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Fatigue Behavior of AAR Class A Railroad Wheel Steel at Ambient and Elevated Temperatures

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* Fraser J. McMaster and Guadalupe B. Robledo

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U.S. Department of Transportation
Research and Innovative Technology Administration
John A. Volpe National Transportation Systems Center
55 Broadway
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*Southwest Research Institute
6220 Culebra Road
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13. ABSTRACT (Maximum 200 words)

This report documents a test program to determine the material properties (chemical composition, tensile, and fatigue) at ambient and elevated temperatures of a Class A wheel steel as designated by the Association of American Railroads. The 3 temperatures examined included ambient room temperature, 500 °F, and 1000 °F. The fatigue properties determined at ambient temperature are required to address rail vehicle wheels equipped with disc brakes, which are not exposed to frictional heating during stop-braking. Researchers performed fatigue testing to determine the S-N curves at each of the three temperatures. Furthermore, the research team performed a large number of fatigue tests at R-ratios of -1.0 and 0.05 for each of the test temperatures to enable reliable estimates of the Sines parameters, *A* and *α*.

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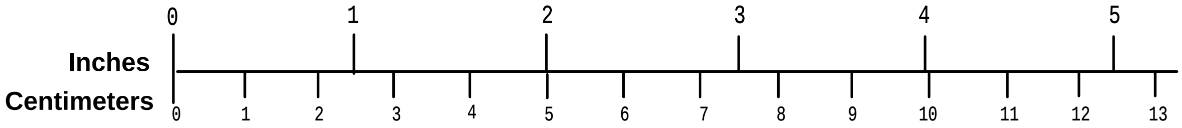
ENGLISH TO METRIC		METRIC TO ENGLISH	
LENGTH (APPROXIMATE)		**LENGTH** (APPROXIMATE)	
1 inch (in)	= 2.5 centimeters (cm)	1 millimeter (mm)	= 0.04 inch (in)
1 foot (ft)	= 30 centimeters (cm)	1 centimeter (cm)	= 0.4 inch (in)
1 yard (yd)	= 0.9 meter (m)	1 meter (m)	= 3.3 feet (ft)
1 mile (mi)	= 1.6 kilometers (km)	1 meter (m)	= 1.1 yards (yd)
		1 kilometer (km)	= 0.6 mile (mi)
AREA (APPROXIMATE)		**AREA** (APPROXIMATE)	
1 square inch (sq in, in^2)	= 6.5 square centimeters (cm^2)	1 square centimeter (cm^2)	= 0.16 square inch (sq in, in^2)
1 square foot (sq ft, ft^2)	= 0.09 square meter (m^2)	1 square meter (m^2)	= 1.2 square yards (sq yd, yd^2)
1 square yard (sq yd, yd^2)	= 0.8 square meter (m^2)	1 square kilometer (km^2)	= 0.4 square mile (sq mi, mi^2)
1 square mile (sq mi, mi^2)	= 2.6 square kilometers (km^2)	10,000 square meters (m^2)	= 1 hectare (ha) = 2.5 acres
1 acre = 0.4 hectare (he)	= 4,000 square meters (m^2)		
MASS - WEIGHT (APPROXIMATE)		**MASS - WEIGHT** (APPROXIMATE)	
1 ounce (oz)	= 28 grams (gm)	1 gram (gm)	= 0.036 ounce (oz)
1 pound (lb)	= 0.45 kilogram (kg)	1 kilogram (kg)	= 2.2 pounds (lb)
1 short ton = 2,000 pounds (lb)	= 0.9 tonne (t)	1 tonne (t)	= 1,000 kilograms (kg)
			= 1.1 short tons
VOLUME (APPROXIMATE)		**VOLUME** (APPROXIMATE)	
1 teaspoon (tsp)	= 5 milliliters (ml)	1 milliliter (ml)	= 0.03 fluid ounce (fl oz)
1 tablespoon (tbsp)	= 15 milliliters (ml)	1 liter (l)	= 2.1 pints (pt)
1 fluid ounce (fl oz)	= 30 milliliters (ml)	1 liter (l)	= 1.06 quarts (qt)
1 cup (c)	= 0.24 liter (l)	1 liter (l)	= 0.26 gallon (gal)
1 pint (pt)	= 0.47 liter (l)		
1 quart (qt)	= 0.96 liter (l)		
1 gallon (gal)	= 3.8 liters (l)		
1 cubic foot (cu ft, ft^3)	= 0.03 cubic meter (m^3)	1 cubic meter (m^3)	= 36 cubic feet (cu ft, ft^3)
1 cubic yard (cu yd, yd^3)	= 0.76 cubic meter (m^3)	1 cubic meter (m^3)	= 1.3 cubic yards (cu yd, yd^3)
TEMPERATURE (EXACT)		**TEMPERATURE** (EXACT)	
[(x-32)(5/9)] °F	= y °C	[(9/5) y + 32] °C	= x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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EXECUTIVE SUMMARY

Service loading conditions for railroad wheels include those due to wheel-on-rail contact, as well as thermal loads from frictional heating during on-tread braking. Studies have shown that the wheel surface temperatures can reach 1000 °F during stop-braking. Current wheel design acceptance criteria deal primarily with wheel designs for North American freight applications, whereas the American Public Transportation Association (APTA) Passenger Rail Equipment Safety Standards Group is presently developing a companion fatigue-based standard for passenger and transit wheels.

The group developing the new standard is exploring the potential applicability of two fatigue-based acceptance criteria. Unfortunately, limited fatigue data exists for wheel steels, especially in the as-forged service condition. This report documents a material property test program to determine the material properties (chemical composition, tensile, and fatigue) at ambient and elevated temperatures of a Class A wheel steel as designated by the Association of American Railroads (AAR). Previous testing focused on the fatigue performance of a Class B wheel steel. The 3 temperatures examined included ambient room temperature, 500 °F, and 1000 °F. The fatigue properties determined at ambient room temperature are required to address rail vehicle wheels equipped with disc brakes, which are not exposed to frictional heating during stop-braking. Researchers performed fatigue testing to determine the S-N curves for each of the three temperatures. Furthermore, a large number of fatigue tests was performed at R-ratios of -1.0 and 0.05 for each of the test temperatures to enable reliable estimates of the Sines parameters, A and α.

Chemical composition analysis indicated that both wheel samples were within the range for a Class A railroad wheel, as given in AAR specification M-107/208. Monotonic tensile tests were undertaken for the Class A wheel steel at room temperature, 500 °F, and 1000 °F. Room-temperature test results were in accordance with AAR baseline values, as given in AAR Standard S-660. Similar ultimate tensile strength and yield stress results were found for the room-temperature and 500 °F tests. However, a 50-percent reduction in ultimate tensile strength and a 35-percent reduction in yield strength were observed for the 1000 °F tensile tests compared to both the room-temperature and the 500 °F tests. The research team observed a large decrease in the percent elongation and reduction in area for all 500 °F tests compared to room-temperature and 1000 °F tests. This variation in tensile properties was also observed during a previous test program utilizing a Class B wheel steel material.

The vast majority of testing was performed at stress ratios of 1.0 and 0.05 to enable the full S-N curves to be developed. The remainder of testing was undertaken to obtain the endurance limit at 10^7 cycles for R-ratios of 0.5 and 0.7. The degree of scatter for fatigue tests averaged approximately one order of magnitude (10x) for all tests performed at replicate stress levels. Endurance limit data was obtained for all R-ratios at each of the three test temperatures. For the 1000 °F tests, however, the usual endurance limit transition did not appear at the lower stress levels, as was found with the room-temperature and 500 °F tests. Based on the endurance limit

data for R-ratios of -1.0 and 0.05, personnel conducting the tests obtained an estimation of the Sines parameters, A and α, for each of the 3 test temperatures.

1. Introduction

The APTA Passenger Rail Equipment Safety Standards Group on wheel design is working toward the development of fitness-for-service design criteria for railroad wheels used in transit and passenger applications. Currently, AAR Standard S-660 specifies design acceptance criteria [1]. This standard deals primarily with wheel designs for North American freight applications, whereas the APTA Committee is seeking to develop an equivalent standard for passenger and transit wheels.

The service loading conditions include those due to wheel-on-rail contact, as well as thermal loads from frictional heating during on-tread braking. Studies conducted at the Volpe National Transportation Systems Center (Volpe Center) [2] have shown that wheel surface temperatures can reach 1000 °F during stop-braking. Since the combination of contact and thermal loads results in multiaxial stress fields in wheels, no standard way exists to apply conventional acceptance criteria.

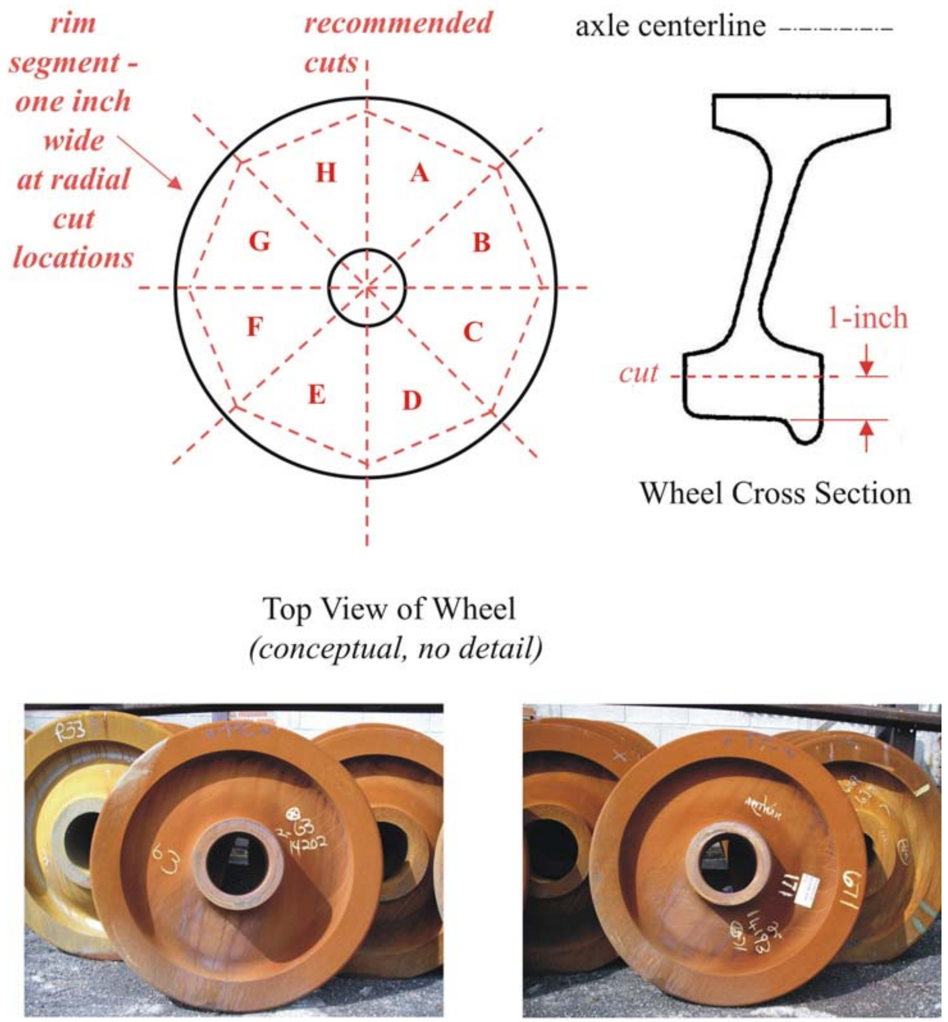
The group developing the new standard is exploring the potential applicability of two fatigue-based acceptance criteria. Unfortunately, limited fatigue data exists for wheel steels, especially in the as-forged service condition. The objective of this program is to determine the material properties (chemical composition, tensile, and fatigue), at ambient and elevated temperatures, of Class A wheel steel as designated by AAR. Previous testing has focused on the fatigue performance of a Class B wheel steel [3]. The 3 temperatures examined included ambient room temperature, 500 °F, and 1000 °F. The fatigue properties determined at ambient room temperature are required to address rail vehicle wheels equipped with disc brakes, which are not exposed to frictional heating during stop-braking.

This report documents the procedures and results obtained from constant amplitude fatigue testing at the Southwest Research Institute (SwRI). The report will discuss issues associated with the procedures used during testing, including test specimen machining and high-temperature test setup. The report presents tabular and graphical descriptions of the experimental results, estimates of fatigue parameters, and a discussion of the relevant trends and characteristics of the recorded data. The concluding section summarizes the results and provides a brief review of the major findings.

2. Material and Experimental Methods

2.1 Material and Specimen Geometries

The AAR Class A railroad wheel steel used in this test program is designed for high-speed service with severe braking conditions and moderate wheel loads when used under passenger car service conditions. The AAR Class A wheel steel required for constant amplitude fatigue testing was supplied from two railroad wheels, sectioned into eight pieces per wheel, as schematically shown in Figure 1. Specimens for tensile, chemical composition, and fatigue tests were extracted from each of the railroad wheels.



Wheel 02-3-14202

Wheel 02-3-14193

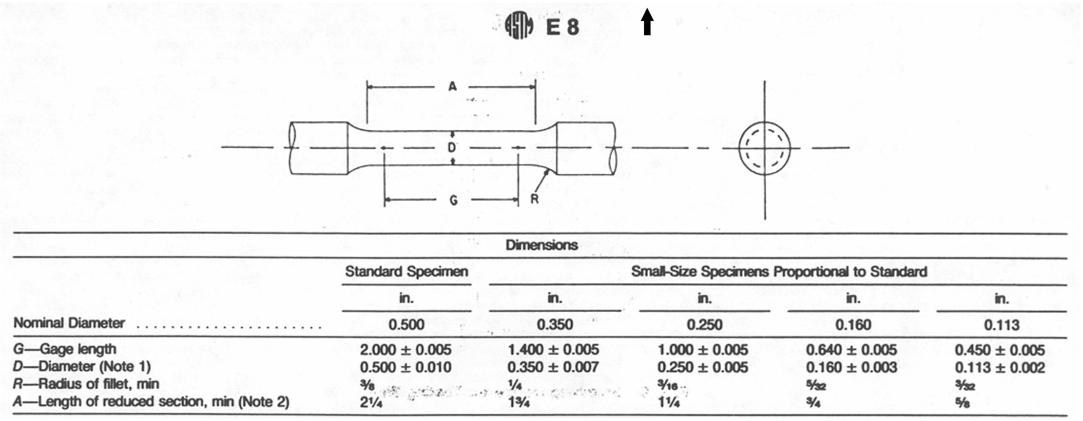
Figure 1. Schematic Showing Extraction of Sections from the Two Railroad Wheels

Individual sections from each of the two railroad wheels were selected to enable a tensile and chemical test sampling of both wheels. The two wheels were produced in February 2003 from steel heat P9871 (Standard Steel, Burnham, PA). The basic geometries generally conformed to the relevant American Society for Testing Materials (ASTM) test specification [4]. The actual specification used to determine the properties evaluated, specimen geometry, and test procedures, however, depended upon the type of test performed:

- Tensile testing: ASTM E8-00 (Standard Test Methods for Tension Testing of Metallic Materials)
- Fatigue testing: ASTM E466-96 (Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials)

The various standards allow for a number of specimen shapes and sizes depending upon requirements of the particular test and raw material form.

The tensile testing was subcontracted with specimen blanks supplied to the vendor (Staveley Services, Glendale Heights, IL). The blanks were machined into second-subsize specimens with gage length diameters of 0.250 inch, as illustrated in Figure 2. Elongation at failure was measured over the specimen's total gage length. The tensile properties were determined only in the circumferential orientation for the railroad wheels, with this being the most relevant orientation in terms of the fatigue specimens. Figure 3 (tensile and chemical) and Figure 4 (fatigue) show schematics indicating how the tensile, chemical, and fatigue test specimens were positioned in the actual railroad wheel. Figure 5 shows the actual fatigue specimen geometry.



Dimensions

	Standard Specimen	Small-Size Specimens Proportional to Standard			
	in.	in.	in.	in.	in.
Nominal Diameter	0.500	0.350	0.250	0.160	0.113
G—Gage length	2.000 ± 0.005	1.400 ± 0.005	1.000 ± 0.005	0.640 ± 0.005	0.450 ± 0.005
D—Diameter (Note 1)	0.500 ± 0.010	0.350 ± 0.007	0.250 ± 0.005	0.160 ± 0.003	0.113 ± 0.002
R—Radius of fillet, min	3⁄8	1⁄4	3⁄16	5⁄32	3⁄32
A—Length of reduced section, min (Note 2)	2 1⁄4	1 3⁄4	1 1⁄4	3⁄4	5⁄8

Figure 2. Specimen Geometry Utilized for Assessing Tensile Strength of the Wheel Material at 72 °F, 500 °F, and 1000 °F (Extracted from ASTM Standard E8 [4])

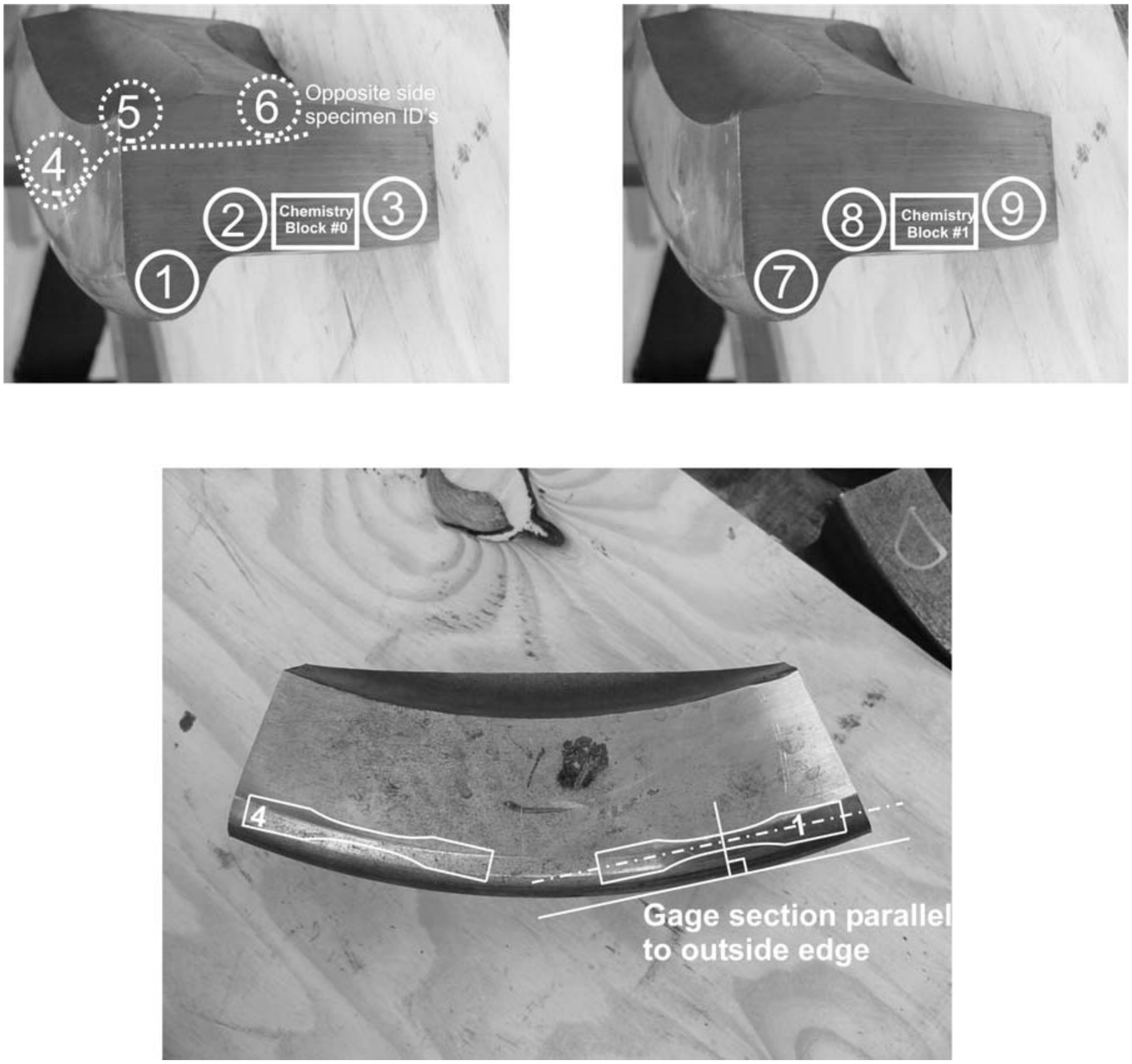
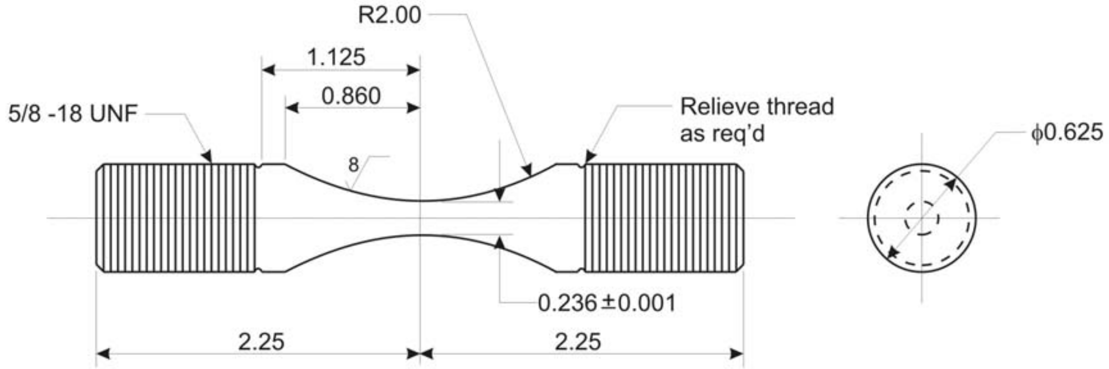


Figure 3. Schematic Layout for the Tensile and Chemical Composition Specimens

Figure 4. Schematic Layout for the Fatigue Specimens in Each Wheel Section



	Drawn By: F. J. McMaster				Southwest Research Institute	
	Date: 3 August 2004				San Antonio, Texas	
Matl: Grade A steel	Tolerances (inches)				**Title:**	Volpe S-N Specimen
	Basic Dimension	2 place	3 place	Frac.		
Finish: As shown	Under 6	±0.005	±0.005	±1/32	**Drawing Number** 18.10798.SN1	**Scale** none
	6-24 incl	±0.010	±0.005	±1/16		
Qty Reqd: 140	Over 24	±0.025	±0.015	±1/8	**Filename** C:\Fraser\SwRI\Projects\Volpe-SN@temp\Specimens\SN-spec.cdr	1 Sheet of 1
	Angles	±0°30'		± 1°0'		

Figure 5. Design Drawing for the Hourglass Fatigue Specimen

A basic code was used to form the identification numbers of the fatigue specimens. This code typically consisted of a number identifying the railroad wheel, a letter identifying the wheel section, and a multi-digit identifier qualitatively indicating position in the product, as outlined below:

- Wheel **0** (Serial No. 02-3-14193), **1** (Serial No. 02-3-14202)
- Wheel Section **A-H** (see Figure 1)
- Specimen Position **1-10** (see Figure 4)

The two chemical test specimens were identified by 0 and 1, indicating the wheel from which they were extracted. Similarly, the tensile test specimens were identified numerically from 1 to 9, with their relevant position in the wheel shown in Figure 3. Table 1 provides a complete list of specimens extracted from the two wheels.

Table 1. Description of the Specimens Used During Tensile, Chemical Composition, and Fatigue Testing

Wheel	Wheel Section	Fatigue Specimen ID	Tensile Specimen ID	Chemical Specimen ID
02-3-14193	A	0A1 *to* 0A10		
	B	0B1 *to* 0B10		
	C	0C1 *to* 0C10		
	D	0D1 *to* 0D10		
	E		1 *to* 6	0
	F	0F1 *to* 0F10		
	G	0G1 *to* 0G10		
	H	0H1 *to* 0H10		
02-3-14202	A	1A1 *to* 1A10		
	B		7 *to* 9	1
	C	1C1 *to* 1C10		
	D	1D1 *to* 1D10		
	E	1E1 *to* 1E10		
	F	1F1 *to* 1F10		
	G	1G1 *to* 1G10		
	H	1H1 *to* 1H10		

2.2 Experimental Test Procedures

As indicated previously, testing was performed in the spirit of the ASTM test specifications and supplemented by experience gained over many years of similar testing. The purpose of this section is to provide additional detail concerning the methods used during tensile, chemical, and fatigue testing.

Researchers performed tensile testing in complete accordance with ASTM E8-00. Three specimens were tested at each of the specified test temperatures: room temperature, 500 °F, and

1000 °F. This resulted in a total of nine tensile tests. The quantities recorded during testing or derived from data included:

- Ultimate tensile strength (σ_{UTS})
- Yield strength (σ_{YS})
- Percent elongation at failure
- Percent reduction in area at failure

Chemical analysis was performed on each of the two railroad wheels to provide verification that the material was within the specification for AAR M107/208 Class A steel. Analysis was performed in accordance with the standard ASTM test specifications [5,6].

The vast majority of testing focused on evaluating the fatigue behavior of the Class A steel under each of the three test temperatures. Four different R-ratios were evaluated during fatigue testing and included R = -1.0, 0.05, 0.5, and 0.7. The testing at R = -1.0 and R = 0.05 included sufficient specimens to generate the complete S-N curve. However, the testing at the higher R-ratio conditions, R = 0.5 and R = 0.7, included only 6 specimens, nominally to determine the endurance limit.

The fatigue testing was performed at SwRI in the Solid and Fracture Mechanics Laboratory using 2 closed-loop servo-hydraulic test frames with high-temperature furnaces required for the 500 °F and 1000 °F tests. Figure 6 shows a photograph of the high-temperature test setup for the 500 °F and 1000 °F tests. Figure 7 shows an overall view of the test setup, illustrating the complexity and multiple components. As shown in Figure 7, a step-down transformer was used to provide a variable high current, through water-cooled cables, to the heating plates. The high-temperature system provided a very controlled and stable temperature for the test specimens. Before starting each fatigue test, the controller set temperature was gradually increased to the desired level to avoid any temperature overshoot that may occur in the specimen during heating.

Testing frequency was in the range of 10-25Hz, depending primarily on the R-ratio. All specimens were tested until failure (2 pieces) or until the runout level of 10 million cycles was reached.

2.3 Fatigue-Based Criteria

The two fatigue-based acceptance criteria currently under consideration by the APTA Passenger Rail Equipment Safety Standards Group are the Sines criterion [7] and the French Societé Nationale des Chemins de Fer (SNCF) criterion [8]. This section will provide additional details of the two criteria. Although the fatigue testing program described in the previous sections is primarily concerned with generating S-N curves for the Class A wheel steel, it is expected that material constants required in the Sines criterion will be able to be extracted from the experimental data.

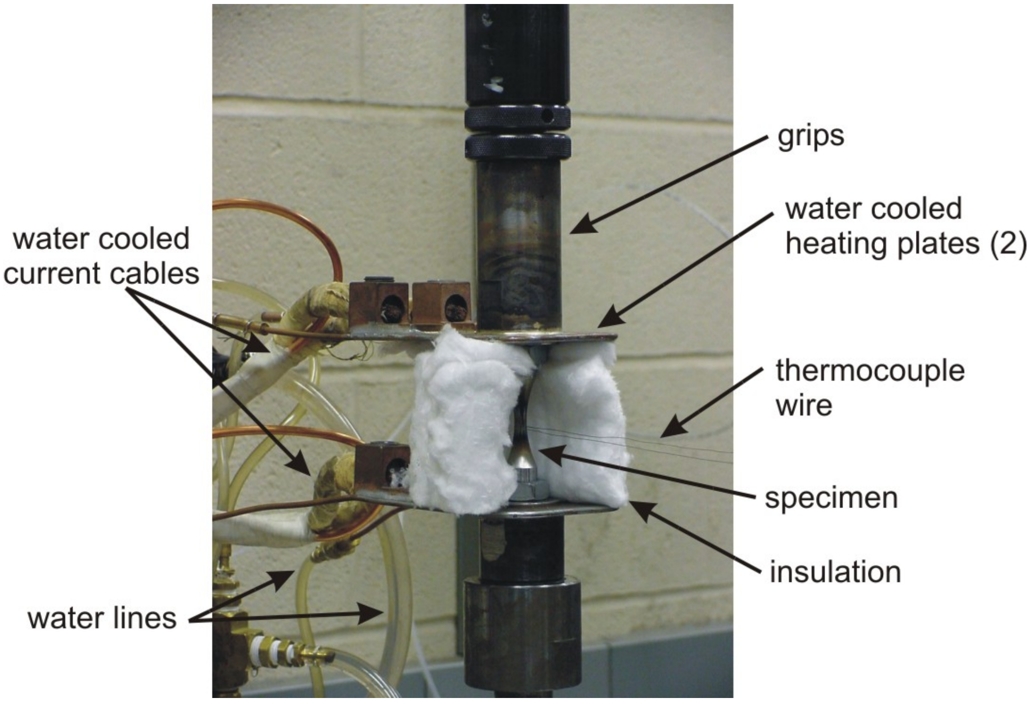


Figure 6. Detailed View of Setup for 500 °F and 1000 °F High-Temperature S-N Fatigue Testing

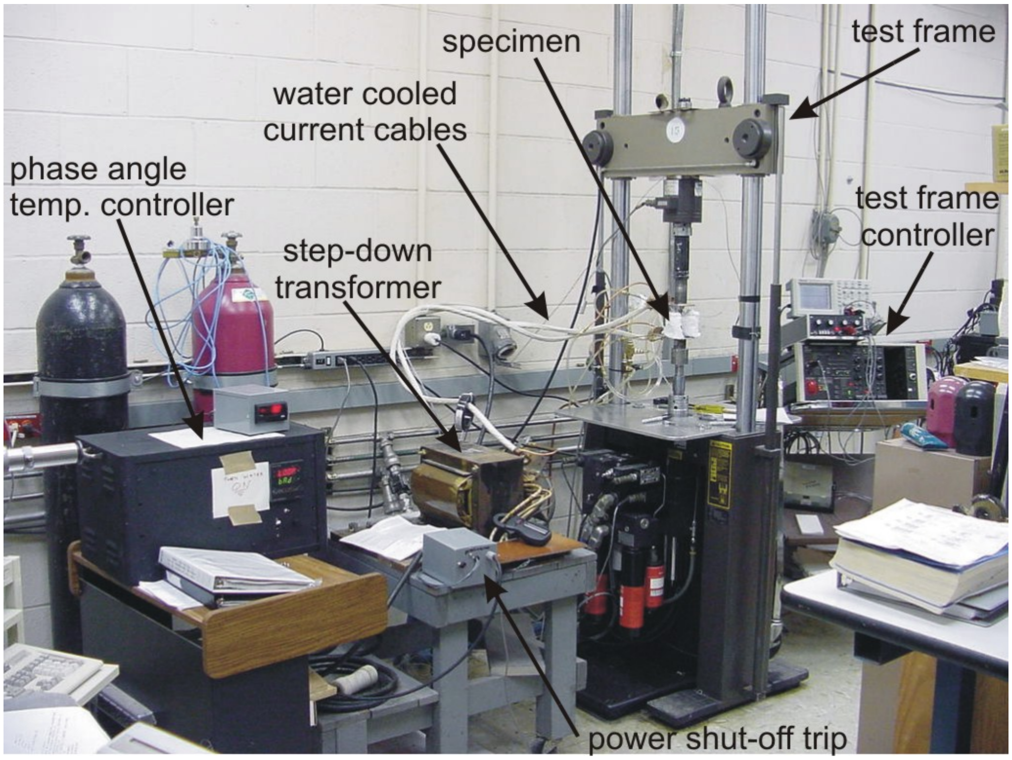


Figure 7. Overall Setup for High-Temperature S-N Fatigue Testing

2.3.1 The Sines Criterion

In 1955, Sines [6] reviewed the results of experiments on the effect of different combinations of tensile, compressive, and torsional mean and alternating stresses on fatigue life. He reported that alternating shear stresses seemed to cause fatigue failure. Because of this, Sines studied the influence of mean static stresses on the planes of maximum alternating shear. From this study, he developed the relationship:

$$\frac{1}{3}\sqrt{(P_1 - P_2)^2 + (P_2 - P_3)^2 + (P_1 - P_3)^2} + \alpha(S_x + S_y + S_z) \leq A \qquad (1)$$

where P_1, P_2, P_3 = amplitudes of the alternating principal stresses
S_x, S_y, S_z = orthogonal (any coordinate system) mean stresses
A = material constant proportional to reversed fatigue strength
α = material constant, which gives variation of the permissible range of stress with static stress
A and *α* are materials properties for a given life level

The first term on the left-hand side of Equation 1 is the octahedral shear stress, τ_{oct}. Sines suggested that τ_{oct} averages the effect of shear stresses on many differently oriented slip planes. In addition, a hydrostatic stress term is included in this model by the second term on the left-hand side of Equation 1.

In Sines's equation, *A* and *α* may easily be determined. For example, in a fully reversed uniaxial test, Equation 1 is:

$$\frac{\sqrt{2}}{3}P_1 = A \qquad (P_2 = P_3 = S_x = S_y = S_z = 0) \qquad (2)$$

Letting $P_1 = f_1$ gives:

$$A = \frac{\sqrt{2}}{3}f_1 \qquad (3)$$

where f_1 is the amplitude of reversed axial stress that would cause failure at the desired cyclic life. For 0 to σ_{max} loading (R-ratio = 0),

$$S_x = P_1 \qquad (P_2 = P_3 = S_y = S_z = 0)$$

and Equation 1 becomes:

$$\frac{\sqrt{2}}{3}P_1 = A - \alpha P_1 \qquad (4)$$

Letting $P_1 = f_1'$ yields:

$$\alpha = \frac{A}{P_1} - \frac{\sqrt{2}}{3} = \frac{\sqrt{2}}{3}\left(\frac{f_1}{f_1'} - 1\right) \quad (5)$$

where f_1' is the amplitude of fluctuating stress that would cause failure at the same cyclic life as f_1. Thus, *A* and *α* are described in terms of stress amplitudes f_1 and f_1'.

2.3.2 The SNCF Criterion

The second criterion currently under consideration is a modified Goodman diagram (MGD), as specified by SNCF in its wheel design specification [7]. Figure 8 shows a graphical example of the SNCF MGD. In this case, the mean and alternating stresses are the radial stresses in the plate and plate fillet of the railroad wheel.

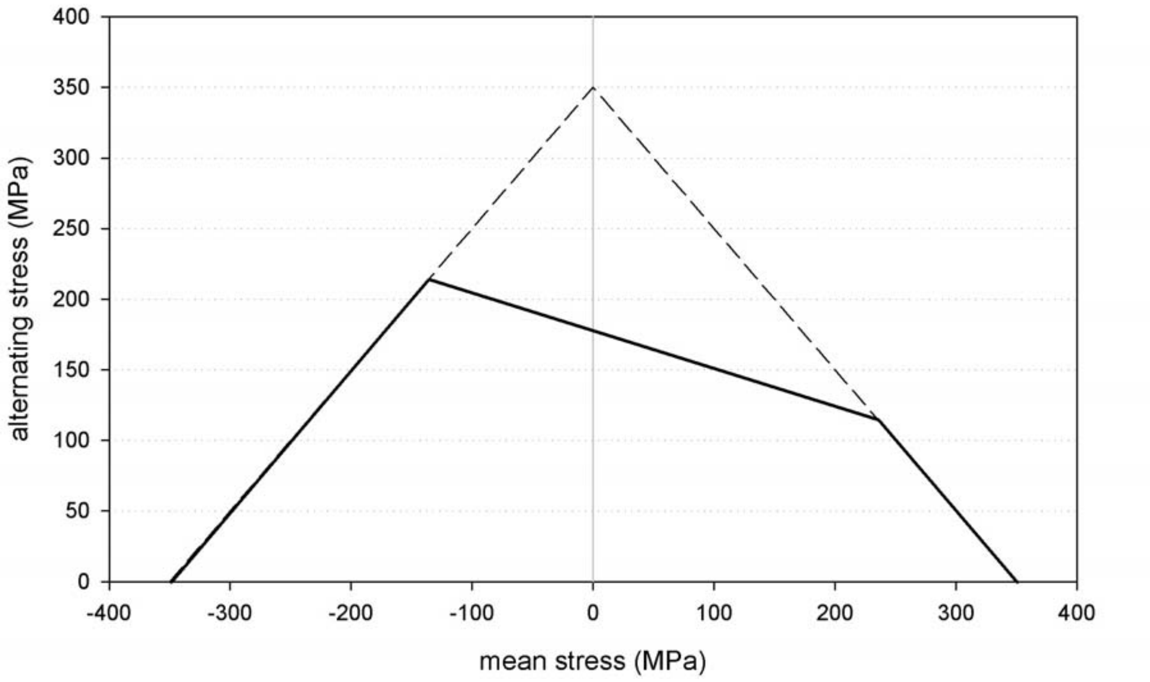


Figure 8. Schematic of the SNCF MGD

The truncation of the MGD is based on empirical data gained from SNCF experience in designing wheels for rail applications. Finite element analysis, under both mechanical and thermal loading, is used to evaluate railroad wheel designs before introducing them into service. The largest values of the radial stresses, predicted using finite element analysis, are used to calculate the mean and alternating radial stresses at each node in the model as follows:

$$\sigma R_{mean} = \frac{(\sigma R_{max} + \sigma R_{min})}{2} \quad \text{and} \quad \sigma R_{alternating} = \frac{(\sigma R_{max} - \sigma R_{min})}{2} \quad (6)$$

The mean and alternating stress pairs are then plotted on the graph shown in Figure 8 for each node in the finite element model. To enable the proposed wheel design to be accepted for service, all results must fall within the prescribed MGD envelope.

3. Test Results and Discussion

3.1 Material Characterization Results

The following section provides tabular and graphical results of the tensile and chemical composition testing. This section also describes the most notable characteristics of the material property data for the tested Class A wheel steel and contrasts these data with the data given in the AAR specification for carbon steel wheels [9]. The tensile and chemical test result summaries are extracted from the actual data tabulated in the Appendix, Tensile and Chemical Properties. This appendix includes additional details regarding the specifics of all the tensile tests.

Table 2 shows a summary of the chemical composition data, with the AAR specification allowables provided for comparison. The results given indicate that both railroad wheel samples contained the required elements within the specified range, below the maximum, or above the minimum given for the Class A steel, as specified in Section 8.1 of AAR Specifications M-107/208 [9].

Table 2. Chemical Analysis Results for the Class A Wheel Steel

Sample ID	Element (Weight Percent)				
	C	Mn	P	S	Si
0	0.51	0.68	0.019	0.019	0.26
1	0.51	0.68	0.019	0.020	0.27
Minimum [9]	0.47	0.60			0.15
Maximum [9]	0.57	0.85	0.050	0.050	

Table 3 shows tensile test results for each of the three temperatures, with the room-temperature baseline tensile data for Class A wheel steel [1] also included for comparison. Room-temperature ultimate tensile strength (σ_{UTS}) was within the AAR baseline range specified.

Two observations are apparent from the test data given in Table 3. First, a dramatic decrease in the ultimate tensile strength and yield strength occurred when testing at a temperature of 1000 °F, with a 50-percent reduction in σ_{UTS} and a 35-percent reduction in σ_{YS}. Second, a decrease in the reduction in area and percent elongation for all 500 °F tests, compared to both room-temperature and 1000 °F tests, was observed. The actual tensile specimens were randomly selected for testing at the three temperatures, with each three-specimen group combined to include at least one specimen from each wheel, as previously shown in Figure 3. Therefore, it is unlikely that the difference in reduction of area for the three temperatures is a consequence of material variation in one specific wheel. This same variation in tensile properties for the three test temperatures was also observed during a previous test program utilizing a Class B wheel steel material.

Table 3. Tensile Tests Results for the Class A Wheel Steel at Room and Elevated Temperature

Temperature (°F)	Specimen ID	σ_{UTS}, ksi	σ_{YS}, ksi	ε, %	RA, %
Room Temperature	1	136.9	93.5	16.0	33.8
	3	133.8	89.7	15.5	31.7
	8	132.3	87.2	15.0	31.5
	Average →	**134.3**	**90.1**	**15.5**	**32.3**
	Class A baseline [1]	**125-160**			
500	2	140.9	80.0	14.0	16.6
	4	147.9	95.7	15.0	16.0
	9	147.4	86.2	13.0	15.1
	Average →	**145.4**	**87.3**	**14.0**	**15.9**
1000	5	71.9	59.1	18.0	53.4
	6	69.2	57.5	19.0	57.6
	7	68.5	53.9	20.0	57.3
	Average →	**69.9**	**56.8**	**19.0**	**56.1**

3.2 Fatigue Test Results

A total of 119 constant amplitude fatigue tests was performed at the 3 different test temperatures.

Tables 4, 5, and 6 give a summary of all fatigue tests performed at room temperature, 500 °F, and 1000 °F, respectively. The tables present data in terms of R-ratio, maximum stress, actual stress range, and cycles to failure. The maximum stress given in the tables is not the stress at which the specimens were tested. Due to the specimen's hourglass geometry, a stress concentration is produced in the specimen. Therefore, the effective test stress is calculated simply as:

$$\sigma_{\text{effective}} = \frac{\sigma_{\text{actual}}}{K_t} \tag{7}$$

where $\sigma_{\text{effective}}$ = stress used during test
σ_{actual} = actual stress induced in specimen
K_t = stress concentration due to hourglass geometry = 1.05

Table 4. Summary of the Fatigue Tests Performed at Room Temperature for the Class A Wheel Steel

R-ratio	Test ID	Maximum Test Stress (ksi)	Actual Stress Range, $K_t\Delta\sigma$ (ksi)	Cycles	Comments
0.05	1C-6	120	119.70	13,864	
	1H-4	105	104.74	23,445	
	0G-1	95	94.76	74,802	
	1H-9	95	94.76	59,086	
	0A-4	90	89.78	65,680	
	1H-5	90	89.78	119,387	
	0G-3	84	83.79	185,950	
	0G-8	84	83.79	166,185	
	0G-9	83	82.79	251,701	
	0G-6	83	82.79	10,000,000	Runout
	0G-5	82.5	82.29	10,000,000	Runout
	0G-7	80	79.80	10,000,000	Runout
-1.00	1H-6	85	178.50	2,781	
	1H-2	75	157.50	8,201	
	1C-3	75	157.50	8,895	
	1G-5	70	147.00	28,724	
	1C-7	70	147.00	21,983	
	1H-8	60	126.00	68,519	
	1C-1	60	126.00	169,414	
	1G-4	59	123.90	66,377	
	1H-7	58	121.80	194,086	
	0G-10	56.5	118.65	2,973,242	
	1G-6	56	117.60	2,692,003	
	0A-9	55	115.50	156,852	
	0A-8	55	115.50	200,000	
	0A-3	55	115.50	89,881	
	0A-10	55	115.50	10,000,000	Runout
	0A-2	54	113.40	155,25	
	1C-8	53	111.30	309,058	
	1E-4	52	109.20	6,476,442	
	1E-5	51	107.10	179,372	
	0A-5	50	105.00	10,000,000	Runout
0.5	1E-1	114	59.85	235,950	
	1E-8	110	57.75	293,281	
	1E-9	106	55.65	381,213	
	0D-5	104	54.60	10,000,000	Runout
	1F-7	103	54.08	10,000,000	Runout
	0D-3	100	52.50	10,000,000	Runout
	1E-7	95	49.88	10,000,000	Runout
0.7	1F-2	135	42.53	316,072	
	1A-5	135	42.53	10,000,000	Runout
	0D-1	130	40.95	10,000,000	Runout
	1A-6	120	37.80	10,000,000	Runout

Table 5. Summary of the Fatigue Tests Performed at 500 °F for the Class A Wheel Steel

R-ratio	Test ID	Maximum Test Stress (ksi)	Actual Stress Range, $K_t\Delta\sigma$ (ksi)	Cycles	Comments
0.05	0H-6	120.00	119.70	47,717	
	0B-8	120.00	119.70	35,030	
	0F-4	110.00	109.70	47,258	
	0B-9	110.00	109.70	14,979	
	1A-10	100.0	99.75	96,000	
	0C-8	95.0	94.80	4,736,989	
	0H-9	95.0	94.80	96,327	
	0H-7	90.0	89.80	66,715	
	1D-3	90.0	89.80	349,041	
	1F-1	85.0	84.80	6,885,450	
	0B-10	85.0	84.80	10,000,000	
	1D-10	84.0	83.80	4,290,017	
	1F-3	84.0	83.80	129,182	
	1D-1	83.0	82.80	10,000,000	
	0C-7	83.0	82.80	10,000,000	
	1A-2	70.0	69.83	10,000,000	
-1.0	1D-8	80.95	170.00	6,198	
	0F-7	80.95	170.00	4,573	
	0F-2	71.43	150.00	14,349	
	0B-4	71.43	150.00	41,979	
	0C-6	69.05	145.00	59,980	
	0H-4	69.05	145.00	10,260	
	0H-2	66.67	140.00	135,956	
	0F-1	66.67	140.00	178,894	
	0C-5	61.90	130.00	2,845,416	
	0B-7	61.90	130.00	162,093	
	1D-6	61.90	130.00	77,024	
	0C-4	57.14	120.00	743,846	
	0B-5	57.14	120.00	4,922,716	
	1D-5	57.14	120.00	10,000,000	
0.5	0F-6	140.00	73.50	95,867	
	1D-2	131.43	69.00	3,755,883	
	IF-9	127.62	67.00	10,000,000	
	0C-9	123.81	65.00	10,000,000	
	1D-4	106.67	56.00	10,000,000	
	0H-8	102.86	54.00	10,000,000	
0.7	0B-2	139.68	44.00	1,252,549	
	0B-3	139.68	44.00	630,157	
	1D-7	136.51	43.00	10,000,000	
	0B-1	133.33	42.00	10,000,000	
	0H-3	126.98	40.00	10,000,000	
	0B-2	46.00	14.49	10,000,000	
	0F-8	44.00	13.86	10,000,000	

Table 6. Summary of the Fatigue Tests Performed at 1000 °F for the Class A Wheel Steel

R-ratio	Test ID	Maximum Test Stress (ksi)	Actual Stress Range, $K_t\Delta\sigma$ (ksi)	Cycles	Comments
0.05	0A-2	60	59.85	1,527	
	1C-2	60	59.85	1,249	
	1E-3	55	54.86	48,351	
	1G-2	50	49.88	58,949	
	1C-5	50	49.88	128,400	
	1H-1	45	44.89	665,484	
	1G-3	45	49.89	295,851	
	1G-8	40	39.90	577,411	
	0A-6	35	34.91	1,369,530	
	1C-4	35	34.91	1,392,951	
	1G-1	30	29.93	4,440,274	
	1C-10	30	29.93	6,048,120	
	1C-9	28	27.93	7,745,408	
	1H-10	27	26.93	10,000,000	Runout
-1.0	0D-10	45	94.50	152,911	
	0D-2	40	84.00	837,479	
	1A-4	40	84.00	107,518	
	1E-6	35	73.50	498,973	
	1A-7	32	67.20	1,021,514	
	1A-1	32	67.20	1,519,360	
	0D-3	30	63.00	5,680,570	
	0D-4	30	63.00	9,200,000	
	1E-5	28	58.80	6,595,892	
	1A-9	28	58.80	10,000,000	Runout
	1E-2	27	56.70	6,256,424	
	0D-9	26	54.60	8,170,979	
	0D-7	25	52.50	10,000,000	Runout
0.5	0D-6	29	15.23	3,596,631	
	1F-8	25	13.13	9,780,461	
	1F-10	24	12.60	9,270,753	
	1A-3	23	12.08	8,215,280	
	1A-8	21	11.03	10,000,000	Runout
0.7	1F-6	23	7.25	5,918,783	
	0F-9	21	6.62	10,000,000	Runout
	0F-5	20	6.30	10,000,000	Runout

Figure 9 shows a summary graph for all fatigue tests at each of the three temperatures and four R-ratios. To better highlight the differences at each temperature, Figures 10, 11, and 12 provide graphical summaries of the fatigue data for room temperature, 500 °F, and 1000 °F. For each graph, cycles to failure are given as a function of actual stress range, ΔS, which includes the stress concentration effect ($K_t = 1.05$). As expected, a certain degree of scatter in fatigue results is shown for each particular stress range, with the highest amount of scatter at the lower stress levels and therefore the higher life regime.

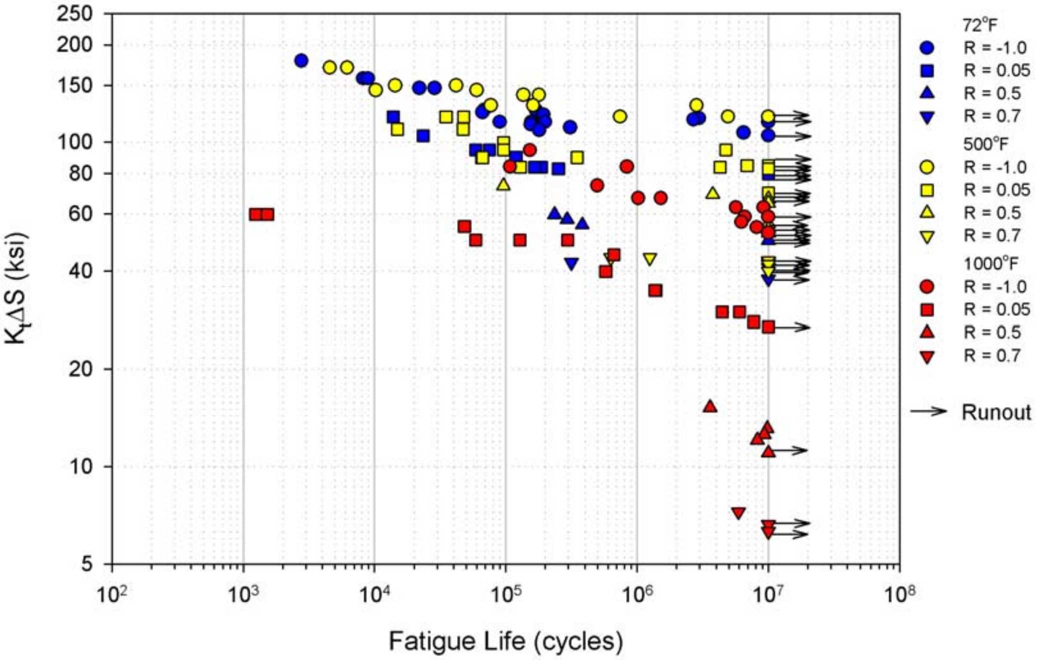


Figure 9. Summary of Fatigue Tests Performed During Test Program

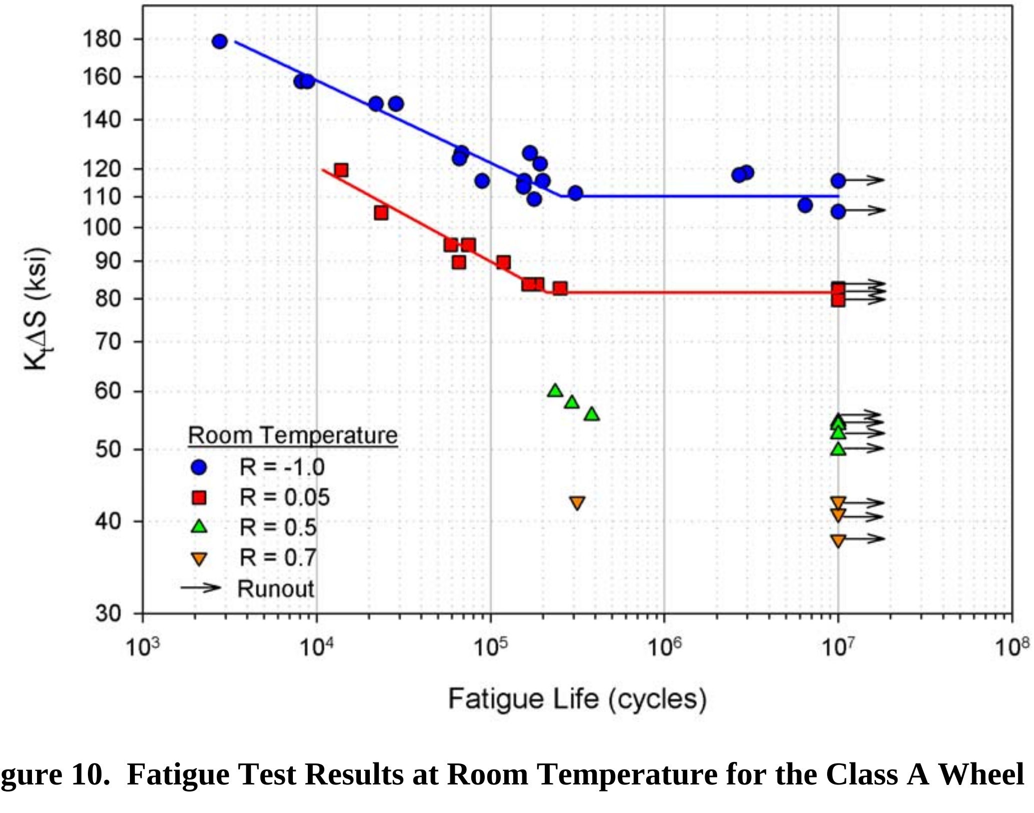


Figure 10. Fatigue Test Results at Room Temperature for the Class A Wheel Steel

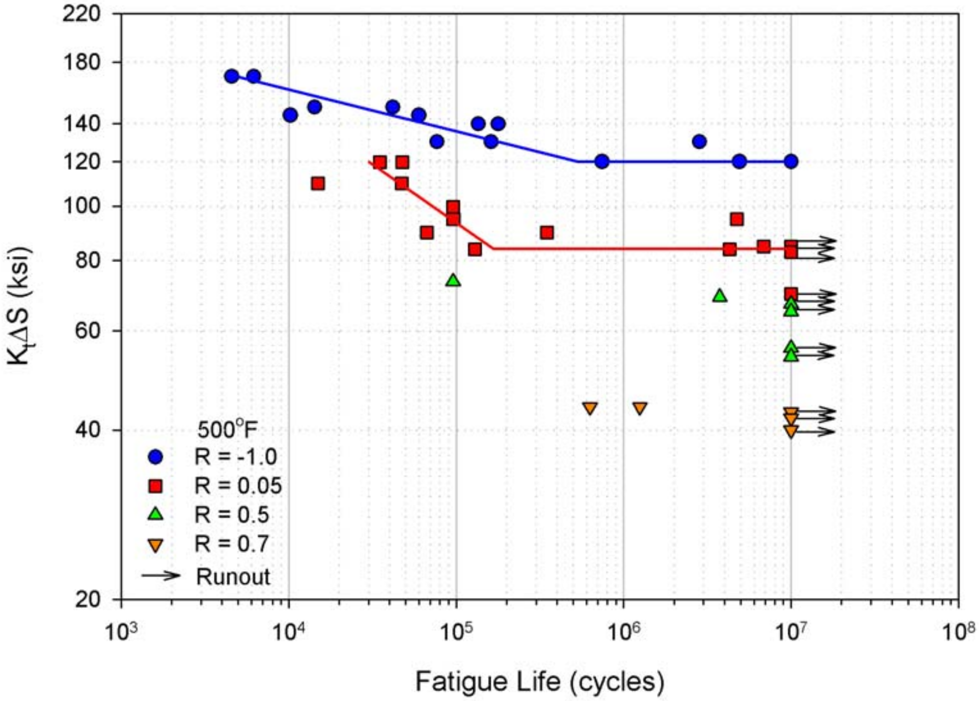


Figure 11. Fatigue Test Results at 500 °F for the Class A Wheel Steel

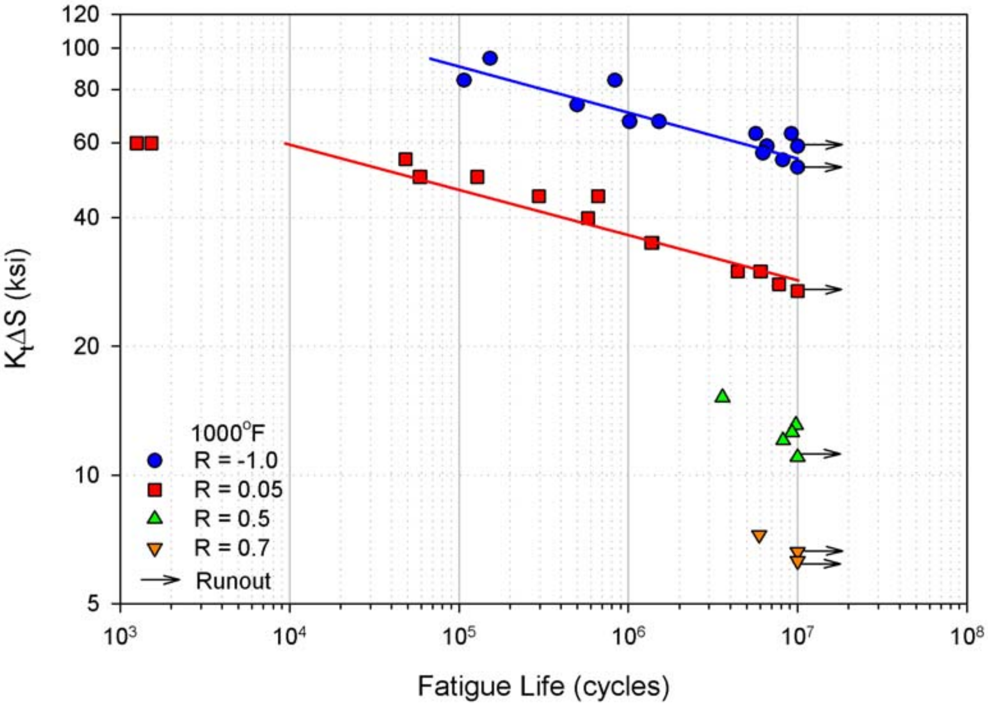


Figure 12. Fatigue Test Results at 1000 °F for the Class A Wheel Steel

Each of the summary plots also provides regression curve fits for the data at the lower R-ratios of R = -1.0 and 0.05. Due to the limited amount of testing at the higher R-ratios of R = 0.5 and 0.7, only the fatigue life at the 10^7 life regime, termed the endurance limit, was obtained. To obtain the curves shown in Figures 10, 11, and 12, a simple linear regression on the fatigue data, up to and including the 10^6 life regime, was performed. A horizontal line, corresponding to an average stress level for all runout data, was then extended out to the 10^7 life regime. For the 1000 °F high-temperature tests, the usual endurance limit transition did not appear to occur at the lower stress levels for each R-ratio, as was found with the room-temperature and 500 °F tests.

Table 7 gives the power law functions for each of the regression fits shown in Figures 10, 11, and 12, with cycles given as a function of stress range.

Due to the large amount of data produced in this fatigue test program over a wide variety of R-ratios, it is possible to develop the endurance limit diagram for the three test temperatures. Figure 13 shows endurance limit diagrams for the room-temperature, 500 °F, and 1000 °F tests together for comparison. Due to the similarity of tensile and fatigue test results for the room-temperature and 500 °F tests, it is not unexpected to see similar endurance limit diagrams for these 2 temperatures. In addition, the vast difference in tensile strength properties when testing at 1000 °F is indicative of the subsequent detrimental effect on the endurance limit diagram.

Table 7. Regression Analysis of Fatigue Data for Each of the Three Test Temperatures

Temperature (°F)	R-ratio	Stress Range, ΔS (ksi)	Power Law Constants		Cycles to Failure
			A	b	
Room Temperature	-1.0	> 110.3	$4.753\text{x}10^{23}$	-8.946	$N = A\Delta S^b$
		≤ 110.3			Runout
	0.05	> 81.6	$1.291\text{x}10^{20}$	-7.734	$N = A\Delta S^b$
		≤ 81.6			Runout
500	-1.0	> 120.0	$4.213\text{x}10^{33}$	-13.419	$N = A\Delta S^b$
		≤ 120.0			Runout
	0.05	> 84.0	$3.035\text{x}10^{14}$	-4.812	$N = A\Delta S^b$
		≤ 84.0			Runout
1000	-1.0	> 55.7	$1.666\text{x}10^{21}$	-8.171	$N = A\Delta S^b$
	0.05	> 26.9	$4.570\text{x}10^{20}$	-9.388	$N = A\Delta S^b$

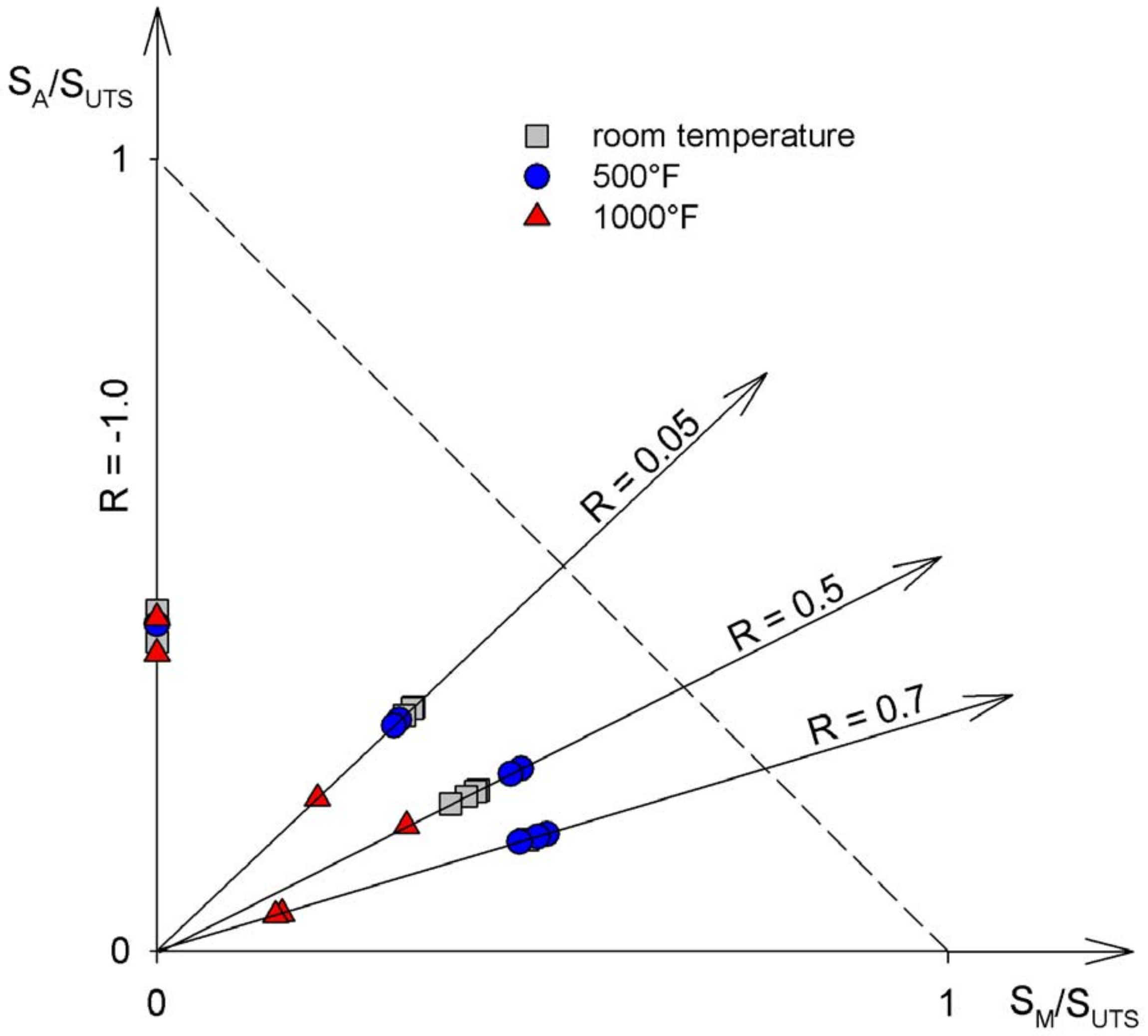
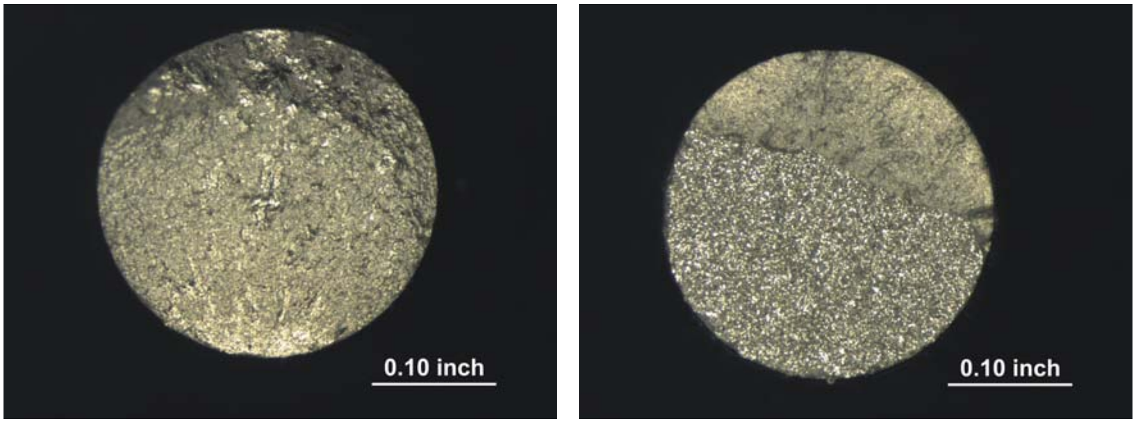


Figure 13. Endurance Limit Diagram for the Room-Temperature, 500 °F, and 1000 °F Tests

Figures 14, 15, and 16 are photographs of typical fracture surfaces for the room-temperature, 500 °F, and 1000 °F tests, respectively. Both surface and sub-surface initiation sites were observed for all test temperatures. This indicates that preferential surface initiation did not occur due to the machining process performed on the specimens. In addition, no preferential initiation site appeared to exist at the point where the thermocouple was in contact with the specimen during high-temperature testing.

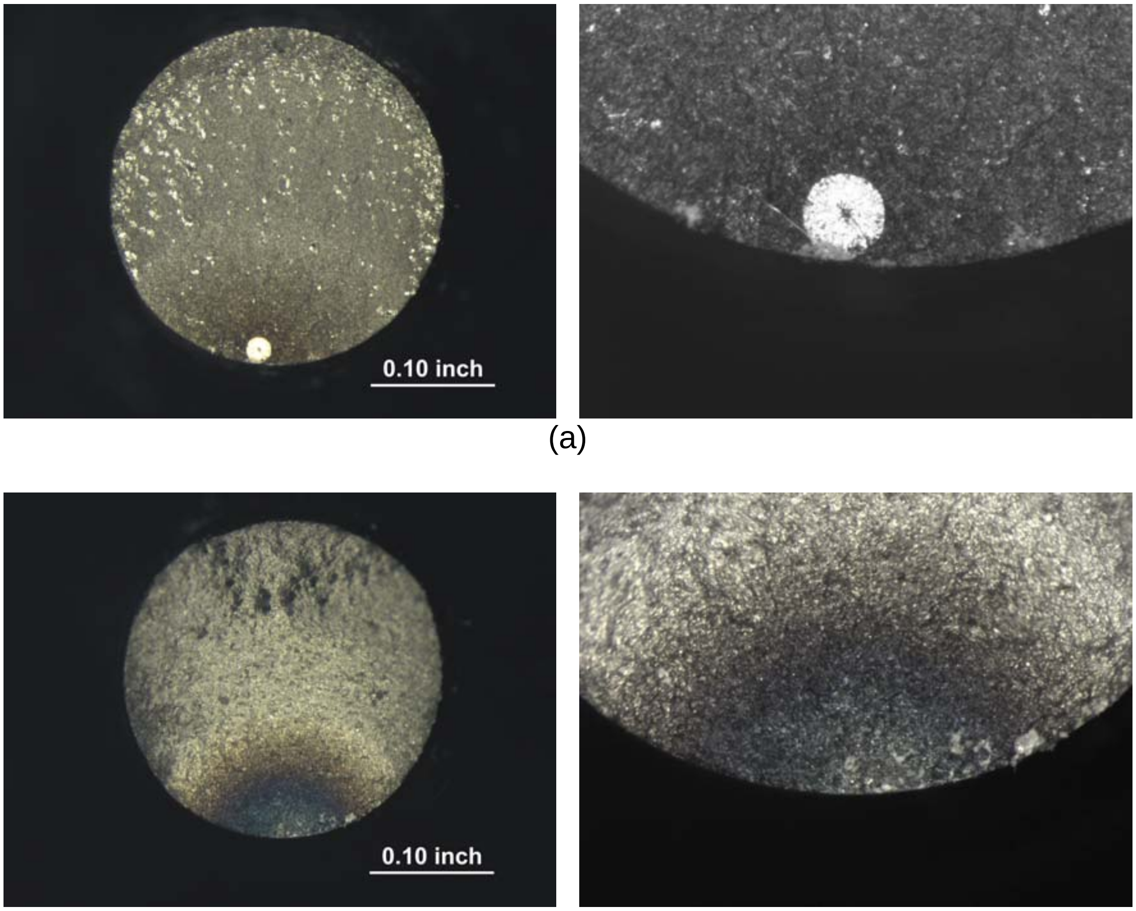
3.3 Estimation of Sines Parameters

Based on the results given in the previous section, it is possible to provide an estimation of the Sines parameters, A and α, for the 10^7 life regime. Endurance limit data at the 10^7 life regime for R-ratios = -1.0 and 0.05 is required to calculate the 2 material constants (see Section 2.3.1). Using Equations 3 and 5, the constants A and α were estimated, with results provided in Table 8.



(a) (b)

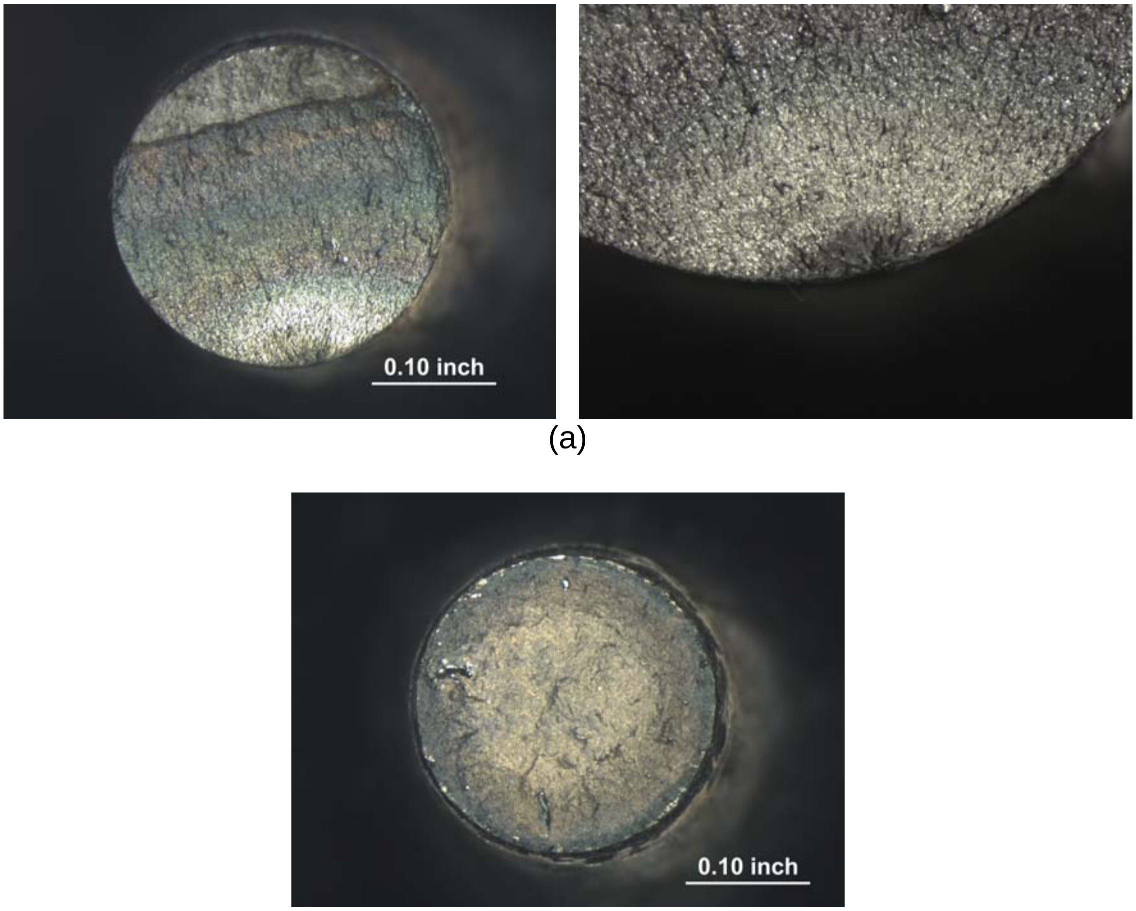
Figure 14. Representative Photographs of Room-Temperature Fatigue Specimens (a) R = -1.0 and (b) R = 0.05



(a)

(b)

Figure 15. Representative Photographs of 500 °F Fatigue Specimens (a) R = -1.0 and (b) R = 0.05



(a)

(b)

Figure 16. Representative Photographs of 1000 °F Fatigue Specimens
(a) R = -1.0 and (b) R = 0.05

Similar Sines parameters were calculated for the room-temperature and 500 °F fatigue tests. The Sines parameters for the 1000 °F fatigue tests, however, are dramatically different from those of the lower temperature fatigue tests. This is not surprising considering the large difference in both tensile and fatigue properties obtained for the 1000 °F tests when compared to the room-temperature and 500 °F tests.

Table 8. Sines Criterion Material Constant Estimates for the Three Test Temperatures

Temperature (°F)	R-ratio	Sines Constants at Endurance Limit (10^7 Life Regime)			
		Stress Amplitude (ksi)		A (ksi) [1]	α [2]
		f_1	f_1'		
Room Temperature	-1.0	55.1		26.0	0.165
	0.05		40.8		
500	-1.0	60.0		28.3	0.202
	0.05		42.0		
1000	-1.0	27.8		13.1	0.499
	0.05		13.5		

---

[1] $A = \frac{\sqrt{2}}{3} f_1$

[2] $\alpha = \frac{\sqrt{2}}{3}\left(\frac{f_1}{f_1'} - 1\right)$

4. Summary

The material property evaluations described herein provide an assessment of the chemical, tensile, and fatigue behavior observed for the Class A wheel steel material. Fatigue testing was performed to determine the S-N curves for each of the 3 temperatures: ambient room temperature, 500 °F, and 1000 °F. Furthermore, a large number of fatigue tests was performed at R-ratios of -1.0 and 0.05 for each of the test temperatures to enable reliable estimates of the Sines parameters, A and α. The following briefly summarizes chemical, tensile, and fatigue results, with the major conclusions indicated.

1. Two chemical analysis tests and nine tensile tests were undertaken to characterize the Class A railroad wheel steel material. Individual sections from each of the two railroad wheels were selected to enable a material characterization test sampling of both wheels.

2. Chemical composition analysis indicated that both wheel samples were within the range for a Class A railroad wheel, as given in AAR specification M-107/208 [9].

3. Monotonic tensile tests were undertaken for the Class A wheel steel at room temperature, 500 °F, and 1000 °F. Room-temperature test results were found to be in accordance with AAR baseline values, as given in AAR Standard S-660 [1].

4. Similar ultimate tensile strength and yield strength results were found for the room-temperature and 500 °F tests. However, a 50-percent reduction in ultimate tensile strength and a 35-percent reduction in yield strength were observed for the 1000 °F tensile tests when compared to the room-temperature and 500 °F tests.

5. A large decrease in the percent elongation and reduction in area for all 500 °F tests compared to room-temperature and 1000 °F tests was observed. This variation in tensile properties was also observed during a previous test program utilizing a Class B wheel steel material.

6. A total of 119 constant amplitude fatigue tests was completed at the 3 test temperatures. The vast majority of testing (75 percent) was performed at R-ratios of 1.0 and 0.05 to enable the S-N curves to be developed. The remainder of testing was undertaken to obtain the endurance limit at 10^7 cycles for R-ratios of 0.5 and 0.7.

7. The degree of scatter for fatigue tests averaged approximately 1 order of magnitude (10x) for all tests performed at replicate stress levels, with a scatter range of between 1.02x–111.3x. As expected, greater levels of scatter and less repeatability were apparent at the lower stress levels.

8. Fracture surfaces indicated both surface and sub-surface initiation sites at all test temperatures. The thermocouple position during high-temperature testing did not appear to provide a preferential initiation site.

9. Endurance limit data was obtained for all R-ratios at each of the three test temperatures. For the 1000 °F tests, however, the usual endurance limit transition did not appear to exist at the lower stress levels, as was found with the room-temperature and 500 °F tests. Endurance limit diagrams for the three test temperatures were constructed.

10. Based on the endurance limit data for R-ratios of -1.0 and 0.05, an estimation of the Sines parameters, A and α, was obtained for each of the 3 test temperatures. Similar parameters were calculated for the room-temperature and 500 °F fatigue tests, with significantly different parameters obtained for the 1000 °F fatigue tests.

5. References

[1] Association of American Railroads, Standard S-660, Procedure for the Analytic Evaluation of Locomotive and Freight Car Wheel Designs, Manual of Standards and Recommended Practices, Section G, Wheels and Axles, 2004.

[2] Gordon, J.E. and Orringer, O., Investigation of the Effects of Braking System Configurations on Thermal Input to Commuter Car Wheels, Volpe National Transportation Systems Center, Cambridge, MA. Report No. DOT/FRA/ORD-94-01, March 1994.

[3] McKeighan, P.C., McMaster, F.J., and Gordon, J. Fatigue Performance of AAR Class B Railroad Wheel Steel at Ambient and Elevated Temperatures, ASME International Mechanical Engineering Congress and Exposition, 17-22 November 2002. New Orleans, LA.

[4] Annual Book of ASTM Standards, Section 3: Metals Test Methods and Analytical Procedures, Vol. 3.01 Metals-Mechanical Testing; Elevated and Low-Temperature Tests; Metallography, 2000.

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[6] ASTM E415-99a, Standard Test Method for Optical Emission Vacuum Spectrometric Analysis of Carbon and Low-Alloy Steel. Annual Book of ASTM Standards, Section 3: Metals Test Methods and Analytical Procedures, Vol. 3.05, American Society for Testing and Materials, West Conshohocken, PA.

[7] Sines, G. Behavior of Metals Under Complex Static and Alternating Stresses. *Metal Fatigue*, G. Sines and J.L. Waisman, Eds., McGraw-Hill, New York, pp. 145-169, 1959.

[8] Homologation Technique des Roues Monobloc. UIC Minutes, MTEL P 98016, October 1998.

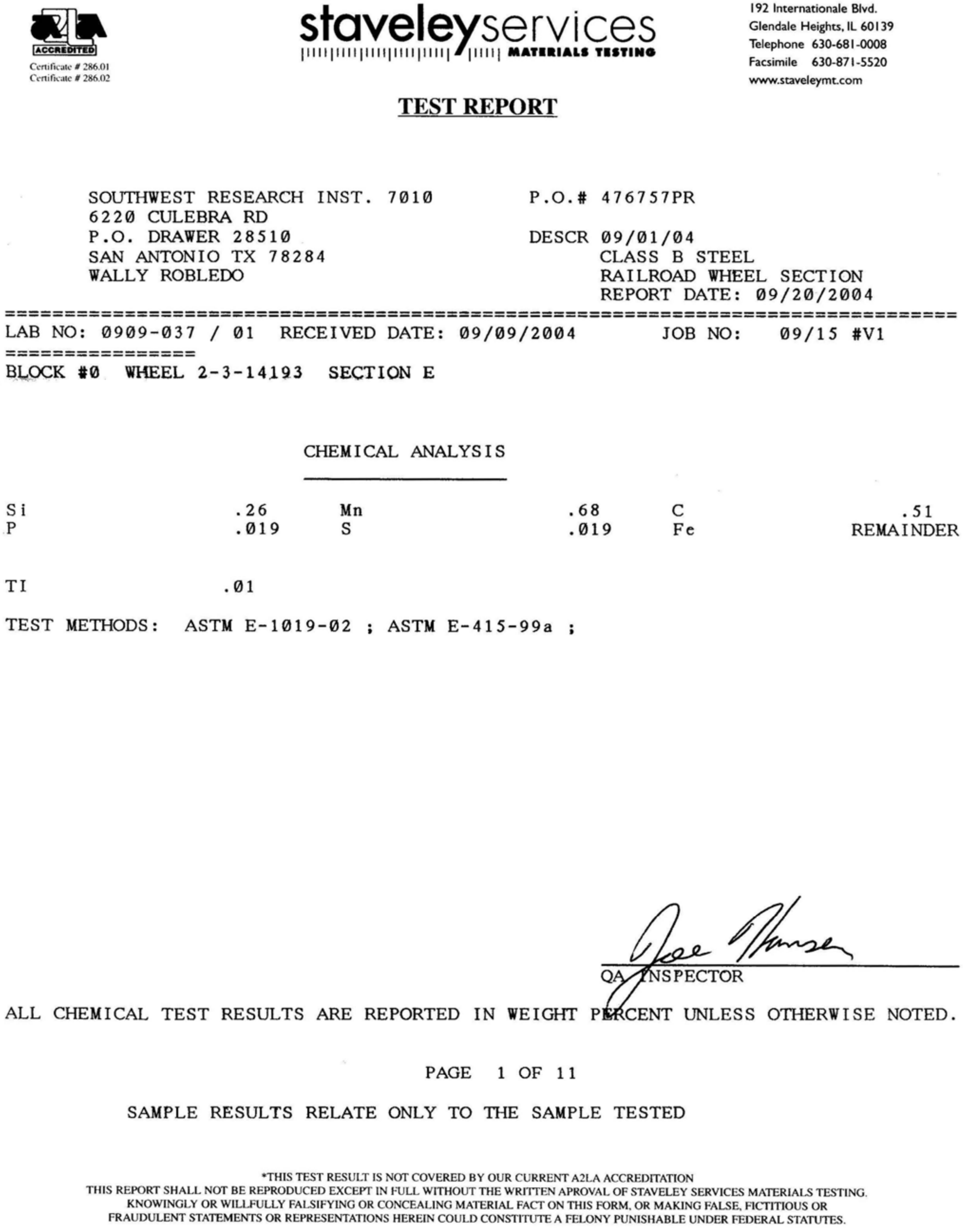
[9] Association of American Railroads, Specification M-107/208, Wheels, Carbon Steel. Manual of Standards and Recommended Practices, Section G, Wheels and Axles, 2004.

Appendix.

Tensile and Chemical Properties

Organization:	Chemical composition analysis results Tensile test results
Contents:	Test data sheet (each specimen)

Chemical Composition Analysis Results



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TEST REPORT

SOUTHWEST RESEARCH INST. 7010
6220 CULEBRA RD
P.O. DRAWER 28510
SAN ANTONIO TX 78284
WALLY ROBLEDO

P.O.# 476757PR

DESCR 09/01/04
CLASS B STEEL
RAILROAD WHEEL SECTION
REPORT DATE: 09/20/2004

LAB NO: 0909-037 / 01 RECEIVED DATE: 09/09/2004 JOB NO: 09/15 #V1

BLOCK #0 WHEEL 2-3-14193 SECTION E

CHEMICAL ANALYSIS

Si	.26	Mn	.68	C	.51
P	.019	S	.019	Fe	REMAINDER

TI	.01

TEST METHODS: ASTM E-1019-02 ; ASTM E-415-99a ;

QA INSPECTOR

ALL CHEMICAL TEST RESULTS ARE REPORTED IN WEIGHT PERCENT UNLESS OTHERWISE NOTED.

PAGE 1 OF 11

SAMPLE RESULTS RELATE ONLY TO THE SAMPLE TESTED

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TEST REPORT

SOUTHWEST RESEARCH INST. 7010
6220 CULEBRA RD
P.O. DRAWER 28510
SAN ANTONIO TX 78284
WALLY ROBLEDO

P.O.# 476757PR

DESCR 09/01/04
CLASS B STEEL
RAILROAD WHEEL SECTION
REPORT DATE: 09/20/2004

LAB NO: 0909-037 / 02 RECEIVED DATE: 09/09/2004 JOB NO: 09/15 #V2

BLOCK #1 WHEEL 2-3-14202 SECTION B

CHEMICAL ANALYSIS

Si	.27	Mn	.68	C	.51
P	.019	S	.020	Fe	REMAINDER
TI	.01				

TEST METHODS: ASTM E-1019-02 ; ASTM E-415-99a ;

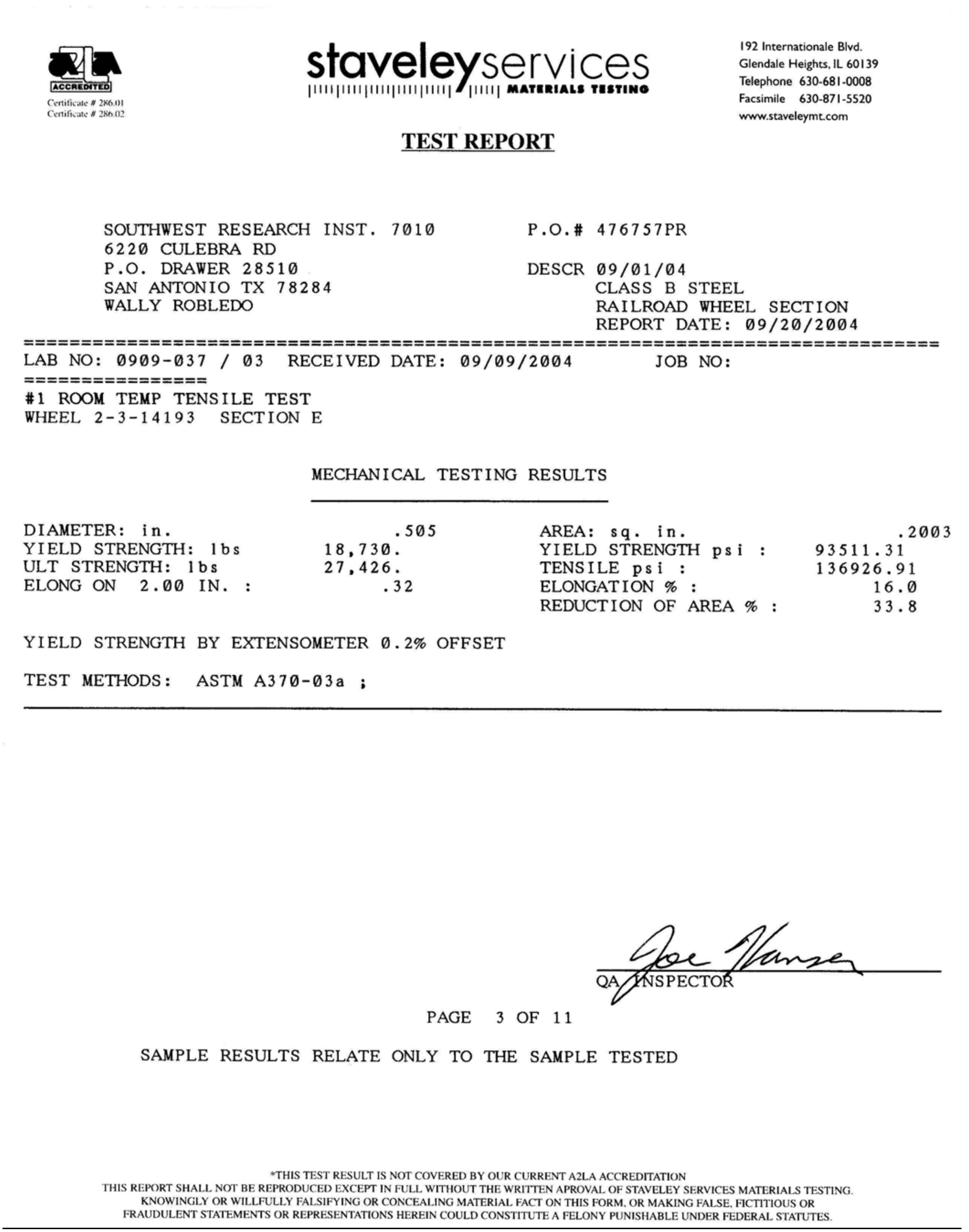
Joe Hansen
QA INSPECTOR

ALL CHEMICAL TEST RESULTS ARE REPORTED IN WEIGHT PERCENT UNLESS OTHERWISE NOTED.

PAGE 2 OF 11

SAMPLE RESULTS RELATE ONLY TO THE SAMPLE TESTED

Tensile Test Results



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Certificate # 286.02

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TEST REPORT

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P.O. DRAWER 28510
SAN ANTONIO TX 78284
WALLY ROBLEDO

P.O.# 476757PR

DESCR 09/01/04
CLASS B STEEL
RAILROAD WHEEL SECTION
REPORT DATE: 09/20/2004

LAB NO: 0909-037 / 03 RECEIVED DATE: 09/09/2004 JOB NO:

#1 ROOM TEMP TENSILE TEST
WHEEL 2-3-14193 SECTION E

MECHANICAL TESTING RESULTS

DIAMETER: in.	.505	AREA: sq. in.	.2003
YIELD STRENGTH: lbs	18,730.	YIELD STRENGTH psi :	93511.31
ULT STRENGTH: lbs	27,426.	TENSILE psi :	136926.91
ELONG ON 2.00 IN. :	.32	ELONGATION % :	16.0
		REDUCTION OF AREA % :	33.8

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM A370-03a ;

Joe Hanser
QA INSPECTOR

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SAMPLE RESULTS RELATE ONLY TO THE SAMPLE TESTED

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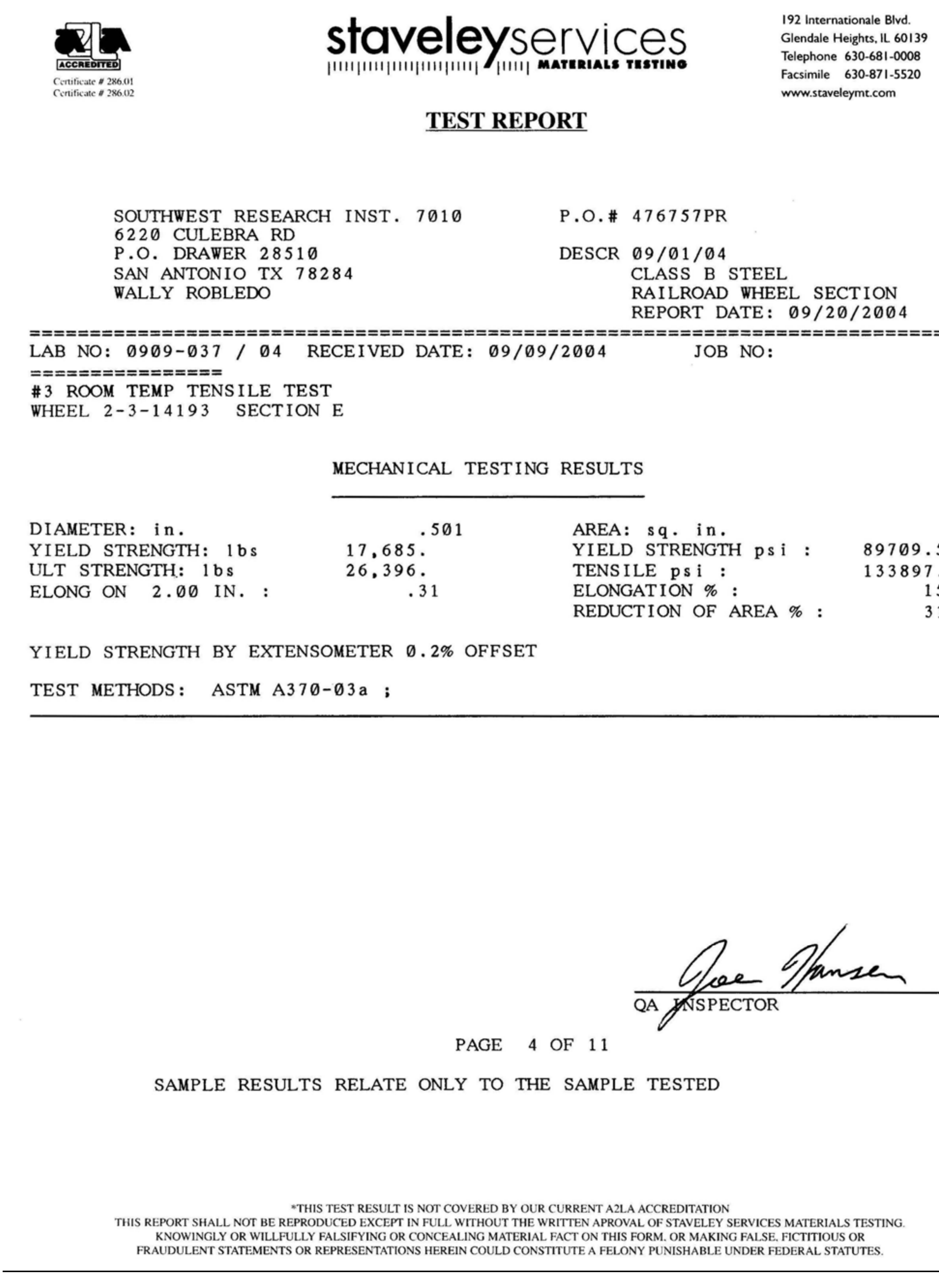

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6220 CULEBRA RD
P.O. DRAWER 28510
SAN ANTONIO TX 78284
WALLY ROBLEDO

P.O.# 476757PR

DESCR 09/01/04
CLASS B STEEL
RAILROAD WHEEL SECTION
REPORT DATE: 09/20/2004

LAB NO: 0909-037 / 04 RECEIVED DATE: 09/09/2004 JOB NO:

#3 ROOM TEMP TENSILE TEST
WHEEL 2-3-14193 SECTION E

MECHANICAL TESTING RESULTS

DIAMETER: in.	.501	AREA: sq. in.	.1971
YIELD STRENGTH: lbs	17,685.	YIELD STRENGTH psi :	89709.56
ULT STRENGTH: lbs	26,396.	TENSILE psi :	133897.28
ELONG ON 2.00 IN. :	.31	ELONGATION % :	15.5
		REDUCTION OF AREA % :	31.7

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM A370-03a ;

Joe Hansen
QA INSPECTOR

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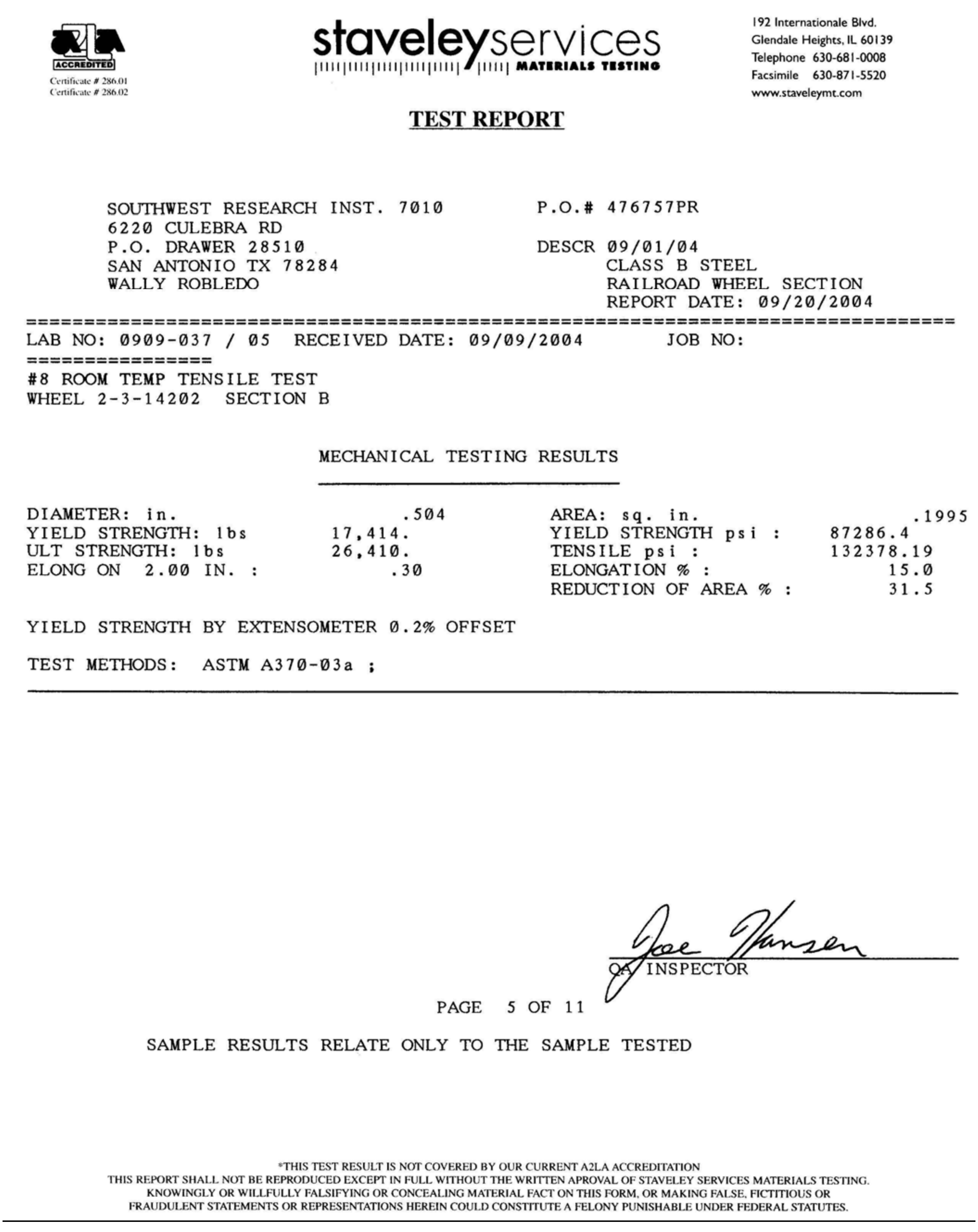
SAMPLE RESULTS RELATE ONLY TO THE SAMPLE TESTED



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DESCR 09/01/04
CLASS B STEEL
RAILROAD WHEEL SECTION
REPORT DATE: 09/20/2004

LAB NO: 0909-037 / 05   RECEIVED DATE: 09/09/2004   JOB NO:

#8 ROOM TEMP TENSILE TEST
WHEEL 2-3-14202   SECTION B

MECHANICAL TESTING RESULTS

DIAMETER: in.	.504	AREA: sq. in.	.1995
YIELD STRENGTH: lbs	17,414.	YIELD STRENGTH psi :	87286.4
ULT STRENGTH: lbs	26,410.	TENSILE psi :	132378.19
ELONG ON 2.00 IN. :	.30	ELONGATION % :	15.0
		REDUCTION OF AREA % :	31.5

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM A370-03a ;

Joe Hansen
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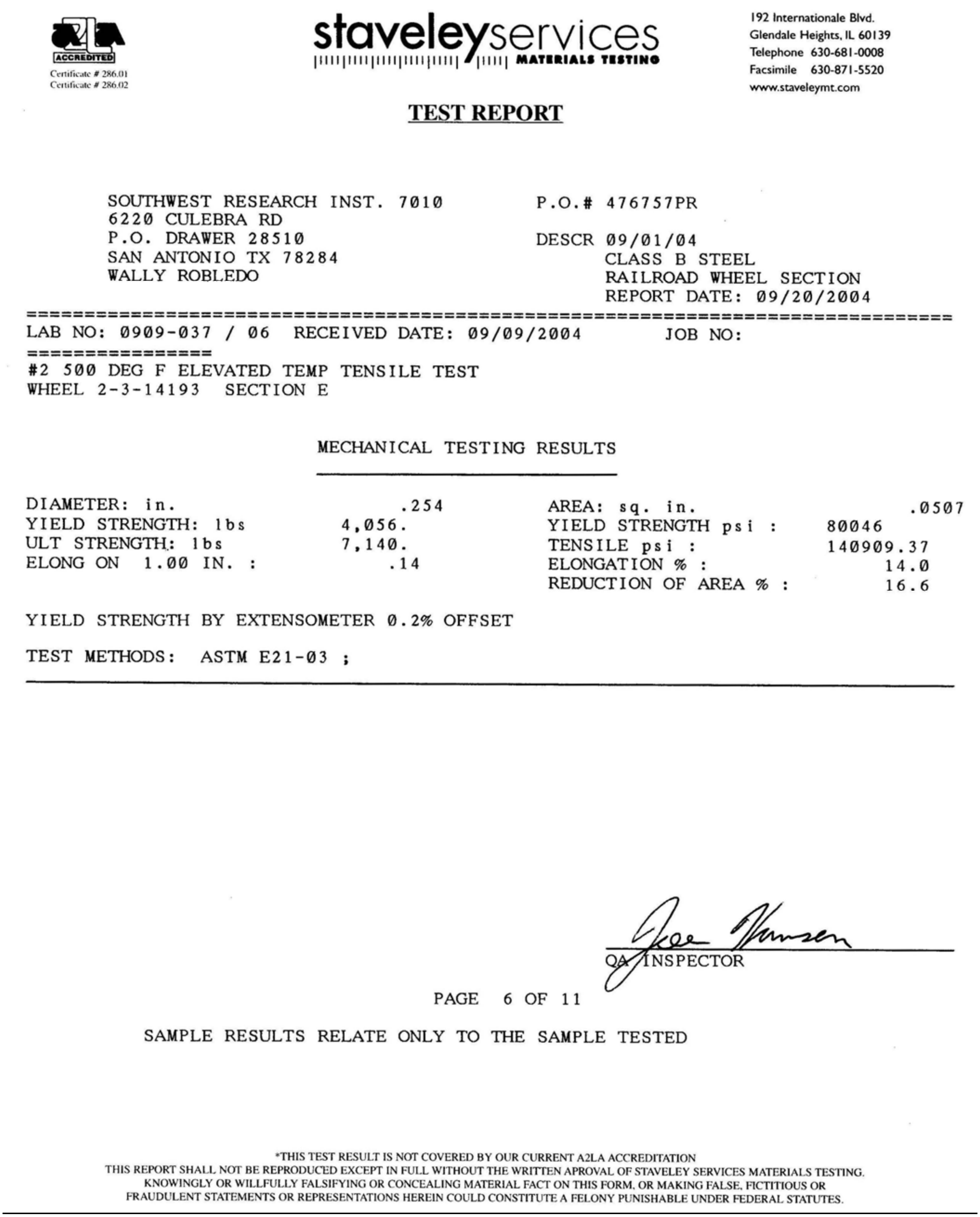
SAMPLE RESULTS RELATE ONLY TO THE SAMPLE TESTED



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DESCR 09/01/04
CLASS B STEEL
RAILROAD WHEEL SECTION
REPORT DATE: 09/20/2004

LAB NO: 0909-037 / 06 RECEIVED DATE: 09/09/2004 JOB NO:

#2 500 DEG F ELEVATED TEMP TENSILE TEST
WHEEL 2-3-14193 SECTION E

MECHANICAL TESTING RESULTS

DIAMETER: in.	.254	AREA: sq. in.	.0507
YIELD STRENGTH: lbs	4,056.	YIELD STRENGTH psi :	80046
ULT STRENGTH: lbs	7,140.	TENSILE psi :	140909.37
ELONG ON 1.00 IN. :	.14	ELONGATION % :	14.0
		REDUCTION OF AREA % :	16.6

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM E21-03 ;

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SAMPLE RESULTS RELATE ONLY TO THE SAMPLE TESTED

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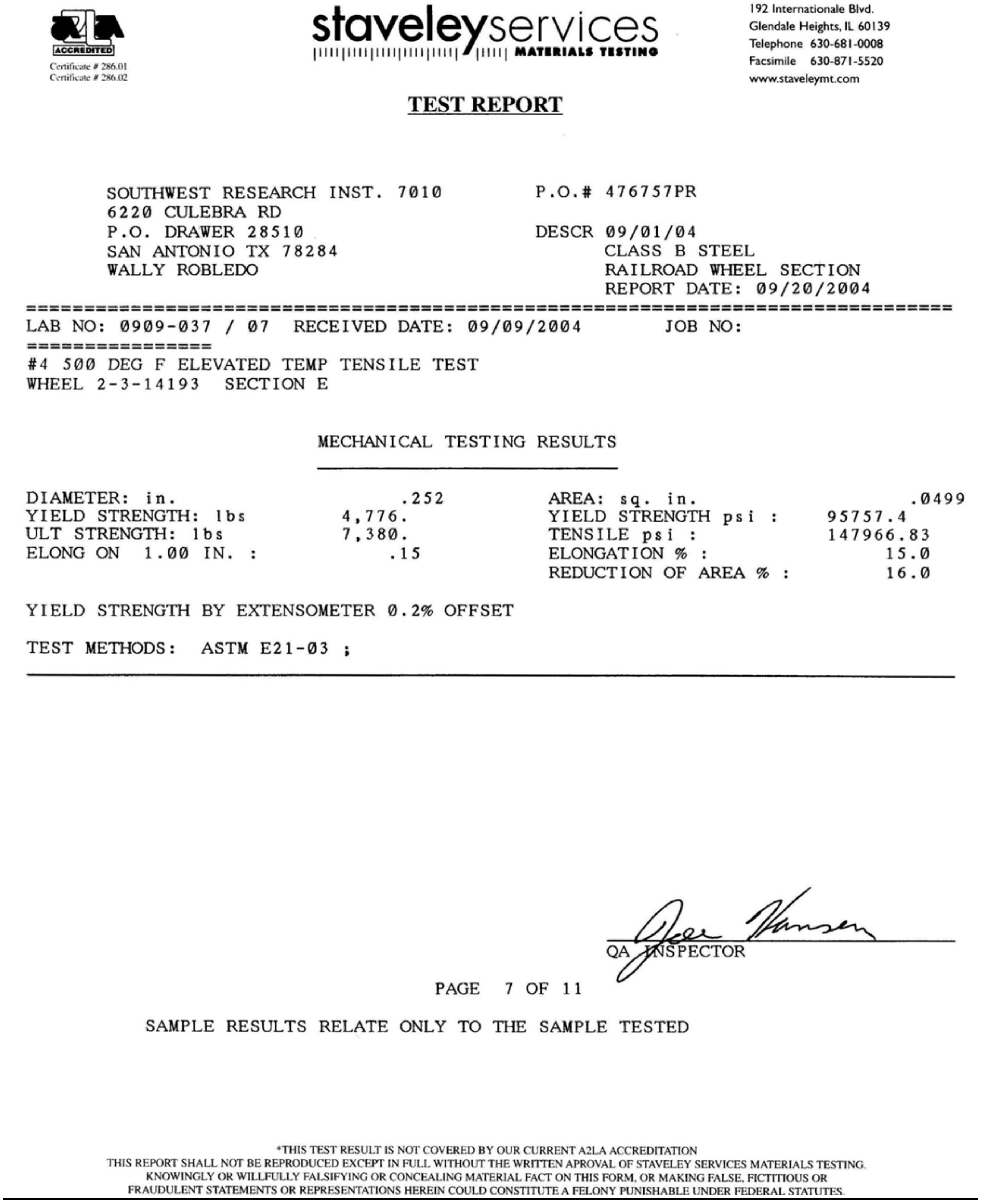

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DESCR 09/01/04
CLASS B STEEL
RAILROAD WHEEL SECTION
REPORT DATE: 09/20/2004

LAB NO: 0909-037 / 07 RECEIVED DATE: 09/09/2004 JOB NO:

#4 500 DEG F ELEVATED TEMP TENSILE TEST
WHEEL 2-3-14193 SECTION E

MECHANICAL TESTING RESULTS

DIAMETER: in.	.252	AREA: sq. in.	.0499
YIELD STRENGTH: lbs	4,776.	YIELD STRENGTH psi :	95757.4
ULT STRENGTH: lbs	7,380.	TENSILE psi :	147966.83
ELONG ON 1.00 IN. :	.15	ELONGATION % :	15.0
		REDUCTION OF AREA % :	16.0

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM E21-03 ;

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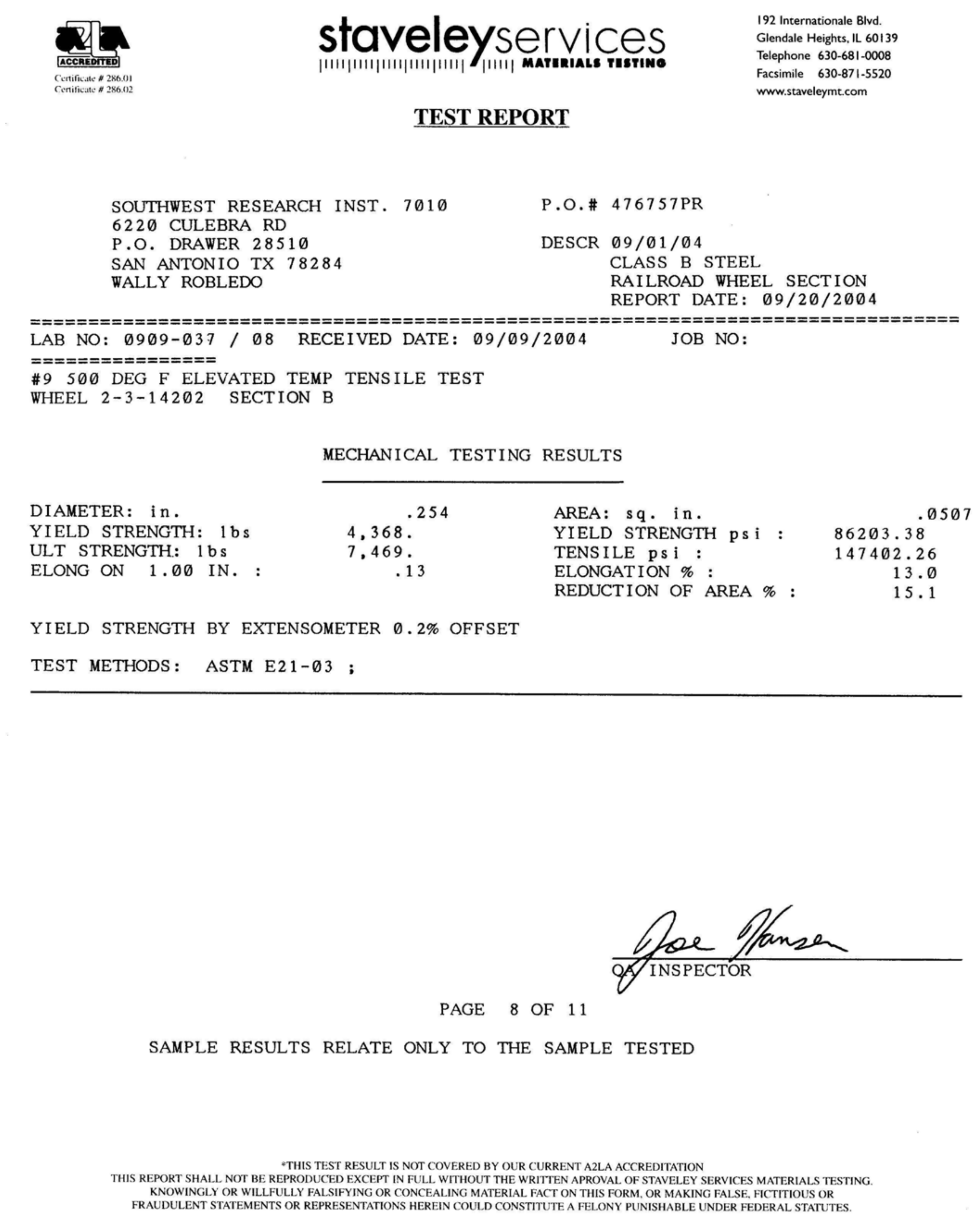
SAMPLE RESULTS RELATE ONLY TO THE SAMPLE TESTED



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CLASS B STEEL
RAILROAD WHEEL SECTION
REPORT DATE: 09/20/2004

LAB NO: 0909-037 / 08 RECEIVED DATE: 09/09/2004 JOB NO:

#9 500 DEG F ELEVATED TEMP TENSILE TEST
WHEEL 2-3-14202 SECTION B

MECHANICAL TESTING RESULTS

DIAMETER: in.	.254	AREA: sq. in.	.0507
YIELD STRENGTH: lbs	4,368.	YIELD STRENGTH psi :	86203.38
ULT STRENGTH: lbs	7,469.	TENSILE psi :	147402.26
ELONG ON 1.00 IN. :	.13	ELONGATION % :	13.0
		REDUCTION OF AREA % :	15.1

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM E21-03 ;

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PAGE 8 OF 11

SAMPLE RESULTS RELATE ONLY TO THE SAMPLE TESTED

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CLASS B STEEL
RAILROAD WHEEL SECTION
REPORT DATE: 09/20/2004

LAB NO: 0909-037 / 09 RECEIVED DATE: 09/09/2004 JOB NO:

#5 1000 DEG F ELEVATED TEMP TENSILE TEST
WHEEL 2-3-14193 SECTION E

MECHANICAL TESTING RESULTS

DIAMETER: in.	.249	AREA: sq. in.	.0487
YIELD STRENGTH: lbs	2,880.	YIELD STRENGTH psi :	59142.94
ULT STRENGTH: lbs	3,503.	TENSILE psi :	71936.71
ELONG ON 1.00 IN. :	.18	ELONGATION % :	18.0
		REDUCTION OF AREA % :	53.4

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM E21-03 ;

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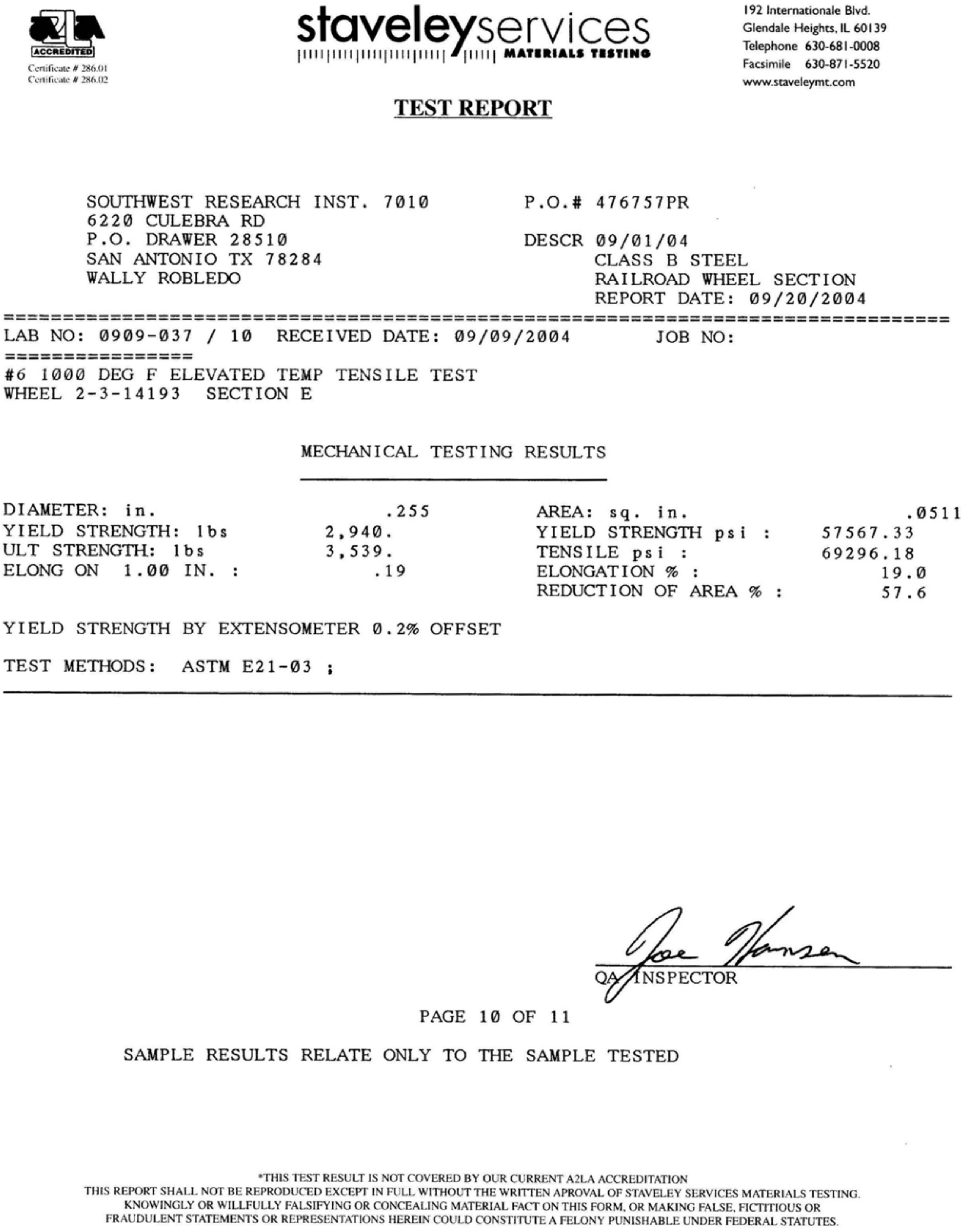
SAMPLE RESULTS RELATE ONLY TO THE SAMPLE TESTED



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REPORT DATE: 09/20/2004

LAB NO: 0909-037 / 10 RECEIVED DATE: 09/09/2004 JOB NO:

#6 1000 DEG F ELEVATED TEMP TENSILE TEST
WHEEL 2-3-14193 SECTION E

MECHANICAL TESTING RESULTS

DIAMETER: in. .255
YIELD STRENGTH: lbs 2,940.
ULT STRENGTH: lbs 3,539.
ELONG ON 1.00 IN. : .19

AREA: sq. in. .0511
YIELD STRENGTH psi : 57567.33
TENSILE psi : 69296.18
ELONGATION % : 19.0
REDUCTION OF AREA % : 57.6

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM E21-03 ;

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QA INSPECTOR

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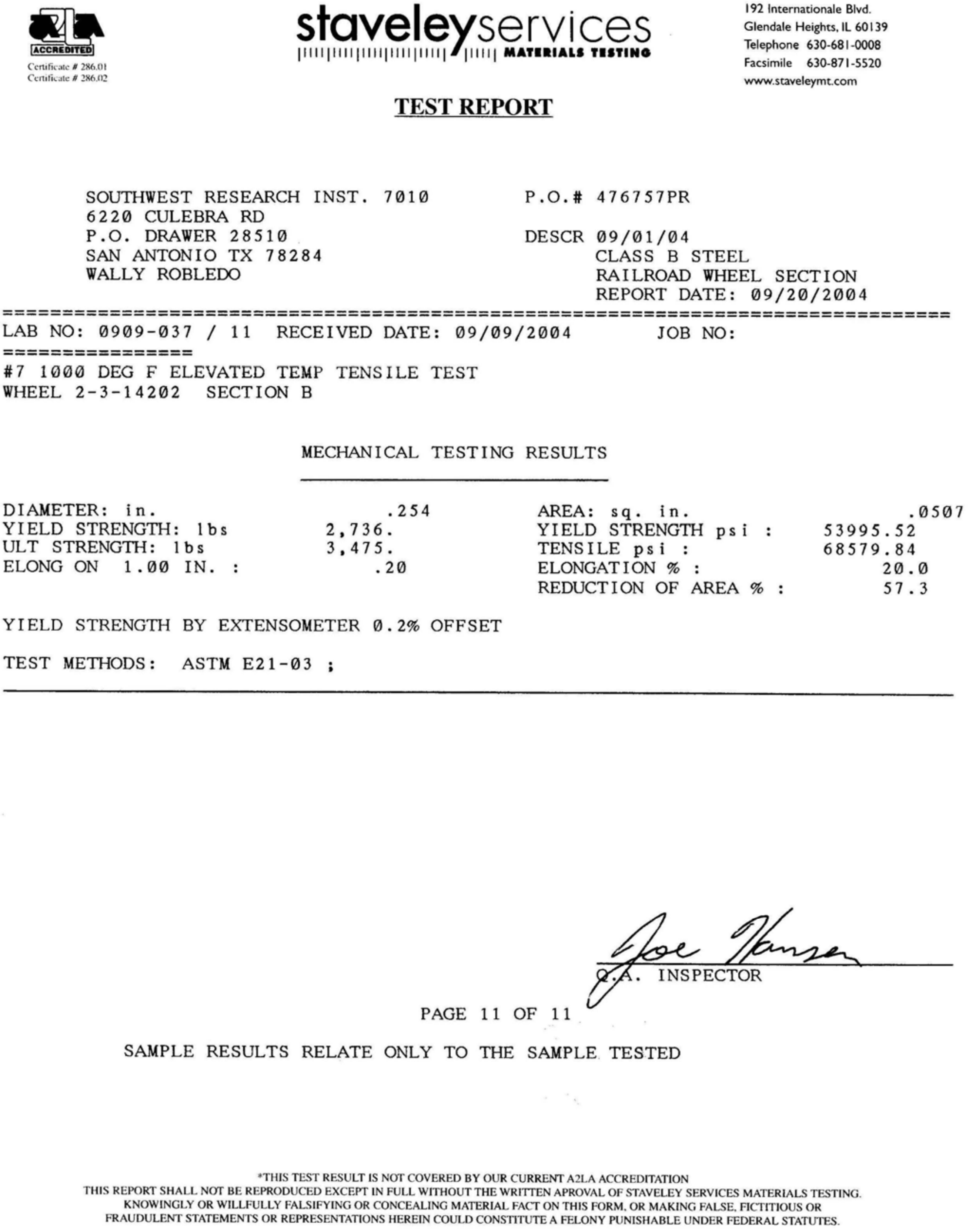

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REPORT DATE: 09/20/2004

LAB NO: 0909-037 / 11 RECEIVED DATE: 09/09/2004 JOB NO:

#7 1000 DEG F ELEVATED TEMP TENSILE TEST
WHEEL 2-3-14202 SECTION B

MECHANICAL TESTING RESULTS

DIAMETER: in.	.254	AREA: sq. in.	.0507
YIELD STRENGTH: lbs	2,736.	YIELD STRENGTH psi :	53995.52
ULT STRENGTH: lbs	3,475.	TENSILE psi :	68579.84
ELONG ON 1.00 IN. :	.20	ELONGATION % :	20.0
		REDUCTION OF AREA % :	57.3

YIELD STRENGTH BY EXTENSOMETER 0.2% OFFSET

TEST METHODS: ASTM E21-03 ;

Joe Hansen
Q.A. INSPECTOR

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SAMPLE RESULTS RELATE ONLY TO THE SAMPLE TESTED

Acronyms and Symbols

A	Sines criteria material constant
AAR	Association of American Railroads
APTA	American Public Transportation Association
ASTM	American Society for Testing Materials
f_1	amplitude of reversed axial stress
f_1'	amplitude of fluctuating stress causing failure
FRA	Federal Railroad Administration
K_t	stress concentration factor
MGD	modified Goodman diagram
N	cyclic fatigue life of a given specimen
P_i	principal stress amplitude
R	stress ratio, ratio of minimum to maximum applied stress
RA	reduction of area at failure
S_i	orthogonal mean stresses
S-N	stress-life
SNCF	Société Nationale des Chemins de Fer
SwRI	Southwest Research Institute
VNTSC	Volpe National Transportation Systems Center
α	Sines criterion material constant
ε	percent elongation at failure
$\Delta\sigma$	effective applied stress range
σ_{max}	maximum applied stress
σ_{UTS}	ultimate tensile strength
σ_{YS}	0.2% yield strength
τ_{oct}	octahedral shear stress
ΔP	load range applied to specimen
ΔS	specimen section stress range (minimum diameter)