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INTERNATIONAL
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SURFACE VEHICLE STANDARD

Submitted for recognition as an American National Standard

SAE J431

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(R) Automotive Gray Iron Castings

1. ***Scope***—This SAE Standard covers the hardness, tensile strength, and microstructure and special requirements of gray iron sand molded castings used in the automotive and allied industries. Specific requirements are provided for hardness of castings. Test bar tensile strength/Brinell hardness (t/h) ratio requirements are provided to establish a consistent tensile strength-hardness relationship for each grade to facilitate prediction and control of tensile strength in castings. Provision is made for specification of special additional requirements of gray iron automotive castings where needed for particular applications and service conditions.

NOTE—This document was revised in 1993 to provide grade specific t/h control. In 1999 the document was revised to make SI metric units primary. To better align the grading system with long established production methods and grades produced, the previous system of grading by fixed combinations of tensile strength and hardness was changed in 1999 to a system of grading by variable combinations of test bar t/h ratio and casting hardness grades. The number of hardness grades was increased relative to the number of previously available ranges to facilitate centering of casting mean hardness in the specification range so that dependence of cost optimization on controlling near the low or high sides of specification ranges is minimized.

2. *References*

2.1 Applicable Publications—The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

2.1.1 SAE PUBLICATION—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J417—Hardness Tests and Hardness Number Conversions

2.1.2 ASTM PUBLICATIONS—Available from ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959.

ASTM A 48—Specification for Gray Iron Castings
ASTM A 247—Recommended Practice for Evaluating the Microstructure of Graphite in Iron Castings
ASTM A 438—Transverse Testing of Gray Cast Iron
ASTM E 10—Test for Brinell Hardness of Metallic Materials
ASTM E 562—Determining Volume Fraction by Systematic Manual Point Count

2.2 Related Publications—The following publications are provided for information purposes only and are not a required part of this document. Additional information concerning gray iron castings, their properties, and use can be obtained from:

1. Metals Handbook, Vol. 1, 10th Edition, ASM International, Materials Park, OH
2. Cast Metals Handbook, American Foundrymen's Society, Des Plaines, IL
3. 1981 Iron Castings Handbook, Iron Castings Society, Inc., Cleveland, OH
4. H.D. Angus, “Physical and Engineering Properties of Cast Iron,” British Cast Iron Research Association, Birmingham, England, 2nd Edition, 1976
5. “Gray, Ductile, and Malleable Iron Castings Current Capabilities,” STP-455, American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959
6. G.N.J. Gilbert, “Engineering Data on Grey Cast Iron,” BCIRA (1977), Alvechurch, Birmingham, England
7. “Tables for Normal Tolerance Limits, Sampling Plans and Screening,” R.E. Odeh and D.B. Owen, Marcel Dekker, Inc., New York and Basel, 1980
8. “Fatigue Properties of Gray Cast Iron,” L.E. Tucker and D.R. Olberts, SAE Paper 690471

3. Grade definition and Designation.

3.1 Iron Grade—Gray iron grades, defined by their minimum test bar t/h ratio, are designated by the letter G followed by a number equaling the defining minimum test bar t/h ratio multiplied by 100. The units used for this purpose are MPa for both tensile strength and hardness. The t/h ratio is dimensionless.

EXAMPLE—G10 designates a gray iron having minimum test bar t/h = 0.100.

3.2 Hardness Grade—Hardness grades, defined by minimum hardness exhibited in castings, are designated by the letter H followed by a number equaling the minimum casting hardness divided by 100. The casting hardness unit used for this purpose is the MPa.

EXAMPLE—H18 designates minimum casting hardness of 1800 MPa.

3.3 Casting Grade—SAE gray iron casting grades are defined and designated by combining the iron grade and the hardness grade designations.

EXAMPLE—G10H18 designates iron in castings with minimum test bar t/h of 0.100 MPa/MPa and minimum casting hardness of 1800 MPa.

3.4 Special Requirements—Special requirements, defined for special applications, are designated by a lowercase suffix letter placed at the end of the casting grade designation.

EXAMPLE—11H20b designates iron meeting special requirements of special service brakedrums.

3.5 Equivalency and Conversion—Equivalency information for engineering purposes, between this and other standards, is provided in A.4.1, A.4.6, and A.4.7. Grades of this document can have multiple equivalents with grades of previous SAE and most other standards as exemplified by grades G3000 and G4000. Determination of current grade equivalent for castings established in production under previous SAE or other documents, shall be by the producer, in accordance with 5.5.3, based on historical or current test data from the established process, and reported to and approved by the purchaser. When the producer does not have access to the applicable historical data, grade determination shall be based on samples provided by producer and approved by purchaser.

4. *Grades*

4.1 Iron Grades—Iron grades and their t/h lower limit requirements are shown in Table 1.

TABLE 1—IRON GRADES

Grade	Test Bar t/h Ratio Lower Limit[1] MPa/MPa[2]	Test Bar t/h Ratio Lower Limit(1) psi/HB[3][4]
G7	0.070	100
G9	0.090	128
G10	0.100	142
G11	0.110	156
G12	0.120	171
G13	0.130	185

1. Statistically defined
2. Both tensile and hardness in MPA units
3. For reference only. The MPa/MPa SI metric values are primary. See Section 1.
4. Units of HB are kgf per mm^2.

4.2 Hardness Grades—Hardness grades and their required lower hardness limits are shown in Table 2.

TABLE 2—HARDNESS GRADES

Grade	Casting Hardness Lower Limit[1] MPa[2]	Casting Hardness Lower Limit[1] HB[3]
H10	1000	102
H11	1100	112
H12	1200	122
H13	1300	133
H14	1400	143
H15	1500	153
H16	1600	163
H17	1700	173
H18	1800	184
H19	1900	194
H20	2000	204
H21	2100	214
H22	2200	224
H23	2300	235
H24	2400	245

1. Statistically Defined.
2. Hardness in MPa = HB multiplied by 9.80665.
3. Units of HB are kgf per mm^2.

4.3 Special Requirements—Special additional requirements for particular applications and service conditions and their lower case letter designators are shown in Table 3. Special additional requirements shall not change test bar t/h ratio or casting hardness requirements.

TABLE 3—SPECIAL REQUIREMENTS

Designator	Application	Requirements
a	Brake Drums and Discs and Clutch Plates for Special Service	1. Total Carbon 3.4% minimum. 2. Microstructure: Lamellar Pearlite. Ferrite < 15%(1)
b	Brake Drums and Discs and Clutch Plates for Special Service	1. Total Carbon 3.4% minimum. 2. Microstructure: Lamellar Pearlite. Ferrite or carbide < 5%(1)
c	Brake Drums and Discs and Clutch Plates for Special Service	1. Total Carbon 3.5% minimum. 2. Microstructure: Lamellar Pearlite. Ferrite or carbide < 5%(1)
d	Alloy Hardenable Gray Iron Automotive Camshafts(2)	1. Chromium shall be 0.85 to 1.50%(3) 2. Molybdenum shall be 0.40 to 0.60%(3) 3. Microstructure of cam nose: Extending to 45 degrees on both sides of cam nose centerline and to minimum depth of 3.2 mm from the surface shall consist of primary carbide (cellular and/or acicular) and graphite in a matrix of fine pearlite. 4. The amount of carbide in the cams and method of checking shall be specified by the purchaser. 5. Casting Hardness check location shall be on a bearing surface.

1. See ASTM E 562.
2. As-cast requirements. Camshafts may be flame or induction hardened to specified hardness and depth on cam surfaces.
3. Ranges for specific castings shall be within the ranges shown.

4.4 Casting Grades—Combination of iron grade, hardness grade, and special requirement designation, if any, defines casting grade. A partial list of casting grades in common production and use, identified as reference grades and considered standard, is given in Table 4 with current and previous SAE designations. Other combinations of iron grade and hardness grade which are established in production and use or become so in the course of application development, or in accordance with 3.5 and 5.5.3, are also considered standard.

TABLE 4—REFERENCE GRADES(1)

SAE Casting Grade	Previous SAE Designation(2)
G9H12	G1800
G9H17	G2500
G10H18	G3000
G11H18	G3000
G11H20	G3500
G12H21	G4000
G13H19	G4000
G7H16 c	G1800 h(3)
G9H17 a	G2500 a
G10H21 c	G3500 c
G11H20 b	G3500 b
G11H24 d	G4000 d

1. Established in production and use and having near equivalents with previous SAE designations.
2. Equivalency based on tensile strength in 30 mm diameter test bars. See Table A4.
3. The h suffix was previously used to designate both t/h and carbon requirements for this grade.

NOTE—For castings successfully established in production and use under previous designations, the current SAE casting grade shall be determined by the producer and approved by the purchaser (see 3.5).

5. Tensile Strength to Hardness Ratio, Hardness, and Casting Tensile Strength

5.1 Tensile strength values for the t/h ratio determination shall be obtained as shown in Figure 1 from separately cast 30 mm test bars (type “B”) in accordance with ASTM A 48 except sampling frequency shall be as needed for statistical analysis to determine conformance of t/h ratio with requirements of this document. Test specimens shall be at room temperature, defined as between 10 and 35 °C, during tensile testing.

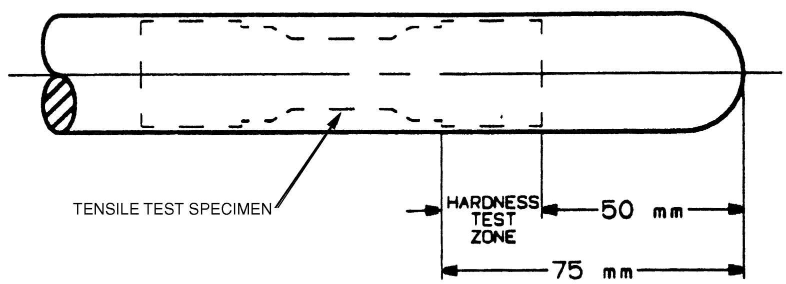

FIGURE 1—TEST BAR HARDNESS LONGITUDINAL TEST ZONE
IN RELATION TO TENSILE SPECIMEN

5.2 Test bar hardness for the t/h ratio determination shall be taken on the tensile test bar between bar center and midpoint of the as-cast radius, and between 50 and 75 mm from the as-cast bar end as shown in Figures 1 and 2.

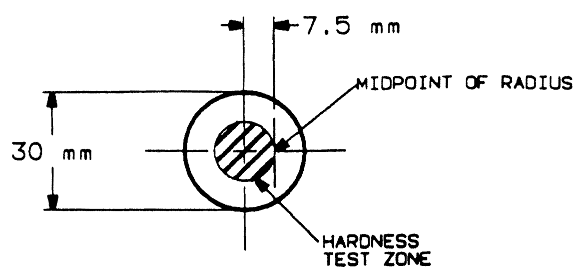

FIGURE 2—TEST BAR HARDNESS RADIAL TEST ZONE

5.3 Brinell Hardness is considered standard for test bars and production castings and shall be determined according to ASTM E 10 after sufficient material has been removed from the casting surface to insure representative hardness readings. The 10 mm ball and 3000 kgf load shall be used unless physically precluded by specimen dimensions as given in ASTM E 10. Test specimens shall be at room temperature, defined as between 10 and 35 °C, during hardness testing.

5.3.1 When a hardness test other than the Brinell test with 10 mm ball and 3000 kgf load must be used, conversion to the 3000 kgf 10 mm ball equivalent shall be by applicable conversion table in SAE J417 or by on-site calibration using Standard Brinell Bars.

5.4 A non-destructive casting hardness test location on the casting for monitoring conformance to grade limits shall be established by agreement between purchaser and producer or determined by producer. It should be readily accessible for convenience in performing the test to ensure adequate quantity, consistency, and accuracy of accumulated data for statistical validity in service of general variance control. Targeting of hardness measurement at service function related locations shall not be considered a requirement unless specified in accordance with 5.4.1.

5.4.1 In special cases, casting hardness at particular casting locations considered critical by the designer but difficult to access or requiring casting destruction may be specified by the purchaser with producer agreement. In such cases, hardness grade conformance may be established directly by hardness readings so obtained or indirectly by hardness readings at an accessible location using an agreed method of correlation.

5.5 The foundry shall exercise the necessary controls and inspection techniques to ensure compliance with the specified hardness and t/h ratio minimums. When samples exhibit normal variance patterns, conformance with grade requirements for t/h and casting hardness shall be determined by long term analysis of production samples using Normal Curve statistical methods. For sample sizes less than 30, the lower limit shall be taken as 3 standard deviations below the mean. For sample sizes larger than 30, the lower limits for t/h and casting hardness control may be optionally taken as the lower 3 standard deviation limit or the lower 99% population limit of the one-sided normal distribution at 95% confidence calculated by the confidence interval method (see A.1.5).

5.5.1 Test bar samples to confirm test bar t/h ratio conformance shall be random samples. Frequency of sampling may be specified by purchaser or determined by producer. Minimum frequency per grade shall be 1 per 8 h shift. Sample period may be any time interval or accumulation of time intervals in which the targeted mean t/h of producer's process control specifications is unchanged.

5.5.2 Casting samples to confirm casting hardness conformance shall be random samples. Frequency of sampling may be specified by purchaser or determined by producer. Minimum frequency shall be the least of 5 per 8 h shift or 100% of production. Sample period may be any time interval or accumulation of time intervals during which the targeted mean casting hardness of producer's process control specifications is unchanged.

5.5.3 Parts successfully established in production and use under previous SAE or other Standards shall be reclassified under this document, without change in mean test bar t/h or mean casting hardness, by appropriate selection of iron grade from Table 1, casting hardness grade from Table 2, and casting hardness range under 5.6.

5.5.4 Casting t/h data obtained by casting hardness tests as described in 5.4 or 5.4.1 and casting tensile tests as described in 5.7, shall be considered informational only and shall not be used for grade conformance assessment.

5.5.5 When casting hardness and/or test bar t/h variance patterns have too much skewness or otherwise do not support Normal Curve methods of analysis, an alternate method shall be established by agreement of purchaser and producer which achieves population limit control equivalent to that described in 5.5.

5.6 Casting hardness range may be specified by the purchaser to provide a non-statistical upper limit for machinability control. The standard range shall be 600 MPa or 60 HB, taken above the required grade minimum, and this shall be the assumed range when not specified. Purchasers shall not specify narrower ranges than this without prior agreement of the producer. Producers shall not exceed this range without prior agreement of the purchaser.

5.7 A minimum value for tensile strength determined by destructive testing at specified locations in castings may be specified as an additional, part number specific, conformance requirement by agreement between purchaser and producer on the applicable lower limit and statistical definition, sampling rate,and any special testing methods required. The agreed minimum shall be obtained with a standard grade as defined in this document. Information for estimating and experimentally determining the tensile minimum which can be expected for a given grade at specific locations in castings for purposes of design and development is given in Section A.4.

5.8 A statistical lower limit for tensile/hardness ratio determined by destructive testing at specified locations in castings may be specified as an additional, part number specific, conformance requirement by agreement between purchaser and producer on the applicable lower limit and statistical definition, sampling rate, and any special testing methods required. The agreed minimum shall be obtained with a standard grade as defined in this document. Information for estimating and experimentally determining the tensile/hardness ratio minimum which can be expected for a given grade at specific locations in castings for purposes of design and development is given in Section A.4.

6. Heat Treatment

6.1 Castings of hardness grades H10 through H17 may be annealed to meet hardness requirements. Castings of grades H21 through H24 may be quenched and tempered to meet hardness requirements.

6.2 Appropriate heat treatment for removal of residual stresses, or to improve machinability or wear resistance, may be specified. Heat treated castings must meet hardness requirements of the grade.

7. Microstructure

7.1 Unless otherwise specified, gray iron covered by this document shall be substantially free of primary cementite and/or massive steadite and shall consist of flake graphite in a matrix of ferrite or pearlite or mixtures thereof.

7.2 Unless otherwise specified, the graphite structure shall be primarily type A in accordance with ASTM A 247.

8. Castings for Special Applications with Controlled Composition and Microstructure

8.1 Heavy-Duty Brake Drums and Clutch Plates

8.1.1 These castings are considered as special cases and are covered in Tables 3 and 4.

8.2 Alloy Iron Automotive Camshafts

8.2.1 These castings are considered as special cases and are covered in Table 3 and 4.

9. General Requirements

9.1 Castings furnished to this document shall be representative of good foundry practice and shall conform to dimensions and tolerances specified on the casting drawing.

9.2 Approval by purchaser of location on the casting and method to be used is required for any casting repair.

9.3 Additional casting requirements such as vendor identification, other casting information, and special testing may be agreed upon by purchaser and supplier. These should appear as product specifications on the casting or part drawing.

10. Notes

10.1 Marginal Indicia—The change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions have been made to the previous issue of the report. An (R) symbol to the left of the document title indicates a complete revision of the report.

PREPARED BY THE SAE IRON AND STEEL TECHNICAL COMMITTEE DIVISION 9—
AUTOMOTIVE IRON AND STEEL CASTINGS OF THE
SAE IRON AND STEEL TECHNICAL EXECUTIVE COMMITTEE

APPENDIX A

NOTE—Information in the Appendix is for reference only and does not constitute requirements.

A.1 Definition and Control of Gray Iron

A.1.1 Gray iron is a cast iron in which the graphite is present in flake form instead of nodules or spheroids as in malleable or ductile iron. Because its graphite has this flake structure, gray iron exhibits much greater sensitivity of mechanical properties to carbon content than malleable or ductile. As in malleable and ductile, the metallic matrix in which the graphite of gray iron resides is normally either eutectoid or hypo-eutectoid silicon steel with a working range of hardness of about 150 to 600 HB (1.5 to 6 GPa). In special cases, the matrix may be martensitic or hyper-eutectoidal with working hardness up to about 800 HB (8 GPa)

A.1.2 Gray iron naturally divides into a family or series of grades having different tensile strength to hardness (t/h) ratios uniformly regulated by eutectic graphite content up to the eutectic composition as shown in Figure A1 with carbon equivalent(CE) as the graphite parameter. Decline in t/h ratio continues as CE increases above the eutectic, but at a much smaller and less predictable rate. Constant t/h lines of this figure are essentially lines of constant graphite effect on mechanical properties. Properties sensitive to both graphite and matrix, such as bulk tensile strength and bulk hardness, vary in constant proportionality to each other and to their matrix counterparts—matrix tensile strength and matrix hardness—along constant t/h lines. Elastic modulus and damping capacity vary mainly only with graphite and are therefore highly constant along the constant t/h lines. Since these lines are also lines of constant eutectic graphite and CE, the most important castability parameters, they are logical grade lines for foundry control as well as for mechanical property control.

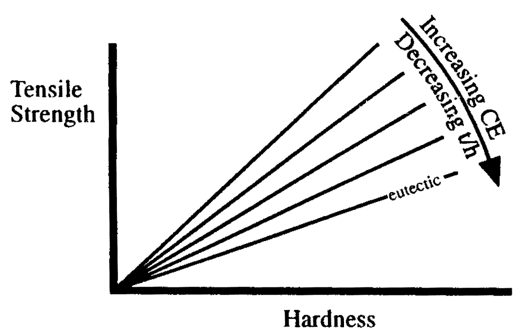

FIGURE A1—CHARACTERISTIC t/h RATIOS OF GRAY IRONS

A.1.3 Specification control of gray iron, since it is a composite material, requires joint classification by at least two property parameters of which one should be mainly graphite microstructure related and the other mainly a function of the matrix microstructure. Limited effectiveness of control by a single bulk property is illustrated in Figures A2 and A3. Figure A2 exemplifies grading by tensile strength alone—any given grade so defined is seen to traverse a wide range of possible hardness minimums. Likewise, in Figure A3, hardness is used as a single defining property and a wide range of possibilities exists for the tensile minimum. In both cases, t/h ratio and therefore, elastic modulus, damping capacity and castability are undefined. Figure A4 illustrates improved control obtainable by jointly specifying two property parameters. In this example, t/h ratio and hardness are the joint control parameters. A tensile minimum is now defined and, in general, all properties including castability are effectively controlled.

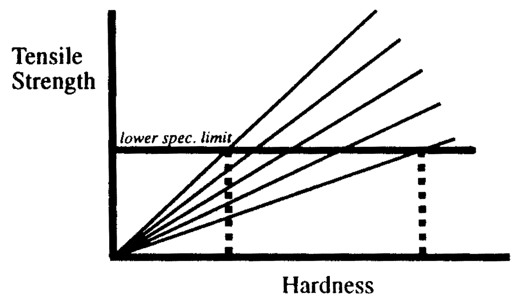

FIGURE A2—GRADING BY TENSILE

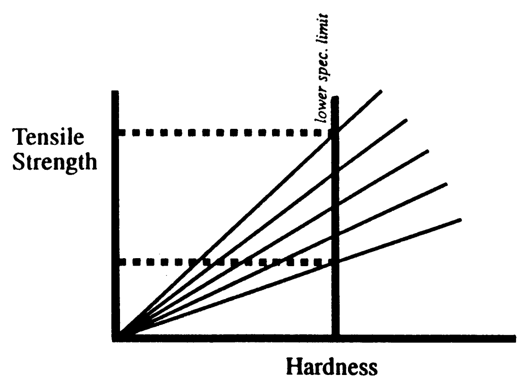

FIGURE A3—GRADING BY HARDNESS

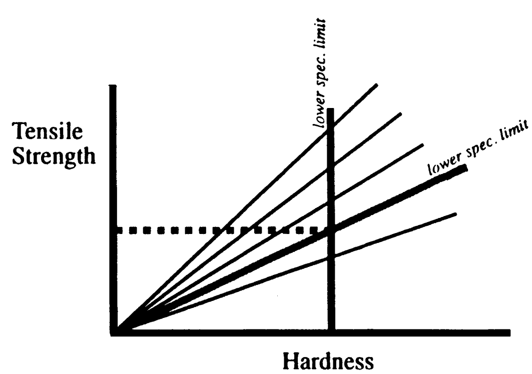

FIGURE A4—GRADING BY t/h RATIO AND HARDNESS

A.1.4 The control parameters used to classify gray iron in this document are test bar t/h ratio and casting hardness, selected because they meet the criteria cited in A.1.3 and are well established, widely used tests. The t/h ratio in this document is dimensionless, reflecting long established practice in the metric countries, where identical units have historically been used for both tensile strength and hardness. Hardness units will be in kg/mm^2 when reported as HB and are multiplied by g = 9.80665 to convert to MPa and form the dimensionless ratio with tensile strength in MPa units. For a number of purposes, it is useful to know the matrix hardness. Examples of its use are -- process control of the hardness property, simplification of bivariate statistical analysis of hardness and tensile strength, and engineering selection of iron grade for best wear resistance or fatigue life in strain limited loading. The matrix hardness can be estimated with sufficient accuracy for most purposes from the bulk hardness and t/h ratio with the relation:

$$H_{matrix} = H_{bulk} / [1 - k^{*}(1 - t/h\ \text{ratio}/0.35)] \qquad \text{(Eq. A1)}$$

in which k is a graphite structure related constant with a usual range in sand cast gray iron of 0.60 to 0.65.

A.1.5 With continuous production processes used for automotive casting production conformance to specification control limits can be assessed by analysis of periodic samples using the Confidence Interval method. This method predicts population limits of parent production in standard deviation units, at various confidence levels, as multiples of the sample standard deviation measured from the sample mean. Tabulations of such multipliers versus sample size are widely published (one of many possible references is given in 2.2). The curve of Figure A5 is a plot of such a tabulation showing how the multiplier typically varies with sample size. The curve of Figure A5 is drawn for 99% population limits of a one-sided normal distribution at 95% confidence. For a sample size of about 300 bars, the –2.5 sigma limit of the sample would be the 99% population limit for the parent production.

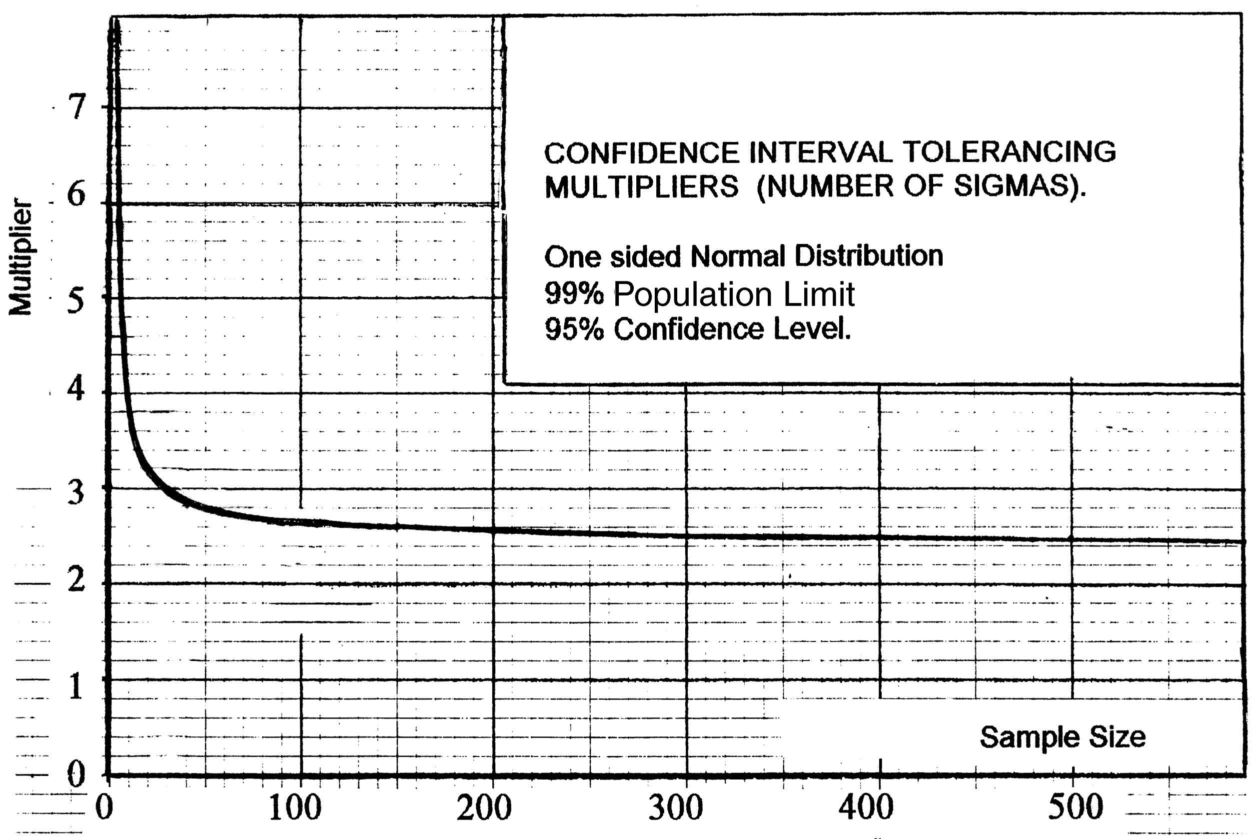

FIGURE A5—CONFIDENCE INTERVAL TOLERANCING MULTIPLIERS (NUMBER OF SIGMAS)

A.2 Chemical Composition

A.2.1 Typical base composition ranges generally employed for the iron grades are shown in Table A1. The base composition does not include alloys such as Cu, Cr, Mo, Ni, or others which may be added for hardness or t/h control, or to meet mandatory composition limits of special irons given in Table 3 of the main body of this document.

TABLE A1—TYPICAL BASE COMPOSITIONS

Iron Grade	Previous Designation	Carbon	Silicon	Manganese	Sulfur Max.	Phosphorus max	C. E.(1) (Approx.)
G7	G1800h	3.50 - 3.70	2.30 - 2.80	0.60 - 0.90	0.14	0.25	4.35 - 4.55
G9	G2500	3.40 - 3.65	2.10 - 2.50	0.60 - 0.90	0.12	0.25	4.15 - 4.40
G10	G3000	3.35 - 3.60	1.90 - 2.30	0.60 - 0.90	0.12	0.20	4.05 - 4.30
G11	G3000	3.30 - 3.55	1.90 - 2.20	0.60 - 0.90	0.12	0.10	4.00 - 4.25
G12	G3500	3.25 - 3.50	1.90 - 2.20	0.60 - 0.90	0.12	0.10	3.95 - 4.20
G13	G4000	3.15 - 3.40	1.80 - 2.10	0.70 - 1.00	0.12	0.08	3.80 - 4.05

1. C. E. (Carbon Equivalent) = %C + (1/3) %Si.

A.2.2 Typical base composition ranges may vary for specific grades depending on casting section size or metallurgical factors such as trace element content, or to satisfy mandatory composition requirements of special irons as given in Table 3.

A.2.3 Typical composition ranges including typical alloy content for camshaft iron, grade G11H24d, are shown in Table A2.

TABLE A2—TYPICAL CHEMICAL COMPOSITION OF ALLOY GRAY IRON AUTOMOTIVE CAMSHAFTS, GRADE G11H24d (PREVIOUS 4000d)

Constituent	Wt %
Total Carbon	3.10 to 3.60
Silicon	1.95 to 2.40
Manganese	0.60 to 0.90
Phosphorus	0.10 max
Sulfur	0.15 max
Chromium	0.85 to 1.50
Molybdenum	0.40 to 0.60
Nickel	0.20 to 0.45
Copper	Residual

A.3 Microstructure

A.3.1 The as-cast microstructure of gray iron covered by this document consists of a mixture of flake graphite in a matrix consisting of ferrite, ferrite and pearlite, or pearlite, as described in Table A3. The quantity of flake graphite and size of the flakes vary with iron grade. The amount and fineness of pearlite vary with the hardness grade. The pearlite is usually lamellar but may be partially spheroidal in slowly cooled sections or where heat treatment has been applied.

TABLE A3—TYPICAL MICROSTRUCTURES OF REFERENCE GRADES

SAE Casting Grade	Previous Designation	Microstructure Graphite[1]	Microstructure Matrix
G9H12	G1800	Type VII A & B	Ferritic - Pearlitic
G9H17	G2500	Type VII A & B	Pearlitic - Ferritic
G10H18	G3000	Type VII A	Pearlitic
G11H18	G3000	Type VII A	Pearlitic
G11H20	G3500	Type VII A	Pearlitic
G12H21	G4000	Type VII A	Pearlitic
G13H19	G4000	Type VII A	Pearlitic
G7H16 c	G1800 h	Type VII A, B, & C size 1-3	Lamellar Pearlite
G9H17 a	G2500 a	Type VII A size 2-4	Lamellar Pearlite
G10H21 c	G3500 c	Type VII A size 3-5	Lamellar Pearlite
G11H20 b	G3500 b	Type VII A size 3-5	Lamellar Pearlite
G11H24 d	G4000 d	Type VII A & E size 4-7(1)	Pearlitic - Carbidic[2]

1. See ASTM A 247.
2. In cam nose. As cast. matrix pearlite in cam may be transformed to tempered Martensite by subsequent Flame or induction hardening.

A.3.2 The size and distribution of graphite flakes in gray iron depend upon chemistry, liquid metal treatment (inoculation), and cooling rate during solidification. The primary, but not sole, chemical determinant is carbon equivalent, defined as C+Si/3.

A.3.2.1 Alloying elements used for pearlite hardness control have small but non-negligible effects on graphite size. Since some elements operate as coarsening and others as refining agents, combinations can be used for a neutral effect.

A.3.2.2 When alloying elements are used to produce a mixed structure of primary carbide and graphite, as in the cams of alloy hardenable gray iron automotive camshafts, eutectic graphite is reduced and significant flake refinement results.

A.3.2.3 The graphite microstructure of gray iron cannot be changed by heat treatment.

A.3.3 Hardness of the ferrite in the gray iron matrix is unaffected by cooling rate but is affected by alloy elements in solid solution, the most noticeable being silicon, which increases ferrite hardness about 35 HB for each 1% of Silicon present. Heat treatment is required to decompose all pearlite and produce a fully ferritic structure.

A.3.4 The amount and hardness of pearlite depend jointly on cooling rate and alloy chemistry, which are balanced in the foundry to control pearlite amount and hardness and, consequentially, casting hardness. Both the amount and hardness of pearlite can be altered by heat treatment.

A.3.5 In special cases such as alloy hardenable iron camshafts, alloy is also used to obtain controlled percentages of carbides, detracting from graphite, in cam and valve lifter surfaces where maximum contact stress occurs. The as-cast matrix structure in these cases is pearlite; in the contact surfaces, the matrix is transformed to tempered martensite by surface heat treatment.

A.3.6 Gray iron castings can be through-hardened by liquid quenching or selectively surface-hardened by either flame or induction methods.

A.4 Mechanical Properties of Castings For Design

A.4.1 The calculated tensile strength minima shown in Table A4 for 30 mm diameter test bars assume Normal Curve statistics with foundry industry typical variance levels and are in good agreement with typical production data. Values are also given in the table for a quantity called the Casting Strength Index which is defined as the multiple of the statistical grade minima of test bar t/h ratio and casting hardness. Since the iron grade number equals the t/h ratio times 100 and the hardness grade number equals the hardness (in MPa) divided by 100, the casting strength index also equals the product of iron grade number times hardness grade number and is also in MPa. Casting hardness is specified as a direct measure on the casting and controlled in common foundry practice by ladle alloy additions as needed to offset section size effects. The t/h ratio in castings is subject to section sensitivity but in a given section has a parallel relationship with t/h ratio in the test bar. For these reasons, with uniform statistical definition, the Casting Strength Index defined as the product of the statistical minima of casting hardness and test bar t/h is a valid relative measure of casting strength for design purposes. When section sensitivity of the t/h ratio is quantitatively known, this index can also be used to make a first working estimate of the absolute value of casting tensile strength. Both test bar tensile strength and Casting Strength Index values can be used to determine tensile equivalency with iron graded by other specifications and to optimize SAE grade choice.

A.4.1.1 Method of defining Casting Strength Index as minimum casting hardness multiplied by minimum test bar t/h and its relationship to the statistical limits of tensile strength and hardness are shown graphically in Figure A6.

TABLE A4—TENSILE STRENGTH CHARACTERISTICS AND TENSILE EQUIVALENTS OF SAE REFERENCE GRADES(1)

SAE Casting Grades	Former SAE Grades(2)	Non-SAE Tensile Grades(3) SI	Non-SAE Tensile Grades(3) Inch-lb	Theoretical Tensile Strength Minimums of SAE Casting Grades Casting Strength Index(4) MPa	Theoretical Tensile Strength Minimums of SAE Casting Grades Casting Strength Index(4) ksi	Theoretical Tensile Strength Minimums of SAE Casting Grades 30 mm Dia. Test Bars(5) MPa	Theoretical Tensile Strength Minimums of SAE Casting Grades 30 mm Dia. Test Bars(5) ksi
G9H12	G1800			108	15.7	124	18.0
G9H17	G2500	175	25	153	22.2	170	24.6
G10H18	G3000	200	30	180	26.1	198	28.7
G11H18	G3000	225	30	198	28.7	217	31.5
G11H20	G3500	250	35	220	31.9	239	34.7
G12H21	G4000	275	40	252	36.5	272	39.4
G13H19	G4000	275	40	247	35.8	268	38.9
G7H16 c	G1800 h(6)			112	16.2	127	18.4
G9H17 a	G2500 a	175	25	153	22.2	170	24.6
G10H21 c	G3500 c	225	35	210	30.5	228	33.1
G11H20 b	G3500 b	250	35	220	31.9	239	34.7
G11H24 d	G4000 d	275	40	264	38.3	284	41.2

1. Established in production and use and having near equivalents in previous SAE standards and test bar tensile strength equivalents in other standards.
2. Former SAE grades having near equivalence with t/h and hardness requirements, and theoretical test bar tensile strength minimums of the current SAE casting grades.
3. Grades of standards based solely on test bar tensile strength such as ASTM A 48 and 48 M, ISO 185, EN 1561, and others, having near equivalence with theoretical test bar tensile strength minimums of the current SAE casting grades.
4. Multiple of test bar t/h ratio and casting hardness minimum of the current SAE casting grade. Numerically equal to multiple of iron number multiplied by casting hardness grade number.
5. 99% population lower limit of SAE casting grade at 95% confidence, one-sided normal distribution, 300 bar sample (–2.5 σ). Hardness and t/h minimums at –3 σ, hardness range 500 MPa, t/h range 0.35 for iron grades 7 to 11 and 0.30 for iron grades 12 to 13.
6. The h suffix was previously used to designate both t/h and carbon requirements of this grade.

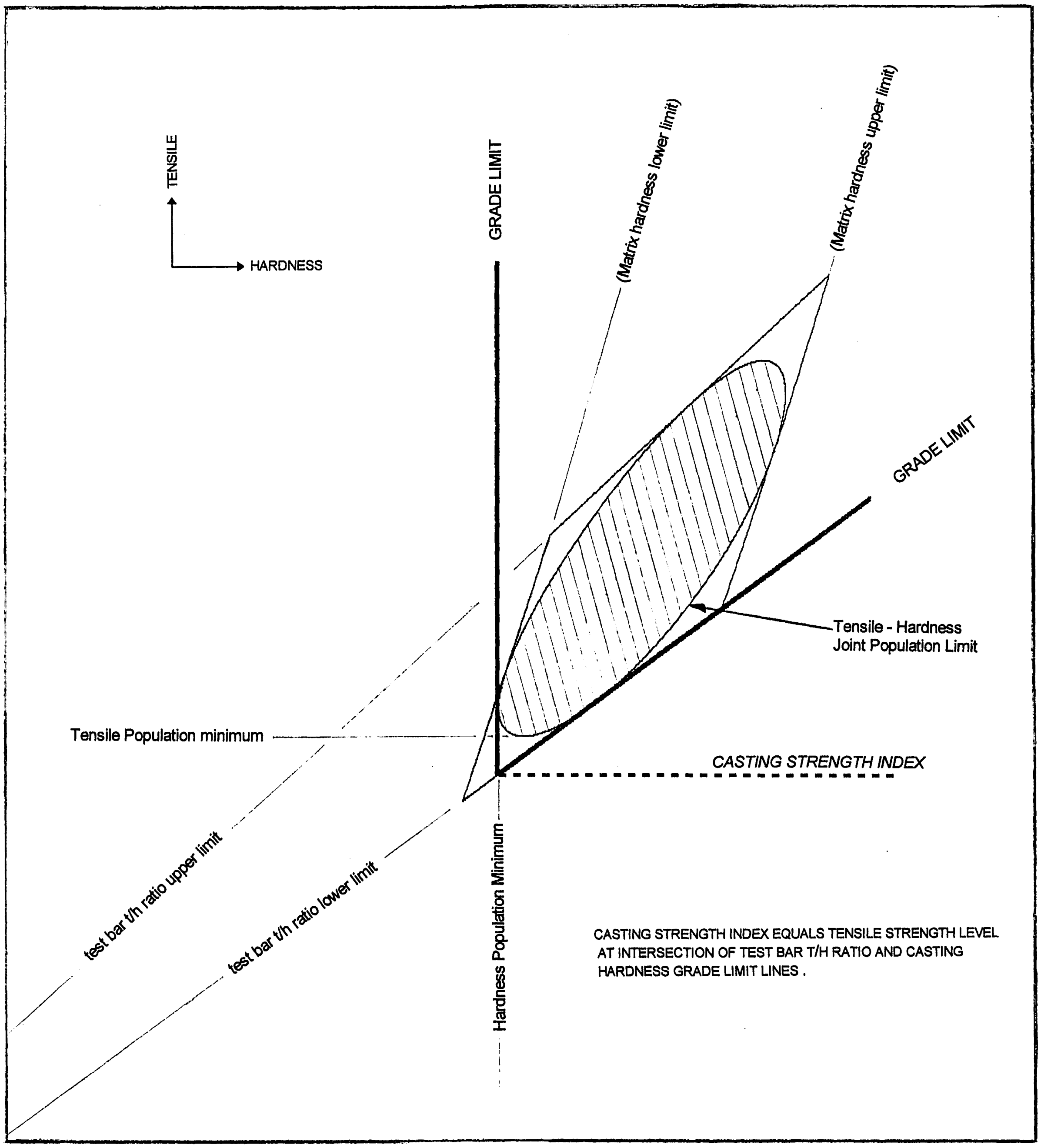

FIGURE A6—METHOD OF DEFINING CASTING STRENGTH INDEX

A.4.2 Tensile to hardness ratio (t/h) of cast iron is determined by graphite structure and is an independent parameter quantifying the effect of graphite structure on mechanical properties. In gray iron the dominant structural aspect affecting t/h ratio is comprised of the length, width and quantity of graphite flakes. The primary process control parameter determining this aspect is carbon equivalent. However, inoculation practice, alloy content and solidification time as controlled by casting thickness are important secondary factors. Although the solidification time or thickness effect is sometimes neutralized by the metallurgical factors, resulting in little or no decline, decline of t/h ratio as thickness increases is more typical. Average results of tests showing such decline, up to 100 mm equivalent wall thickness, have indicated t/h ratio does not usually decline to less than about 80% of the value obtained in the standard 30 mm diameter test bar (approximately 15 mm equivalent thickness). The curve of Figure A7, drawn from data of such tests, gives t/h in thickness up to 100 mm as a percentage of the 30 mm diameter test bar (15 mm equivalent thickness) value and is linearized between points for convenient use in estimating t/h, in various section thicknesses, from the 30 mm test bar value. Figure A7 can be used to make working estimates subject to experimental confirmation in castings. Microporosity, though rare in gray iron, can occur in underfed sections and is an issue in t/h ratio control. It is difficult to assess by microsopic examination but can be detected by means of density measurements.

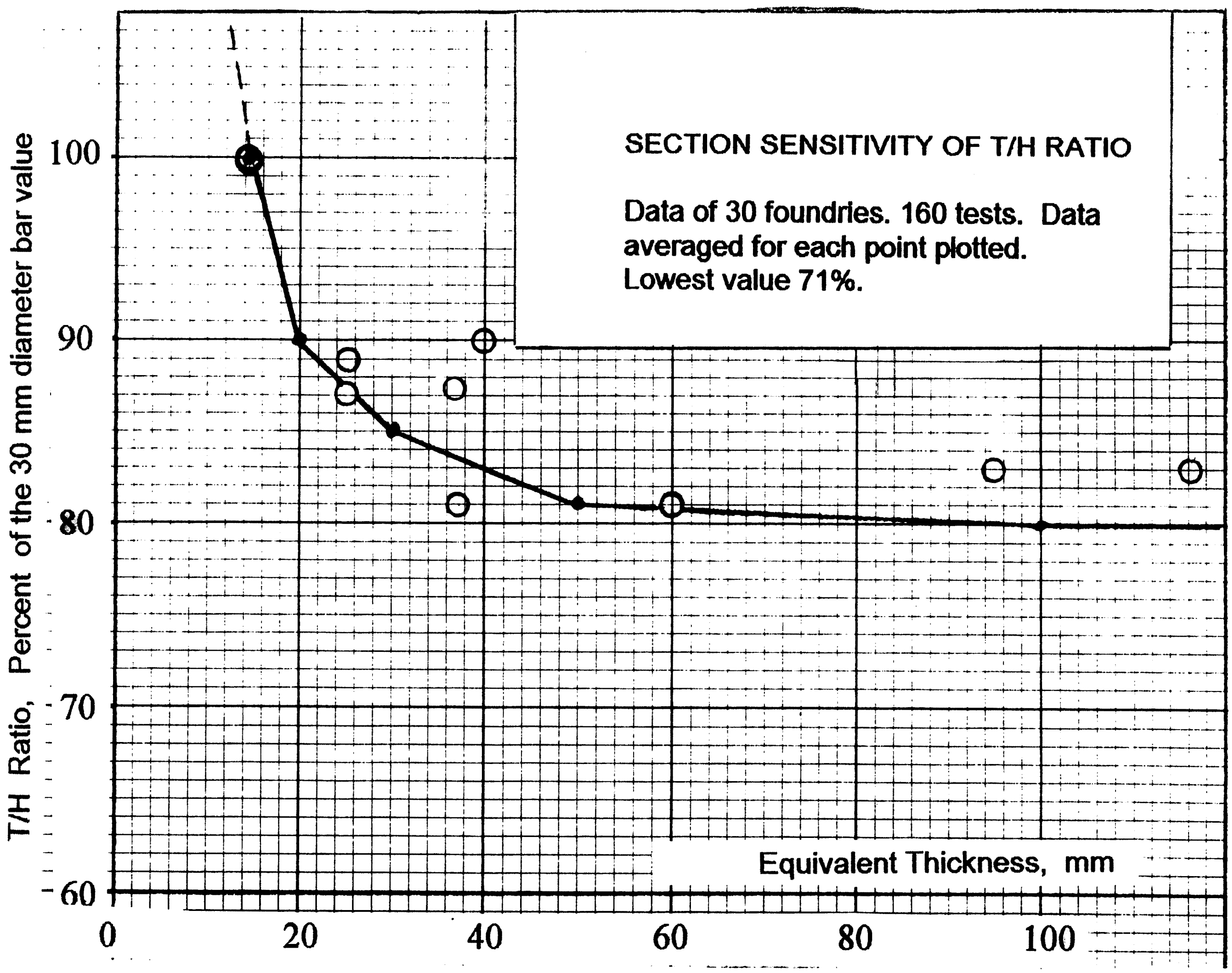

FIGURE A7—SECTION SENSITIITY OF T/H RATIO

A.4.3 Since the probability of minimum t/h ratio and minimum hardness occurring simultaneously in a casting is less than the probability of either occurring alone, the minimum tensile limit given by their product; i.e., the Casting Strength Index defined in A.4.1 and Figure A6, is always conservatively low. This is illustrated in Figure A8 with a typical data plot. The Casting Strength Index can be determined as a statistical limit by a bivariate normal analysis or estimated with sufficient accuracy for equivalency evaluations as about 20% farther from the tensile mean, measured in Sigma (standard deviation) units, than the control limit used for casting hardness and test bar t/h ratio; e.g., about –3-1/2 σ when the casting hardness and test bar t/h minima are at –3 σ, or –3 σ when test bar t/h and casting hardness are at –2-1/2 σ. Without correction for section thickness effect on the t/h property, this conservative margin may diminish when casting section thickness increases above 15 mm thickness; it will also tend to diminish if for any reason distributions become skewed with truncation or data concentration on the low side, or when metallurgical control ranges become either very small or very large (coefficient of variance for hardness or t/h ratio less then about 2% or greater than about 6%).

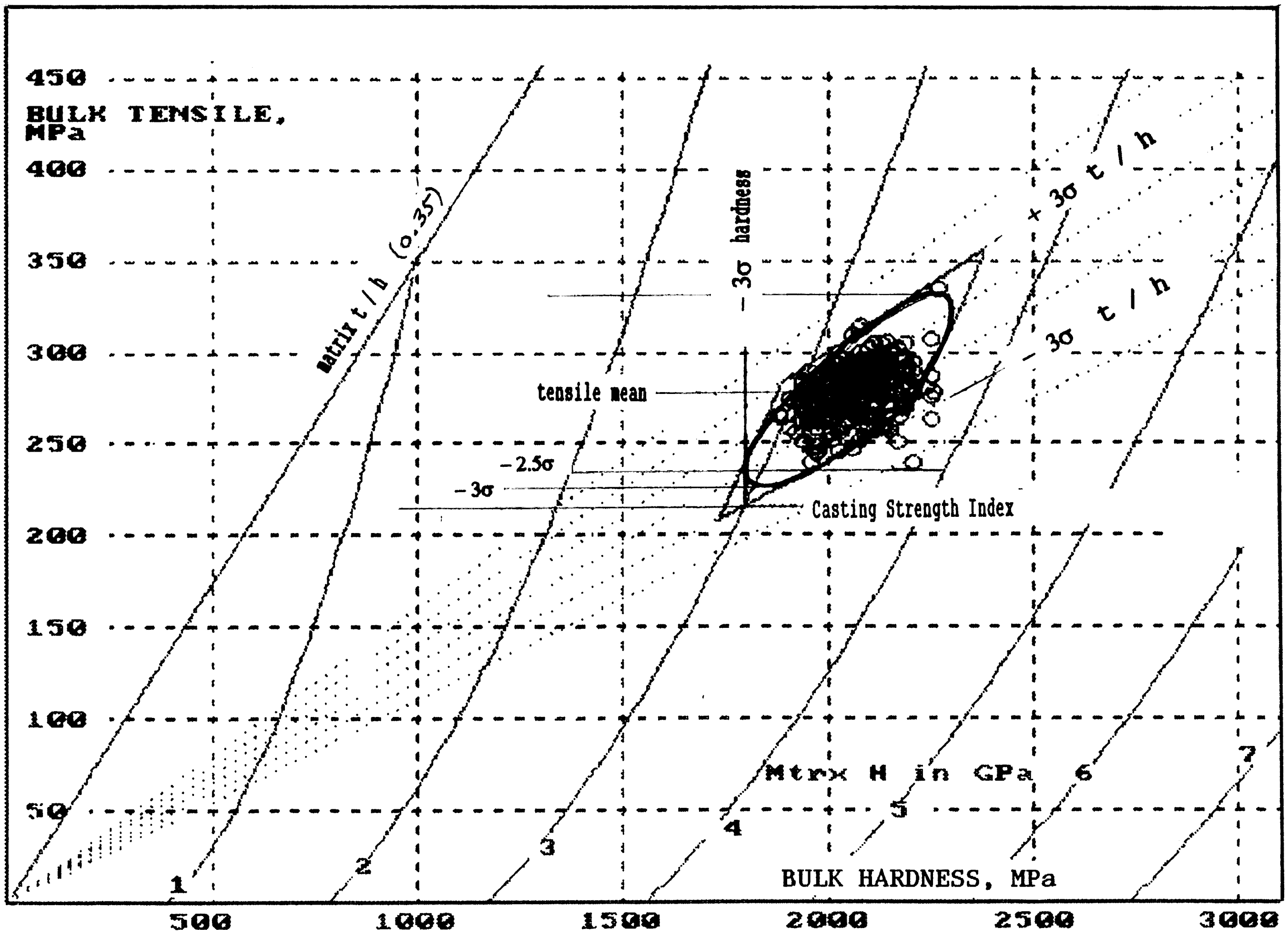

FIGURE A8—BIVARIATE FIELD FOR G12H18 WITH DATA APPROXIMATING THIS GRADE

A.4.4 When casting design is developed primarily by simulated service testing of prototypes correlated by the Casting Strength Index defined in A.4.1 as a relative measure, standard 30 mm test bars should always be poured with the prototype castings so that the actual test bar t/h ratio and casting hardness product of the prototype castings is known in relation to the specification minimum as represented by the Casting Strength Index.

A.4.5 When casting design is based primarily on the absolute value of casting tensile strength, destructive testing of castings is required of prototypes during development and of production samples for ongoing control. The casting strength index defined in A.4.1 can however be used as a first working estimate of tensile strength by correcting for thickness effect on t/h as shown in the example of A.4.7. The equivalent thickness can be estimated by geometric analysis and the relation that equivalent thickness equals volume/surface ratio multiplied by two or from solidification time, measured by thermocouple placement in prototype or production castings, and the Chvorinov relationship which gives equivalent thickness in mm equal to the square root of solidification time in seconds for cast iron in sand molds.

A.4.6 Equivalency between grades of this document and previous SAE grades can be determined from Table A4. Test bar tensile strength equivalency between grades of this and non-SAE tensile based standards can also be determined from Table A4. For casting grade optimization at constant tensile strength the casting strength index, as given in Table A4 or estimated from other limits or data in accordance with A.4.3 can be used. For example, if needed for a complex shape, G9H20 would provide higher castability than G10H18 with the same strength, since casting strength index for both is 180 MPa.

A.4.7 Equivalency between SAE grades of this document and grades classified by casting tensile strength according to section thickness can be assessed by correcting for section sensitivity of t/h ratio as given in Figure A7, which gives t/h ratio in various sections as a percentage of the t/h ratio in 15 mm thickness or 30 mm diameter. When statistical limits are not given or insufficient data is available for statistical analysis, the equivalent SAE grade will be that having the product of casting hardness multiplied by the corrected test bar t/h ratio equaling or exceeding the tensile strength requirements of the grade and section size being assessed. For example, SAE G13H19, with t/h corrected to section thickness of 50 mm, will ,in accordance with Figure A7, have estimated minimum t/h ratio in the 50 mm section of 80% of 0.13, or 0.105; the corrected product of t/h multiplied by casting hardness will be 0.105 x 1900 = 199.5 MPa, and equivalency is indicated with a grade requiring 200 MPa minimum in a 50 mm section thickness. In this case, use of the low ($-3.5\ \sigma$ value) is made to compensate for uncertainty of the statistically unknown case and for the small error introduced by the simplifying step of applying the 80% factor to the minimum instead of average t/h.

A.4.8 Transverse Strength—Table A5 provides estimates of transverse strength and deflection as obtained for 30 mm diameter test bars broken under centered transverse loading with a span of 457.2 mm (18 in) between supports. The test is usually performed on the as-cast bar without machining. The test is standardized under ASTM A 438. The values shown in Table A5 are carried forward from previous versions of SAE J431 and are typical of results long reported in the literature for unmachined sand cast bars and used in standards. This test is now rarely used and the data has mainly historical significance. Use of this test for any new application should be based on new data obtained for the grade of iron used.

TABLE A5—ESTIMATED MINIMUMS FOR TRANSVERSE STRENGTH

SAE Casting Grade	Previous Designation	Transverse Stregnth, Minimum kN (lb)	Transverse Deflection Minimum mm (in)
G9H12	G1800	7.65 (1720)	3.6 (0.14)
G9H17	G2500	8.90 (2000)	4.3 (0.17)
G10H18	G3000	9.79 (2200)	5.1 (0.20)
G11H18	G3000	9.79 (2200)	5.1 (0.20)
G11H20	G3500	10.90 (2450)	6.1 (0.24)
G11H21	G4000	11.56 (2600)	6.9 (0.27)
G13H19	G4000	11.56 (2600)	6.9 (0.27)
G7H16 c	G1800 h	7.65 (1720)	3.6 (0.14)
G9H17 a	G2500 a	8.90 (2000)	4.3 (0.17)
G10H21 c	G3500 c	10.68 (2400)	6.1 (0.24)
G11H20 b	G3500 b	10.68 (2400)	6.1 (0.24)
G11H24 d	G4000 d	11.56 (2600)	6.9 (0.27)

A.5 Application of Gray Iron Castings

A.5.1 Typical applications of both the regular and special reference grades given in Table 4 are shown in Table A6. Iron grade combinations considered standard are not limited to these reference grades.

TABLE A6—TYPICAL AUTOMOTIVE APPLICATIONS OF GRAY IRON REFERENCE GRADES

SAE Grade	Previous Designation	General Data
G9H12	G1800	Miscellaneous soft castings (as cast or annealed) with relatively low strength requirements. Exhaust manifolds, alloyed or unalloyed. Annealed as necessary to prevent growth cracking in service due to heat.
G9H17	G2500	Small cylinder blocks, cylinder heads, air cooled cylinders, pistons, clutchplates, oil pump bodies, transmission cases, gear boxes, clutch housings, light-duty brake drums.
G10H18	G3000	Passenger car and light-duty truck cylinder blocks and heads, flywheels, differential carrier castings, pistons, medium-duty brake drums and discs, clutch plates, hydraulic castings, and refrigerant compressor castings.
G11H18	G3000	Same general uses as G10H18 with suitability for larger section sizes or where tensile strength or duty requirements are higher.
G11H20	G3500	Medium and heavy-duty truck and tractor diesel cylinder blocks and heads, heavy flywheels, transmission cases, axle housings, and miscellaneous heavy gear boxes.
G12H21	G4000	Extra heavy-duty diesel engine cylinder heads, liners, and pistons.
G13H19	G4000	Large heavy-duty diesel engine and construction equipment castings. Heavy-duty hydraulic castings.
G7H16 c	G1800 h	Brake drums and discs where very high damping capacity is required.
G9H17 a	G2500 a	Brake drums and clutch plates for moderate service requirements and where high carbon iron is desired to minimize heat checking.
G10H21 c	G3500 c	Extra heavy-duty service brake drums.
G11H20 b	G3500 b	Brake drums and clutch plates for heavy-duty service where high carbon and high hardness are both required to minimize heat checking and provide higher strength.
G11H24 d	G4000 d	Alloy hardenable iron automotive engine camshafts.

A.5.2 The castability, thermal conductivity, and vibration damping capacity of gray iron all relate closely and directly with its largely graphitic carbon content and, therefore, vary inversely with iron grade as numerically defined in this document. Machinability and wear resistance are more influenced by hardness which is controlled more by matrix hardness than by graphite content. Tensile strength is directly proportional with both iron and hardness grades and can be regulated with either one. Since castability is constant with iron grade, it is often more practical to obtain a needed strength increment by using alloy ladle additions to change the hardness grade rather than to change the iron grade. Iron grade can also be changed by ladle alloy additions which change the size of graphite flakes rather than the quantity. This has an intermediate effect on castability that is often more tolerable and therefore less limiting of design freedom than changing iron grade by changing carbon equivalent.

A.5.3 With grade differentiation by t/h ratio comparative fatigue behavior of different grades of gray iron differs with the type of loading; i.e., whether strain limited or stress limited. In the case of strain limited cyclic loading, fatigue life ("strain life," in this case) tends to be mainly controlled by matrix strength and ductility and shows little variation with t/h ratio. This means that changing iron grade as defined in this document without altering matrix metallurgy, for example by changing only carbon equivalent, will not significantly change strain life even though there is substantial change in t/h ratio and tensile strength. This behavior is shown in reference 8 (see 2.2). For this reason, when service loads are strain limited, the lower t/h iron grades are often more optimum because of their better castability and also because, with a given matrix hardness, the lower t/h grades have a lower ratio of bulk hardness to matrix hardness and hence better machinability at a given strain life. The usual way of increasing matrix hardness -- by pearlite refining alloy additions -- also increases matrix ductility. Examples of strain limited loads are temperature gradient induced loads as in brake drums and water jacketed combustion chambers, and secondary loads carried by gray iron parts incorporated in structures with stronger components as the primary load carrying members and determinants of strain. However, fatigue life of gray iron parts subjected to stress limited loads is influenced by both t/h ratio and matrix hardness, and maximum fatigue life ("stress life") in these cases occurs in the highest t/h and hardness grades. Typical examples of castings subject to stress controlled loading are engine blocks and hydraulic castings.

A.6 Special Applications of Gray Iron

A.6.1 Heavy-Duty Brake Drums and Clutch Plates—Automotive brake drums and clutch plates for heavy-duty service are considered special cases. Mandatory minimum limits for carbon content and matrix microstructure requirements are given in Table 3. Typical base chemistry is given in Table A1. Alloy is normally used to meet casting hardness requirements of grades G10H21c and G11H20b.

A.6.2 Alloy Hardenable Iron Automotive Camshafts—Alloy hardenable automotive camshafts are also considered as special cases. Mandatory alloy content and microstuctural requirements are given in Table 3. Typical base chemistry is shown in Table A1. Typical overall composition ranges are given in Table A2.

A.6.2.1 In casting hardenable iron for camshafts, the aim is to obtain a suitable microstructure in critical locations of the casting and balance the composition to obtain response to induction or flame hardening. These depend not only on the chemistry of the iron but also on the equivalent thickness and details of the melting and liquid metal processes. In making a given casting, it is normal practice to adjust the chemistry to narrow limits within the ranges of Table A2.

A.6.2.2 The cam and bearing surfaces are critical performance areas of automotive camshafts. Carbide content and metallurgical response to flame or induction hardening of the cams in terms of hardness, depth, and area covered are specified for each part number. Requisite hardness results both from the Martensite produced by hardening and the presence of eutectic carbides, which approximately equal the martensite in hardness and contribute to bulk hardness both by their own hardness and by reducing eutectic graphite content. Apart from their contribution to hardness, some minimum limit on carbide content in the cams is also usually necessary for a scuff resistant surface topography.

Rationale—Not applicable.

Relationship of SAE Standard to ISO Standard—Not applicable.

Application—This SAE Standard covers the hardness, tensile strength, and microstructure and special requirements of gray iron sand molded castings used in the automotive and allied industries. Specific requirements are provided for hardness of castings. Test bar tensile strength/Brinell hardness (t/h) ratio requirements are provided to establish a consistent tensile strength-hardness relationship for each grade to facilitate prediction and control of tensile strength in castings. Provision is made for specification of special additional requirements of gray iron automotive castings where needed for particular applications and service conditions.

NOTE—This document was revised in 1993 to provide grade specific t/h control. In 1999 the document was revised to make SI metric units primary. To better align the grading system with long established production methods and grades produced, the previous system of grading by fixed combinations of tensile strength and hardness was changed in 1999 to a system of grading by variable combinations of test bar t/h ratio defined and casting hardness grades. The number of hardness grades was increased relative to the number of previously available ranges to facilitate centering of casting mean hardness in the specification range so that dependence of cost optimization on controlling near the low or high sides of specification ranges is minimized.

Reference Section

SAE J417—Hardness Tests and Hardness Number Conversions

ASTM A 48—Specification for Gray Iron Castings

ASTM A 247—Recommended Practice for Evaluating the Microstructure of Graphite in Iron Castings

ASTM A 438—Transverse Testing of Gray Cast Iron

ASTM E 10—Test for Brinell Hardness of Metallic Materials

ASTM E 562—Determining Volume Fraction by Systematic Manual Point Count

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H.D. Angus, “Physical and Engineering Properties of Cast Iron,” British Cast Iron Research Association, Birmingham, England, 2nd Edition, 1976

“Gray, Ductile, and Malleable Iron Castings Current Capabilities,” STP-455, American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959

G.N.J. Gilbert, “Engineering Data on Grey Cast Iron,” BCIRA (1977), Alvechurch, Birmingham, England

"Tables for Normal Tolerance Limits, Sampling Plans and Screening," R.E. Odeh and D.B. Owen, Marcel Dekker, Inc., New York and Basel, 1980

"Fatigue Properties of Gray Cast Iron," L.E. Tucker and D.R. Olberts, SAE Paper 690471

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