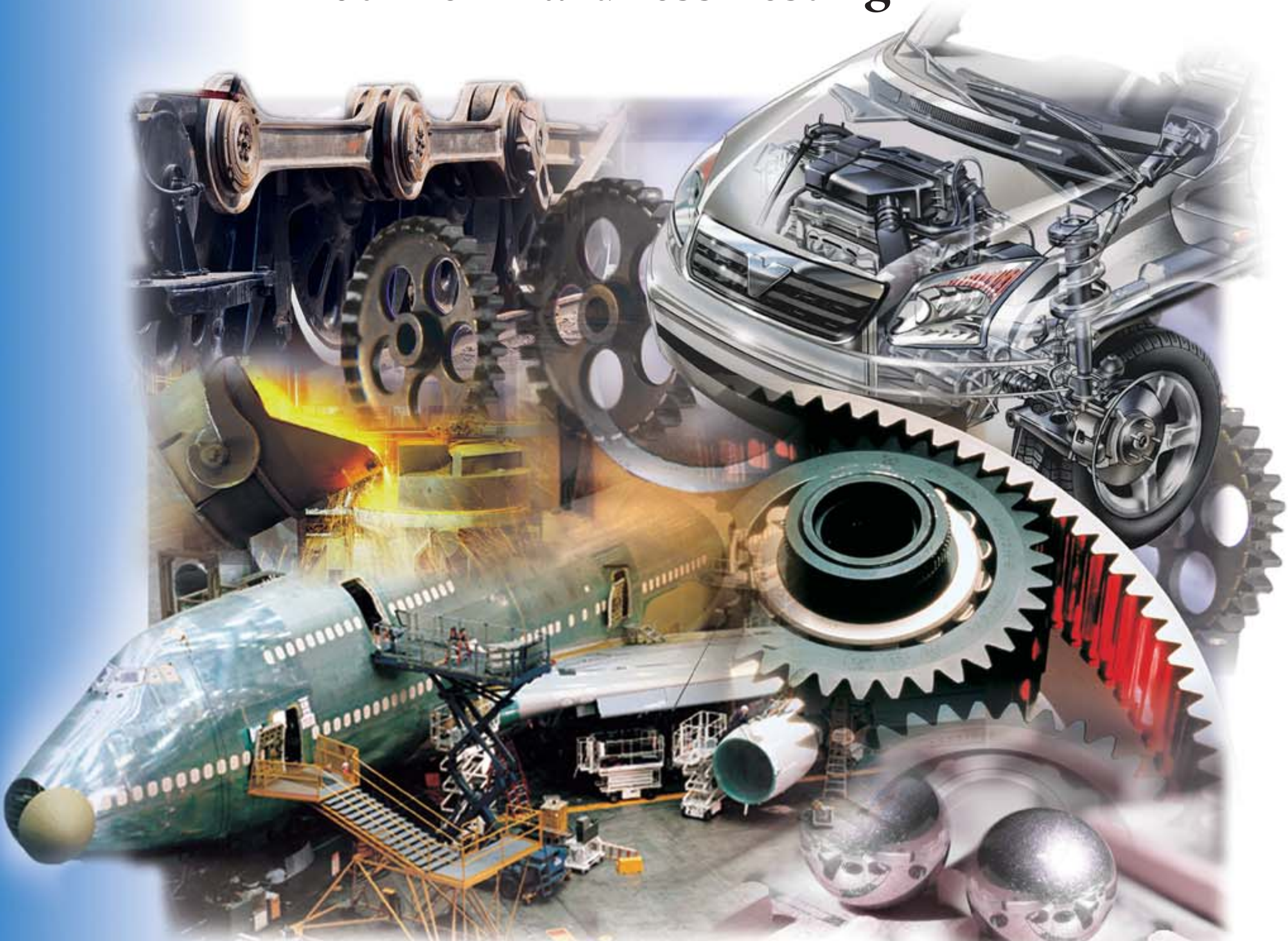
Fundamentals of Rockwell Hardness Testing



Wilson® Instruments
An Instron® Company

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Like the Brinell, Vickers, Knoop, Scleroscope and Leeb tests - all of which fall in the general category of indentation hardness tests - the Rockwell test is a measure of the resistance of material, specifically metals, to permanent indentation. Indentation hardness is not a fundamental property of a material. However, reliable relationships have been established between the various tests and important properties of materials, such as tensile strength and machinability. Furthermore, indentation hardness has become one of the most reliable controls of the heat treatment and quality of manufactured parts. Rockwell testing is covered by ASTM test method E 18.

While all indentation hardness tests generally serve the same purpose, each one has definite advantages that make the test more applicable to certain types of materials and part geometries. Brinell is used primarily on forgings and cast iron. The rebound test is used on large rolls. Vickers and Knoop tests are used on very small or thin parts and for case depth determinations on parts such as gear tooth profiles. The Rockwell test is the most popular indentation hardness test and is used in a wide variety of applications.

Advantages of the Rockwell Test

There are several reasons for the popularity of the Rockwell test. The test itself is very rapid. On a manually operated unit, a Rockwell test takes only five to ten seconds, depending upon the size and hardness of the specimen, as well as pre-load and dwell time. Also, the indentation is extremely small and usually does not need to be removed by machining, making this a non-destructive test. A Rockwell C scale test on hardened steel, for example, penetrates to a depth of approximately 0.0035 inch, with the diameter of the indentation only 0.019 inch, which is barely visible. The Rockwell test is applicable to a wide range of part sizes. Sheet metal as thin as 0.006 inch can be tested on the Rockwell® superficial tester, and as long as the surface area is large enough, there is no actual limitation to the size of your specimen. The Rockwell test is based on measurement of the depth of penetration with the hardness number read directly from the dial gauge or digital display that is part of every tester. In comparison, tests such as the Brinell and Knoop require optical measurement of the diameter and length respectively. Direct indication of the Rockwell hardness number is possible only because of the unique feature of the application of the minor load (preliminary test force) which seats the penetrator in the work and establishes a reference or SET position from which the depth of penetration under the heavier or major load (total test force) can be measured. This SET point establishes the same starting point with every specimen.

Principle of Test

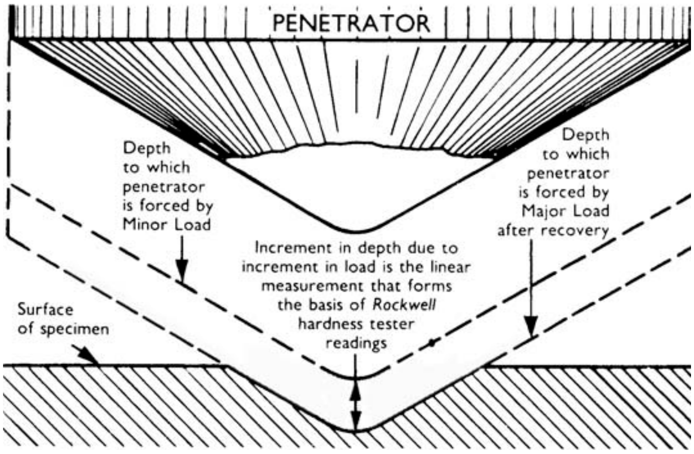
The Rockwell test consists of measuring the additional depth to which a carbide ball or Brale® diamond penetrator is forced by a heavy (major) load beyond the depth of a previously applied light (minor) load (SET point).

The minor load is applied first and a SET position is established on the dial gauge or displacement sensor of the Rockwell tester. Then the major load is applied. Without moving the piece being tested, the major load is removed and, with the minor load still applied, the Rockwell hardness number is automatically indicated on the dial gauge or digital display.

The Brale diamond penetrator is used for testing materials such as hardened steels and cemented carbides. The carbide ball penetrators, available with 1/16 inch, 1/8 inch, 1/4 inch, and 1/2 inch diameter, are used when testing materials such as steel-copper alloys, aluminum and plastics to name a few.

Rockwell testing falls into two categories: Regular Rockwell testing (e.g., C and B scales) and Rockwell superficial testing (e.g., 30 N and 30 T scales).

High Rockwell hardness numbers represent hard materials and low numbers soft materials.



▲ **Brale is Wilson®'s trademark for a diamond penetrator with a conical shape, an included angle of 120 °, and a spherical tip with a radius of 0.200 mm, all in accordance with ASTM E 18.**

Regular Rockwell Testing

In regular Rockwell testing the minor load is always 10 kgf (kilograms of force). The major load can be any of the following loads: 60 kgf, 100 kgf or 150 kgf.

No Rockwell hardness value is specified by a number alone. It must always be prefixed by a letter signifying the value of the major load and type of penetrator (e.g. HRC 35). A letter has been assigned for every possible combination of load and penetrator, as given in Table 1. Each test yields a Rockwell hardness value on your tester. Testers with dial gauges have two sets of figures: red and black. When the Brale® diamond penetrator is used, the readings are taken from the black divisions. When testing with any of the ball penetrators, the readings are taken from the red divisions. Testers with digital displays have a scale selection switch, allowing an automatic display of the Rockwell hardness number on its screen.

The regular Rockwell scales are established such that an infinitely hard material will read 100 on the diamond penetrator scales and 130 on the ball penetrator scales.

One regular Rockwell number represents a penetration of 0.002 mm (0.000080 inch). Therefore, a reading of C60 indicates penetration from minor to major load of (100 to 60 Rockwell points) x 0.002 mm = 0.080 mm or 0.0032 inch. A reading of B80 indicates a penetration of (130 to 80 Rockwell points) x 0.002 = 0.100 mm or 0.004 inch.

Superficial Rockwell Testing

In superficial Rockwell testing the minor load is always 3 kgf. The major load can be one of the following loads: 15 kgf, 30kgf or 45 kgf. As with the regular scales, a scale designation has been assigned for every possible combination of load and penetrator as given in Table 2.

Infinitely hard material will read 100 on both the diamond and ball penetrator superficial scales. One superficial Rockwell number represents a penetration of 0.001 mm (0.000040 inch).

Scale Symbol	Penetrator	Load in Kilograms- Force
A*	Brale®*	60
B	1/16 in ball	100
C	*Brale*	150
D	*Brale*	100
E	1/8 in ball	100
F	1/16 in ball	60
G	1/16 in ball	150
H	1/8 in ball	60
K	1/8 in ball	150
L	1/4 in ball	60
M	1/4 in ball	100
P	1/4 in ball	150
R	1/2 in ball	60
S	1/2 in ball	100
V	1/2 in ball	150

▲
Table 1: Regular Rockwell scales.
* Two scales- cabide and steel.

Scale Symbol	Penetrator	Load in Kilograms- Force
15 N	N *Brale*	15
30 N	N *Brale*	30
45 N	N *Brale*	45
15 T	1/16 in ball	15
30 T	1/16 in ball	30
45 T	1/16 in ball	45
15 W	1/8 in ball	15
30 W	1/8 in ball	30
45 W	1/8 in ball	45
15 X	1/4 in ball	15
30 X	1/4 in ball	30
45 X	1/4 in ball	45
15 Y	1/2 in ball	15
30 Y	1/2 in ball	30
45 Y	1/2 in ball	45

▲
Table 2: Superficial Rockwell scales.

Selecting the Proper Scale

In many instances Rockwell hardness tolerances are indicated on drawings. At times, however, the Rockwell scale must be selected to suit a given set of circumstances.

Many Rockwell applications are covered by the B and C scales, which are used for testing steel and copper as well as their alloys. The ever-increasing use of materials other than steel and brass, as well as thin materials, is making it even more important to have some basic knowledge of the factors that must be considered in choosing the scale that will assure an accurate Rockwell test.

The choice is not only between the regular hardness tester and superficial hardness tester, with three different major loads for each, but also between the diamond penetrator and the steel and carbide ball penetrators - a combination of 30 different scales.

A valuable source of information pertaining to Rockwell scales in use by industry on a wide variety of materials is the American Society for Testing and Materials (www.astm.org). Many specifications will be found under both ferrous and non-ferrous metals in which the applicable Rockwell scale is given. In some cases tolerances are also stated.

In the event no specification exists or there is doubt about the suitability of the specified scale, an analysis should be made of four controlling factors important in the selection of the proper scale. These factors are found in the following categories:

- Type of material
- Thickness of specimen
- Width of area to be tested
- Scale limitations

Types of material included in ASTM Designation E 18 is a listing of all regular Rockwell scales and typical materials for which these scales are applicable. This table provides an excellent starting point for choosing the correct scale, load and penetrator to be used for your test (Table 3).

While Table 3 includes only the regular Rockwell scales, this information can be a helpful guide even when one of the superficial scales may be required. For example, note that the C, A and D scales are used on hard materials such as steel and tungsten carbide. Any material in this hardness category would be tested with the diamond penetrator. The choice to be made is whether the C, A, D, 45 N, 30 N or the 15 N scale is applicable. In any event, the possible scales have been reduced to six. The next step is to find the scale, whether it be regular or superficial, which will guarantee accuracy, sensitivity and repeatability. This will normally be determined by a sample size, thickness and hardness. Testing under the correct conditions is the objective of any measuring instrument, particularly the Rockwell® tester.

Scale Symbol	Typical Applications of Scales
B	Copper alloys, soft steels, aluminum alloys, malleable iron, etc.
C	Steel, hard cast irons, pearlitic malleable iron, titanium, deep case hardened steel and other materials harder than B 100
A	Cemented carbides, thin steel and shallow case hardened steel
D	Thin steel and medium case hardened steel and pearlitic malleable iron
E	Cast iron, aluminum and magnesium alloys, bearing metals
F	Annealed copper alloys, thin soft sheet metals
G	Phospor bronze, beryllium copper, malleable irons, Upper limit G 92 to avoid possible flattening of ball
H	Aluminum, zinc lead
K L M P R S V	Bearing metals and other very soft or thin materials, including plastics (see ASTM D 785). Use smallest ball and heaviest load that do not give anvil effect

▲ Table 3: Typical scale applications.

Thickness of Specimen

The material immediately surrounding a Rockwell indentation is considered 'cold-worked'. The extent of the cold-worked area depends on the type of material and previous work hardening of the test specimen. The depth of material affected has been found by extensive experimentation to be on the order of 10 times the depth of the indentation. Therefore, unless the thickness of the material being tested is at least 10 times the depth of the indentation, an accurate Rockwell test cannot be expected. This 'minimum thickness' ratio of 10:1 should be regarded only as an approximation.

Computation of the depth of penetration for any Rockwell test requires only simple arithmetic, however charts exist that display 'minimum thickness' values already. These minimum thickness values (Table 5, page 13) generally do follow the 10:1 ratio, but they are actually based on experimental data accumulated on varying thicknesses of low carbon steels, hardened and tempered strip steel.

A typical example of the use of the minimum thickness and conversion tables should be helpful. Consider a requirement to check the hardness of a strip of steel 0.014 inch thick of approximate hardness C63. According to Table 5, material in the C63 range must be approximately 0.028 inch for an accurate Rockwell C scale test. Therefore, this specimen should not be tested on the C scale. It is necessary, at this point, to detemine the approximate converted hardness on the other Rockwell scales equivalent to C63. These values, taken from the conversion chart (Table 6, page 14), are: D73, A83, 45 N 70 N, 30 N, 80 N, 15 N and 91.5 N.

Referring once again to Table 5, for hardened 0.014 inch material there are only three Rockwell scales to choose from: 45 N, 30 N and 15 N. The 45 N scale is not suitable as the material should be at least 45 N, 74 N. On the 30 N scale, 0.014 inch material must be at least 30 N, 80 N. On the 15 N scale the material must be at least 15 N, 76 N. Therefore, either the 30 N or 15 N scale may be used. After all limiting factors have been eliminated and a choice exists between two or more scales, the scale applying the heavier load should be used. The heavier load will produce a larger indentation covering a greater portion of the material, and a Rockwell hardness number more representative of the material.

Therefore the conversion chart will also show that a one point difference on the HRC scale is 0.5 on the HR30 N scale. Smaller differences in hardness can be determined using the 30 N scale. The above approach would also apply in determining the scale to use which would accurately measure the correct hardness when approximate case depth and hardness are known.

Minimum thickness charts and the 10:1 ratio serve only as guides. After determining the Rockwell scale based on minimum thickness values, an actual test should be made and the surface directly beneath the indentation examined to determine if the material was disturbed or if a bulge exists. If so, the material was not sufficiently thick for the applied load, resulting in a condition known as 'anvil effect,' and the Rockwell scale applying the next lighter load should be used. On softer materials the high stress concentration due to insufficient thickness will result in flow of the material.

When either anvil effect or flow exists the Rockwell hardness number obtained may not be a true value. It is not allowed to use several specimens, one on top of the other. The slippage between the contact surfaces of the several specimens makes a true value impossible to obtain. The one and only exception is in the testing of plastics: use of several thicknesses when anvil effect is present is recommended in ASTM Designation D 785.

Specifications do exist, and in fact are in common use, permitting minimum thickness values below those established by the above approach. However, in most instances these specifications are widely used and serve the purpose of providing comparison information. An example is ASTM Designation B 36 for brass sheet and strip, where the Rockwell B scale is referred to for thicknesses of 0.020 inch. and the Rockwell 30 T scale for thicknesses of 0.012 inch for inspection purposes. For this application, the Rockwell test is a substitution for a tensile test for which correlation has been established on thicknesses to 0.020 inch and 0.012 inch.

When testing specimens where anvil effect exists, the condition of the supporting surface of the anvil must be carefully watched. After a number of tests this surface will become marred, or a small indentation will be produced. Either condition will affect the Rockwell test, since under the major load the test material will sink into the indentation in the anvil and a lower reading will result. If a specimen has been found after testing to be too thin, the anvil surface should be inspected and if damaged, relapped or replaced. The anvil should not be used if it is marred.

When testing with a ball penetrator on the superficial tester on a specimen where anvil effect or material flow is present, a diamond spot anvil can be used in place of the standard steel anvil. If testing is restricted to the ball penetrators and the superficial scale loads, there is no danger of damaging the hard diamond surface when testing thin materials. Furthermore, with materials that flow under load the hard polished diamond provides a somewhat standardized frictional condition with the underside of the specimen.

Width of Area

In addition to the limitation of indentation depth into a specimen for a given thickness and hardness, there is also a limiting factor on the minimum width of material. If the indentation is placed too close to the edge of a specimen (or too close to another indent), the material will yield and the Rockwell hardness number will decrease accordingly.

Experience has shown that to assure an accurate test, the distance from the center of the indentation to the edge of the specimen must be at least 2½ diameters. Therefore, when testing in a narrow area, the width of this area must be at least five diameters when the indentation is placed in the center. The appropriate scale must be selected for this minimum width. While the diameter of the indentation can be calculated, for practical purposes the minimum distance can be determined by an indentation hardness test ‘cold works’ the surrounding material. If another indentation is placed within this cold worked area, the Rockwell hardness test will be affected. Usually the readings will be higher than obtained on the virgin material. Experience tells us the distance from center to center of indentations must be at least three diameters. Usually the softer the material, the more critical the spacing, but three diameters will be sufficient for most materials.

Conversion

Conversion charts are of value only as a guide. Rockwell hardness numbers should be reported on the same scale on which the actual test was made (this is a direct reading as opposed to a converted reading). In the event it is absolutely necessary to report converted values, the fact that the numbers are converted should be indicated. Comparison between different hardness scales on a conversion chart does not apply if the actual test was improperly made. For example, if sheet metal is so thin that tests made on the Rockwell B scale show bulges on the underside of the sheet, then values of Rockwell 30 T cannot be obtained by merely carrying those incorrect B scale values to the chart but can only be found by actually making a test on the 30 T scale. If an accurate 30 T scale reading is determined by test, the conversion chart may be referred to for the equivalent B scale hardness numbers although the material is too thin for an accurate B scale test. Proper use of the chart requires a valid and proper reading.

▲
Wilson® Rockwell® 2000 series tester performing hardness test on sheet using diamond spot anvil.

Scale Limitations

Use of the diamond penetrator when readings fall below HRC20 is not recommended since there is loss of sensitivity. Brale® diamond penetrators are not calibrated below HRC25. If used on softer materials there may not be agreement in results when replacing the penetrators. Another scale should be used, for example, the B scale.

There is no limitation to the hardest material that can be tested with the diamond penetrator. However, the C scale should not be used on tungsten carbide. The material will fracture, or the diamond life will be considerably reduced. The A scale is the accepted scale in use today by the carbide industry. The carbide A scale indenters are calibrated to the hardness levels maintained by the CCPA (Cemented Carbide Producers Association) and therefore give different readings than normal HRA Steel Brales.

Although scales using the ball penetrator (for example, the B scale) range to 130, readings above approximately 100 should be done with caution. In this region, due to the blunt shape of the penetrator, the sensitivity of most scales is poor. Also, with the smaller diameter penetrator there is danger of flattening the ball under the high pressure developed on the small area of contact. If values above 100 are obtained, the next heavier load or next smaller penetrator should be used. If readings below zero are obtained, the next lighter load or larger penetrator should be used. Carbide balls are now used for Rockwell testing. The harder carbide balls are less likely to be damaged by readings over 100.

Readings below zero are not recommended on any Rockwell scale, primarily due to the confusion and possible misinterpretation that can result from the use of negative values.

On non-homogeneous materials a scale should be selected which will give relatively consistent readings. If a ball penetrator too small in diameter or too light is used the resultant indentation will not cover an area sufficiently representative of the material to yield consistent hardness readings.

Specimen Support

It is important for the accuracy of the test that the specimen be held securely during the application of the major load. Consider that one regular Rockwell hardness number represents a vertical movement of the penetrator of approximately 80 millionths of an inch (0.000080 inch) and one superficial Rockwell number approximately 40 millionths of an inch (0.000040 inch). A vertical shift of the part being tested of only 0.001 inch will lower the Rockwell reading by more than 10 numbers on the regular and 20 numbers on the superficial scale.

Sheet metal, small pieces or other pieces that do not have flat supporting surfaces are tested on the pedestal spot anvil, which has a small elevated flat surface.

An anvil with a large flat surface should be used for supporting large parts. Anvils with a supporting surface greater than approximately three inches in diameter should be attached to the elevating screw by a threaded section rather than inserted in the anvil hole in the elevating screw.

Round work should be supported in a hardened Vee anvil or in a cylindron anvil, which consists of two hardened parallel cylinders. When testing small rounds, it is essential that the center of the Vee be aligned with the center of the penetrator. The piece must be straight.

Irregularly shaped pieces must be properly supported on specially designed fixtures if an accurate test is to be made.

Tubes and hollow pieces must be supported by a mandrel to ensure rigidity under the test loads. This will prevent the tube from deforming under the major load, thus causing a lower hardness reading.

▲ Gooseneck extension for ease of internal testing.

Cylindrical Corrections

The Rockwell test is a measure of the resistance of the material being tested to permanent indentation. There is less lateral support to the penetrating force on a convex surface than on a flat surface. Consequently, the penetrator will sink further into the material with the result that the Rockwell hardness number will be lower on the convex surface than on a flat piece of the same material. For a concave surface (or ID) the opposite is true.

Above diameters of one inch the difference is negligible but for diameters of one inch and smaller the effect of the curvature must be taken into consideration. Approximate 'Cylindrical Correction Values' will be found in Table 7. The cylindrical corrections are added to the dial gauge or digital display reading when testing on the OD (convex surface) and subtracted when testing on the ID (concave surface). On diameters down to $\frac{1}{4}$ inch the regular Rockwell scales can be used; the superficial scales can by used to $\frac{1}{8}$ inch. Below $\frac{1}{8}$ inch cylindrical corrections are not available nor is Rockwell testing normally recommended. The Knoop hardness test is preferred on diameters under $\frac{1}{8}$ inch.

To avoid the problem of curvature, a flat can be ground in the area to be tested. But in doing so, extreme care must be exercised not to affect the hardness of the part, and the ground area must provide the minimum $2\frac{1}{2}$ inch diameter distance from the center of the indentation to the edge of the flat.

Only results obtained on flat surfaces or values corrected for curvature should be used when referring to conversion charts. When testing small diameter work, alignment of the piece with the penetrator is vital. The smaller the diameter, the more critical this alignment becomes.

The Importance of Standardized Testing

When two or more parties must agree on the hardness of a material or part, it becomes vitally important that the parties have a mutual understanding of how the test will be performed. It is not unusual for a supplier, for example, to promise his customer that all parts shipped will fall within a certain hardness range. Prior to shipment, a wise supplier performs a hardness test on the parts, either on a sampled basis or as a 100% check. The customer normally inspects the same parts as they are received. Unless an agreement has been made on such things as the apparatus to be used, preparation of the test specimen, calibration, test procedure and method of reporting, the possibility of disagreement is high.

Most companies look to recognized standards organizations to provide this information. These standards organizations generally form committees to pool the knowledge and experience of users from various industries and formulate detailed written standards. In the U.S., the American Society for Testing and Materials has prepared ASTM Designation E 18 entitled 'Standard Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials.' This has become the recognized standard for Rockwell testing in the United States and many countries around the world. The comparable ISO Standard is 6508.

In some cases, testers may be used, which for reasons of speed or portability, do not perform a standard Rockwell test. Caution should be exercised when reporting results from these testers, as the readings may not be identical to those made on a standard Rockwell® hardness tester for all scales, materials, or part geometries.

▲ Standard V.

▲ Shallow V.

▲ Cylindron.

▲ Gooseneck.

▲ Plane.

▲ Spot.

▲ Diamond spot anvil.

Standardized Test Blocks

If a tester is in constant use, verifying your tester with test blocks should be a daily procedure. This check indicates if the tester is out of calibration or if the penetrator is damaged.

If a tester is used throughout a given scale, the recommended practice is to check it at the high, low and middle range of this scale. For example, to check the complete C scale, the tester should be checked at C63, C45 and C25. If, on the other hand, only one or two ranges are used, test blocks should be chosen which fall within ±5 hardness numbers on any scale using the diamond penetrator and ±10 numbers on any scale using the ball penetrator.

A minimum of five tests should be made on the standardized surface of the block and the average must fall within the tolerances indicated on the block for the tester to be considered in calibration. In addition, the spread of the five readings (i.e., the difference between the highest and lowest reading) must not be greater than the value specified in Table 4 for the hardness range of the test block. Only the standardized surface should be used, as this is the only surface for which the values marked on the side of the block apply.

If the average of the five readings falls outside the test block limits, the difference between this average and the test block average can be noted as the error of the machine, and this error can be compensated for when evaluating test results. Recommended practice, however, is either to clean and examine the tester according to the instruction manual or to call in a factory trained service representative.

Before assuming that the tester is the prime cause of readings outside of test block limits, replace the ball in the ball penetrator or examine the diamond point of the diamond penetrator. Replace the penetrator if it is damaged. Spacing of indentations on the test block is important.

The same rule applies as when testing any material: the distance from center to center of indentations must be at least three diameters. The readings, usually higher, from any indentations spaced too closely together should be disregarded.

Range of Standardized Hardness Test Blocks	The Repeatability of the Test Block Readings Shall be not Greater Than:
Rockwell C Scale:	
60 and Greater Below 60	0.5 1.0
Rockwell B Scale:	
45 and Greater Below 45 to 1.5, inclusive	1.0 1.5
Rockwell A Scale:	
80 and Greater Below 80 to 60.5, inclusive	0.5 1.0
Rockwell 30 N Scale:	
77.5 and Greater Below 77.5 to 41.5, inclusive	0.7 1.0
Rockwell 30 T C Scale:	
46.2 and Greater Below 46.2 to 15.0, inclusive	1.0 1.5

Note: See ASTM E 18 for other scales.

▲ Table 4: Range of test block readings.

▲ Rockwell calibration set.

Apparatus

Stanley P. Rockwell, who was a metallurgist in a New England ball bearing manufacturing plant, designed the Rockwell® hardness tester in 1919. At that time there was no entirely satisfactory method for controlling the hardness of ball bearing races and many other hardened steel parts. As a result of his study and experiments for a means of accurately measuring their hardness, he invented the tester that has become known as the Rockwell hardness tester. The word Rockwell as applied to the tester and also as applied to test blocks has long been registered as a trademark in the United States and many other countries. Wilson® Instruments is the original manufacturer of the Rockwell hardness tester and Rockwell test blocks.

The early model Rockwell tester consisted of a sturdy, hollow cast frame, together with a plunger that held the testing point at one end; the other end was abutted against a delicate measuring device. A series of levers with knife-edges connected that plunger with a weight. By shifting the position of this weight, more or less weight was applied to the testing point at will, to suit testing conditions. This weight, originally called the final weight, was applied and released by a hand lever. An elevating screw with chuck or anvil held the work. An initial pressure was applied by compressing a spring in the head of the machine. The hardness was read directly as the increment of depth caused by the increment in load as indicated by a measuring device.

Since 1919 the tester has been refined and improved. However, the test principle remains the same. Modern Rockwell scale hardness testers are available in the following general categories:

- Bench models - digital and dial
- Portable and mobile models
- Automatic/production models
- Models for special applications

Since 1993 Wilson Instruments has been owned by Instron® Corporation. As a result, a new series of Rockwell testers have been designed using Instron's closed loop technology. These new closed loop instruments have advanced Rockwell testing to a new level of accuracy and repeatability.

Bench Models

The bench model Rockwell testers are precision instruments with load application, measurement, and other features strictly in accordance with ASTM Standard E -18. The original system was one of weights and levers, operating on a knife-edge fulcrum, with a free-floating friction less plunger system. The plunger rod carries the penetrator and moves up and down within the head of the machine. Only the penetrator contacts the surface being tested, and the point of test is visible at all times. The most recent system is a closed-loop system, which uses a load cell and motorized load application. The greatest degree of hardness in a metal that can be tested is limited only by the ability of a diamond penetrator to withstand the stress.

Depending upon the age of the tester, the rate of load application is controlled either by a dashpot mechanism or through a motorized mechanism, which is micro-processor controlled.

Bench model testers are available for testing on the regular or superficial scales. A combination tester, known as the Rockwell Twintester, can perform tests on both regular and superficial scales.

Bench model Rockwell testers can be equipped with a dial gauge or digital display of hardness. Most manufactured tester models are motorized for automatic application and removal of the major load.

Bench model testers are available in a wide range of vertical capacities: the smallest is approximately 6 inches and the largest as great as 14 inches. The throat depth for most models is approximately $5\frac{1}{4}$ inches. In choosing the vertical capacity, not only must the size of the part be considered, but also the size of the anvil or supporting fixture.

▲
Hardness family.

Automatic/Production Models

With the ever-increasing cost of labor and the great emphasis on quality products, there is a growing need for automatic hardness testers.

Fully-automatic systems can be custom engineered to suit the testing requirements for a particular part. These systems can be interfaced with an existing production line to provide automatic and rapid Rockwell testing. The basic component of a fully automatic test system is a test head such as the Wilson® Instruments highspeed Rockwell® test head. The Wilson Instruments high-speed Rockwell test head performs an indentation type hardness test, using the same principle as the standard Rockwell test.

The minor and major loads for the high-speed tester are developed by feeding two known air pressures into a bellows assembly in proper sequence. The application of a known air pressure on a fixed air bellows will produce a known force. The depth of penetration is measured by a unique electronic system.

This system automatically remembers the minor load position and the major load position and then subtracts the two to obtain the desired result. The output has a DC voltage that is equal to 0.1 volts per point or 10 volts full scale. High and low hardness limit controls are included to allow automatic hardness sorting.

These limits are simply set on the control console by screw adjustments. Colored lights indicate if the part is soft, within limits, or too hard.

The standard Rockwell test requires approximately three to six seconds to complete the loading, testing and unloading cycle. The custom high-speed hardness tester can be designed to require less than one second to go through the same cycle. There is considerably less time for plastic flow of the sample during the test. This difference in time can produce small but measurable differences in depth of penetration between the standard Rockwell test and the high-speed test. Therefore, the manufacturer cannot claim that the high-speed tester performs a true Rockwell test, but it does produce a test that gives similar results. For ease of application, the high-speed tester is calibrated using standard Rockwell test blocks.

▲
Rockwell series 2000 tester integrated with Instron® universal test system designed for automatic loading and testing with a robot.

Portable Models

Many different types of portable testers are available. The ideal choice is the tester that handles the job for which it is intended while providing the degree of accuracy required. Because of the limitations imposed on the design to keep weight to a minimum, portable hardness testers are not as a rule as accurate as bench model testers, therefore, they should only be considered when the part cannot be easily brought to the tester. In fact, some designs do not operate on the Rockwell principle, but they are usually graduated in 'equivalent Rockwell C scale hardness number' and as such are of the order of accuracy of a conversion chart.

Several portable testers that follow the Rockwell principle are available. In one such unit, the only deviation from the procedure followed on a bench model tester is the clamping of the part in the C clamp of the unit. The loads are applied by calibrated springs. Many portable testers are available for unusual applications (for example, internal testing), and the manufacturer should be contacted for additional information.

Models for Special Applications

Rockwell® hardness testers have been designed for a variety of special applications. The hardness of plastics can be measured on standard digital Rockwell testers. On certain digital Rockwell testers, dwell and recovery times are programmable. The user can select the duration of time during which the major load is applied (between 1 and 99 seconds) and the amount of time after removal of the major load before the depth is measured (also between 1 and 99 seconds).

High temperature testing can be performed with a special Rockwell tester equipped with a furnace and temperature recording system. Special penetrators permit testing up to +1800 °F.

Custom designed frames can be built to test parts too large for bench testers. Special testers are also available for testing odd-shaped parts or internal or hard-to-reach surfaces.

Conclusion

The Rockwell tester, while a rugged piece of equipment, is also a precision instrument with many features suitable for production testing. To utilize this instrument to its full potential, consideration must be given to the factors governing selection of the appropriate scale as well as the curvature of the specimen and the importance of adequate support under test. With all limiting factors taken into account and with properly designed equipment in good calibration, the Rockwell test can be a versatile procedure capable of measuring small differences in hardness.

▲
Wilson® Instruments mobile model M51.

▲
Wilson Instruments portable model M3.

▲
Wilson Instruments model M-250 Portable LEEB type hardness tester with printer.

Any greater thickness and hardness can be safely tested on indicated scale	Rockwell Superficial Hardness Scales			Rockwell Regular Hardness Scales		
	15N	30N	45N	A	D	C
	15 kgf	30 kgf	45 kgf	60 kgf	100 kgf	150 kgf
Thickness inches (mm)	N Brale indenter			Brale indenter		
.006 (0.15)	92	-	-	-	-	-
.008 (0.20)	90	-	-	-	-	-
.010 (0.25)	88	-	-	-	-	-
.012 (0.30)	83	82	77	-	-	-
.014 (0.36)	76	78.5	74	-	-	-
.016 (0.41)	68	74	72	86	-	-
.018 (0.46)	X	66	68	84	-	-
.020 (0.51)	X	57	63	82	77	-
.022 (0.56)	X	47	58	79	75	69
.024 (0.61)	X	X	51	76	72	67
.026 (0.66)	X	X	37	71	68	65
.028 (0.71)	X	X	20	67	63	62
.030 (0.76)	X	X	X	60	58	57
.032 (0.81)	X	X	X	X	51	52
.034 (0.86)	X	X	X	X	43	45
.036 (0.91)	X	X	X	X	X	37
.038 (0.96)	X	X	X	X	X	28
.040 (1.02)	X	X	X	X	X	20
Any greater thickness and hardness can be safely tested on indicated scale	Rockwell Superficial Hardness Scales			Rockwell Regular Hardness Scales		
	15-T	30-T	45-T	F	B	G
	15 kgf	30 kgf	45 kgf	60 kgf	100 kgf	150 kgf
Thickness inches (mm)	1/16" Ball indenter			1/16" Ball indenter		
.010 (0.25)	91	-	-	-	-	-
.012 (0.30)	86	-	-	-	-	-
.014 (0.36)	81	80	-	-	-	-
.016 (0.41)	75	72	71	-	-	-
.018 (0.46)	68	64	62	-	-	-
.020 (0.51)	X	55	53	-	-	-
.022 (0.56)	X	45	43	-	-	-
.024 (0.61)	X	34	31	98	94	94
.026 (0.66)	X	X	18	91	87	87
.028 (0.71)	X	X	4	85	80	76
.030 (0.76)	X	X	X	77	71	68
.032 (0.81)	X	X	X	69	62	59
.034 (0.86)	X	X	X	X	52	50
.036 (0.91)	X	X	X	X	40	42
.038 (0.96)	X	X	X	X	28	31
.040 (1.02)	X	X	X	X	X	22

▲ Table 5: Minimum thickness chart.

X: No minimum hardness

These values are approximate only and this chart is intended primarily as a guide. Materials thinner than shown in this chart may be tested on the Tukon™ microhardness tester. The thickness of the specimen should be at least 1.5 times the diagonal on the indentation when using the 136 diamond pyramid indenter, and at least ½ times the long diagonal when using the Knoop indenter.

About Conversion Charts (Table 6)

Although conversion tables dealing with hardness can only be approximate, it is of considerable value to be able to compare different hardness scales. This table is based on the assumption that the metal tested is homogeneous to a depth several times as great as the depth of the indentation.

The indentation hardness values measured on the various scales depend on the work hardening behavior of the material during the test, and this in turn depends on the degree of previous cold working of the material. The B-scale relationships in the table are based largely on annealed metals for the low values and cold worked metals for the higher values. Therefore, annealed metals of high scale B-scale hardness, such as austenitic stainless steels, nickels and high nickel alloys, do not conform closely to these general tables. Neither do cold-worked metals of low B-scale hardness, such as aluminum and softer alloys. Special correlations are needed for more exact relationships in these cases. Where applicable, the values are consistent with ASTM E 140 Tables 1 and 2, and ASTM A 370 Tables 3A and 3B. All other conversions shown, including the microficial number values, were developed in the Wilson® Instruments standards library.

Rockwell				Superficial			Vickers	Knoop	Brinell	Tensile Strength	Micro ficial
C	A	D	G	15-N	30-N	45-N	HV	HK	HB	KSI	WMN
150 kg Brale	60 kg Brale	100 kg Brale	150 kg 1/16" ball	15 kg N Brale	30 kg N Brale	45 kg N Brale	10 kg	500 gm & over	3000 kg 10mm ball	1000lbs/ sq. in.	1000 gm
80	92.0	86.5	▲	96.5	92.0	87.0	1865	–	▲	▲	–
79	91.5	85.5		96.3	91.5	86.5	1787	–			–
78	91.0	84.5		96.0	91.0	85.5	1710	–			–
77	90.5	84.0		95.8	90.5	84.5	1633	–			–
76	90.0	83.0		95.5	90.0	83.5	1556	–			–
75	89.5	82.5		95.3	89.0	82.5	1478	–			–
74	89.0	81.5		95.0	88.5	81.5	1400	–			–
73	88.5	81.0		94.8	88.0	80.5	1323	–	NOTE 1	NOTE 2	–
72	88.0	80.0		94.5	87.0	79.5	1245	–			–
71	87.0	79.5		94.3	86.5	78.5	1160	–			–
70	86.5	78.5		94.0	86.0	77.5	1076	972			953
69	86.0	78.0		93.5	85.0	76.5	1004	946			949
68	85.6	76.9		93.2	84.4	75.4	940	920			945
67	85.0	76.1		92.9	83.6	74.2	900	895			942
66	84.5	75.4		92.5	82.8	73.3	865	870	NA		938
65	83.9	74.5		92.2	81.9	72.0	832	846	739		934
64	83.4	73.8		91.8	81.1	71.0	800	822	722		930
63	82.8	73.0		91.4	80.1	69.9	772	799	706		926
62	82.3	72.2		91.1	79.3	68.8	746	776	688		922
61	81.8	71.5		90.7	78.4	67.7	720	754	670		917
60	81.2	70.7		90.2	77.5	66.6	697	732	654	NA	913
59	80.7	69.9		89.8	76.6	65.5	674	710	634	351	909
58	80.1	69.2		89.3	75.7	64.3	653	690	615	338	904
57	79.6	68.5		88.9	74.8	63.2	633	670	595	325	900
56	79.0	67.7		88.3	73.9	62.0	613	650	577	313	896
55	78.5	66.9		87.9	73.0	60.9	595	630	560	301	891
54	78.0	66.1		87.4	72.0	59.8	577	612	543	292	887
53	77.4	65.4		86.9	71.2	58.6	560	594	525	283	883
52	76.8	64.6		86.4	70.2	57.4	544	576	512	273	879
51	76.3	63.8		85.9	69.4	56.1	528	558	496	264	874
50	75.9	63.1		85.5	68.5	55.0	513	542	481	255	870
49	75.2	62.1		85.0	67.6	53.8	498	526	469	246	865
48	74.7	61.4		84.5	66.7	52.5	484	510	455	238	861
47	74.1	60.8		83.9	65.8	51.4	471	495	443	229	856
46	73.6	60.0		83.5	64.8	50.3	458	480	432	221	851
45	73.1	59.2		83.0	64.0	49.0	446	466	421	215	847
44	72.5	58.5		82.5	63.1	47.8	434	452	409	208	842
43	72.0	57.7		82.0	62.2	46.7	423	438	400	201	837
42	71.5	56.9		81.5	61.3	45.5	412	426	390	194	832
41	70.9	56.2		80.9	60.4	44.3	402	414	381	188	827
40	70.4	55.4		80.4	59.5	43.1	392	402	371	182	822
39	69.9	54.6		79.9	58.6	41.9	382	391	362	177	817
38	69.4	53.8		79.4	57.7	40.8	372	380	353	171	812
37	68.9	53.1		78.8	56.8	39.6	363	370	344	166	807
36	68.4	52.3		78.3	55.9	38.4	354	360	336	161	802
35	67.9	51.5		77.7	55.0	37.2	345	351	327	156	798
34	67.4	50.8		77.2	54.2	36.1	336	342	319	152	793
33	66.8	50.0		76.6	53.3	34.9	327	334	311	149	788
32	66.3	49.2		76.1	52.1	33.7	318	326	301	146	783
31	65.8	48.4	NA	75.6	51.3	32.5	310	318	294	141	778
30	65.3	47.7	92.0	75.0	50.4	31.3	302	311	286	138	773
29	64.6	47.0	91.0	74.5	49.5	30.1	294	304	279	135	768
28	64.3	46.1	90.0	73.9	48.6	28.9	286	297	271	131	762
27	63.8	45.2	89.0	73.3	47.7	27.8	279	290	264	128	757
26	63.3	44.6	88.0	72.8	46.8	26.7	272	284	258	125	751
25	62.8	43.8	87.0	72.2	45.9	25.5	266	278	253	123	746
24	62.4	43.1	86.0	71.6	45.0	24.3	260	272	247	119	741
23	62.0	42.1	84.5	71.0	44.0	23.1	254	266	243	117	736
22	61.5	41.6	83.5	70.5	43.2	22.0	248	261	237	115	730
21	61.0	40.9	82.5	69.9	42.3	20.7	243	256	231	112	725
20	60.5	40.1	81.0	69.4	41.5	19.6	238	251	226	110	720

▲
Table 6: Conversion charts
Note 1: A 10 mm steel ball is used for 450 BHN and below.
A 10 mm carbide ball is used above 450 BHN.

Note 2: The tensile strength relation to hardness is inexact, even for steel, unless it is determined for a specific material.

The values shown are approximate only and these charts are intended primarily as a reference guide.

Scales C, D, A

Brale **Diamond Indenter**
Diameter of specimen - inches (mm)

Observed Reading	1/8 (3.2)	1/4 (6.4)	3/8 (10)	1/2 (13)	5/8 (16)	3/4 (19)	7/8 (22)	1 (25)	1-1/4 (32)	1-1/2 (38)
90	NA	0.5	0	0	0	0	0	0	0	0
85		0.5	0.5	0.5	0	0	0	0	0	0
80		0.5	0.5	0.5	0.5	0.5	0	0	0	0
75		1.0	0.5	0.5	0.5	0.5	0.5	0	0	0
70		1.0	1.0	0.5	0.5	0.5	0.5	0.5	0	0
65		1.5	1.0	1.0	0.5	0.5	0.5	0.5	0	0
60		1.5	1.0	1.0	0.5	0.5	0.5	0.5	0	0
55		2.0	1.5	1.0	1.0	0.5	0.5	0.5	0.5	0
50		2.5	2.0	1.5	1.0	1.0	0.5	0.5	0.5	0.5
45		3.0	2.0	1.5	1.0	1.0	1.0	0.5	0.5	0.5
40		3.5	2.5	2.0	1.5	1.0	1.0	1.0	0.5	0.5
35		4.0	3.0	2.0	1.5	1.5	1.0	1.0	0.5	0.5
30		5.0	3.5	2.5	2.0	1.5	1.5	1.0	1.0	0.5
25		5.5	4.0	3.0	2.5	2.0	1.5	1.0	1.0	1.0
20	▼	6.0	4.5	3.5	2.5	2.0	1.5	1.5	1.0	1.0

Scales B, F, G

1/16" Ball Indenter
Diameter of specimen - inches (mm)

Observed Reading	1/8 (3.2)	1/4 (6.4)	3/8 (10)	1/2 (13)	5/8 (16)	3/4 (19)	7/8 (22)	1 (25)	1-1/4 (32)	1-1/2 (38)
100	NA	3.5	2.5	1.5	1.5	1.0	1.0	0.5	NA	NA
90		4.0	3.0	2.0	1.5	1.5	1.5	1.0		
80		5.0	3.5	2.5	2.0	1.5	1.5	1.5		
70		6.0	4.0	3.0	2.5	2.0	2.0	1.5		
60		7.0	5.0	3.5	3.0	2.5	2.0	2.0		
50		8.0	5.5	4.0	3.5	3.0	2.5	2.0		
40		9.0	6.0	4.5	4.0	3.0	2.5	2.5		
30		10.0	6.5	5.0	4.5	3.5	3.0	2.5		
20		11.0	7.5	5.5	4.5	4.0	3.5	3.0		
10		12.0	8.0	6.0	5.0	4.0	3.5	3.0		
0	▼	12.5	8.5	6.5	5.5	4.5	3.5	3.0	▼	▼

Scales 15-N, 30-N, 45-N

N Brale **Diamond Indenter**
Diameter of specimen - inches (mm)

Observed Reading	1/8 (3.2)	1/4 (6.4)	3/8 (10)	1/2 (13)	5/8 (16)	3/4 (19)	7/8 (22)	1 (25)	1-1/4 (32)	1-1/2 (38)
90	0	0	0	0	0	0	0	0	NA	NA
85	0.5	0.5	0.5	0.5	0	0	0	0		
80	1.0	0.5	0.5	0.5	0.5	0	0	0		
75	1.5	1.0	0.5	0.5	0.5	0.5	0	0		
70	2.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5		
65	2.5	1.5	1.0	0.5	0.5	0.5	0.5	0.5		
60	3.0	1.5	1.0	1.0	1.0	0.5	0.5	0.5		
55	3.5	2.0	1.5	1.0	1.0	0.5	0.5	0.5		
50	3.5	2.0	1.5	1.0	1.0	1.0	1.0	0.5		
45	4.0	2.0	1.5	1.0	1.0	1.0	1.0	1.0		
40	4.5	2.5	1.5	1.5	1.0	1.0	1.0	1.0		
35	5.0	2.5	2.0	1.5	1.0	1.0	1.0	1.0		
30	5.5	3.0	2.0	1.5	1.5	1.0	1.0	1.0		
25	5.5	3.0	2.0	1.5	1.5	1.5	1.5	1.0		
20	6.0	3.0	2.0	1.5	1.5	1.5	1.5	1.5	▼	▼

Scales 15-T, 30-T, 45-T

1/16" Ball Indenter
Diameter of specimen - inches (mm)

Observed Reading	1/8 (3.2)	1/4 (6.4)	3/8 (10)	1/2 (13)	5/8 (16)	3/4 (19)	7/8 (22)	1 (25)	1-1/4 (32)	1-1/2 (38)
90	1.5	1.0	1.0	0.5	0.5	0.5	0.5	0.5	NA	NA
80	3.0	2.0	1.5	1.5	1.0	1.0	1.0	0.5		
70	5.0	3.5	2.5	2.0	1.5	1.0	1.0	1.0		
60	6.5	4.5	3.0	2.5	2.0	1.5	1.5	1.5		
50	8.5	5.5	4.0	3.0	2.5	2.0	2.0	1.5		
40	10.0	6.5	4.5	3.5	3.0	2.5	2.0	2.0		
30	11.5	7.5	5.0	3.5	3.5	2.5	2.0	2.0		
20	13.0	9.0	6.0	4.5	4.5	3.0	2.0	2.0	▼	▼

Cylindrical work for correction to be added to observed Rockwell number for scales indicated.

These corrections are approximated only and represent the averages to the nearest ½ Rockwell number.

Rockwell							Superficial			Knoop	Brinell	Brinell 10mm Vickers136°	Tensile Strength	Microficial
B	F	G	A	E	H	K	15-T	30-T	45-T	HK	HB	HB/HV	KSI	WMN
100 kg 1/16" ball	60 kg 1/16" ball	150 kg 1/16" ball	60 kg Brale	100 kg 1/8" ball	60 kg 1/8" ball	150 kg 1/8" ball	15 kg 1/16" ball	30 kg 1/16" ball	45 kg 1/16" ball	500 gm & over	500 kg 10mm ball	3000 kg 10kg	1000lbs/ sq. in.	1000 gm
100	▲	82.5	61.5	▲	▲	▲	93.1	83.1	72.9	251	201	240	116	730
99		81.0	60.9				92.8	82.5	71.9	246	195	234	114	725
98		79.0	60.2				92.5	81.8	70.9	241	189	228	109	719
97		77.5	59.5				92.1	81.1	69.9	236	184	222	104	713
96		76.0	58.9				91.8	80.4	68.9	231	179	216	102	707
95		74.0	58.3				91.5	79.8	67.9	226	175	210	100	701
94		72.5	57.6				91.2	79.1	66.9	221	171	205	98	696
93		71.0	57.0			NA	90.8	78.4	65.9	216	167	200	94	690
92		69.0	56.4			100	90.5	77.8	64.8	211	163	195	92	684
91		67.5	55.8			99.5	90.2	77.1	63.8	206	160	190	90	679
90		66.0	55.2			98.5	89.9	76.4	62.8	201	157	185	89	674
89		64.0	54.6			98.0	89.5	75.8	61.8	196	154	180	88	668
88		62.5	54.0			97.0	89.2	75.1	60.8	192	151	176	86	662
87		61.0	53.4			96.5	88.9	74.4	59.8	188	148	172	84	656
86		59.0	52.8			95.5	88.6	73.8	58.8	184	145	169	83	651
85		57.5	52.3			94.5	88.2	73.1	57.8	180	142	165	82	646
84		56.0	51.7			94.0	87.9	72.4	56.8	176	140	162	81	640
83		54.0	51.1			93.0	87.6	71.8	55.8	173	137	159	80	634
82		52.5	50.6			92.0	87.3	71.1	54.8	170	135	156	77	629
81		51.0	50.0			91.0	86.9	70.4	53.8	167	133	153	73	624
80		49.0	49.5			90.5	86.6	69.7	52.8	164	130	150	72	618
79		47.5	48.9			89.5	86.3	69.1	51.8	161	128	147	70	612
78		46.0	48.4			88.5	86.0	68.4	50.8	158	126	144	69	607
77		44.0	47.9			88.0	85.6	67.7	49.8	155	124	141	68	602
76	NA	42.5	47.3			87.0	85.3	67.1	48.8	152	122	139	67	596
75	99.6	41.0	46.8			86.0	85.0	66.4	47.8	150	120	137	66	592
74	99.1	39.0	46.3			85.0	84.7	65.7	46.8	147	118	135	65	587
73	98.5	37.5	45.8			84.5	84.3	65.1	45.8	145	116	132	64	581
72	98.0	36.0	45.3	NA		83.5	84.0	64.4	44.8	143	114	130	63	576
71	97.4	34.5	44.8	100		82.5	83.7	63.7	43.8	141	112	127	62	571
70	96.8	32.5	44.3	99.5		81.5	83.4	63.1	42.8	139	110	125	61	566
69	96.2	31.0	43.8	99.0		81.0	83.0	62.4	41.8	137	109	123	60	561
68	95.6	29.5	43.3	98.0		80.0	82.7	61.7	40.8	135	107	121	59	556
67	95.1	28.0	42.8	97.5		79.0	82.4	61.0	39.8	133	106	119	58	551
66	94.5	26.5	42.3	97.0		78.0	82.1	60.4	38.7	131	104	117	57	546
65	93.9	25.0	41.8	96.0		77.5	81.8	59.7	37.7	129	102	116	56	542
64	93.4	23.5	41.4	95.5		76.5	81.4	59.0	36.7	127	101	114	NA	537
63	92.8	22.0	40.9	95.0		75.5	81.1	58.4	35.7	125	99	112		532
62	92.2	20.5	40.4	94.5		74.5	80.8	57.7	34.7	124	98	110		527
61	91.7	19.0	40.0	93.5		74.0	80.5	57.0	33.7	122	96	108		522
60	91.1	17.5	39.5	93.0		73.0	80.1	56.4	32.7	120	95	107		517
59	90.5	16.0	39.0	92.5		72.0	79.8	55.7	31.7	118	94	106		512
58	90.0	14.5	38.6	92.0		71.0	79.5	55.0	30.7	117	92	104		507
57	89.4	13.0	38.1	91.0		70.5	79.2	54.4	29.7	115	91	103		502
56	88.8	11.5	37.7	90.5		69.5	78.8	53.7	28.7	114	90	101		497
55	88.2	10.0	37.2	90.0		68.5	78.5	53.0	27.7	112	89	100		492
54	87.7	8.5	36.8	89.5		68.0	78.2	52.4	26.7	111	87	NA		487
53	87.1	7.0	36.3	89.0		67.0	77.9	51.7	25.7	110	86			482
52	86.5	5.5	35.9	88.0		66.0	77.5	51.0	24.7	109	85			477
51	86.0	4.0	35.5	87.5		65.0	77.2	50.3	23.7	108	84			472
50	85.4	2.5	35.0	87.0		64.5	76.9	49.7	22.7	107	83			468
49	84.8	NA	34.6	86.5		63.5	76.6	49.0	21.7	106	82			463
48	84.3		34.1	85.5		62.5	76.2	48.3	20.7	105	81			458
47	83.7		33.7	85.0		61.5	75.9	47.7	19.7	104	80			453
46	83.1		33.3	84.5		61.0	75.6	47.0	18.7	103	80			448
45	82.6		32.9	84.0		60.0	75.3	46.3	17.7	102	79			444
44	82.0		32.4	83.5		59.0	74.9	45.7	16.7	101	78			439
43	81.4		32.0	82.5		58.0	74.6	45.0	15.7	100	77			435
42	80.8		31.6	82.0		57.5	74.3	44.3	14.7	99	76			430
41	80.3		31.2	81.5		56.5	74.0	43.7	13.6	98	75			426
40	79.7		30.7	81.0		55.5	73.6	43.0	12.6	97	75			422
39	79.1		30.3	80.0		54.5	73.3	42.3	11.6	96	74			417
38	78.6		29.9	79.5		54.0	73.0	41.6	10.6	95	73			413
37	78.0		29.5	79.0	NA	53.0	72.7	41.0	9.6	94	72			409
36	77.4		29.1	78.5	100	52.0	72.3	40.3	8.6	93	72			404
35	76.9		28.7	78.0	99.5	51.5	72.0	39.6	7.6	92	71			401
34	76.3		28.2	77.0	99.0	50.5	71.7	39.0	6.6	91	70			396
33	75.7		27.8	76.5	98.8	49.5	71.4	38.3	5.6	90	69			392
32	75.2		27.4	76.0	98.5	48.5	71.0	37.6	4.6	89	69			388
31	74.6		27.0	75.5	98.0	48.0	70.7	37.0	3.6	88	68			384
30	74.0		26.6	75.0	97.8	47.0	70.4	36.3	2.6	87	67		NOTE 2	380
29	73.5		26.0	74.0	97.5	46.0	70.0	35.6	1.0	87	66			376
28	73.0		25.5	73.5	97.0	45.0	69.3	34.5	NA	86	66			372
27	72.5		25.0	73.0	96.5	44.5	69.5	34.0		85	65			369
26	72.0		24.5	72.5	96.3	43.5	69.0	33.0		84	65			365
25	71.0		24.3	72.0	96.0	42.5	68.8	32.5		83	64			361
24	70.5		24.0	71.0	95.5	41.5	68.5	32.0		82	64			357
23	70.0		23.5	70.5	95.3	41.0	68.0	31.0		82	63			353
22	69.5		23.0	70.0	95.0	40.0	67.8	30.5		81	62			350
21	69.0		22.5	69.5	94.5	39.0	67.5	29.5		81	62			346
20	68.5		22.0	68.5	94.3	38.0	67.3	29.0		80	61			343
19	68.0		21.5	68.0	94.0	37.5	67.0	28.5		79	61			339
18	67.0		21.3	67.5	93.5	36.5	66.5	27.5		78	60			335
17	66.5		21.0	67.0	93.0	35.5	66.3	27.0		78	60			332
16	66.0		20.5	66.5	92.8	35.0	66.0	26.0		77	59			329
15	65.5		20.0	65.5	92.5	34.0	65.5	25.5		76	59			325
14	65.0		NA	65.0	92.0	33.0	65.3	25.0		75	59			322
13	64.5			64.5	91.8	32.0	65.0	24.0		75	58			318
12	64.0			64.0	91.5	31.5	64.5	23.5		74	58			314
11	63.5			63.5	91.0	30.5	64.3	23.0		73	57			311
10	63.0			62.5	90.5	29.5	64.0	22.0		72	57			308
9	62.0			62.0	90.3	29.0	63.8	21.5		71	57			304
8	61.5			61.5	90.0	28.0	63.5	20.5		71	56			300
7	61.0			61.0	89.5	27.0	63.0	20.0		70	56			297
6	60.5			60.5	89.3	26.0	62.8	19.5		69	55			293
5	60.0			60.0	89.0	25.5	62.5	18.5		69	55			289
4	59.5			59.0	88.5	24.5	62.0	18.0		69	55			286
3	59.0			58.5	88.0	23.5	61.8	17.0		68	54			283
2	58.0			58.0	87.8	23.0	61.5	16.5		68	54			279
1	57.5			57.5	87.5	22.0	61.0	16.0		63	54			276
0	57.0	▼	▼	57.0	87.0	21.0	60.5	15.0	▼	63	53	▼	▼	272

▲
Table 7: Cylindrical corrrection chart 53.

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