wheel is upside down. The mounting splines on both sides of the wheel are the same, permitting reversed installation.

Figure 17 shows a flash X-radiograph of the shaft-bearing-seal assembly. The shaft axis is nearly horizontal. The bearing balls are clearly visible as is the thickness of the shaft. Closer inspection also reveals various sets of holes drilled into the shaft and other components (the various features are significantly clearer on the original than on the halftone reproduction in this report). The seal assembly, to the left of the bearing, is only partially represented. Most of the seal components were removed before radiographing. The ring directly to the left of the bearing with a conical surface about 35 degrees to the horizontal is one of the stationary members of the seal.

Conclusions and Recommendations

The experiments demonstrated that the 2-megavolt X-rays are sufficiently penetrating to be useful for the turbopump application. The degree of scattering observed, however, is somewhat greater than expected. It is clear that further experiments are needed to determine the effect of numerous variables and methods. For instance, we did not use any photographic optimization techniques nor any shielding techniques to reduce scatter. Specifically, factors which affect the quality of the radiograph and need to be balanced empirically against each other include

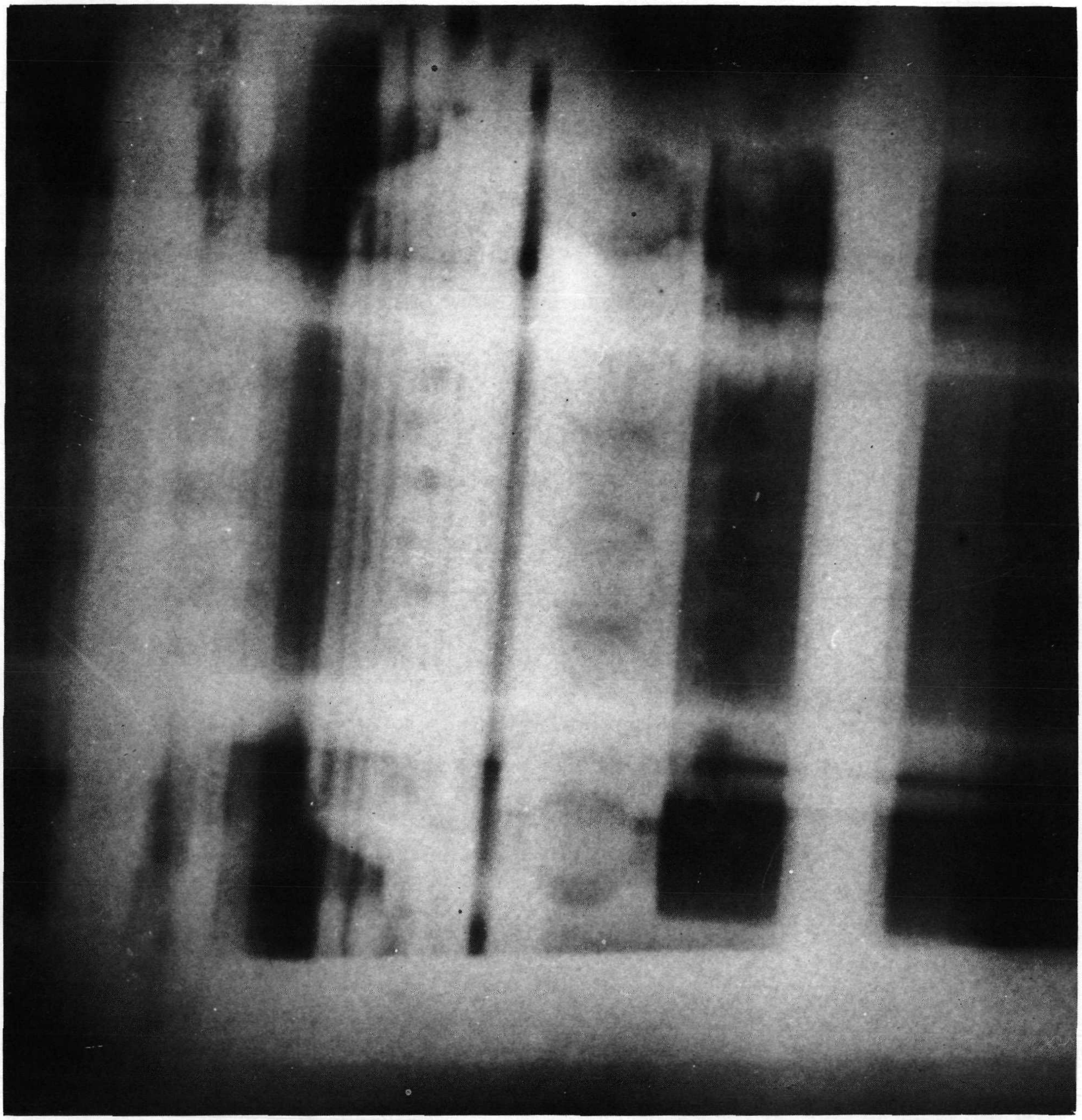


FIGURE 17. FLASH X-RADIOGRAPH OF SHAFT-BEARING-SEAL ASSEMBLY

- Bright areas represent absorption; dark areas represent transmission.
- Exposure obtained with 2-megavolt X-rays.
- Shaft axis horizontal.

(1) Source-to-object distance
(2) Source aperture
(3) Orientation of local areas in the pump with respect to the X-ray beams
(4) Shielding against unwanted scatter
(5) Film type
(6) Screens and filters (for films).

In order to minimize inconvenience and cost, we conducted a search for a closer X-ray machine, and we found an acceptable unit at the National Bureau of Standards, near Washington, D.C. The NBS is willing to cooperate with our needs for experimentation and space, and the use-rate of $25/hr is substantially less than elsewhere. To make the unit appropriate for our use, an X-ray tube costing about $1000 is required. NBS requests prepayment of use-rate to cover the tube purchase.

We have submitted costs requests to NASA-MSFC to cover the use of the NBS equipment, and we will begin experiments as soon as we receive authorization.

FAST-NEUTRON DEVICE

Evaluation during Phase I indicated that thermal neutron devices were not feasible because of insufficient intensity and excessively large source area. Since thermal neutrons are produced by moderating fast neutrons, however, fast neutron intensity may be 10^4 times greater than that for thermal neutrons. A fast-neutron detector was conceived and a Phase I feasibility study was performed.

Figure 18 is a sketch of the fast-neutron detector itself. A glass capillary tube is filled with liquid organic scintillator. Fast neutrons captured by the liquid scintillator ultimately produce light photons which are detected by a photomultiplier tube. Electrical pulses from the photomultiplier are taken through conventional amplifiers and scalers for shaping and storage.

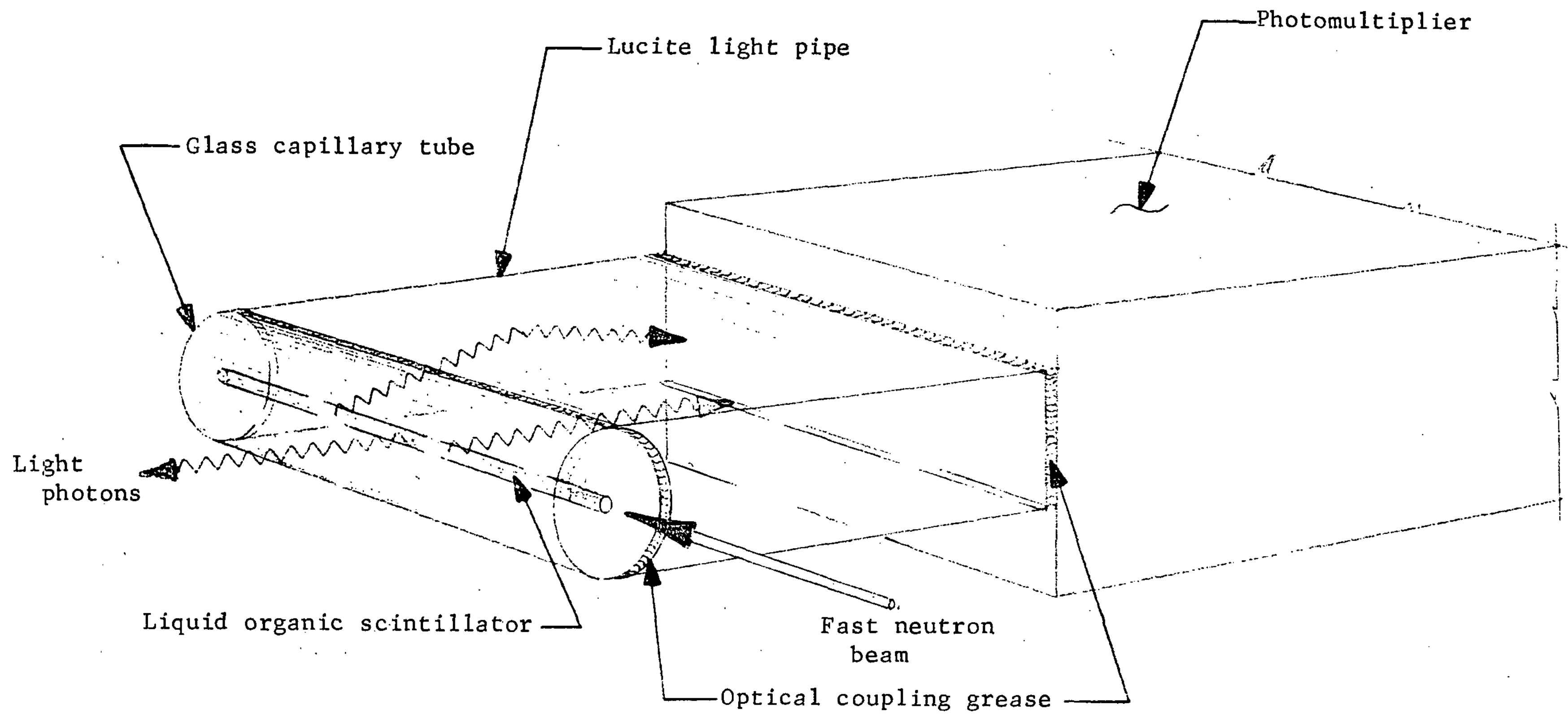


FIGURE 18. SKETCH OF FAST NEUTRON DETECTOR USED FOR EXPERIMENTS

Vibration of turbopump components is measured by locating the neutron source and the detector along the tangent to, say, a radially vibrating shaft or impeller. As the shaft or impeller vibrates in and out of the beam, more or less neutrons are absorbed and the change in intensity is noted at the detector. The use of a long, narrow tube of liquid scintillator is to provide directionality. When the axis of the tube is aligned with the direction of the beam, the intensity is maximum.

Two possible ways exist to make vibration measurements. The electrical signal from the photomultiplier could be gated over a short time interval corresponding to a particular shaft or impeller position, and neutron counts for this position integrated over a number of revolutions. Comparison of two positions 180 degrees apart would yield vibration displacement magnitudes. Such a measurement could be made with a relatively low intensity source. Conversely, the time interval could be enlarged, or the source intensity increased, to make a real-time measurement.

The detector used in the experiments has been a 0.63-cm (1/4 inch) diameter by 2-inch long glass tube with a 1.5 mm hole filled with NE-218 (Nuclear Enterprises, Ltd.). Experiments were performed using a weak plutonium-beryllium fast-neutron source.

Originally, light coupling to the photomultiplier was made through a flexible fiber-optic bundle. Sensitivity was disappointing: about 376,000 neutrons were counted in 10 minutes. In addition, photomultiplier sensitivity to neutrons and gamma radiation tended to obscure the desired signal. The use of the solid light pipe, however, improved the sensitivity by greater than a factor of 20.

Conclusions and Recommendations

Calculations were made on the basis of the experimental results to determine the relationship between them and the counting time required to obtain sufficient neutron counts. A pump diameter equal to a source-to-image distance of 51 cm (20 inches) was assumed, and the pump material was taken to be INCO 718. The calculated sampling time for detectors of from 0.4 mm to 2.5 mm in diameter is 40 milliseconds assuming a 100-mg californium-252 source and a gap varying from 0.25 mm to 0.5 mm (0.25 mm = 10 mils vibration amplitude). Sampling time is the total time the counting system would be gated to accept counts; i.e., if the gating interval were 1/10 revolution at 35,000 rpm, the pump would have to rotate about 240 revolutions, or 0.4 second, to achieve the 40 millisecond sampling time. The use of a 10-milligram source would require 2400 revolutions or 4 seconds.

These calculations are only approximate, but give a good idea of the times involved. To obtain real-time measurements with the above example, an intensity 200 times larger, or 20 g, would be needed. Predictions of costs of californium sources for the late 1970's are $2 to $3 per microgram. On this basis, a 10-mg source appropriate for integrated-time measurements would cost about $25,000, a 100-mg source about $250,000, and a 20-g source would be out of reach. On the other hand, the price of today's sources is considerably less than that predicted a few years ago, so real time measurements may someday be feasible. In any case, the technique has definitely been proved feasible for integrated-time measurements.

FUTURE WORK

Phase II efforts on both the fast-neutron device and the flash X-ray require further authorization. Phase III will be begun for the ultrasonic and the optical devices pending approval of the plans in the Appendix.

COST DATA

Contract value less fee - $95,010
Approximate actual expenditures to February 1, 1972 - $70,650
Estimated expenditures for February - $7,000
Estimated funds to completion - *
Anticipated over/under run - *.

---

* Requests for additional funds were submitted in February. Total contract funding will depend on whether or not the requests are authorized.

APPENDIX

RECOMMENDED PHASE III TEST PLAN

APPENDIX

RECOMMENDED PHASE III TEST PLAN

The following represents our recommended sequence for Phase III (Experimental Verification). The sequence covers the ultrasonic Doppler device and the light-pipe-reflectance. The general plan for the fast-neutron device has been submitted separately. The plan for the flash X-rays will be submitted after the conclusion of Phase II of the X-ray development; however, since the flash X-ray technique is truly a noncontacting technique, we do not anticipate that any cryogen testing or high-pressure evaluation will be necessary. In addition, the 20-nanosecond pulse time is many orders of magnitude shorter than the rotation time at 35,000 rpm, so high-speed testing also appears unnecessary. Unless further Phase II effort identifies problems of which we are now unaware, we will recommend that no Phase III testing is necessary for the flash X-ray technique.

The test plans for Phase III are listed below for the ultrasonic and optical techniques. Of course, Phase III effort will also include submission of a final summary report covering effort over all three phases.

ULTRASONIC DOPPLER DEVICE

We recommend that experiments be conducted to verify measurement capability for vibrational frequencies of 35,000 cpm, to subject ultrasonic transducers to vibrations representative of actual turbopump vibrations, and to measure vibrations of an alternate component in the existing J-2 LOX turbopump. In regard to high pressure or cryogen compatibility, we believe that these are not relevant since the transducers will be mounted on the outside of the case. In regard to acoustic properties of cryogens, we believe that the published data accurately characterizes LOX and LH_2, so no further verification is necessary. The following lists the test sequence.

A. Measurement of 35,000 cpm vibrational frequency

(1) Adapt existing apparatus to produce a 35,000 cpm vibration. This will either be done by driving

a shaft with a single eccentric at 35,000 rpm or a shaft with a multiple eccentric at a correspondingly lower speed, whichever proves more efficient.

(2) Measure vibration amplitude and compare with slow-speed or static-calibration measurements.

B. Vibration tests

(1) Construct a new, rugged set of transducers according to the basic design of Figure 4.

(2) Determine lead noise and efficiency of vibration coupling during operation while vibrating according to pump vibration specifications to be provided by NASA-MSFC.

C. Alternate component-vibration measurements

(1) Select alternate vibrating J-2 pump component (shaft, inducer, seal).

(2) Attach transducers to J-2 pump.

(3) Measure vibration amplitudes while rotating pump.

(4) Compare with static-calibration measurements.

LIGHT PIPE REFLECTANCE

Our Phase III recommendations involve subjecting the fiber optic bundle to conditions representative of turbopump operation, and evaluating the degree of effectiveness afforded by a rigid jacket to protect the probe from high-velocity fluid flow. In regard to measurement of vibration frequencies up to 35,000 cpm, we believe the Phase I effort verified this capability of the device. With respect to shock, our Phase II work has demonstrated the probe's ability to withstand considerable abuse.

The following experimental sequence is recommended.

A. Compatibility with high pressures and cryogens.

(1) Expose fiber-optic probe simultaneously to 7000 psi and 77 F liquid nitrogen.

(2) Measure calibration stability during exposure.

B. Exposure to high-velocity fluid flow.

(1) Fabricate a protective jacket.

(2) Install probe in high-velocity fluid stream.

(3) Verify optical properties following exposure.

MONTHLY AND QUARTERLY PROGRESS REPORT DISTRIBUTION LIST

	No. Copies
National Aeronautics and Space Administration George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812 Attention Contracting Officer (A&TS-PR-M)	1
National Aeronautics and Space Administration George C. Marshall Space Flight Center Marshall Space Flight Center, Alabama 35812 Attention Management Services (A&TS-MS-IL)	1
Security Office (A&TS-MS-S)	1
Mr. Forrest Pitsenberger (S&E-ASTN-EPS) Technical Manager	5
Mr. B. Birdwell (S&E-ASTN-RRI)	1
Mr. H. Attaya (S&E-R-R)	1
National Aeronautics and Space Administration Assistant Director for Propulsion, OART, Code RP Washington, D.C. 20546 Attention Dr. Robert Levine	2
National Aeronautics and Space Administration Lewis Research Center 21000 Brookpark Road Cleveland, Ohio 41135 Attention Mr. Irvin Johnsen	1
Captain Robert Probst Engineering Development Branch Air Force Rocket Propulsion Laboratory Edwards, California 93523	1
Jet Propulsion Laboratory Liquid Propulsion Section 4800 Oak Grove Drive Pasadena, California 91103	1
National Aeronautics and Space Administration Washington, D.C. 20546 Attention Dr. Eldon Hall, Code MTG	1
Mr. Stanley E. Write Defense Supply Agency DCASR-Cleveland Office of Engineering-DCRO-Y 1240 E. 9th Street Cleveland, Ohio 44199	1
Scientific and Technical Information Facility P. O. Box 33 College Park, Maryland 20740 Attention NASA Representative, Code CRT	1