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**DEVELOPMENT OF THE
UNDER-SODIUM ULTRASONIC SCANNER**

AEC Contract No. AT (11-1)-865 Project Agreement No. 14

Division of Reactor Development and Technology

C. C. Scott

Shuh-Pan Ying

October 1967

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ABSTRACT

A scanning system that employs a focusing transducer for producing a single narrow ultrasonic beam for locating and discerning objects in high-temperature opaque media, such as 600 F liquid sodium, has been developed. In this report, the feasibility studies that preceded development of the system and the developmental work involving acoustic parameters, design and analysis of the mechanism, experimental results, and practical demonstrations are discussed. The focusing transducers were operated at frequencies of 2.25 and 5 Mc/sec with lead zirconate-titanate piezoelectric ceramic disks at distances from 1/4 inch to approximately 3 feet from the targets. The zirconium planospherical lenses of the focusing transducers not only provided single focusing points but also, suppressed side lobes radiated from the transducers at distances far beyond the focal points. The direction and the range of a target were read from the orientation of the transducer and the cathode ray oscilloscope, respectively. For display of images of targets, a current-sensitive helix wire recorder was used. The scanner resolution for both distance and orientation was found satisfactory.

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I. PREFACE

A. SCOPE

The scope of the under-sodium scanner test program is to develop and evaluate devices for locating and discerning objects in liquid sodium. With the determination of ultrasonic attenuation in liquid sodium and with the evolution of transducers operating at high temperatures,¹ the concept of the utilization of ultrasonics for general-purpose under-sodium scanning systems has been established and documented.² The present phase of the work includes the following objectives:

1. To develop and evaluate narrow-beam transducers for operation in 600 F sodium that will be used as search units for scanning systems.
2. To engineer, design, fabricate, and initiate testing of under-sodium single transducer scanning systems that will provide locations and images of objects in sodium.

B. RELATIONSHIP TO OTHER PROJECTS

A general-purpose scanning system will have application to projects in which liquid metals are used as the heat transfer media. Such a system will permit objects in liquid sodium to be discerned by means of sound waves and will, therefore, simplify maintenance and fuel handling procedures for nuclear reactors.

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II. INTRODUCTION

The major problem in using ultrasonics for under-sodium scanning is that transducers are not commercially available which can operate in such a medium at high temperatures. To overcome this problem, the conceptual designs of two methods for viewing objects immersed in liquid sodium have been formulated: the single narrow-beam transducer and the electronic acoustic image conversion system. The developmental work for the former, including the results of tests, is discussed in this report. The second method, although promising, is still being developed.

Ultrasonic detection methods are already being used in industry, and applications for such methods are steadily increasing as time continues. For example, ultrasonic nondestructive testing, which is based on the same fundamental principles as the single transducer scanner, is well established in ferrous metallurgical plants and in the machinery and transportation industries. In many instances only ultrasonic detection can be used for control purposes. This is true in the inspection of steam turbine rotors, which frequently are three feet in radius, because neither X rays, gamma rays, nor other electromagnetic waves can penetrate the thickness of the metal. Metal penetration is the basic reason why the ultrasonic method was selected for the under-sodium scanner.

The use of ultrasonic energy for testing was first suggested by Sokolov,³ who used the continuous ultrasonic wave method; however, this method was found to have limited applicability. The use of pulsed ultrasonics^{4,5} though, has largely eliminated most of the problems intrinsic to the continuous-wave method. The pulse technique, in conjunction with recently developed electronic devices, is used in the under-sodium scanner.

Prior to developing the single narrow-beam transducer, both theoretical and experimental results indicated that the attenuation in liquid sodium is sufficiently low for ultrasonic scanning. As can be seen from Figure 1, beams can be transmitted up to 10 feet and more with no significant loss in intensity when transducer frequencies are between 1 and 3 Mc/sec. At higher frequencies (up to 10 Mc/sec) transmitted intensity can be sufficient up to one foot.

When sound waves are traveling in a medium, such as liquid sodium, they will be reflected from and refracted by the surface of an object if that object is large compared to the wave length. Surface reflection and refraction occur because of the discontinuity of acoustic impedances or because of an abrupt change in the elastic properties at the boundary of the medium. For the case of a stainless steel target immersed in liquid sodium, 83% of

FIG. 1 INTENSITY ATTENUATION IN LIQUID SODIUM

the normal incident intensity will be reflected from the target's surface.² This is sufficient reflection for an ultrasonic scanner to locate and discern such objects in that medium. The determination of the direction and distance of an object is based on the directivity of the ultrasonic transducer and on the velocity of sound in liquid sodium. (As the temperature of sodium varies from its melting point to 600 F, the velocity of sound ranges from 2.526×10^5 to 2.412×10^5 cm/sec.)

In the course of developing the under-sodium scanner discussed in this report, two modes of operation were used: the A-scan and the C-scan. The former was used to locate objects and to determine their distances from the transducers, and the latter was used to define objects through line-by-line scanning. Both modes of operation worked satisfactorily in liquid sodium at temperatures as high as 600 F.

III. FEASIBILITY STUDIES

A. THEORY OF ULTRASONIC ATTENUATION IN LIQUIDS

Whenever sound waves propagate through a fluid medium, there is a loss of acoustic energy. The sources of this loss may be divided into two general categories: those associated with conditions at the boundaries of the medium and those due to the dissipation of acoustic energy in the medium itself. The first type of loss is of particular significance when the volume of the fluid is small in comparison with the area of the boundary walls. In an unbounded medium, the intensity of a plane wave decreases in accordance with the equation⁶

$$I = I_0 e^{-2\alpha x} \quad (1)$$

where the intensity I_0 falls to a value I after traveling a distance x , and α is the intensity absorption coefficient of a plane wave. The common explanation of the second type of loss, the absorption of ultrasonic energy in the medium itself, is that it is due to the shear viscosity η_S , the bulk viscosity η_B , and the thermal conductivity K of the fluid. The shear viscosity and thermal conductivity contribute to the so-called "classical absorption" of ultrasonic energy in the medium

$$\alpha_{\text{class}} = \alpha_S + \alpha_T \quad (2)$$

The absorption due to shear viscosity, given by Stokes,⁷ is

$$\alpha_S = 8\pi^2 f^2 \eta_S / 3\rho c^3 \quad (3)$$

where

f = frequency of the sound wave
 ρ = mean density of the medium
 c = velocity of sound in the medium

And the absorption due to thermal conductivity, given by Kirchoff,⁸ is

$$\alpha_T = \left(\frac{2\pi^2 f^2}{\rho c^3} \right) \left(\frac{\gamma - 1}{c_p} \right) K \quad (4)$$

where

$$\begin{aligned}\gamma &= c_p/c_v \\ c_p &= \text{specific heat at constant pressure} \\ c_v &= \text{specific heat at constant volume} \\ K &= \text{thermal conductivity}\end{aligned}$$

In most liquids, as a result of various relaxation processes, the measured absorption is greater than the classical value. The excess absorption is formally accounted for by the introduction of a bulk viscosity leading to an absorption⁹

$$a_B = 2\pi^2 f^2 \eta_B / \rho c^3 \quad (5)$$

The expression for the commonly observed absorption can be expressed by

$$a_{\text{obs}} = a_S + a_T + a_B \quad (6)$$

B. ULTRASONIC ABSORPTION IN LIQUID SODIUM

Ultrasonic absorption in liquid sodium has been measured in the temperature range of 220 to 600 F with frequencies of 4 and 5 Mc/sec. As the distance of travel for sound waves increases, the intensity decreases exponentially; this agrees with the case of Eq (1). From Eqs (3) through (6), the absorption coefficient and the frequency have the relation

$$\frac{a}{f^2} = \frac{2\pi^2}{\rho c^3} \left[\frac{4}{3} \eta_S + \eta_B + \left(\frac{\gamma - 1}{c_p} \right) K \right] = \text{constant} \quad (7)$$

at constant temperature.

For almost all liquids, Eq (7) is satisfied experimentally over a wide range of frequencies, i. e., the experimental results agree with this relation. The experimental data which are the average value of the comparable results for the measurements at each temperature are presented in Figure 2. The solid line was obtained by the method of least squares from experimental data. At the temperature of 600 F, the experimental data of a/f^2 is $21 \times 10^{-17} \text{ sec}^2 \text{ cm}^{-1}$. This is lower than that of water where a/f^2 is $24 \times 10^{-17} \text{ sec}^2 \text{ cm}^{-1}$ at 59 F.¹⁰

C. ACOUSTIC VELOCITY, COMPRESSIBILITY, AND SPECIFIC HEAT OF LIQUID SODIUM

From Eq (7), the absorption coefficient is inversely proportional to the cube of the velocity of sound. Therefore, it was necessary to determine the velocity of sound in liquid sodium in the temperature range of attenuation measurements to investigate experimental data. Figure 3 shows the velocity of sound in liquid sodium measured at various temperatures. The results are in good agreement with data obtained by Pochapsky.¹¹

FIG. 2 ULTRASONIC ABSORPTION IN LIQUID SODIUM

FIG. 3 VELOCITY OF SOUND IN LIQUID SODIUM

The specific heat at constant volume c_v in Eq (4) can be calculated from values obtained from the measurements of acoustic velocity. Since adiabatic compressibility K_S is given by

$$K_S = 1/\rho c^2 \quad (8)$$

where

S = constant entropy
 ρ = density
 c = velocity of sound

the isothermal compressibility K_T can be calculated from

$$K_T - K_S = T\beta^2/\rho c_p \quad (9)$$

where

β = coefficient of volume expansion
 T = temperature, $^{\circ}\text{K}$
 c_p = specific heat at constant pressure

It follows, then, that specific heat at constant volume c_v can be obtained from

$$c_v = K_S c_p / K_T \quad (10)$$

Data are available at temperatures below 522 F;¹² therefore, K_S , K_T , and c_v are calculated only at 600 F from the results of the acoustic velocity measurements at this temperature. The results are listed in Table 1, together with data at lower temperatures.

D. CLASSICAL CALCULATION OF ABSORPTION COEFFICIENT

To obtain a comparison between the experimental data of ultrasonic attenuation and the values derived from classical theory, values for the relation $\alpha_{\text{class}}/f^2$ were calculated from 220 to 600 F, using Eqs (2), (3), and (4). A part of the data for the calculations is listed in Table 2; other data were obtained from Sittig.¹² The results are shown in Figure 2. The dotted line, which was obtained by the method of least squares from the results of classical calculations, can be represented by the following equation:

$$\frac{\alpha_{\text{class}}}{f^2} \times 10^{17} = (4.68867 + 0.0219582t) (\text{sec}^2 \text{ cm}^{-1}) \quad (11)$$

where

t = temperature of liquid sodium, F

TABLE 1 - COMPRESSIBILITY AND SPECIFIC HEAT OF LIQUID SODIUM

Temperature, F	$c \times 10^{-5}$, cm/sec	ρ , gram/cm ³	$K_S \times 10^5$, atm ⁻¹	$K_t \times 10^5$, atm ⁻¹	c_p , cal/C gram	c_v , cal/C gram
208.1	2.526	0.9270	1.713	1.888	0.33088	0.30025
300	2.499	0.9155	1.771	1.986	0.32517	0.29001
400	2.471	0.9028	1.836	2.095	0.31970	0.28008
500	2.441	0.8898	1.911	2.225	0.31479	0.27041
600	2.412	0.8770	1.986	2.356	0.31065	0.26160

TABLE 2 - ULTRASONIC ABSORPTION COEFFICIENT AND
BULK VISCOSITY OF LIQUID SODIUM

Temperature, F	$(a_{\text{class}}/f^2) \times 10^{17}$, sec ² cm ⁻¹	$(a_{\text{obs}}/f^2) \times 10^{17}$, sec ² cm ⁻¹	η_S , Centipoise	η_B , Centipoise
208.1	9.258	11.365	0.690	1.587
300	11.276	13.294	0.545	1.460
400	13.472	15.392	0.445	1.325
500	15.668	17.490	0.376	1.195
600	17.864	19.587	0.329	1.075

E. SUMMARY OF EXPERIMENTAL RESULTS

A comparison of the results of ultrasonic attenuation derived from classical calculations and those obtained from measurements indicates that liquid sodium exhibits relatively little excess absorption. The excess absorption is mainly due to the bulk viscosity η_B which is ignored in the classical calculation of ultrasonic attenuation. Since the bulk viscosity of a monatomic fluid, such as a liquid metal, can possibly be caused by a structural relaxation process, and since $\partial\eta_B/\partial T$ is usually negative,¹³ η_B of liquid sodium derived from experimental results and classical calculations have similar values at temperatures below 500 F. From 500 to 600 F, experimental results indicate an excess absorption of 7%, which is possibly caused by an increase in impurities in the sodium. Experimental results applying this correction can be expressed by the following equation, using the method of least squares:

$$\frac{a_{\text{obs}}}{f^2} = (6.99836 + 0.0209836t) (\text{sec}^2 \text{ cm}^{-1}) \quad (12)$$

where

$$\begin{aligned} a_{\text{obs}} &= \text{measured absorption coefficient} \\ f &= \text{frequency} \\ t &= \text{temperature of liquid sodium, F} \end{aligned}$$

Therefore, from Eqs (11) and (12) the excess absorption of liquid sodium can be obtained for various temperatures, and the bulk viscosity can be calculated from the excess absorption and Eq (5)

$$\eta_B = \frac{\rho c^3}{2\pi} \left(\frac{a_{\text{obs}} - a_{\text{class}}}{f^2} \right) \quad (13)$$

The values obtained from Eqs (11), (12), and (13) are listed in Table 2 which indicates $\partial\eta_B/\partial T$ is negative. The ratio of η_B/η_S is 3 at 400 F, and changes approximately 20% for temperature changes between 208.1 and 600 F.

IV. ULTRASONIC SCANNING SYSTEM COMPONENTS

A. TRANSDUCERS

To obtain high resolution of an image from an ultrasonic transducer, such as the transducer shown disassembled in Figure 4, a narrow radiation beam is very desirable. The selection of a planospherical lens material is difficult, however, because it is necessary to have a good acoustic impedance match between the lens and the piezoelectric disk (lead zirconate-titanate) and between the lens and the sodium into which the ultrasonic waves are transmitted. At the same time, it is necessary to have a velocity of sound in the lens that is different from that in the sodium. The requirements for index of refraction and acoustic impedance may be stated as follows:

$$n = c_1/c_2 \neq 1 \quad (14)$$

$$r_{12} = c_1 \rho_1 / c_2 \rho_2 \approx 1 \quad (15)$$

where

- n = the index of refraction
- r_{12} = the ratio of characteristic acoustic impedance of medium 1 and medium 2
- c_1 = the velocity of sound in medium 1
- c_2 = the velocity of sound in medium 2
- ρ_1 = the density of medium 1
- ρ_2 = the density of medium 2

Although materials can be found that satisfy these requirements, many of them cannot be used in high-temperature liquid sodium. For example, Ernst¹⁴ and Sette¹⁵ have pointed out the suitability of two plastics, Plexiglas and polystyrene, for use as converging lenses for sound waves. However, neither of these materials can be used in 600 F liquid sodium. Of those materials that can be used in such an environment, zirconium was found to possess the best overall qualities for a planospherical lens. As can be seen from Table 3, zirconium, when compared to other focusing transducer materials, exhibits satisfactory acoustic matching with both sodium and lead zirconate-titanate (commercially known as PZT-5). Also indicated in Table 3 is a list of the indexes of refraction of various focusing transducer materials--the metals with respect to sodium and the plastics with respect to water. From this list, it can be seen that zirconium has a slightly higher but still quite acceptable index of refraction when compared to those of the two plastics.

TABLE 3 - ACOUSTIC PARAMETERS OF FOCUSING
TRANSDUCER MATERIALS

<u>Material</u>	<u>Characteristic Acoustic Impedance x 10⁻⁶, g/cm²-sec</u>	<u>Index of Refraction, n</u>	<u>Surrounding Medium</u>
Sodium	0.2131	1.000	
Polystyrene	0.26	1.60	Water
Plexiglas	0.33	1.90	Water
Zirconium	2.98	1.92	Liquid Sodium
Nickel	4.85	1.97	Liquid Sodium
Steel	4.67	2.39	Liquid Sodium
Tungsten	10.00	2.25	Liquid Sodium
Lead Zirconate- Titanate, PZT-5	2.80		

The focal length of a planospherical concave lens is dependent upon the radius of curvature of the lens and upon the acoustic index of refraction of the lens in a given medium. The relation among the focal length f , index of refraction n , and radius of curvature R is given by

$$f = R \left(1 - \frac{1}{n} \right)^{-1} \quad (16)$$

Twelve zirconium lenses with various diameters and radii of curvature were procured for evaluation. The diameters, radii of curvature, and focal lengths of the lenses were calculated from Eq (16) for both liquid sodium and water environments. Table 4 is a compilation of the calculated values. Since the cross section of the beam width at the focal plane is related to the physical size of the lens, the lenses that were procured provided different focal lengths with various beam widths. The results of the evaluation of the lenses operating in both liquid sodium and water were obtained analytically and are presented in Section V of this report.

To reduce the effect of multiple reflections from the boundary of the lens and sodium medium, a backing block should be attached to the back face of the piezoelectric disk, as is shown in Figure 5. Several geometrical shapes of the backing block were investigated to obtain optimum attenuation. By using the ray theory of reflection, the transmission paths can be easily found. A typical normal incident ray path in a backing block is shown in Figure 6. As can be seen from Figure 6, the geometry of the block consists

FIG. 4 NARROW-BEAM TRANSDUCER COMPONENTS

FIG. 5 FOCUSING TRANSDUCER WITH METAL LENS

FIG. 6 A TYPICAL RAY PATH IN BACKING BLOCK

of two cones (θ_1 , θ_2) and two cylinders. The ray will not return to the incidence point A on the piezoelectric disk if the angle θ_2 is slightly greater than the angle θ_1 . In the present design $\theta_1 = 30^\circ$, $\theta_2 = 35^\circ$, and surface S_1 is a convex cone. Evidently, either a concave conical surface or a concave spherical surface can be used to obtain optimum attenuation. In either case, the reflection rays from the back surface S_1 will transmit divergently into the backing block.

TABLE 4 - DIMENSIONS OF ZIRCONIUM LENSES AND
THEIR CALCULATED FOCAL LENGTHS

Lens No.	Diameter, Inches	Radius of Curvature, R, Inches	Focal Length, f, Inches	
			in Liquid Sodium ($n = 1.92$)	in Water ($n = 3.14$)
1	1.250	4.000	8.36	5.88
2	1.250	2.500	5.25	3.68
3	1.250	1.500	3.14	2.21
4	1.000	2.000	4.18	2.94
5	1.000	1.250	2.67	1.84
6	1.000	0.750	1.57	1.10
7	0.750	3.000	6.27	4.41
8	0.750	1.000	2.09	1.47
9	0.688	0.375	0.78	0.55
10	0.625	0.500	1.04	0.735
11	0.625	0.375	0.78	0.55
12	0.563	0.250	0.52	0.368

B. ELECTRONIC SYSTEM

A block diagram of the electronic system used in the test and evaluation program is shown in Figure 7. Pulses used to synchronize the pulse transmitter, the gating system, and the oscilloscope were provided by a pulse generator. Pulse widths of 1 μ sec or less were often used. A receiver, a Transigate E550, and a Type S digital amplifier were used to accept the signals from the transducer. The electronic equipment had carrier frequencies of 2.25, 5, and 10 Mc/sec, and the output of the pulse transmitter with a load was greater than 1 kv peak-to-peak. A coaxial cable RG-63B/U with low distribution capacitance to reduce distortion of the narrow high-frequency pulses was used for the transmission line between the electronic receiver and the ultrasonic transducer. The receiver had sufficient gain and excellent signal-to-noise ratio. Its maximum output to the Transigate was about 7 volts peak-to-peak.

FIG. 7 BLOCK DIAGRAM OF ELECTRONIC SYSTEM

The Transigate was used for both the gate generator and the gate. It established specific, controllable gated areas or zones within the detection distance. Reflection signals appearing within the gate were monitored automatically to operate visual and/or audible alarms. Simultaneously, the Transigate also provided a digital signal of constant amplitude (-10 volts DC) that was used for solenoid operation of the C-scan recorder pin. The gate starting point and the gate length could be varied over a range from 2 to 3000 μ sec, which corresponded to a range in sodium of 0.2 inch to 23 feet. The output of the digital amplifier was adjustable from 0 to 60 volts at 200 ohms impedance, and maximum current was 0.30 amp. Automatic short circuit protection was provided.

The output of the receiver was also fed into channel A of a dual trace oscilloscope which, in turn, indicated the time separation between the transmitted pulse and the echo from a target to form an A-scan. Channel B of the oscilloscope accepted the signal from the gate generator and indicated the gate waveform on the screen. With this display, the gate starting point and the gate length could be adjusted properly for the echo of interest.

C. SODIUM FACILITY

The tank for conducting the under-sodium scanning tests was made from Type 304 stainless steel. The tank, whose dimensions were 42 inches long, 19.25 inches wide, and 20.5 inches deep, was designed for installation under a dry box (Figure 8) in which argon was circulated to provide the liquid sodium with a dry cover gas. The design of the facility made it possible to adjust the separation of the transducer, reflector, and target up to a maximum distance of 30 inches. In addition, the design permitted easy adjustment of all three in azimuth or elevation. A cover gas purification system, model HE-93, manufactured by the Vacuum/Atmospheres Corporation, was installed on the facility, and during the experiments, this system maintained an atmospheric purity of 1 ppm of oxygen and 0.1 ppm moisture. DuPont reactor grade sodium, with impurities listed by volume at 50 ppm chlorides and 400 ppm calcium, was used in the experiments. The sodium was first melted in the original shipping container and then transferred to the test tank through a filter and a stainless steel tube by pressurizing the shipping container with argon. Once in the test tank, the sodium was heated to 600 F by electric resistance heaters that were controlled by a manual and automatic temperature control system.

D. SCANNING MECHANISM

The primary function of the scanning mechanism (Figure 9) is to provide a means by which an ultrasonic scanner type of spatial mapping can be investigated in a liquid sodium environment. The mechanism is comprised of three main units, which are as follows:

FIG. 8 UNDER-SODIUM TEST FACILITY

FIG. 9 SODIUM FACILITY GLOVE BOX INTERIOR SHOWING MOUNTED C-SCAN MECHANISM

- The first unit is an X-Y positioning system that is driven by stepping motors. Mounted on the positioning system is the transducer for C-scan mapping. The transducer is capable of traversing an area of 9.25 by 9.25 inches.
- The second unit is a recording system that is positioned by stepping motors. This system accepts the output current of the digital amplifier from the electronic receiving system when the transducer, which moves synchronously with the recording system, receives reflection signals from the target. This current provides modulation intensity to the recorder pen. The recorder paper utilized, made by Alfax Paper & Engineering Company, is current sensitive. The Alden Electronics Company helix wire recorder, Model 311 DA, can thus be used to provide, with appropriate probe signal ranging, a quasi-three-dimensional picture of the volume scanned.
- The third unit is a central control system. This system contains all the control functions and indicating devices for automatic operation. The basic scan rate of the system in the horizontal X direction is 1-1/2 inches per second. With the recorder system resolution set at 0.010 inch, the levels of vertical Y-direction increments are 0.025, 0.050, 0.100, and 0.200 of an inch.

V. EXPERIMENTAL INVESTIGATIONS OF TRANSDUCERS

The resolution of an object that can be obtained by an ultrasonic scan is a function of the cross section of the ultrasonic beam at the object. Ultrasonic beam cross sections were measured in water to obtain a knowledge of the beam patterns radiated from the zirconium lenses. This was essential because no technical information on zirconium lenses was available. Measurements made in liquid sodium at 600 F later in the program confirmed that transducer characteristics in room-temperature water and 600 F liquid sodium are similar.

The ultrasonic beams were measured at their calculated focal planes by fixing the transducers in stationary positions and moving 0.187-inch stainless steel targets perpendicularly to the principal axes of the beams. The distances between transducers and targets were determined from the calculated focal points shown in Table 4. While the targets were being moved, the echoes of different amplitudes were read from an oscilloscope screen. Target positions were read from an indicator with a resolution better than 0.001 inch.

A typical experimental result is shown in Figure 10. The experiment was conducted with a transducer having a concave zirconium lens and a lead zirconate-titanate piezoelectric disk that operated at 2.25 Mc/sec. The focal point for the transducer in water, calculated from Eq (16), was 5.86 inches. It should be noted that the cross section of the ultrasonic beam at an intensity of -3db is 0.088 inch when the distance between the lens and the target is 5.3 inches.

An experiment was conducted to determine the acoustic beam diameter at a distance well beyond the focal point of the transducer. A 1/8-inch-wide aluminum plate was positioned at a distance of 16 inches from the transducer. The transducer was rotated on an axis that was perpendicular to the direction of sound propagation, and the intensities of the echoes were measured at various transducer angles. Figure 11 is a measured radiation pattern from a transducer with a 1/2-inch-diameter lead zirconate-titanate piezoelectric disk and a 1-inch-diameter zirconium lens with a 3-inch radius of curvature. The piezoelectric disk was operated at a frequency of 2.25 Mc/sec and generated wave lengths of 0.0262 inch in water at room temperature. The beam width, as shown in Figure 11, was 1.67° at the -3db intensity level, and there were essentially no side lobes above the -50db level. In Figure 12, a calculated acoustic pattern for a similar transducer is shown. It should be noted that the beam width is 2.94° at the -3db intensity level, with strong side lobes of 4.93° and 8.2° at relative intensities of -16.3db and -31db, respectively. The experimental results indicate that the acoustic beam from the piezoelectric disk can be collimated by the spherical concave lens, and

FIG. 10 INTENSITY DISTRIBUTION AT FOCAL PLANE

**FIG. 11 REFLECTION PATTERN OBTAINED BY FOCUSING
TRANSDUCER FROM AN ALUMINUM STRIP**

FIG. 12 CALCULATED RADIATION PATTERN FROM THEORY OF PISTON TRANSDUCER

that side lobes can be suppressed to intensities that are negligible when compared to the main lobe.

Measurements were made to determine the widths of ultrasonic beams at different focal points (Figure 13). One-half-inch-diameter lead zirconate-titanate piezoelectric disks vibrating at frequencies of 2.25 and 5 Mc/sec were operated with zirconium lenses of different radii of curvature. The widths of the ultrasonic beams were larger at longer focal points for a given disk frequency. The beam widths were less for piezoelectric disks vibrating at higher frequencies at fixed focal points. In Figure 14 are indicated the experimental results obtained from lenses with different radii of curvature and piezoelectric disks operating at a frequency of 2.25 Mc/sec but with two diameters of disks. Figure 15 shows the widths of ultrasonic beams as functions of the diameters of piezoelectric disks vibrating at the same frequency and operating with the same lens.

Tests were conducted to determine beam width as a function of the radius of curvature of three different lenses at a distance of 16 inches from the transducers. The results shown in Figure 16 were derived from a 0.5-inch-diameter piezoelectric disk vibrating at 2.25 Mc/sec. It was found that the smallest lens produced the sharpest acoustic beam at a fixed point.

FIG. 13 BEAM WIDTH AT FOCAL POINT FOR VARIOUS FOCAL LENGTHS WITH
FIXED DIAMETER PIEZOELECTRIC DISKS

FIG. 14 BEAM WIDTH AT FOCAL POINT FOR VARIOUS FOCAL LENGTHS WITH A FIXED FREQUENCY

FIG. 15 BEAM WIDTH AT FOCAL POINT AS A FUNCTION OF THE DIAMETER OF THE PIEZOELECTRIC DISK

FIG. 16 BEAM WIDTH AT ABOUT 16 INCHES AS A FUNCTION OF THE RADIUS OF CURVATURE OF THE LENS

VI. OPERATION OF UNDER-SODIUM SCANNER

A. LOCATING OBJECTS WITH A-SCAN SYSTEMS

A-scan systems were used to locate objects in liquid sodium at temperatures ranging from sodium's melting point up to and including 600 F. The intensity and the resolution of the transducers operating in that environment were entirely satisfactory. A thin layer of high-temperature Aeroshell grease No. 15 was applied to the surface of the piezoelectric disk of each transducer to provide good acoustic contact between the disk and the acoustic metal lens. A solid electrolytic copper O-ring was used to seal each of the transducers. The transducers were leak-tested with a helium mass spectrometer before immersion in sodium. Satisfactory sealing occurred when the covers of the transducers were tightened to a value of 900 lb-in, as indicated by a one-foot torque wrench.

The A-scan tests were conducted in the sodium facility that was discussed earlier. The maximum detection range for the systems was limited by the physical size of the sodium tank. The multiple reflection echoes between transducers and objects and the high signal-to-noise ratio, higher than 60 db, indicated that operating distances up to 10 feet are entirely feasible. A typical A-scope photograph obtained from the readout oscilloscope is presented in Figure 17. The scale of the horizontal axis in this photograph is 50 μ sec/div and the distance between the transducer and the stainless steel target, as indicated by the separation of the transmitted and echo pulses, was 14.05 inches.

The width of the transmitted pulse shown in Figure 17 was 20 μ sec. Based on the measured sound velocity in 600 F sodium, a total round trip distance of 1.895 inches is required to discern between the 20 μ sec transmitted pulse and the echo pulse. Thus, the minimum distance between a transducer that is transmitting a 20 μ sec pulse and a target is 0.947 inch. However, the transmitted pulse width can be reduced to 5 μ sec with proper and easily achieved damping of the piezoelectric disk. Therefore, an operating distance of less than 1/4 inch between transducer and target can be readily achieved. Hence, A-scan systems can be used in liquid sodium at temperatures up to and including 600 F at distances between transducers and targets ranging from 1/4 inch to 10 feet.

Tests were conducted to determine piezoelectric disk damping characteristics, and it was observed that all discernible multireflection signals resulting from acoustic impedance mismatching between the piezoelectric disks, the zirconium lenses, and sodium (or water) could be eliminated by a suitable backing block.

FIG. 17 TYPICAL A- SCAN DISPLAY

Excellent distance discrimination was demonstrated using the Transigate unit and the A-scan presentation. The alarm circuits of the Transigate unit were triggered when a target located 30 inches from the transducer was moved less than 0.005 inch. The distance between the transducer and the target was limited to 30 inches by the sodium tank. An observation of pulse wave fronts in multiple reflections from transducers to the tank walls and back indicated that distance discrimination of 0.005 inch or less can be obtained with a distance of 5 feet between a transducer and a target.

The capability of the system to discriminate between objects that are adjacent to each other was demonstrated. The beam widths of transducers at or near their focal points are functions of the operating frequencies and the diameters of the piezoelectric disks and the diameters and radii of curvature of the lenses. By proper choice of these parameters, two flat objects, side by side, separated by a distance of 0.030 inch, can be individually identified.

B. DISCERNING OBJECTS WITH C-SCAN SYSTEMS

As indicated previously in this report, a complete C-scan system works satisfactorily for under-sodium scanning in the temperature range of 300 to 600 F. By appropriate adjustment of the various parameters, a target can be selected on the basis of its distance from the transducer and on the amplitude of the echo received from the target. A target which protrudes as little as 1/16 inch from another target can be selected and identified. Pattern recognition has been demonstrated by scanning characters that were recessed in metal bars. Scanning performance in 600 F liquid sodium was compared with that in room-temperature water. Figure 18 shows an under-water scan of an aluminum bar with milled flat-bottom characters, 1/4-inch deep and 1/4-inch wide. The light area represents the 2-inch-wide aluminum bar. The scan was obtained with a transducer having a 4.5-inch focal length, operating at 5 Mc/sec, with the target approximately at the focal point of the transducer. Figure 19 shows an under-sodium scan at a temperature of 600 F of a stainless steel bar with 1/4-inch-wide and 1/4-inch-high characters. The scan was made with a 1-inch-diameter, 2 Mc/sec piezoelectric disk and a zirconium lens with a 4-inch radius of curvature. The results of the two scans indicate that the C-scan system has satisfactory and similar performance in water and in sodium. Figure 20 is a photograph of a stainless steel target with various milled grooves that was scanned to measure system resolution. A flat-bottomed groove, 1/8-inch deep and 1/8-inch wide, was readily detected. A groove width of 1/4 inch was accurately scanned and recorded. Good resolution of objects 1/32-inch wide and 1/16-inch deep was obtained. The bottom of a 1/8-inch deep V-shaped groove was accurately detected and recorded.

FIG. 18 ULTRASONIC C-SCAN IN WATER

FIG. 19 C-SCAN REPRODUCTION OF TARGET IN 600 F SODIUM

FIG. 20 STAINLESS STEEL TARGET FOR C-SCAN TESTING

VII. CONCLUSIONS

The feasibility of operating ultrasonic transducers immersed in liquid sodium at temperatures up to and including 600 F has been demonstrated. The characteristics of the transducers in liquid sodium have been experimentally defined and no anomalies were observed. A-scan techniques for finding objects and defining their locations have been demonstrated. C-scan principles have been applied, and satisfactory pattern recognitions have been obtained. In summary, the proof-of-principle for A-scan and C-scan systems in liquid sodium at temperatures to and including 600 F has been established.

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APPENDIX A:

SCHEMATIC DRAWINGS OF UNDER-SODIUM
SCANNER SYSTEM COMPONENTS AND
TEST FACILITY

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FIG. A.3 FOCUSING TRANSDUCER — DETAILS — SHEET NO. 2

DET. NO.	DWG. NO.	DESCRIPTION & STL. SIZE	NO. REQ'D	MAT'L	DET. NO.	DWG. NO.	DESCRIPTION & STL. SIZE	NO. REQ'D	MAT'L
1	6XN-6032	PLATE 1/2" 20" 39 1/2"	1	304SS	40	6XN-6035	BOSTON BRONZE B-46-4	2	ALTER
2	THIS SHT.	FLAT WASHER 29/32 I.D.	8	STD.	41	6XN-6034	CRANK SHAFT 5/16" D. 4" B ³ / ₄ "	1	304SS
3	THIS SHT.	HEX HD. BOLT 5/8"-11" x 2 3/4"	4	STD.	42	THIS SHT.	NYLOK CONE PT. 10-32 x 1/2"	1	STD.
4	6XN-6033	SEAL PLATE 1 x 8 x 15	1	ALUM	43	6XN-6035	BOSTON BRONZE B-51-5	4	ALTER
5	6XN-6035	STRAP 1/4" x 1 1/2" x 40 1/2"	2	304SS	44	6XN-6033	CARE PLATE 1 x 8 x 15	1	304
6	6XN-6036	BOOT	2	SILICONE RUBBER	45	THIS SHT.	FLAT HD. ALLEN SCR 10-32 x 3/8"	8	S.S.
7	THIS SHT.	HOSE CLAMP 4 1/2" DIA.	2	STD.	46	6XN-6035	GIB 1/2" x 1 x 3 1/2"	4	304SS
8	6XN-6036	GRDMET PLUG	1	SILICONE RUBBER	47	6XN-6035	SEAL COVER 5 1/2" DIA x 1/2"	1	304SS
9	THIS SHT.	SOC. HD. SCR. 3/8" 16 x 3/4"	2	ALTER	48	6XN-6031	"O" RING SILICONE 5 9/16" D x 3/8" D	2	STD
10	THIS SHT.	DOWEL PIN 1/8" DIA x 7/8"	2	D.R.	49				
11	THIS SHT.	GASKET BY A.P.D.A.	1	-	50	6XN-6040	ANGLE 1/4" x 2" x 2" x 24"	2	AISI 304
12	THIS SHT.	SIEWEK "M" CLAMP NO. 623	36	STD.	51	6XN-6040	CHANNEL 3/16" x 2" x 2" x 44 1/4"	2	
12A	6XN-6034	SIEWEK "M" CLAMP NO. 623	1	ALTER	52	6XN-6040	ANGLE 3/8" x 2" x 2" x 17 1/4"	4	
13	6XN-6034	BRACE 3/4" x 2" x 7 1/2"	2	ALUM	53	6XN-6040	ANGLE 3/8" x 2" x 2" x 43 1/2"	2	
14	THIS SHT.	DOWEL PIN 1/8" DIA x 5/8"	2	D.R.	54	6XN-6040	BRACE 1/4" x 2" x 2" x 6"	16	
15	6XN-6034	GUIDE BAR 5/16" D. x 14"	2	304SS	55	6XN-6040	ANGLE 3/8" x 2" x 2" x 21 3/4"	2	
16	6XN-6035	GUIDE 1 1/4" x 6" x 7"	1	304SS	56	6XN-6040	HEX NUT 3/8"-16 N.C.		STD
17	6XN-6034	LEAD SCREEN 3/8" DIA x 14 1/2"	2	304SS	57	6XN-6038	FLANGE	1	304SS
18	THIS SHT.	NYLOK CONE PT 1/4"-20 x 3/8"	2	STD	58	6XN-6038	NECK BAND	1	304SS
19	6XN-6034	BRACE 3/4" x 2" x 7 1/2"	2	ALUM	59	6XN-6039	BODY END	2	304SS
20	THIS SHT.	CARE LANE FINGER PIN	2	CL-2-FR	60	6XN-6039	WRAPPER	1	304SS
21	6XN-6034	HAND CRANK 2" DIA x 3/4"	2	ALUM	61	THIS SHT.	3/8"-16 N.C. x 3/4" SET. S.C.R.	38	S.S.
22	6XN-6033	SPACER PLATE 1 1/8" x 2 1/8" x 7"	4	304SS	62	THIS SHT.	5/16"-18 N.C. 3/4" SET. SCR.	40	S.S.
23	6XN-6033	SPACER PLATE 1 1/8" x 2 1/8" x 7"	1	304SS	63	THIS SHT.	1/8" TUBE MALE CONNECTOR		
24	THIS SHT.	SOC. HD. SCR 1/4"-20 x 5/8"	16	STD.			(SWAGelok 200-1-2-3/16 BT)	1	
25	6XN-6034	SHAFT GUIDE 5/8" x 1 1/2" x 2"	2	ALUM	64	THIS SHT.	1/2" SCH 40 SOC. WELD. ELBOW	2	304SS
26	6XN-6033	MOUNTING PLATE 1 1/8" x 6 1/8" x 1 1/8"	1	304SS	65	THIS SHT.	1/2" SCH 40 1/2" LG. NIPPLE	1	304SS
27	6XN-6034	CLAMP BLOCK 5/8" x 5/8" x 1 1/8"	8	T.S.	66	6XN-6323	TANK	1	WELDED CONST
28	6XN-6035	PIVOT PLATE 5 1/2" DIA. x 1/2"	1	304SS	67	6XN-6037	3/8"-16 x 5 1/4" THREADED BAR STL.	4	STD
29	6XN-6036	SEAL COVER 1 x 8 x 15	1	304SS					
30	THIS SHT.	SIEWEK SWIVEL SCR. 9/16" 18 x 2"	2	1226B					
31	THIS SHT.	SOC. HD. SCR. 3/8"-16 x 3/4"	66	STD					
32	6XN-6033	JAM BLOCK 1 1/8" x 1 1/2" x 2"	2	304SS					
33	THIS SHT.	GASKET BY A.P.D.A.	1	-					
34	THIS SHT.	GASKET BY A.P.D.A.	1	-					
35	6XN-6035	STRAP 1/4" x 1 1/2" x 25 1/2"	2	304SS					
36	THIS SHT.	HEX NUT 5/8"-11	4	STD					
37	6XN-5573	FURNISHED BY A.P.D.A.	2						
38	6XN-6035	RETAINER RING	2	304 TUBING N3-1-AB-S					
39	THIS SHT.	P.I.C. GEAR SET.	2 PR						

FIG. A.4 SODIUM SCANNER TEST TANK AND SODIUM POT SUPPORT (STOCK LIST)

FIG. A.5 SODIUM SCANNER TEST TANK AND SODIUM POT SUPPORT (FIXTURE LAYOUT)

FIG. A.10 SODIUM SCANNER TEST TANK AND SODIUM POT SUPPORT (DETAIL SHEET)

FIG. A.14 SODIUM SCANNER TEST TANK AND SODIUM POT SUPPORT

FIG. A.17 ULTRASONIC SCANNER TANK ELECTRIC HEATER SCHEMATIC

DIM 3.750 (QW) WAS 3.725 REF A754 CASH/16		DET 28.125 (QW) WAS 28.125	
4	6.397	7.25	7.25
6.397	6.397	7.25	7.25
REVISION	DATE	DR	CH
MICHIGAN RESEARCH CORPORATION			
DESIGNED BY A. F. A.	CHECKED S. B. L.	APPROVED	
REFERENCE M.E.C. #6610	SCALE	FULL	
ALL DIMENSIONS IN INCHES		DO NOT SCALE	
TOLERANCES EXCEPT AS NOTED		125	
T" MACHINED SURFACE POLISHED UNLESS NOTED		V	
SURFACE TREATMENT			
MATERIAL AND HEAT TREATMENT		APPROVED	
TYPE 302-304 STAINLESS STEEL		DATE	
NAME (C-SCAN DRIVE MECHANISM) PLATE BASE			
PART NO	SNT 4		OF 12
18070 - 15			

FIG. A.21 C-SCAN MECHANISM PLATE BASE

FIG. A.22 C-SCAN DRIVE MECHANISM RAIL—SUPPORT

LETTER	REVISION	DATE	DP	CR
MICHIGAN RESEARCH CORPORATION				
DRAWN BY L. MATE	CHECKED BY F. MATE	APPROVED		
REFERENCE MRC 46610	SCALE FULL			
ALL DIMENSIONS IN INCHES DO NOT SCALE				
TOLERANCES UNLESS NOTED: .125				
T MACHINED SURFACE ROUGHNESS UNLESS NOTED				
SURFACE TREATMENT: ELECTROLESS NICKEL				
PLATE .0005" .0010" ALL OVER				
BASK 400°F ONE HOUR R6-50				
MATERIAL AND HEAT TREATMENT				
AISI 4620 STEEL				
CARB-NITRIDE .00008" DP				
RC 50-55				
NAME C-SCAN DRIVE MECHANISM RAIL-SUPPORT				
PART NO. 18070-40	SHEET 6 OF 12			

FIG. A.23 C-SCAN DRIVE MECHANISM RAIL-SUPPORT

FIG. A.24 C-SCAN DRIVE MECHANISM DETAILS

MICHIGAN RESEARCH		DATE	BY	CHK
CORPORATION				
DESIGN BY	DATE	REVISED		
BY CLOAK	10-3-66	REWORK		
REVIEWED BY	DATE	SCALE		
BY HEC-6610		FULL		
ALL DIMENSIONS IN CHES		DO NOT SCALE		
TOLERANCES EXCEPT AS NOTED		1/25		
XXX - 1.00 XX - 0.010		1/16 ANGLE 1/16		
T MACHINED SURFACE ROL		WHERE UNIFORMITY IS REQUIRED		
SURFACE TREATMENT				
MATERIAL AND HEAT TREATMENT		APP'D BY		
SEE DETAIL.		DATE		
NAME				
C-SCAN DRIVE MECHANISM				
DETAILS				
PART NO				SHEET
18070-17-28-47-19				8 OF 12

FIG. A.25 C-SCAN DRIVE MECHANISM DETAILS

⑬ PULLEY NEGATOR
TEFLON
2 REQD FINISH SIZE $\frac{74}{100}$ DIA X .60 LONG EACH

⑭ SHAFT COUPLING TAPE SPLICER
TYPE #46 STAINLESS STEEL
ONE REQD FINISH SIZE $\frac{1.03}{1.5}$ DIA X $\frac{1.03}{1.9}$ LONG

⑭ BRACKET TAPE
6061-T6510 ALUMINUM
ONE REQD
FINISH SIZE $(.87 \times 1.7 \times 3.6 \text{ LONG})$

⑮ PULLEY TAPE
6061-T651 ALUMINUM
ONE REQD FINISH SIZE $(1.68 \text{ DIA} \times 1.060 \text{ LONG})$

⑯ GUIDE BLOCK
AMPCO #8 ALUMINUM BRONZE
ONE REQD
FINISH SIZE $(1.6 \times .875 \times 1.50 \text{ LONG})$
OPTION $(1.50 \text{ DIA} \times .6 \text{ LONG})$

⑰ WIPER BLOCK - NEGATOR
TEFLON
2 REQD
FINISH SIZE $.37 \times .375 \times 1.060 \text{ LONG EACH}$

LETTER	REVISION	DATE	BY	CHK
MICHIGAN RESEARCH CORPORATION				
DESIGNED BY	CLOCK	CHECKED BY	FRANK	APPROVED
DATE	2-27-66	SCALE	FULL	
REFERENCE	REC #6610	DO NOT SCALE		
ALL DIMENSIONS IN INCHES				
TOLERANCES EXCEPT AS NOTED				
XXX = 1.00, .XX = .10, .X = .01, .XX = .01, .XX = .01, .XX = .01				
MACHINED SURFACE ROUGHNESS UNLESS NOTED				
SURFACE TREATMENT				
MATERIAL AND HEAT TREATMENT				
SEE DETAIL				
NAME				
C-SCAN DRIVE MECHANISM				
DETAILS				
PART NO	18070-2.3-14-21-24-43	SHEET	9	OF 12

FIG. A.26 C-SCAN DRIVE MECHANISM DETAILS

FIG. A.27 C-SCAN DRIVE MECHANISM DETAILS

FIG. A.29 SODIUM C-SCAN DEVICE WIRING SCHEMATIC

Sheet 1 of 2

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