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PRACTICAL APPROACH TOWARDS ENHANCED ACCURACY WITH FIELD HARDNESS MEASUREMENTS

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ABSTRACT

Hardness, Strength and Ductility are the most important material physical properties which are interrelated. Generally, hardness can be readily measured and it is directly proportional to Strength and inversely to the Ductility. Hardness simply is a measure of the resistance to deformation or penetration. It is well understood that hardness measurement / verification plays a vital role, not only during the normal Quality Control (QC) checks but more importantly during metallurgical failure investigation process, as hardness virtually speaks a lot about material properties.

The very first scientific attempt in hardness measurements was comparing the object hardness against a set of selected stones with varied surface hardness. Currently, there are several established techniques to assess metal hardness both in laboratories and in the field, and also in both micro and macro ranges. The hardness is measured in several different Units, characteristic to each measuring technique, and hence, no single unit can be universally adopted. Thus the hardness conversion charts and/or factors become very essential information for comparison purpose.

Most of the modern field hardness gauges employ bouncing ball methodology to measure the metal’s macro hardness and the manufacturer provided Conversion Charts are made available or Conversion Logics are Built-in to the Instrument Display Units. These factory-established Conversions are based on the laboratory conditions and can vary widely with the site-specific conditions as to Surface Preparations, Object Thickness, Curvature, Testing Positions and Operator Skills. Due to this reason, the validity of factory-established conversions had been in question among majority of the field-users of these Instruments. In many occasions, the alternative methods have had shown significant differences in the equivalent (converted) value of the measured hardness.

Realizing the importance of the accuracy of this critical material property measurement and driven by the consistently noted significant differences between equivalent (converted) hardness values obtained from different test-methods, a practical study / research was conducted by Saudi Aramco Mobil Refinery (SAMREF), aimed at assessing the accuracy of the currently available field Hardness measurement instruments as well as establishing a reasonable "**Correction Factor**" for these instruments in reference to the Laboratory equipment. This paper, therefore, presents the step-by-step practical approach followed in conducting the subject study, also, it shares the achieved results as well as the drawn conclusions.

1.0 INTRODUCTION

Hardness, Strength, & Ductility are the most important physical properties of metals. These properties are related to each other. Generally, when Hardness and Strength increases, the ductility decreases (thus increasing brittleness). Hardness can be readily measured and generally, is directly proportional to strength and, inversely proportional to ductility and toughness[1]. *However, lately it was discovered that addition of certain alloying elements in right quantities helped improving the strength and hardness without a significant sacrifice in ductility& toughness.*

Hardness is a measure of the resistance to deformation or a measure of resistance to penetration. These definitions represent the resistance of metal surface to be damaged, dented, worn away, or deteriorated against a mechanical force.

The very first scientific attempt in hardness measurements was comparing the object hardness against a set of selected stones with varied surface hardness. This qualitative method, Moh's Scale Hardness Testing, is still used among Geologists. It is similar to File Hardness that triggers materials harder or softer than the normal file. The most of the other established testing procedures makes a dent or a cut on the metal surface using a penetrator or a pointer and then the resulting damage, either the depth or the width of the penetration, is measured as the data representing the material hardness.

The modern field hardness gauges employ bouncing balls thus quantifying the reduction in bouncing velocity which will then be translated in to a hardness value. Also, with the Sonodur Method, the hardness effect on resonance vibration of a standard rod in tight contact against the test object is quantified and utilized to measure hardness. In general, two (2) categories of hardness measurement techniques are used in the industry, namely, Macro-Hardness and Micro-Hardness. More details on each type is provided in the next section. There are nine (9) established techniques to measure steel hardness namely, Rockwell, Rockwell Superficial, Brinell, File, Shore Scleroscope, Vickers, Knoop, Sonodur, and Mohs Scale Hardness Testing Methods. These techniques utilize different approaches to measure a representative parameter/property that can be translated in to Brinell or Rockwell Values. In this regard, Hardness Conversion Charts are very essential information.

As stated earlier, the purpose of this paper is to assess the accuracy of the currently available field Hardness measurement instruments as well as establishing a reasonable "**Correction Factor**" for these instruments in reference to the Laboratory equipment. Also, it shares the achieved results as well as the drawn conclusions. The methodology that was followed in conducting this study is spilled out in section 6.0. The prior sections, however, covered hardness measurements categories and shed some lights on the basic techniques that are used for each category with some examples. Also, units of hardness measurements were covered in a separate section of this paper. Moreover, the typical applications and the methods of hardness measurements in SAMREF were among the subjects that were covered in the paper. At the end, the paper offered the final conclusions based on the data analysis results.

2.0 HARDNESS MEASUREMENT METHODS

2.1 Macro Hardness:

In the Macro-hardness measurement method, relatively large indentations are made using a penetrator and therefore, the received material response is the average response from that larger contour (large number of grains). This large indentation method is not suitable for delicate objects as it makes a relatively large impression. For example, the Brinell Macro Hardness Value will be computed using the following formula:

$$\text{Brinell Hardness BHN} = \text{Load F (kg)} / \text{Surface Area (mm}^2) = 2F/(\pi D(D-(D^2-d^2)^{1/2})$$

Where
D = Ball Penetrator Diameter

d = diameter of the impression on the test surface.

Among the various available hardness measurement methods, three (3) basic measurement techniques are used to measure Macro-hardness.

- ***Penetration hardness***: Very accurate measuring technique in which the Penetrator is forced against the metal sample. The size of the impression is measured and then translated (converted) in to the hardness number. The technique is straightforward and hence, the operator dependency is relatively low. Rockwell, Rockwell Superficial, and Tele-brinellar Hardness are examples of this technique.

- ***Bouncing Velocity Method***: An impact body with a special test tip is impelled by spring force against a test surface from which it rebounds. The ratio between rebound velocity and impact velocity is a measure of the hardness. Examples of this method include Shore Scleroscope and Equotip.

- ***The Resonant Frequency Method:*** The resonant frequency of a 0.75 mm diameter diamond tipped magnetostrictive rod that is held in contact with the test surface was noted varying with the macro hardness value of the test part. This is a latest development producing very accurate results. Sonodur is an example for this method.

2.2 Micro Hardness:

In this method, small loads and sharply pointed penetrators are used, in which they make very small indentations, thus, encompassing relatively minute areas. This approach will pick any localized hardness differences particularly in the mostly stressed areas such as Weld Heat Affected Zone (HAZ). The Micro-hardness is calculated as per the following formula:

Diamond Pyramid Hardness DPH = Load F (kg) / Surface Area (mm^2) = $1.85\ F/t^2$

Where
t = diagonal length of indentation on the test surface

The only method used to measure micro-hardness is through penetration. A very small indentation is made with a diamond tipped penetrator under very low loads (up to 50 kg with Vickers and 4 kg with Knoop). The diagonal of the square-based pyramidal indentation is measured using a microscope to convert in to micro-hardness of the tested area. Examples of micro hardness include Vickers & Knoop.

Notes:
See Appendix-A for further guidelines in Hardness Measurements
See Appendix-B for Comparison between Various Hardness Testing Methods

3.0 UNITS OF HARDNESS MEASUREMENTS

Hardness is measured in many different units. To date, no single unit is universally adopted. Instead each type of instrument tends to have its own units. Therefore, many conversion charts are required to convert the units of one testing method to those of another hardness scale. Namely,

- Rockwell number R_C (Depends on the Penetrator Shape & Load; Nine (9) numbers are defined with the suffix A – H & K)
- Rockwell Superficial Hardness 15N (or 30-T)
- BHN Brinell Hardness Number
- Shore Units
- DPH (Diamond Pyramid Hardness) for Vickers

4.0 TYPICAL APPLICATIONS OF HARDNESS MEASUREMENTS IN SAMREF

Similar to any other industry, Samref has also specific applications where hardness measurements are used to assure the required material and work quality. Other than routine and mandatory applications, hardness monitoring is basically a technical judgment call by the Inspection Engineer. The hardness values may also speak a lot in case of metallurgical failure analysis.

The following are some of the Routine and /or Mandatory stages where Hardness Measurement is utilized:

4.1 Hardness Measurements at Material Receiving Point

- On A 105 Flanges on random basis (if MTC does not show the hardness result). As per ASTM Standard and under Supplementary Requirements the flange hardness shall be between 137 -187 HB.
- On A 193 –B7M Material (Low strength bolting can only be distinguished utilizing hardness – 235 HB max)
- On all Austenitic SS Bolts (Max hardness varies between 192 – 321 HB with type of heat treatment)
- On Gaskets (for specified maximum).
- To verify Case Hardened or Hard faced Areas
- Hardness checks along with PMI could be helpful to identify items with no clear stamp.

4.2 Hardness Measurements During Welding / Fabrication

Micro-hardness measurements on the weld HAZ and weld cross section are mandatory on Weld Procedure Qualification Test Specimens.

- Representative for all low alloy steel fabrications (1 1/4 Cr – 9 Cr Steels) after PWHT (Max hardness allowed 225 – 241 HB).

- All Carbon Steel welds and HAZ in H2S, Amine, Caustic and HF Services. Weld joints/HAZ exceeding a measured macro hardness of 200 HB will need stress relieving. Hardness checks should be performed even after PWHT when required.

- For the Martensitic stainless steels (11-13 % Cr), when hardened above certain level they are subjected to hydrogen assisted cracking (HAC).Therefore hardness value is critical for those metals depending on the operating temperature.

4.3 Hardness Measurements For in Service Equipment

- Hardness is one of the key data required during any failure investigation.

- In the process heaters periodic hardness checks are performed on tubes to evaluate the effects of potential overheating/ flame impingement.

In a nutshell, accurate hardness result is extremely important element especially during any failure investigations process. With the new Risk Based Approach, a simple hardness reading would help establishing right and optimum strategy for certain equipment components as hardness, virtually provides valuable insights about material properties.

5.0 HARDNESS MEASUREMENT METHODS USED IN SAMREF

At SAMREF, only Macro Hardness instruments are used for Hardness measurements. SAMREF possesses the following hardness testing equipment:

1. **Tele Brinellar equipment.**

The Tele Brinellar is a portable equipment that leaves a small impression on the test surface. It is difficult to use on short radius curved surfaces and on relatively thin sections. Careful and precise applications can produce very accurate results comparable with the macro-measurements in the bench tester. See Appendix A for Useful Hints for effective usage of Tele-Briellar.

2. **Rockwell Hardness Tester (Bench).**
Rockwell Hardness (Misawa Seiki) Tester is the most accurate equipment in Samref's possession but its application is limited to laboratory tests. However, Rockwell hardness tester can be used as the periodic comparator/ reference for the accuracy of other two methods. *The Rockwell hardness method eliminates the effects of surface imperfections by applying a preliminary minor load to the sample before the hardness is measured.*

3. Equotip Hardness Tester (Field Tester)
Equotip equipment is a portable and field-friendly, and create no impression on the object surface. The technique is best used in flat positions with the probe in vertical positions.

6.0 FIELD HARDNESS MEASUREMENTS STUDY METHODOLOGY

As mentioned earlier, realizing the importance of obtaining accurate hardness results, especially for material intended in critical applications or during failure investigation process, and driven by the consistently noted significant differences between equipment hardness values obtained via different test methods, the need for this study has become a very obvious necessity for SAMREF.

6.1 Study Objectives
6.2

The objective of this study is to assess the accuracy of the currently available field hardness measurement instruments at SAMREF as well as establishing a reasonable "**Correction Factor**" for these instruments in reference to the laboratory equipment.

In fact, assessing the accuracy of Equotip & Tele-brinellar Hardness Measurement Methods is an important step towards improving the Hardness Measurement Skills within SAMREF Inspection Group. In this regard, a series of hardness tests were conducted aimed at establishing reasonable "Corrective Factors" for both field instruments, Equotip and Tele-Brinellar Testers in reference to the Rockwell Tester in the metallurgy Laboratory.

6.3 Study Scope

In general, the study scope called for performing sets of field hardness measurements on prepared test specimens, using three different measurements methods:

- Equotip Instruments
- Tele Brinellar Equipment
- Rockwell Hardness Tester

These test specimens were prepared taking into account two main variables which are,

- Radius of curvature of the test surface and
- Thickness of the specimens

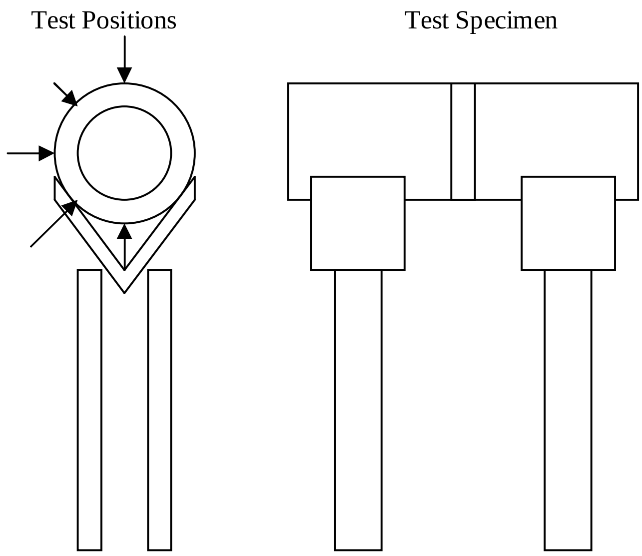
Another variable was also considered, only for Euotip instrument, which is the test position. Noted is that the surface preparation as a variable was maintained the same for all test specimens.

6.3.1 Specimens Preparation

6.3.1.1 The following pipe specimens (1 foot long) with a middle groove weld were prepared to satisfy the main two variable as mentioned above

- 2” Sch 40, 80 and 160 (3 –Specimens)
- 4” Sch 40, 80 and 160 (3 –Specimens)
- 6” Sch 40 and 80 (2 –Specimens)

6.3.1.2 Five (5) test positions were selected as shown in the sketch below to satisfy the Equotip instrument requirements.



6.3.1.3 The Surface Preparation (Variable 4) was maintained same for all applications. An area equal to ½” to ¾” was ground smoothly to make a flat surface as the test points. The test-specimens were mounted freely on anvils as shown above a coupling paste was then applied for all the contact points to avoid flexing.

6.3.2 <u>Hardness Testing Procedure</u>

6.3.2.1 The first set of hardness readings were recorded using the Equotip Hardness Tester on all five (5) positions for eight (8) test specimens

- PROCEQ SA
- Equotip Model Vers.1.16
- Serial Number 716-1372
- Probe Model - D15
- Calibrated on 2003.12.27

Measuring Units - L-Number & Converted to Brinell number using the Equoptip Library.

6.3.2.2 The second set of readings, on the same locations was recorded using the bench-mounted Rockwell Hardness Tester.

- Manufacturer –Misawa Seiki
- Serial Number MFD 9528
- Calibrated – 2 R_B on Block # 92.5 HRB

Measuring Units – Rockwell B Scale & Converted to Brinell Number using the Chart.

6.3.2.3 The third set of readings, on the same locations was recorded using the Tele-Brineller Hardness Tester.

- Manufacturer - Tele Weld
- Calibrated on 182 HB & 217 HB Bars

Measuring Units – Brinell hardness

6.3.2.4 In this experiment, 36 to 58 spot readings were recorded for one specimen using the Equotip Tester. With the basis of one spot reading being averaged from minimum three readings, a total of 108 to 174 readings were obtained for a single test-part. Impact from a previous dent was avoided to an extent required to achieve a good representative result

6.3.2.5 When measuring with the Rockwell Tester, each reading was averaged from minimum 5 spots and increasing up to about 17 spots maximum, depending on the range of readings, to minimize the error. The Rockwell bench tester readings were adjusted using the average error obtained with standard calibration block (2 -3 R_B)

6.3.2.6 The Tele-brineller Method was used to record only one (1) reading per spot (total 5-reading/specimen).

7.0 STUDY DATA ANALYSIS AND DISCUSSION

The study data is tabulated in Attachment # 1 – x. The principal objective of the study was to capture the patterns of Equotip & Tele-brinellar Reading deviations in relation to the absolute hardness. Nevertheless, with the available facilities, Rockwell Tester readings with the Zero Correction (2 -3 R_B) were treated as the base reference which is assumed most close to the absolute value.

Field Hardness Results are normally affected by thickness, mass, surface finish, and strength of materials. Obtained results were scrutinized against many parameters. Nevertheless, most interested behavior was seen against the test-specimen thickness. Hence, the following Analytical Strategy was adopted and the collected data was collated in the following sequence:

7.1 Calculate the average Equotip Hardness for each test position (Use converted Brinell number).

7.2 Calculate the average Rockwell Hardness around the same location (convert to Brinell number using Chart).

7.3 Calculate the average Tele-brinellar Hardness in each location.

7.4 Calculate the Equotip (average) Reading Deviation with respect to average Rockwell Hardness.

7.5 Calculate the Tele-brineller (average) Reading Deviation with respect to average Rockwell Hardness.

7.6 Plot Equotip & Tele-brineller Reading Deviations over Rockwell Readings against the test piece thickness.

7.7 Also the Equotip Reading Deviation over Rockwell was plotted against Test Position (see Graph # 10).

As illustrated by the Curves # 1 through 8, the difference between the average Equotip hardness value and the average Rock Well Tester hardness value (the deviation) increases with the decrease of pipe schedule. This difference is around 40-60 HB when the specimen thickness is below 8.5mm.When thickness increases beyond 8.5mm the difference decreases but it will not diminish as expected. The overall error remains almost constant (30 HB) after about 10.5mm thickness. (See the graph # 9).

Also Equotip readings are affected by the impact direction. As illustrated in the Graph # 10, the lowest average error was reported on the down hand position. This can be explained with the primary design direction, minimum operator error, and good contact with surface as well as relative easiness of holding the probe. Also this direction allows impact and repulsing action along the centre of gravity of the probe.

From the collected data, it was noted that, each hardness measurement process produces a different system-related parameter and hence, the measuring units, can be various. This eventually requires each process to have a specific hardness scale based on each parameter (or units of measurement). For example, the Brinell hardness is not directly measured by Equotip and it is converted from non dimensional "L" hardness value to dimensional "HB" hardness. These conversions can result in inaccurate results. Also Equotip readings highly depend on surface finish and the straightness with the contacting surface. As Equotip results are also affected by thickness and the mass, finally it will result in a significant error. The research study has very clearly shown that Equotip method is not producing a comparative reading with Rockwell Macro Hardness. The study output statistics were used to predict imperial correction factors for the measured range of hardness values with most common Carbon Steel applications. Also note that, in this experiment the probe # D+15 was used as it is widely used in Samref. Also pipe specimens were used as it is the most common objects of which hardness checking is required. But for the other probes (D probe) and other objects (Plates) these figures can be slightly different.

The mechanism in both Tele-brineller (Field) and Rockwell (Laboratory) Hardness Measurements is identical except the impression size. The Tele-brinellar makes a larger (preferably 3.0 mm dia) diameter impression where the Rockwell Impression is hardly visible. With this fact Tele-brinellar hardness value becomes more generalized (averaged) over a larger domain in comparison to a relatively localized region under the Rockwell impression. Generally, the average of a larger domain should read relatively less hardness. The other reason that counts negative on Tele-brinellar technique is the possible Operator Error during the Punching (out of roundness of impressions) and microscopic reading errors. However, provided that:

- The right Reference Bar is selected (recommended within ±15 HB from the work hardness)
- The impression size is managed around 3.0 mm and round

The Tele-brinellar can be used very effectively within only ±5% deviation from the absolute hardness. The research work has proved this fact registering an average deviation on the Tele-brinellar result over Rockwell Result within this range.

8.0 CONCLUSIONS

The subject Research Study has concluded the following:

1. The Equotip Field Test Method significantly under-reads the actual macro-hardness of the test spots irrespective of test part thickness, test position or part configuration.

2. Equotip Readings will require positive (+ve) correction of 40 to 60 HB for test-part thicknesses below 8.5 mm. The exact correction for the subject hardness range (175 – 225 HB) can be computed by interpolation or using the Graph # 9. For test part thicknesses equal or in excess of 8.5 mm, add 30HB flat correction

3. The most accurate test position for Equotip Tester is the Vertical Probe Position and Flat Test Part Position.

4. The Tele-brineller Test Method showed very close readings with the Rockwell Tester. The average deviation was within ± 4.5 % and this is anticipated due to

- Differences in the Impression Size & Shape
- Operator errors.

See Graph # 10 for more details on the obtained results.

REFERENCES:

1. ASM Metals Handbook Vol-1 10th Edition
2. Metallurgy Fundamentals by Daniel A. Brandt & J.C. Warner
3. Equipment Manuals (Equotip, Rockwell & Tele Brinellar)
4. Corrosion of Stain Steel by C.P. Dillon

APPENDIX –A

SOME USEFUL HINTS FOR ACCURATE FIELD HARDNESS MEASUREMENTS

TELE_BRINELLAR TECHNIQUE:

1. Grind flush the test area. If it is the weld cap flush grind it to provide a level surface to place the microscope.
2. Estimate the rough values for the expected hardness (use Equotip to find the close range which is 30-60 HB away from the absolute).
3. Accordingly, select the right reference bar with a marked hardness within ±5 % of the intended measurement.
4. Ensure that approximately 3.0 mm impression is made on the bar.
5. Measure both impressions on the Reference Block and the Test Surface and use Converter Charts for translate the impression reading in to macro-hardness of the test area.

EQUOTIP TECHNIQUE:

Following parameters should be considered to achieve accurate results in measurement hardness from equotip.

Preparation of the Surface

The test location surface finish affects significantly the readings obtained from equotip. The recommended roughness values are given below.

Impact device type	Roughness depth (µm)	Average roughness (µm)
D,DC,D+15,E	10	2
G	30	7
C	2.5	0.4

When preparing the surface, the condition of the material may be affected due to heating or by cold working and the hardness can be affected as well. Excessive surface roughness results in lower hardness values. Cold worked surfaces produces excessively higher values.

Supporting of the Samples During Testing

For heavy samples no special attention is required for supporting. But smaller and lighter work pieces are affected by the impact force and will change the normal repulsive behavior of the surface significantly. Hence smaller, lighter and thin regions of heavy sections create excessively large variations thus resulting very low hardness values. Therefore following precautions need to be taken in supporting the specimens.

- Medium weight, heavy samples with protruded sections or thin walled sections should be placed on a support so that they do not move during the test impact.

- Light weight samples should be rigidly coupled on a thick base plate. A thin layer of coupling paste should be applied to the contact surface of the sample. Then the sample should be pressed against the supporting surface in a circular movement to ensure that there is no metallic contact between parts. To achieve the best results the contact surface of the sample and coupling surface of the supporting surface should be flat, parallel to each other and smooth. Also the direction of the impact should be perpendicular to the coupled surface. Minimum thickness of the sample for coupling is given below.

Type of device	Minimum thickness (mm)
D,DC,D+15,E	3

G	10
C	1

Improper coupling can be identified by a rattling noise upon impact of the test tip.

Curved Surfaces

Minimum radii of curvature recommended for measurements are given below

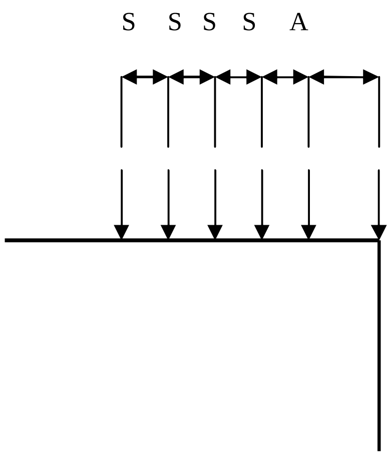
Method	**Basis**	**Penetrator**	**Load**	**Reading Symbol**

Type of device	**Minimum radius of curvature (mm)**
D,DC,D+15,C,E	30
G	50

Hardness Measuring Tips

Following parameters need to be paid attention.

- Each measuring area should be tested with at least 3 impacts
- Do not impact the same point more than once
- Impact should be perpendicular to the surface
- If the range of the readings (R) within the same measuring area exceeds 30, check for the required surface finish and /or the adequate sample support.
- Minimum spaces of the impact points should be as per the table below



Impact device type	S (mm)	A (mm)
D,DC,D+15,E	3	5
C	2	4
G	4	8

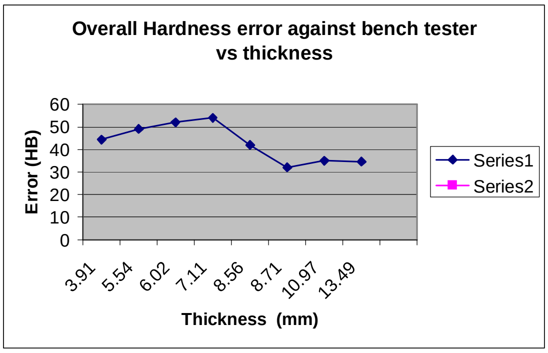
Rockwell	Depth of Penetration	Diamond point 1/16" Ball or 1/8" Ball	60-100-150 kg	R_C etc
Rockwell Superficial	Depth of Penetration	Diamond point 1/16" Ball or 1/8" Ball	15-30-45 kg	15N $30T^{etc}$
Brinell	Area of Penetration	10mm Ball	500-3000 kg	BHN
File	Appearance of Scratch	File	Manual	None
Shore Scleroscope	Height of Bounce	40 Grain Weight	Gravity	Units Shore
Vickers	Area of Penetration	Pyramidal Diamond	5 to 120 kg	DPH
Knoop	Area of Penetration	Pyramidal Diamond	25-3600 grams	Units Knoop
Sonodur	Frequency of Vibration	Magnetostrictive Rod	N.A	BHN
Mohs Scale	Appearance of Scratch	10 Stones	Manual	Units Mohs

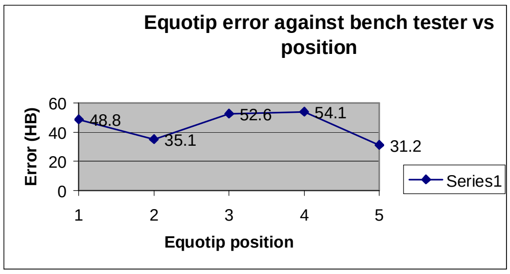
APPENDIX –B

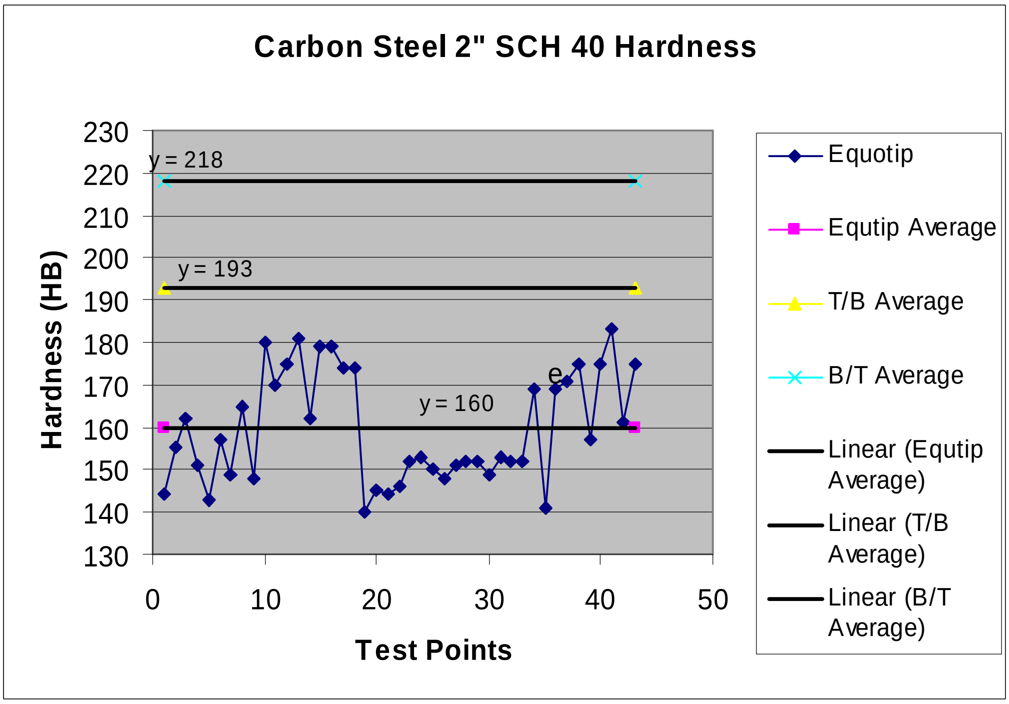
COMPARISON OF VARIOUS HARDNESS MEASURING TECHNIQUES

	Thickness	Error vs bench
2 SCH 40	3.91	44.35
2 SCH 80	5.54	49
4 SCH 40	6.02	52
6 SCH 40	7.11	54
4 SCH 80	8.56	42
2 SCH 160	8.71	32
6 SCH 80	10.97	35
4 SCH160	13.49	34.6

Size	Position		Error
	↑	1	48.8
2"	↗	2	35.1
	→	3	52.6
	↘	4	54.1
	↓	5	31.2







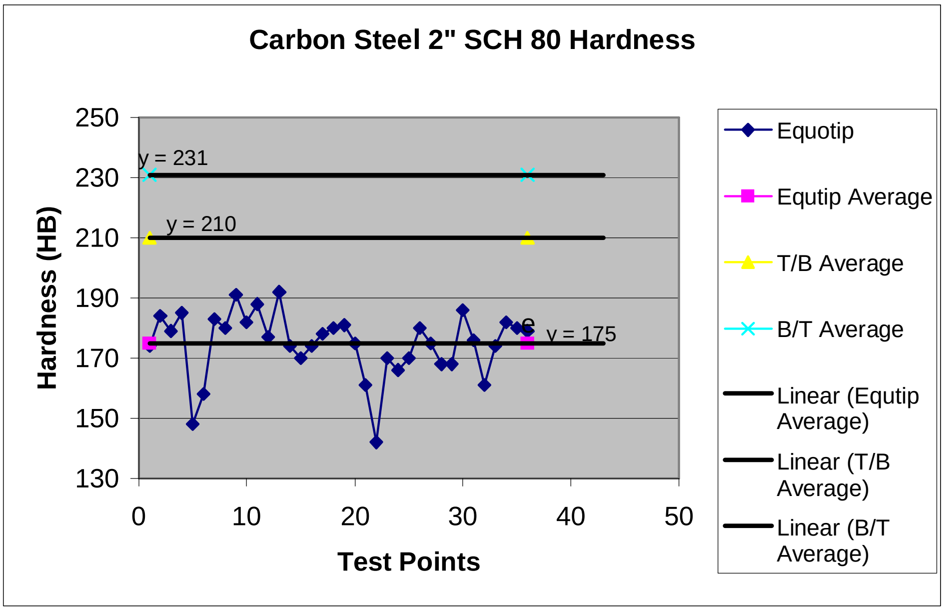

Carbon Steel 2" SCH 80 Hardness
Hardness (HB)
250
230
210
190
170
150
130
y = 231
y = 210
y = 175
0
10
20
30
40
50
Test Points
Equotip
Equtip Average
T/B Average
B/T Average
Linear (Equtip Average)
Linear (T/B Average)
Linear (B/T Average)

Fig-2

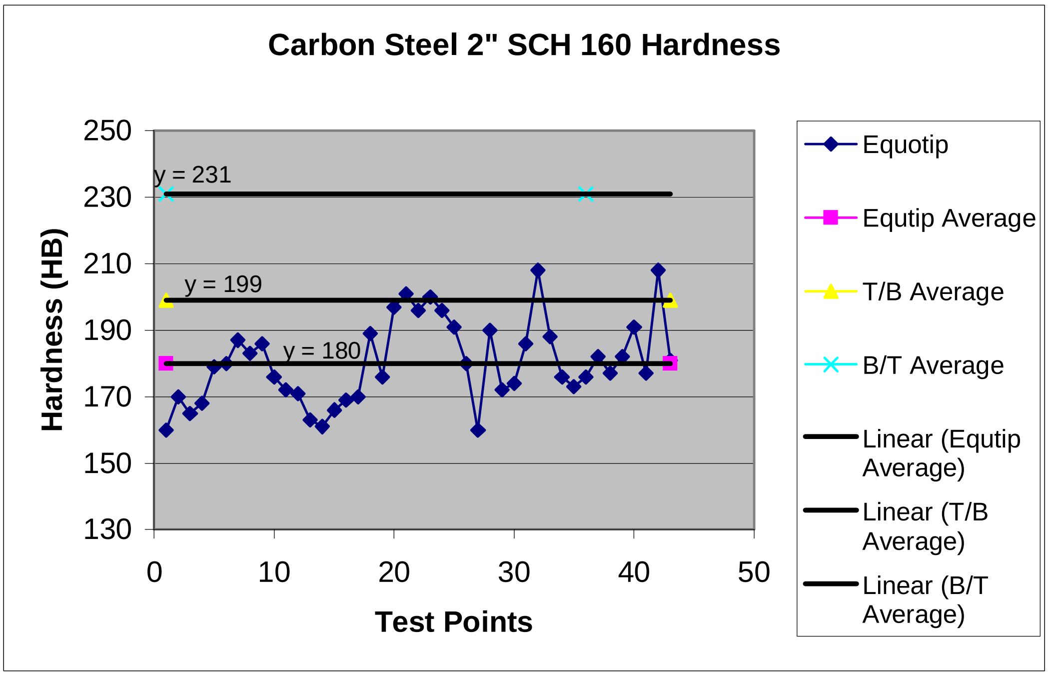

Carbon Steel 2" SCH 160 Hardness
Hardness (HB)
250
230
210
190
170
150
130
y = 231
y = 199
y = 180
0
10
20
30
40
50
Test Points
Equotip
Equtip Average
T/B Average
B/T Average
Linear (Equtip Average)
Linear (T/B Average)
Linear (B/T Average)

Fig-3

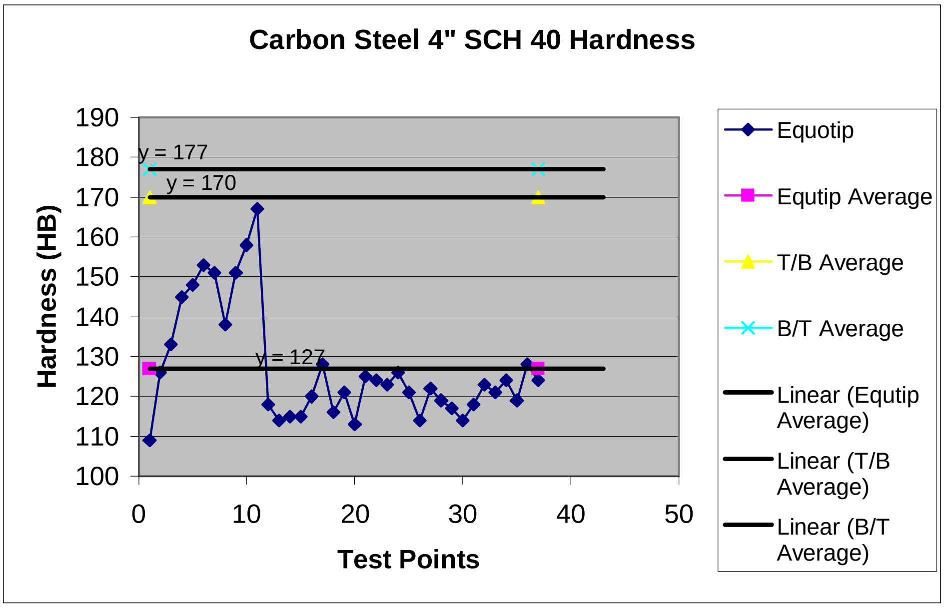

Carbon Steel 4" SCH 40 Hardness
Hardness (HB)
190
180
170
160
150
140
130
120
110
100
0
10
20
30
40
50
Test Points
y = 177
y = 170
y = 127
Equotip
Equtip Average
T/B Average
B/T Average
Linear (Equtip Average)
Linear (T/B Average)
Linear (B/T Average)

Fig-4

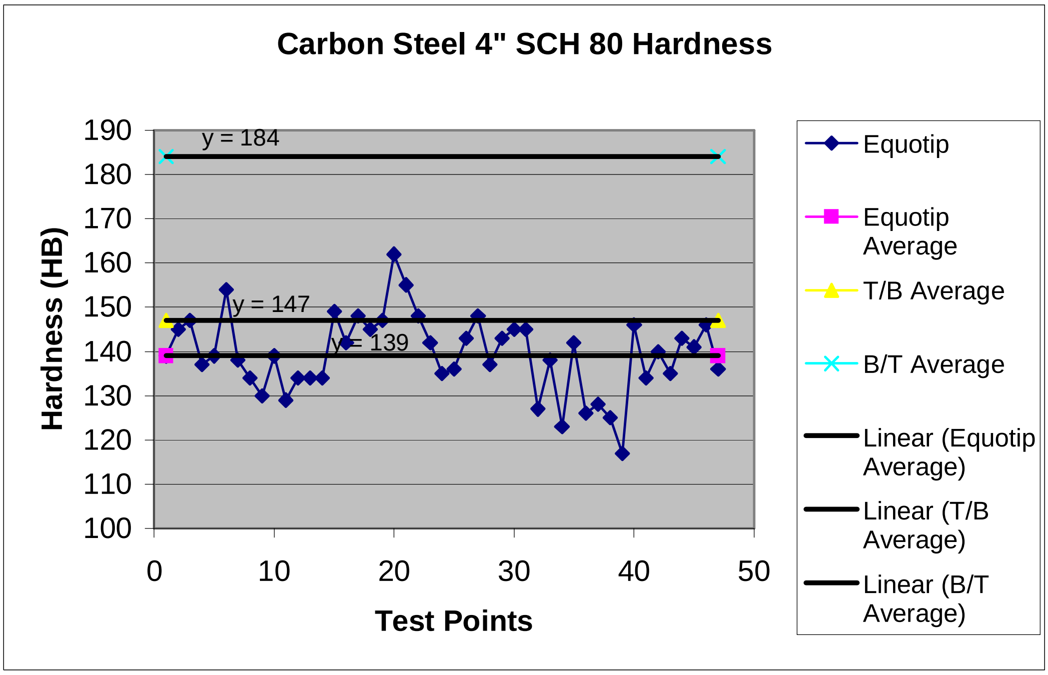

Carbon Steel 4" SCH 80 Hardness
Hardness (HB)
190
180
170
160
150
140
130
120
110
100
0
10
20
30
40
50
Test Points
y = 184
y = 147
y = 139
Equotip
Equotip Average
T/B Average
B/T Average
Linear (Equotip Average)
Linear (T/B Average)
Linear (B/T Average)

Fig-5

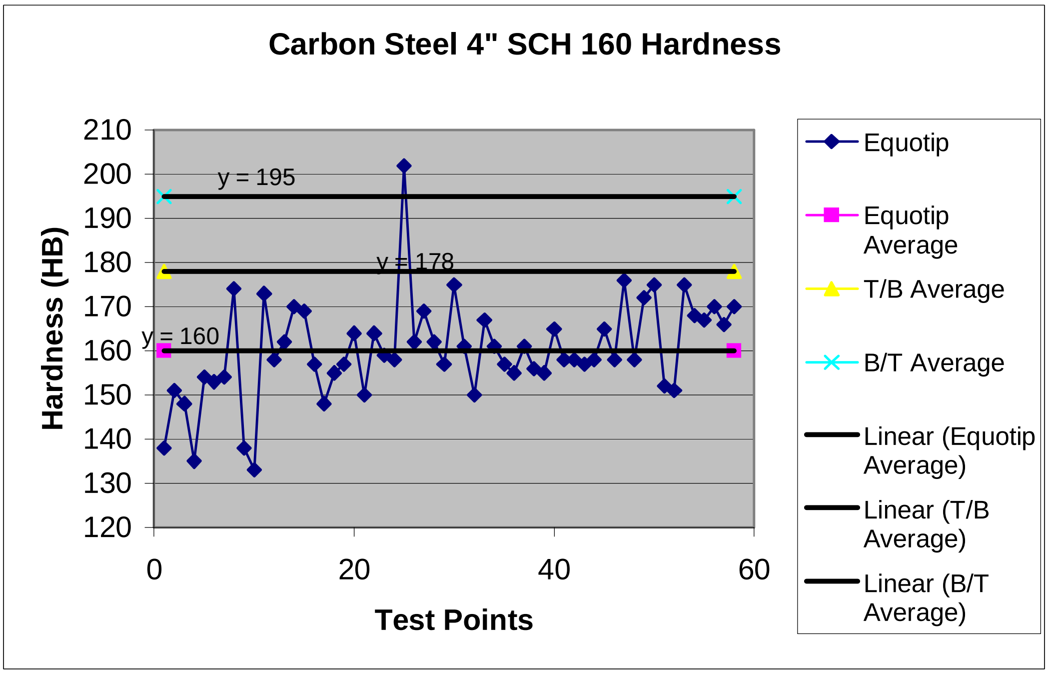

Carbon Steel 4" SCH 160 Hardness
Hardness (HB)
210
200
190
180
170
160
150
140
130
120
0
20
40
60
Test Points
y = 195
y = 178
y = 160
Equotip
Equotip Average
T/B Average
B/T Average
Linear (Equotip Average)
Linear (T/B Average)
Linear (B/T Average)

Fig-6

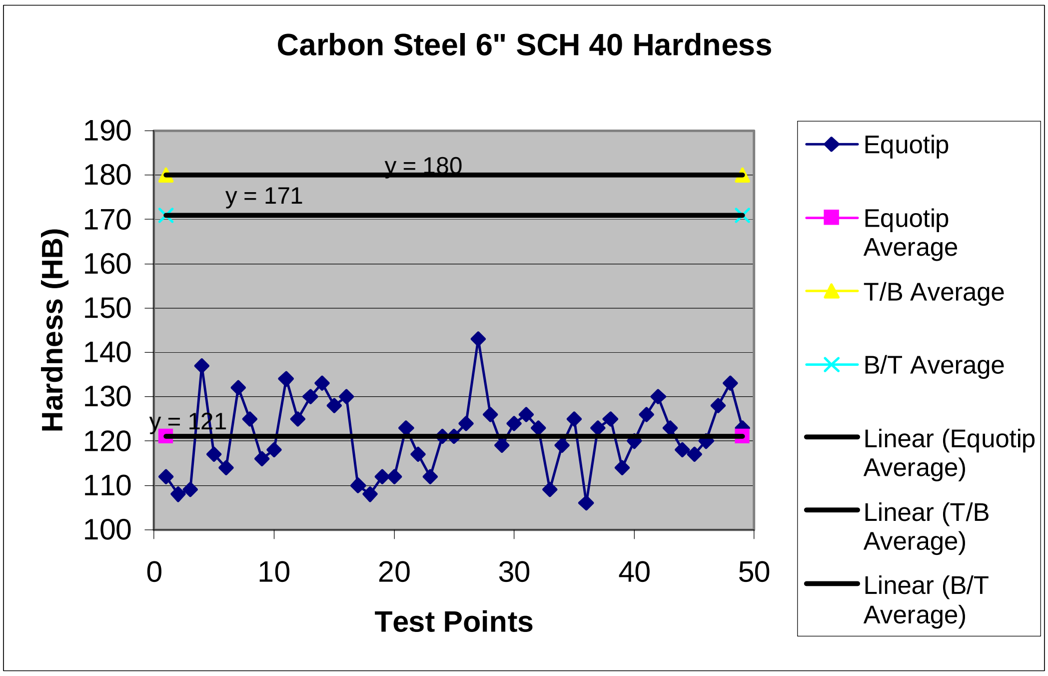

Carbon Steel 6" SCH 40 Hardness
Hardness (HB)
190
180
170
160
150
140
130
120
110
100
0
10
20
30
40
50
Test Points
y = 180
y = 171
y = 121
Equotip
Equotip Average
T/B Average
B/T Average
Linear (Equotip Average)
Linear (T/B Average)
Linear (B/T Average)

Fig-7

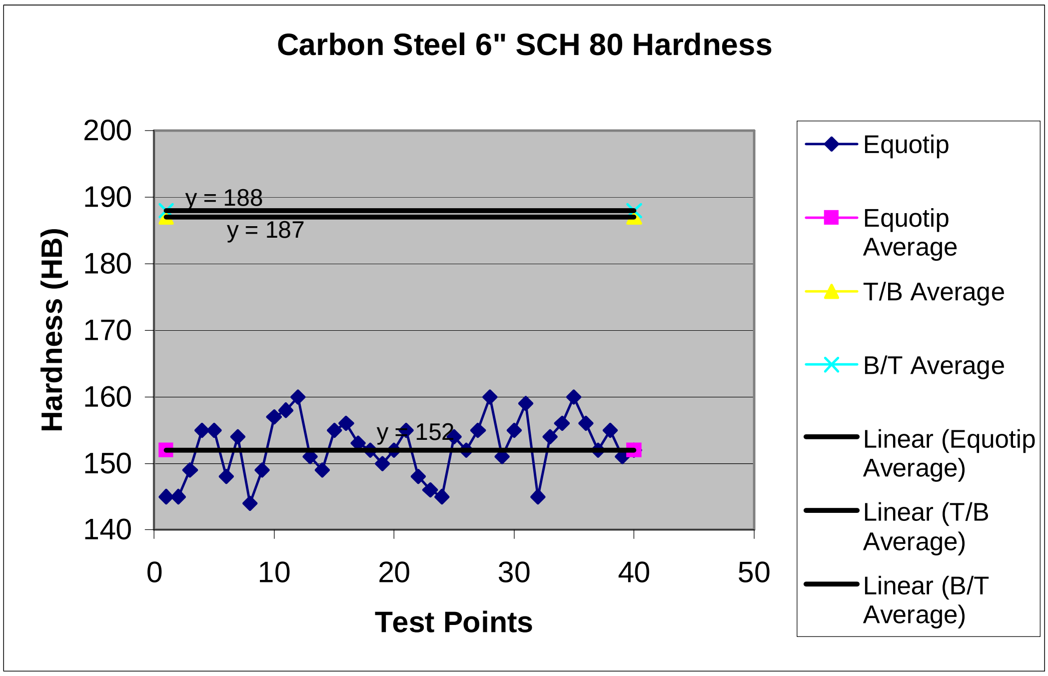

Carbon Steel 6" SCH 80 Hardness
Hardness (HB)
200
190
180
170
160
150
140
y = 188
y = 187
y = 152
0
10
20
30
40
50
Test Points
Equotip
Equotip Average
T/B Average
B/T Average
Linear (Equotip Average)
Linear (T/B Average)
Linear (B/T Average)

Fig-8

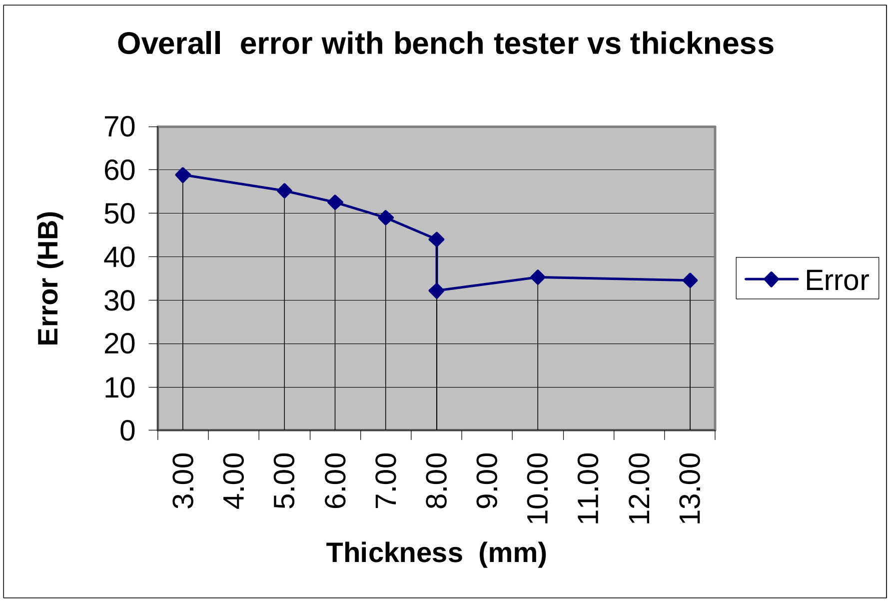

Overall error with bench tester vs thickness
Error (HB)
70
60
50
40
30
20
10
0
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
11.00
12.00
13.00
Thickness (mm)
Error

Fig-9

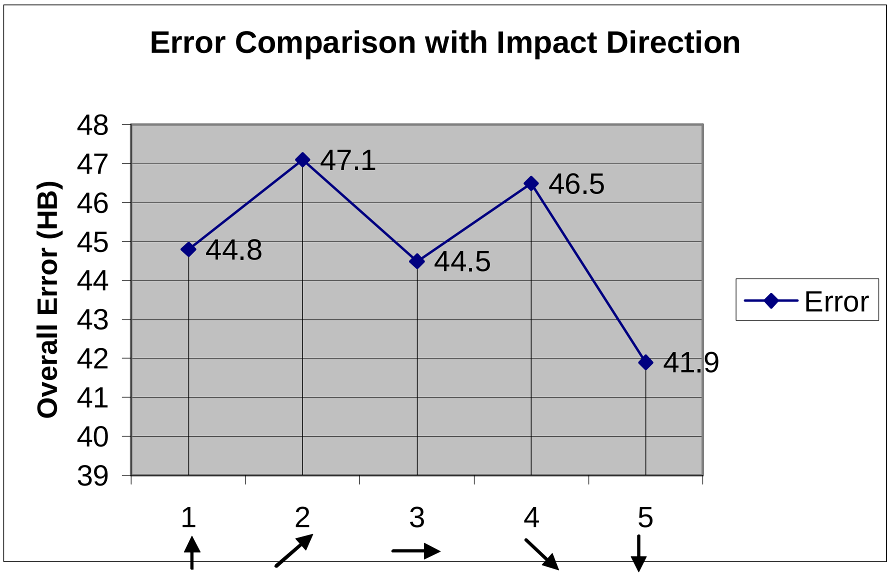


Fig-10

Position		Error
↑	1	44.8
↗	2	47.1
→	3	44.5
↘	4	46.5
↓	5	41.9