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ULTRASONIC MEASUREMENT OF STRESS IN RAILROAD WHEELS AND IN LONG LENGTHS OF WELDED RAIL

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16. ABSTRACT

Emergency braking of high speed trains generates excessive heat in wheel rims and can cause explosive type failures. Stress-related rail failures also occur as seasonal variations of temperature cause high thermal stresses to build up in long, continuous lengths of welded track. Obviously, there is a definite need for a reliable nondestructive method of measuring stress in thick steel so improperly stressed components can be identified and replaced or adjusted before hazardous failures occur. An applicable method utilizing ultrasonic velocity measurements is described in this report. Certain problems associated with material variability, transducer coupling techniques, and calibration procedures are evaluated. Typical experimental results show that reliable ultrasonic velocity measurements can be made and that the magnitude of velocity changes can be related to stress level changes in wheels and to residual stress in rail. Thus, the ultrasonic method of measuring stress is feasible and the current state-of-the-art justifies a practical, field type verification of its utility.

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ULTRASONIC MEASUREMENT OF STRESS IN RAILROAD WHEELS AND IN LONG LENGTHS OF WELDED RAIL

SUMMARY

Many stress related material failures are associated with high speed rail transportation. High compressive residual stresses exist in the rims of new wheels. Emergency braking of high speed trains generates excessive heat in the rims, reducing the stress levels existing there. Consequently, cracks in a rim and explosive type wheel failures can result if the high initial compressive stress becomes too low. Many stress-related rail failures also occur. Thermal stresses that can cause failure build up in long, continuous lengths of welded track. In summer, heat-induced compressive stresses may cause rail to buckle and the low temperatures in winter result in tensile stresses that can break rail. Work described in this report was initiated to develop nondestructive methods of measuring stress in thick steel so improperly stressed wheels and rail can be identified and replaced or adjusted before hazardous failures occur. Applicable ultrasonic techniques have been applied to these problems.

The determination of stress levels using the ultrasonic method consists essentially of measuring the ultrasonic velocity through the stressed material. Although stress and numerous material properties affect the velocity of sound in a medium, effects of property variations can be accounted for by adequate calibration procedures. Thus, additional velocity changes can be attributed to stress. Satisfactory calibration procedures include a determination of the velocity change/stress change ratio and the establishment of a calibration factor based on material variability. Subsequent to the preliminary work, on small rectangular specimens, ultrasonic velocity measurements were made on several railroad wheels and on incrementally loaded rail segments. This work demonstrated that reliable ultrasonic velocity measurements can be made and that the magnitude of velocity changes can be related to stress level changes in wheels and to residual stress in rail.

INTRODUCTION

Current trends toward higher rail speeds seem to be pushing present wheel designs beyond their capacity. Railroad equipment is capable of speeds up to 150 miles per hour but it is restricted to lower speeds primarily because of the inability of wheels to withstand emergency braking at high speeds. High speed braking generates thermal cracks in wheel tread which can result in explosive type failures. More specifically, compressive residual stresses in the rims of wheels are eventually reduced to zero by excessive heat and, subsequently, cracking occurs as additional braking loads the tread in tension. Thus, rapid and effective methods of detecting and measuring stress changes in wheels are needed to avoid catastrophic failures. Additionally, many stress-related rail failures also occur. Modern railroads use long lengths of welded rail in building track to increase the safety and comfort of passengers and to reduce operational costs. However, all maintenance problems are not eliminated by welding rail. Thermal stresses that can cause failure build up in long, continuous lengths of track. In summer weather, heat-induced compressive stresses may cause rail to buckle and the low temperatures in winter result in tensile stresses that can break rail. These failures occur as excessive stress builds up in specific track sections when the uniform distribution of the thermal stresses is disturbed by improper conditions of ties, ballast, or rail anchors. Since these conditions cannot always be avoided, effective methods of detecting and measuring excessive stress levels are required.

Ultrasonic techniques have been used at Marshall Space Flight Center (MSFC) for several years to measure stress changes in aluminum and to some extent in steel. These techniques are based on the principle that stress will change the velocity of ultrasonic waves propagating in metallic materials. Thus, with adequate calibration, an accurate velocity determination becomes a measure of stress. Ultrasonic velocity changes per unit load or stress level change are less for steel than for aluminum. However, the significance of this negative fact is diminished by the high stress levels usually existing in steel structures. Thus, high expected stress levels and uniform wheel and rail geometries make the ultrasonic method attractive as a possible solution for both of the stress-related railroad problems.

Objectives of the program initiated for the purpose of solving the problems included the determination of feasibility and practicality of using ultrasonic techniques to nondestructively measure stress in rail and to determine the relationship of residual stress changes in the rim and subsequent thermal crack growth on the tread to the number of high speed stops for railroad wheels.

Experimental work associated with the program included an evaluation of the effects of material variability, geometric variability, temperature, and transducer coupling techniques on measurement accuracy. In addition, initial ultrasonic velocity (stress) and attenuation measurements made on specimens of rail and wheel steels showed that excessive attenuation occurred at 7 MHz, the frequency used for measuring stress in aluminum alloys. Consequently, the test frequency had to be changed to reduce signal attenuation. Transducers suitable for 2 MHz operation were then designed, fabricated, and tested to overcome this problem. Attenuation at this lower frequency was acceptable and permitted accuracy in measurements.

TECHNIQUE AND INSTRUMENTATION UTILIZED IN MEASURING STRESS

The determination of stress levels using the ultrasonic method consists essentially of measuring the ultrasonic velocity through the stressed material. Although stress and numerous material properties affect the velocity of sound in a medium, effects of property variations can be accounted for by adequate calibration procedures. Thus, additional velocity changes can be attributed to stress.

The selected technique of measuring velocity is basically a differential time measurement as depicted in part by Figure 1. Two ultrasonic transducers are energized by a single pulse generator. One of the transducers is placed on a stressed specimen and the other on an unstressed reference block. Each signal is monitored on a separate channel of a dual beam oscilloscope. The time base of the oscilloscope is expanded until each cycle of the narrow pulses can be observed. The distance or time between corresponding peaks of the two signals is proportional to the stress level in the specimen. An accurate value for the distance between peaks can be obtained by turning the delay-time multiplier knob on the oscilloscope until both signals are coincident. Photographs illustrating the mechanics of making stress measurements in railroad components are shown in Figures 2 through 5. Figures 2 and 3 show overall and close-up views, respectively, of a shear wave transducer and holding fixture utilized in measuring stress in wheels. Similar coupling methods are used for measuring stress in rail. In each case, a thin layer of highly viscous couplant[1] is used, allowing easy rotation of the transducer. Typical segments

1. The couplant is the resin portion of an adhesive called "Lefkoweld 109."

of reflected pulses from stressed and unstressed materials are shown in Figure 4. Figure 5 depicts the oscilloscope pattern subsequent to the coincidence adjustment.

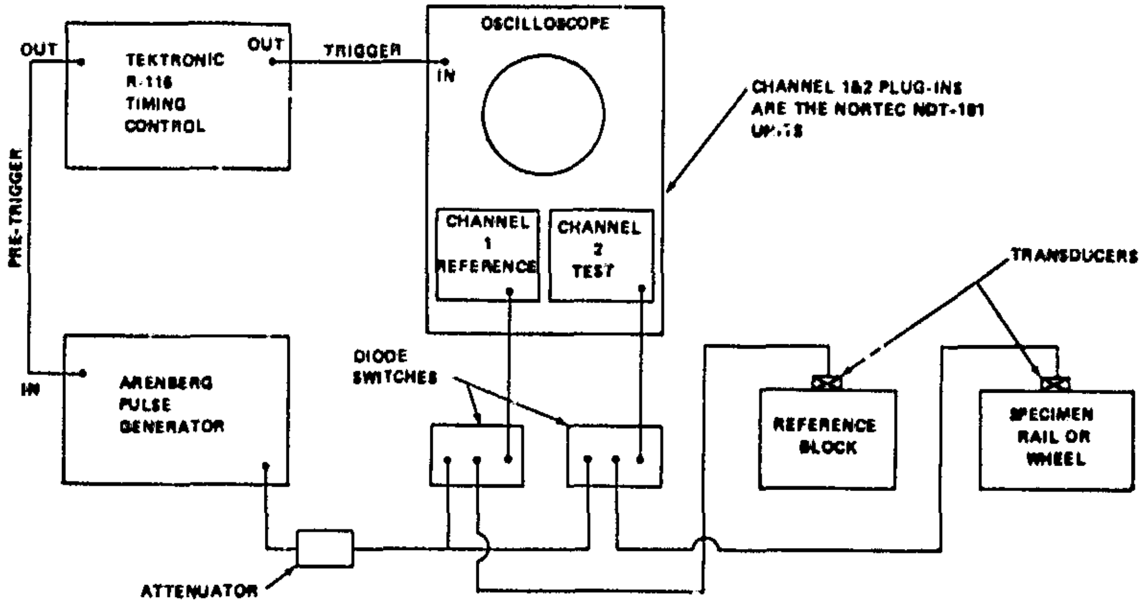

Figure 1. Block diagram of ultrasonic stress measurement instrumentation.

ULTRASONIC MEASUREMENT OF STRESS IN RAILROAD WHEELS

Work described in this section of the report is part of a larger program initiated by the Federal Railroad Administration to determine the relationship of residual stress changes in the rim and thermal crack growth in the tread to the number of high speed stops for railroad wheels. In addition to ultrasonic work at MSFC, nondestructive stress measurements of the Barkhausen noise type have been made at Southwest Research Institute. Necessary metallurgical work, thermal loading of test wheels, and destructive stress and crack growth analyses are responsibilities of the United States Steel Corporation. Subsequent to the completion of all laboratory work, stress values obtained nondestructively will be compared to destructive measurements.

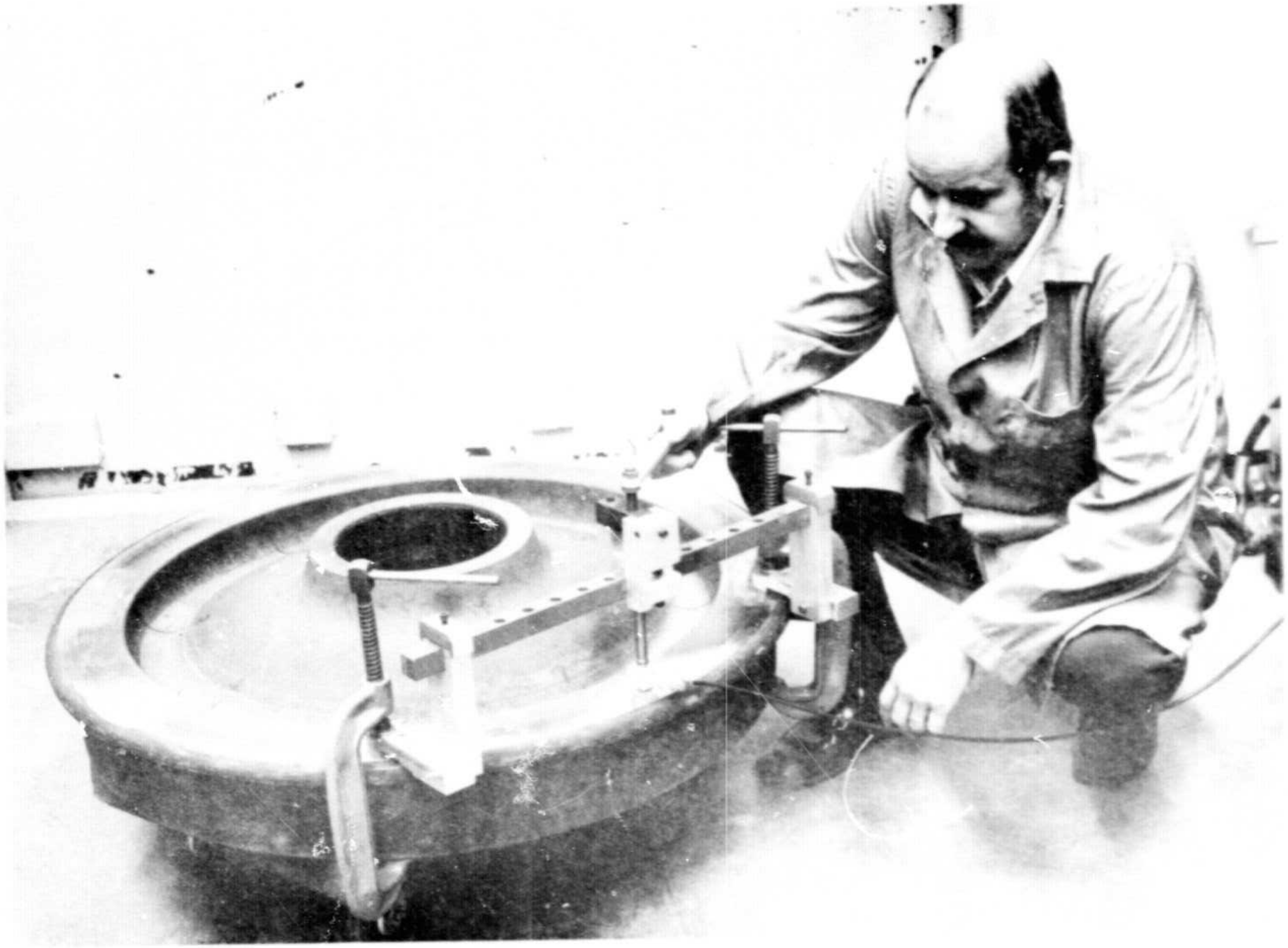

Figure 2. Fixture for clamping adjustable ultrasonic tra sducer to wheel.

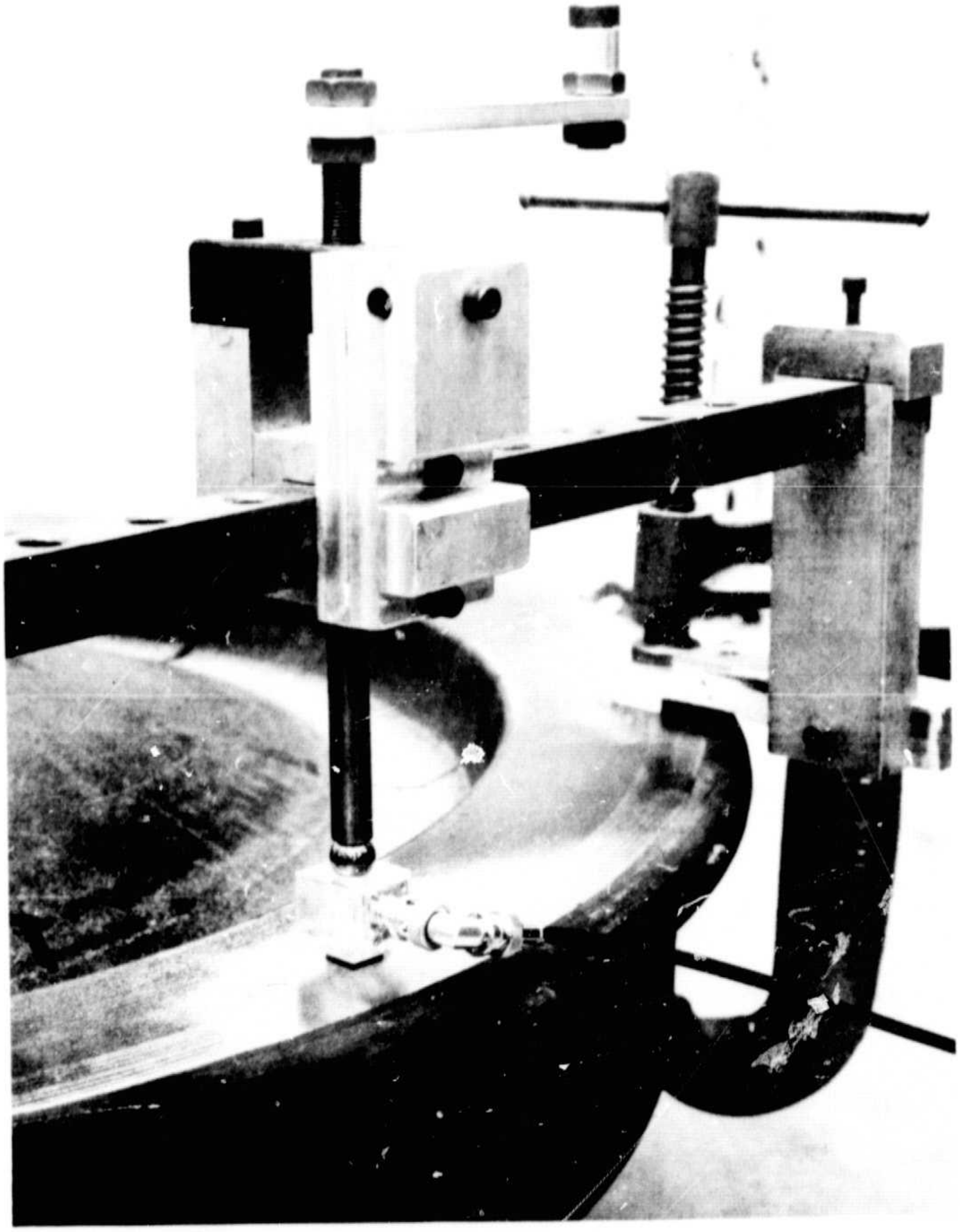

Figure 3. Detailed view of shear wave transducer and method of applying pressure.

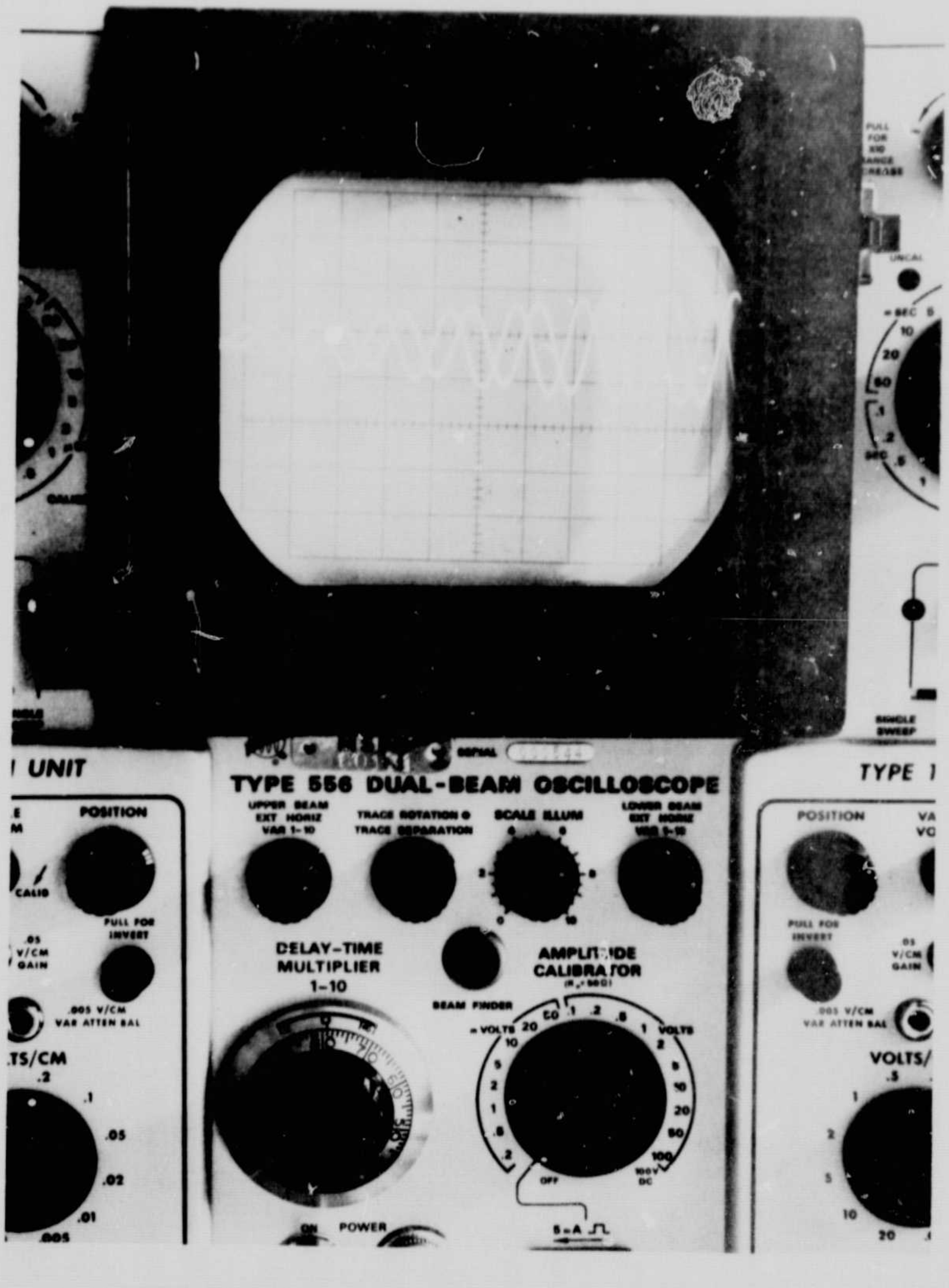

Figure 4. Time base expansion of reflected pulses from stressed and unstressed materials.

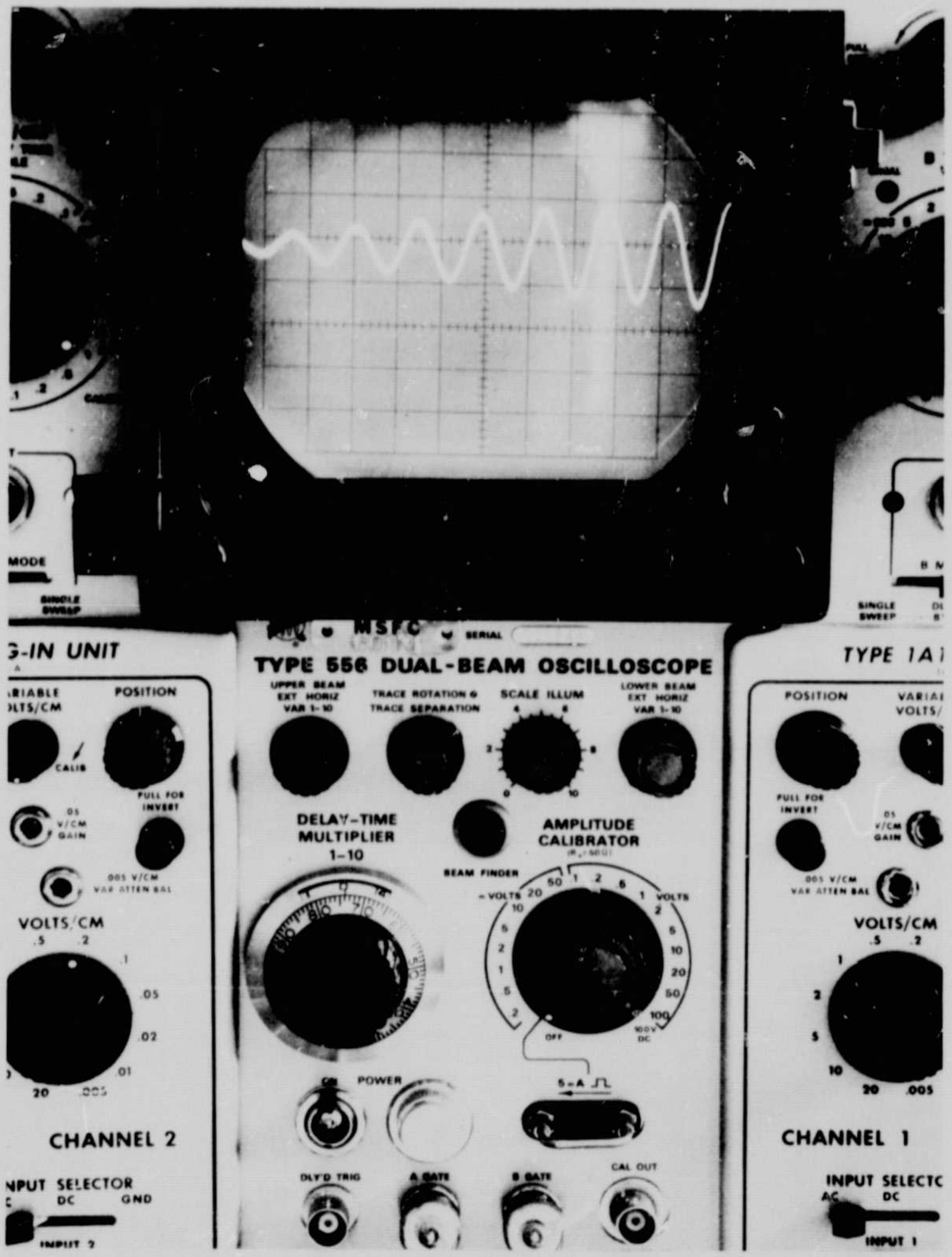

Figure 5. Time delay adjustment makes reference and measuring pulses coincident.

Calibration

Changes in ultrasonic velocity caused by stress are small percentages of the velocity in unstressed material. Consequently, very accurate and reliable measurements are required to obtain useful information. Furthermore, time or velocity change measurements can be made with greater accuracy than absolute measurements. This fact is indicated by the mechanics of the measurement procedure previously described. However, the double refracting or birefringent characteristic of metals and the selection of calibration blocks were not discussed. Briefly, a double refracting or anisotropic material loaded in compression will cause shear waves polarized paralled to the principal stress axis to travel faster than similar waves polarized perpendicular to it. Thus, the velocity difference or phase relationship of these waves subsequent to passing through loaded metal becomes a measure of stress in the material [1, 2, 3, 4, 5]. So in the case of a wheel, the difference in velocity of circumferentially and radially oriented shear waves through the rim is a measure of the average stress existing there. However, since velocity is affected by material properties as well as stress, efforts were made to reduce the effect of these parameters by carefully selecting a suitable calibration block as depicted in Figures 6 and 7. Ideally, this block should be of the same material and have the same preferential grain alignment and exact thickness as the rim of the wheel, and it should be stress relieved. As indicated in Figures 6 and 7, a good approximation of the ideal block can be attained and it serves the following purposes:

1. Used in determining the stress constant.

2. Used as a delay line.

3. Reduces effects of temperature and material property variations on measurement accuracy.

4. Provides potential for measuring stress components rather than only a resultant stress value.

5. Allows some measure of material variability.

The stress constant or ultrasonic velocity change per unit load was determined by placing the block in a press and measuring velocity changes as it was incrementally loaded. Loads were applied as indicated in Figure 6 to simulate compressive circumferential stress in a wheel. An unstressed block

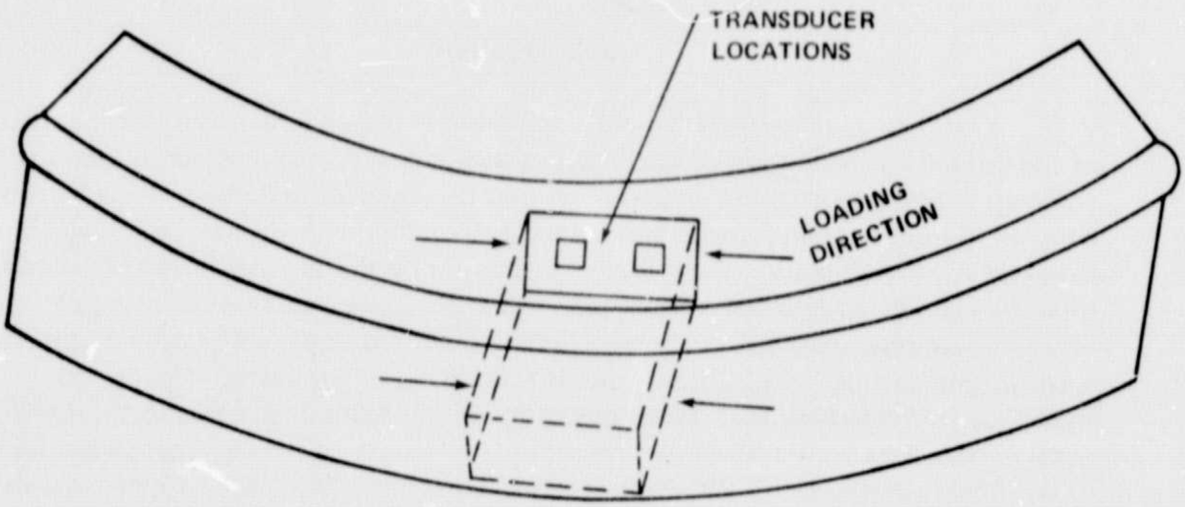

Figure 6. Orientation of calibration block with respect to wheel.

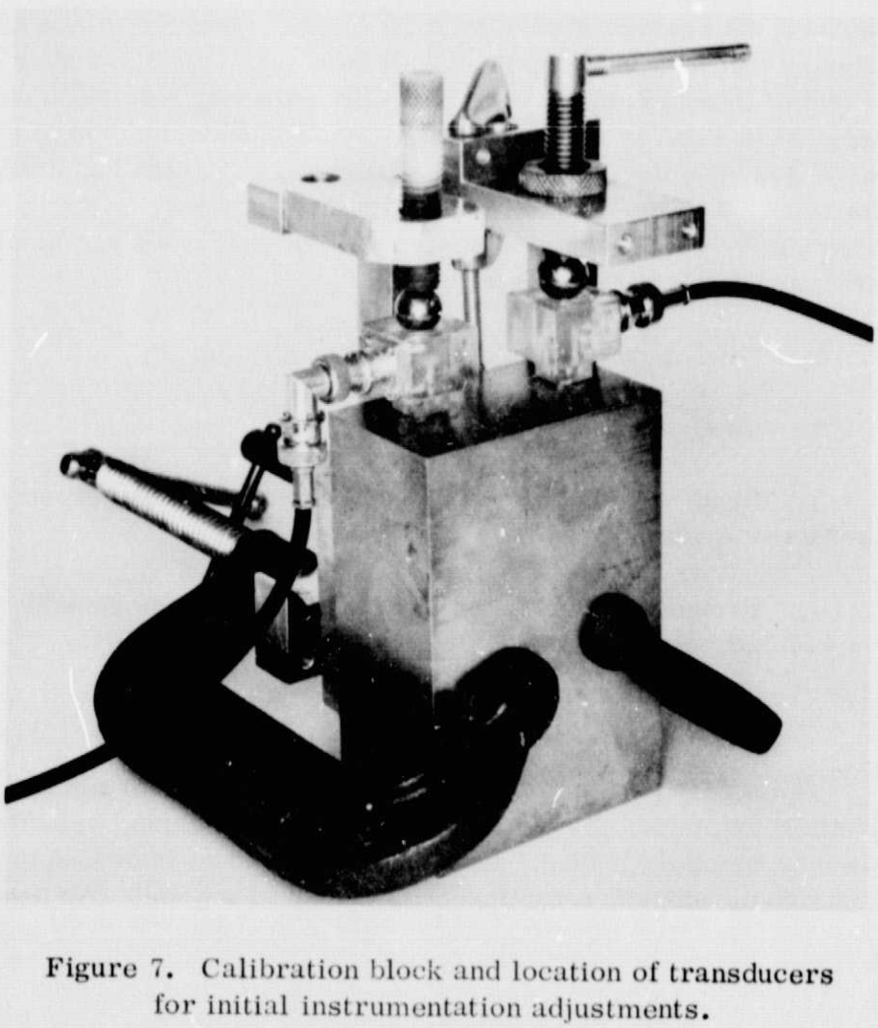

Figure 7. Calibration block and location of transducers for initial instrumentation adjustments.

was used as a delay line to obtain a reference pulse. For each load level, velocity or time change measurements were made with the shear wave transducer polarized parallel to the major stress axis and then perpendicular to it. Results of a typical constant determination are shown in Table 1. Obviously, when ultrasonic waves are polarized parallel to the principal stress axis, time change magnitudes for given load changes are greater than corresponding time changes for waves polarized in a perpendicular direction. Negative numbers indicate shorter ultrasonic propagation times and positive numbers indicate greater time than the reference value. Differences between transit times for the two polarizations were used to obtain the time change per load level change. This information, along with the total path length and the magnitude of each load level change, was used to calculate a stress constant of 2.31×10^{-6} nsec/m/N/m^2 (0.405 nsec/in./ksi). Stress constants for the three types of wheels investigated are shown in Table 2.

Experimental Results

Circumferentially and radially oriented shear wave velocity measurements were made through the rim of each wheel at locations spaced 45 deg apart. Measurement procedures included initial instrumentation adjustments to make the test and reference pulses coincident and to make the time delay control read 300 divisions when both transducers were placed on the same reference block. Then, the test transducer was placed with corresponding polarization on the wheel and a time differential was determined by adjusting the delay control to make both pulses coincident again. A similar determination was then made using a 90 deg change in shear wave polarization. Typical values obtained for eight locations on a wheel are shown in Table 3. The difference between corresponding radial and circumferential time values represents stress.

Knowledge of the ultrasonic path length and the time base setting of the oscilloscope allows a determination of reflection time differences between radially and circumferentially polarized ultrasonic waves in nanoseconds per unit length of stressed material. Data for all wheel measurements made to date are presented in Table 4. These data and the stress constant previously determined can be used to calculate apparent stress in all the wheels and a stress change in wheel number 2476-A. This particular wheel was subjected to simulated high speed braking after the initial ultrasonic velocity determinations were made. Data for a second set of velocity measurements made

TABLE 1. CONSTANT DETERMINATION FOR AN MCR-55 REFERENCE BLOCK

Applied Load $N/m^2 \times 10^7$ (ksi)	Time Change, nsec		Difference In Transit Time	Time Change Per Load Level Change
	Parallel Polarization	Perpendicular Polarization		
0 (0)	0.0	+14.5	14.5	0.0
3.44 (5)	-20.5	+17.0	37.5	23.0
6.88 (10)	-36.0	+23.5	59.5	22.0
10.32 (15)	-59.0	+21.5	80.5	21.0
13.76 (20)	-77.5	+23.5	101.0	20.5
17.20 (25)	-98.5	+26.0	124.5	23.5
				22.0 av

Note: Stress Constant $= \dfrac{\text{Average Time Change}}{\text{Sound Path Length} \times \text{Load Increment}}$

$$K = \frac{22}{0.276 \times 3.44 \times 10^7} = 2.31 \times 10^{-6}\ \text{nsec/m/N/m}^2 \qquad K = \frac{22}{10.874 \times 5} = 0.405\ \text{nsec/in./ksi}$$

TABLE 2. STRESS CONSTANTS FOR SELECTED WHEEL MATERIALS

Type of Wheel	Stress Constant $nsec/m/N/m^2 \times 10^{-6}$ (nsec/in./ksi)
M-CR-33 Multi-Wear Wrought Steel	2.31 (0.405)
I-J-36 Italian Steel Wrought Steel	2.36 (0.413)
C-CJ-36 Cast Steel	2.32 (0.406)

TABLE 3. TYPICAL ULTRASONIC VELOCITY MEASUREMENTS

Transducer Positions	Dial Readings (Divisions)	
	Radial Polarization	Circumferential Polarization
Both on Calibration Block	300	300
Wheel Positions of Test Transducer		
1	201.2	173.5
2	197.8	180.3
3	199.5	199.1
4	200.0	180.9
5	196.4	175.1
6	208.0	186.0
7	202.1	183.5
8	194.8	170.5

TABLE 4. DIFFERENCES IN REFLECTION TIME BETWEEN RADIALLY AND CIRCUMFERENTIALLY POLARIZED ULTRASONIC WAVES (in nanoseconds)

Wheel Position	Wheel Number				
	2476-A New	10191-A Used	2472-A New	2474-A Used	10190-A Used
	per meter (per inch)	per meter (per inch)	per meter (per inch)	per meter (per inch)	per meter (per inch)
1	708 (18.00)	358 (9.10)	500 (12.70)	635 (16.10)	295 (7.50)
2	536 (13.60)	374 (9.50)	318 (8.10)	645 (16.40)	220 (5.60)
3	507 (12.90)	414 (10.50)	370 (9.40)	577 (14.65)	191 (4.85)
4	492 (12.50)	437 (11.20)	346 (8.80)	420 (10.65)	165 (4.20)
5	575 (14.60)	437 (11.20)	385 (9.80)	552 (14.00)	218 (5.55)
6	575 (14.60)	465 (11.80)	398 (10.10)	575 (14.60)	254 (6.45)
7	516 (13.20)	276 (7.00)	338 (8.60)	600 (15.25)	230 (5.85)
8	614 (15.60)	343 (8.70)	441 (11.20)	720 (18.45)	173 (4.40)

subsequent to thermal loading are shown in Table 5. These data show significant velocity changes that are equivalent to an average stress change of 9.6×10^7 N/m^2 (13.9 ksi) for the eight measurements. These thermally induced stress change values are considered accurate since the stress constant previously determined is repeatable.

ULTRASONIC MEASUREMENT OF STRESS IN RAIL

Shear Wave Measurement

Shear wave stress determinations are made, as previously described in detail, by measuring sound wave transit times as a transducer is adjusted so particle motion in the specimen is first longitudinal and then in the transverse direction. The differential time change is a measure of stress in the material. This technique was used to obtain the stress constant or velocity change per unit load change ratio for small [2.54 by 3.81 by 12.70 cm (1 by 1.5 by 5 in.)] rectangular specimens of rail steel. An average value obtained for this ratio was 2.53/nsec/m/N/m^2 (0.442 nsec/in./ksi).

Subsequent to stress constant determination, measurements were made in incrementally loaded rail segments. Initially, these were made with the transducer clamped on top of the rail as shown in Figure 8. Then, at each load level a value for the average stress through the entire rail was determined. Although reliable stress determinations were made in this manner, it was learned that the rail industry is more concerned about stress in rail heads than in entire rails. Consequently, all subsequent shear wave stress measurements were made with the transducer clamped to the side of rail segments as depicted in Figure 9. This figure also shows a reference block consisting of a rail head segment that was utilized in a manner analogous to the previously described calibration block cut from the tread of a railroad wheel. Measurements on an incrementally loaded rail segment are presented in Table 6 in terms of instrument indications as a function of load level. Data reduction and stress constant determination are given in Table 7. Since the oscilloscope was adjusted to make each division of the delay knob equal to 5 nsec, all data in Table 6 were multiplied by 5. Then, the value obtained for the parallel polarization at zero applied load was selected as a reference point for data reduction. All time differences between this and other data points of both

TABLE 5. ULTRASONIC REFLECTION TIME VALUES FOR WHEEL NUMBER 2476-A BEFORE AND AFTER SIMULATED BRAKING

Wheel Position	Time Before, nsec/m (nsec/in.)	Time After, nsec/m (nsec/in.)
1	708 (18.00)	468 (11.90)
2	536 (13.60)	279 (7.10)
3	507 (12.90)	276 (7.00)
4	492 (12.50)	205 (5.20)
5	575 (14.60)	330 (8.40)
6	575 (14.60)	386 (9.80)
7	516 (13.20)	457 (11.60)
8	614 (15.60)	350 (8.90)
Average	565 (14.37)	344 (8.73)

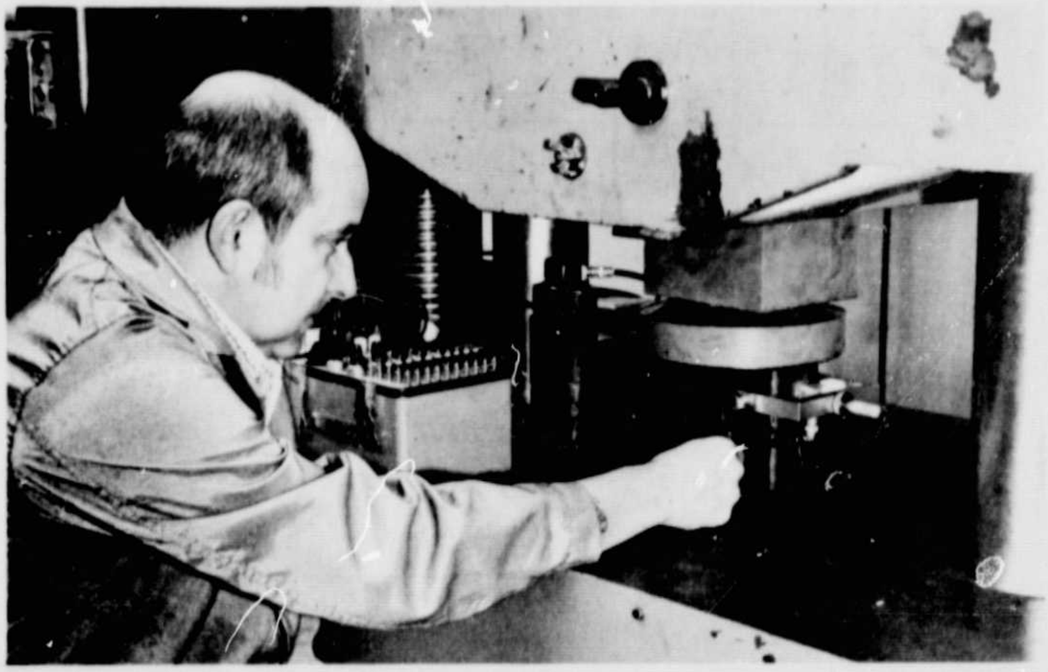

Figure 8. Method of coupling sound into the top of a rail segment.

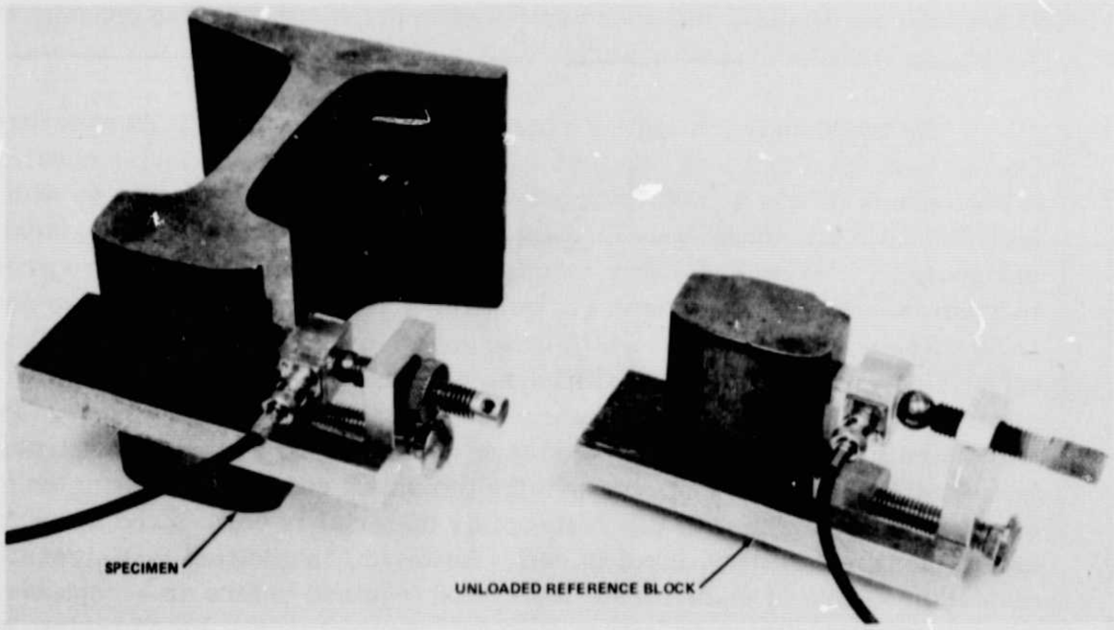

Figure 9. Location selected for transmitting sound into rail heads.

TABLE 6. STRESS MEASUREMENT DATA FOR A RAIL SEGMENT

Applied Load, $N/m^2 \times 10^7$ (ksi)	Dial Readings (Divisions)	
	Parallel Polarization	Perpendicular Polarization
0 (0)	381.9	427.9
3.44 (5)	381.0	429.1
6.88 (10)	378.6	429.6
10.32 (15)	376.8	430.1
13.76 (20)	374.2	430.2

polarizations are shown in Table 7. Negative numbers indicate less ultrasonic propagation time and positive numbers indicate more time than the reference value. Furthermore, parallel orientated vibrations are more sensitive to load changes than perpendicular ones and result in greater time changes for a given stress change. Next, the cumulative load-induced time changes were obtained, as indicated in other columns of the table, and were used with the distance [15.11 cm (5.95 in.)] the sound traveled to calculate a stress constant of 2.40 nsec/m/N/m^2 (0.42 nsec/in./ksi).

As previously stated, an average stress constant of 2.53 nsec/m/N/m^2 (0.442 nsec/in./ksi) was determined for three small rectangular specimens. A photograph of this and other specimen types is shown in Figure 10 which includes all types investigated except the 91.44 cm (36 in.) rail segment designated S_4. Stress constant values for all of these specimens are presented in Table 8. The initial reason for utilizing a rectangular specimen to determine stress constants was to eliminate possible effects of complex rail geometry. Consequently, it is of interest to note that values obtained for rail segments are lower and those for rail heads are higher than average. Perhaps more significantly, the average value of constants for segments S_1 through S_4 is essentially equal to that obtained for the small rectangular specimen. Thus, the constant obtained with the rectangular material is considered adequate for use in measuring stress level in rail. However, in addition to a stress constant, knowledge of material variability is required before an acceptable measurement of stress in long welded rail can be made. This problem and a feasible approach to its solution is addressed in the following paragraphs.

TABLE 7. DATA REDUCTION FOR STRESS CONSTANT DETERMINATION

Applied Load, $N/m^2 \times 10^7$ (ksi)	Time Change, in nsec		Total Transit Time Change Per Load Level Change	Cumulative Load Induced Time Changes
	Parallel Polarization	Perpendicular Polarization		
0 (0)	0	230.0	230.0	0.0
3.44 (5)	- 4.5	236.0	240.5	10.5
6.88 (10)	-16.5	238.5	255.0	25.0
10.32 (15)	-25.5	241.0	266.5	36.5
13.76 (20)	-38.5	241.5	280.0	50.0

Note: $K = \frac{50}{5.95 \times 20} = 0.42$ nsec/in./ksi

$$\frac{0.42 \text{ nsec/in./ksi}}{1.75 \times 10^5} = 2.40 \times 10^6 \text{ nsec/m/N/m}^2$$

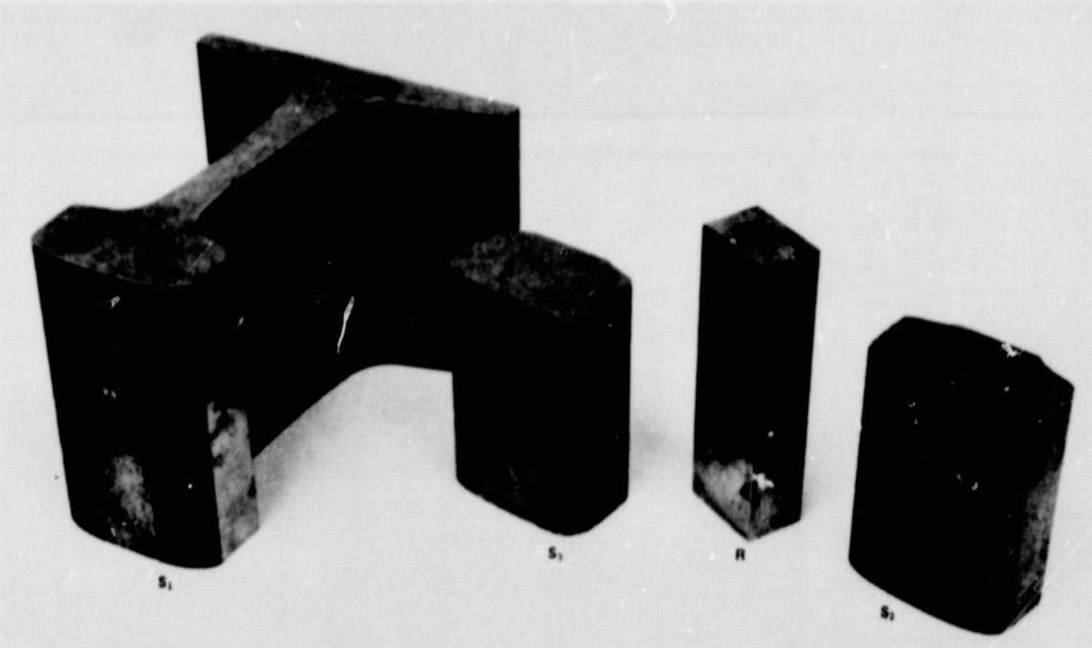

Figure 10. Specimen types utilized in stress constant determinations.

TABLE 8. STRESS CONSTANTS FOR SELECTED RAIL SPECIMENS

Specimen	Stress Constant $nsec/m/N/m^2 \times 10^6$ (nsec/in./ksi)
2.54 by 3.81 by 12.7 cm (1 by 1.5 by 5 in.)	2.53 (0.442)
S_1, 12.7 cm (5 in.) Rail Segment	2.46 (0.431)
S_2, 10.2 cm (4 in.) Rail Head	2.61 (0.456)
S_3, 10.2 cm (4 in.) Rail Head	2.57 (0.450)
S_4, 91.4 cm (36 in.) Rail Segment	2.40 (0.420)
Average — S_1, S_2, S_3, and S_4	2.50 (0.439)

In reference to Table 7, observe that the 230 nsec time change obtained at zero applied stress when the transducer was rotated 90 deg is a measure of the anisotropy in the rail and that it is eliminated when stress change calculations are made. For each particular rail, this time differential at zero applied stress appears to be a reliable indicator of corresponding material anistropy. Of course, evaluations of numerous rail segments are required to establish an adequate statistical basis for this and to determine whether or not additional material parameters must be considered in measuring residual stress. But it is clear that time changes caused by highly oriented, unstressed rail material are large and this fact suggests a procedure for making field type stress measurements. Such a procedure should provide for a measurement of residual as well as applied stress with acceptable accuracy. Major requirements for this procedure are outlined below:

1. Utilize about 5.08 cm (2 in.) on the end of each rail as a standard.

2. Determine the anisotropic factor.

3. Measure the transit time differential between parallel and perpendicular polarizations of sound in a welded rail.

4. Subtract the anistropic factor from the time differential and compute the stress level by dividing the remainder by the stress constant and the ultrasonic path length.

Surface Wave Measurements

Althou h ultrasonic surface wave velocity measurements have been used for years to determine near-surface stress in aluminum alloys and, to a limited extent, in steel, the fundamentals are not as well established as those for shear waves. Published literature does not cover this aspect of surface wave theory very well. However, work at MSFC has shown that accurate and repeatable stress change determinations can be made by utilizing a small ultrasonic transducer having a separation of only 2.54 cm (1 in.) between transmitting and receiving crystals. This technique works especially well in aluminum since the change in velocity for a given load change is much greater for aluminum than for steel. This makes velocity measurements in steel difficult since time change intervals corresponding to velocity changes for the 2.54 cm (1 in.) path length are so short. A longer path length should reduce measurement errors by minimizing the effect of transducer coupling variations.

Consequently, fixtures and transducers suitable for coupling surface waves into long lengths of rail were developed and utilized, as depicted in Figure 11, to achieve this purpose. However, results of measurements over a 76.2 cm (30 in.) path length raised additional questions about the relationship of ultrasonic surface wave velocity to stress. A casual observation of experimental results shown in Table 9 give the impression of a very effective measurement of stress in the rail but this proves to be incorrect. A brief review of measurement procedures may be helpful in illustrating this point.

The short path length transducer is self-contained with a constant 2.54 cm (1 in.) distance between transmitting and receiving crystals and it is applied to specimen after the material is loaded. Thus, data obtained this way do not have to be corrected for strain. Two separate transducers were used to make surface wave measurements over the 76.2 cm (30 in.) path length and for maximum accuracy they were attached to the rail before it was loaded; so a strain correction was required.

Experimental ultrasonic measurements showed a transit time change of 187 nsec over the 76.2 cm (30 in.) path length at maximum load. However, a calculation of the time change caused by compression of the specimen during loading was 189 nsec. Thus, the required strain correction essentially cancelled the time change measured ultrasonically. So for this particular material, the velocity dependence of ultrasonic surface waves on stress is much smaller than previous measurements indicated. Obviously, this contradicts results previously obtained by measuring time changes over 2.54 cm (1 in.) path lengths. The only logical answer, which available evidence appears to support, is that deformations of a surface by short, dual contact transducers effectively change the distance between transmitting and receiving crystals. The magnitude of these deformations is, among other things, a function of stress in the material. Thus, a measurement of surface wave transit time with a dual contact transducer is a measurement of stress, although a path length change rather than a velocity change is the major stress-related parameter for steel. Obviously, path length changes caused by surface deformation becomes less significant as the total ultrasonic path length increases.

In summary, the short transducer can be used to measure stress, but mechanisms involved include velocity changes and surface deformation phenomena. The technique works well with aluminum since both mechanisms are sensitive to stress changes in this relatively soft material; however, neither the short or long path length technique is recommended for steel. The stress-related velocity changes are essentially zero for surface waves in rail steel and the material is too hard to obtain reliable results by the surface deformation mechanism.

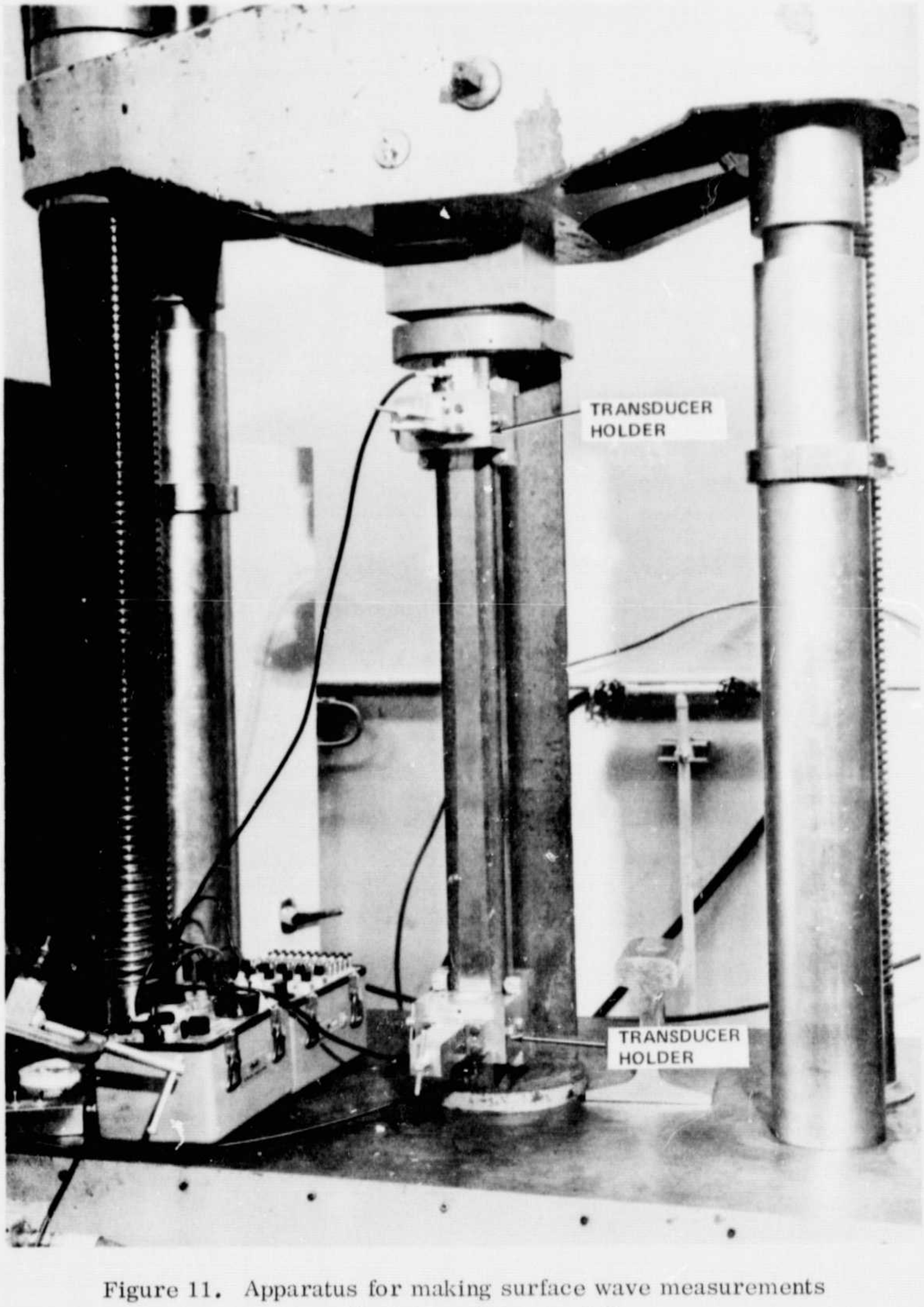

Figure 11. Apparatus for making surface wave measurements on the long rail segment S_4.

TABLE 9. SURFACE WAVE VELOCITY MEASUREMENTS ON A LONG RAIL SEGMENT

Load, $N/m^2 \times 10^7$ (ksi)	Dial Readings (Divisions)	Time Changes, nsec
0 (0)	300.2	0
3.43 (4.98)	291.4	44.0
7.05 (10.23)	281.0	51.0
10.70 (15.54)	271.7	46.5
14.35 (20.82)	262.5	46.0
Total Time Change		187.5

Techniques of Coupling Shear Waves Into Metal At Elevated Temperatures

Practical measurements of stress with ultrasonic shear waves cannot be made in an optimum manner without effective, rapidly coupled transducers that can be easily rotated. A highly viscous couplant meets these requirements when a firm yet moderate pressure is applied to the transducer. As previously described, the resin portion of an adhesive called "Lefkoweld 109" is very satisfactory for this purpose at room temperatures. However, the necessity of measuring stress in either hot or cold rail required an evaluation of the effects of temperature variations on coupling characteristics of the resin. This evaluation was accomplished by attempting to measure stress on a rail specimen heated to 52°C (125°F) with high energy lamps. The resin became less viscous and would not transmit ultrasonic shear waves in a reliable manner. Several other couplants were tested in an effort to overcome the problem before finding that a special mixture of Elmer's waterproof glue would maintain adequate viscosity at 52°C (125°F). This glue consists of a powder catalyst and liquid resin usually mixed in a ratio of 3 to 4 parts, respectively.

But a mixture of one part catalyst to 16 parts of resin produced a viscous material suitable for use as a high temperature couplant.

High pressure coupling of acoustic energy into steel was investigated as an alternate method of solving the problem of measuring stress at elevated temperatures. A special transducer designed for this purpose was fabricated and tested as indicated in Figure 12. The transducer was placed on a block of steel and loaded incrementally in a laboratory press until ultrasonic reflections were obtained from the back side of the block. This required a force of about $8.25 \cdot 10^7$ N/m^2 (12 ksi) to obtain a detectable signal across a steel to steel interface and $12.38 \cdot 10^7$ N/m^2 to $13.76 \cdot 10^7$ N/m^2 (18 to 20 ksi) to obtain effective coupling. Considerably less force was required for coupling the steel transducer to an aluminum block. These tests proved that ultrasonic shear waves can be transmitted across metallic interfaces without the use of a couplant. Because of this finding, fixtures for clamping the transducer loading apparatus to a rail were designed and fabricated. The clamping illustrated in Figure 13 was utilized to measure stress in a rail segment incrementally loaded with a large press. These stress determinations demonstrated feasibility of the pressure technique of coupling sound into steel. Obviously, however, the large coupling forces will affect stress patterns existing in rail and must be accounted for by suitable calibration procedures.

A third method of solving or at least of minimizing the elevated temperature coupling problem was investigated to a limited extent. This involved the use of a transducer containing two crystals side by side having mutually perpendicular polarizations. Sound beams from these crystals overlap to some extent and average the stress over a larger volume of material than occurs when a single crystal is rotated, but it allows the use of a semipermanent adhesive which should maintain coupling integrity over the required temperature range. Although melting and remelting of the adhesive is time consuming, this approach could be useful when only a few stress measurements are required. Verification of the basic technique was accomplished at room temperature and the stress constant obtained was only slightly higher than the average of several single crystal measurements.

It should also be noted that a modification of the dual crystal transducer is applicable to pressure coupled sound insertion and that a transducer of this type could eliminate the requirement of having reference blocks of the type previously described in this report. Only a few changes in the instrumentation would be necessary to accomplish this type of testing.

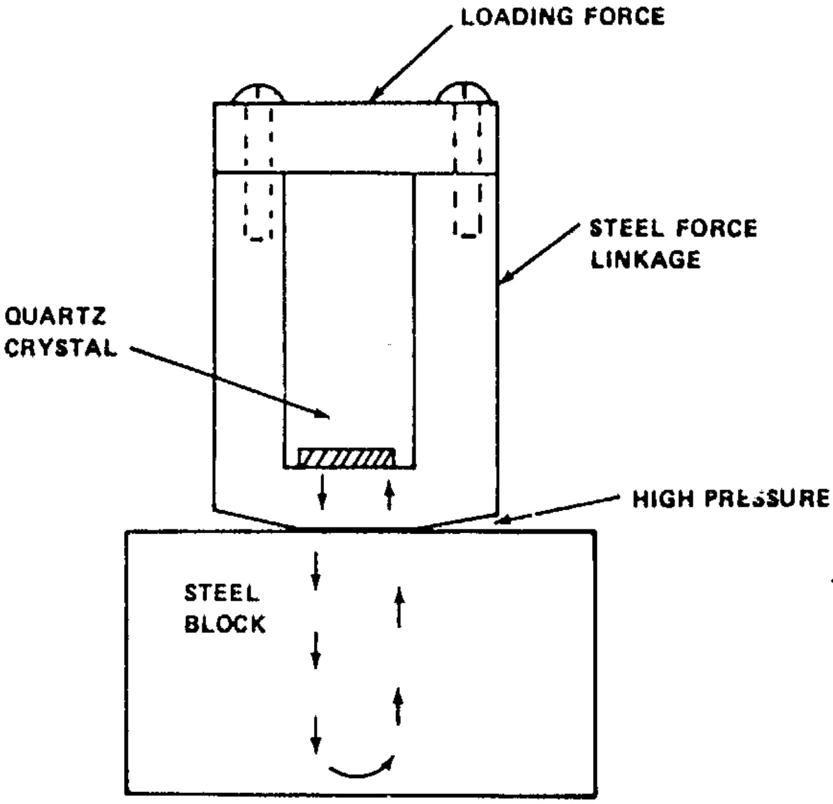

Figure 12. Shear wave sound insertion without use of a viscous couplant.

CONCLUSIONS

Ultrasonic velocity measurements have been made on several railroad wheels, wheel segments, rail segments, and calibration blocks fabricated from representative materials. Repeated measurements vary less than 1 nsec from initial determinations and are of sufficient accuracy to be useful. However, material variability causes variations of ultrasonic velocity in addition to that caused by stress. These variations are small percentages of the characteristic velocity of a specific material but are large compared to velocity changes caused by stress. Nevertheless, stress change measurements can be made with satisfactory accuracy and useful determinations of residual stress are obtainable. However, a careful preliminary evaluation of material characteristics is necessary before acceptable measurements of residual stress can be made.

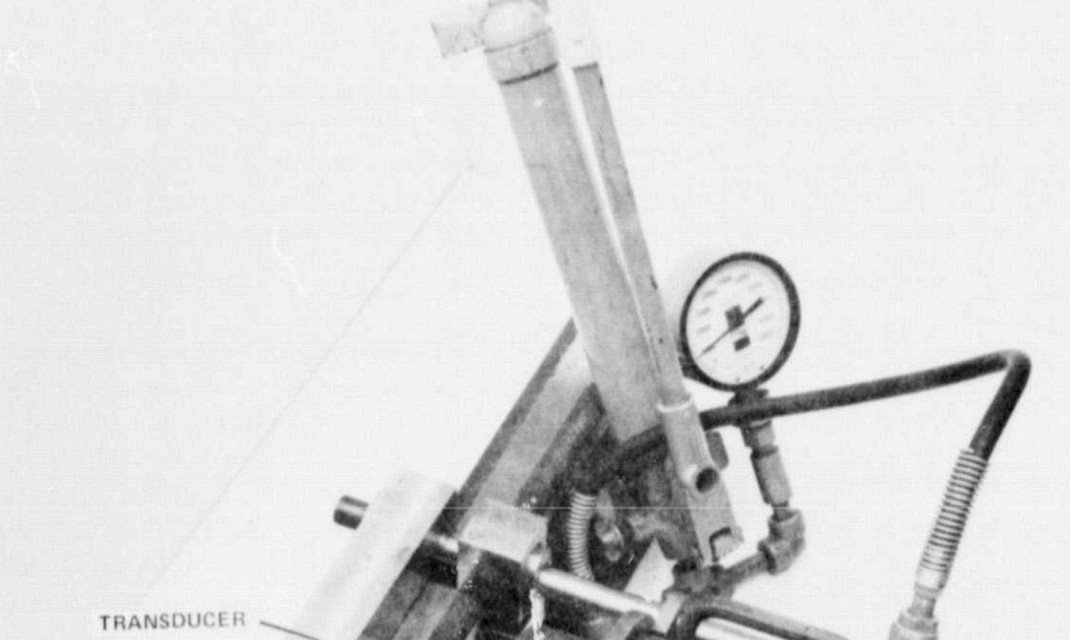

Figure 13. Pressure coupling device.

In addition to the stress constant determination, a calibration factor is required and should include the effects of material anisotropy and any other parameter that affects the characteristic velocity of sound in an unstressed specimen. This factor is more difficult to obtain for wheels than for rails.

There is considerable variability in unloaded reference blocks of wheel steel which causes variations of ultrasonic velocity that are not stress related. This precludes the accurate measurement of total wheel stress until an independent nondestructive method is available for evaluating material variability. However, reliable stress change measurements can be made since all data obtained to date indicate that the stress constant is reliable. Thus, baseline data can be obtained for each new wheel and subsequent measurements on used wheels will reveal stress changes due to thermal loading generated by emergency braking.

Rail geometry accommodates residual stress measurements much better than the wheel configuration. New wheel rims contain high residual stresses and great material variability from wheel to wheel, but the last few inches near the end of each unwelded rail can serve as a convenient reference block since any residual stress is relatively low and material characteristics should be statistically representative of the entire rail. Thus, any measurement on a corresponding rail subsequent to welding will be a useful determination of total stress in the rail head and it will be within acceptable limits of accuracy.

The laboratory work described in this report has demonstrated that reliable stress measurements can be made ultrasonically and that the technology has vast potential utility in the railroad industry.

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APPROVAL

ULTRASONIC MEASUREMENT OF STRESS IN RAILROAD WHEELS AND IN LONG LENGTHS OF WELDED RAIL

By W. N. Clotfelter and E. R. Risch

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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