Improving Coating Weight Measurement for Heavy Coatings

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On-line coating weight measurement accuracy is very important in reducing zinc consumption and insuring that the customer gets the coating weight ordered. On-line coating weight gauge systems over the years have developed accurate measurement of lower coating weights (G25 to G90 - 38 to 138 gsm/side), however accuracy in the upper range (G100 to G235 - 152 to 358 gsm/side) has been very difficult as the measurement system reaches its upper range capability. California Steel Industries recently installed IRM coating weight systems in the cooling tower of their #1 and #2 Continuous Galvanize Lines. CSI worked jointly with IRM to improve the calibration accuracy of this measurement system specific to their product and line conditions. Factors affecting the measurement accuracy including calibration curve order effects, sample accuracy, calibration methodology, pass line deviation, and temperature compensation are discussed.

1. Introduction

California Steel Industries, Inc (CSI) is located approximately 50 miles east of Los Angles in Fontana, California, on what was once part of Kaiser Steel facility. CSI produces galvanize and galvanneal sheet for construction materials for the home and commercial building industries as well as service distribution centers primarily throughout the Western and Midwestern United States. CSI has 2 galvanize lines that both produce galvanize and galvanneal sheet. The #1 CGL produces gauges range from .015 to .165 inches and widths from 27 to 61 inches. Coating weights range from G30 to G235 (.15 to 1.175 oz/sqft/side - 45 to 360 gsm/side). The #2 CGL produces a gauge range from .0098 to .060 inches and widths from 27 to 52 inches. Coating weights range from G30 to G90 (.15 to .45 oz/sqft/side – 45 to 137 gsm/side). Both coating lines have been operating with the same on line coating weight measurement systems for the past 10 years, however measurements of coating weights above G90 (137 gsm/side) were inaccurate and maintenance of these gauges were becoming very difficult. It was decided to replace the gauges on both coating lines. With the increasing cost of zinc as a major driver, many factors were discussed concerning purchase of new gauges. Gauge accuracy was the predominant factor in reducing zinc over coat. It was also determined that quick coating weight feedback, especially for manual control, was very important in reducing overcoat. Even though coating weight control systems have improved feed forward performance over the years, allowing to move the gauge further down stream from the knives, it was demonstrated that quick feedback in automatic control further reduced the overcoat. This determined that it was important to locate the gauge as close to the knives as possible, resulting in locating them in the after pot cooling tower. This location raised concerns with strip stability, temperature compensation, and equipment maintenance in this very warm environment. The biggest challenge was the installation on #1 CGL as it had the largest gauge, width and coating weight ranges. Gauge manufacture selection was based on equipment performance concerning measurement response, repeatability, and accuracy. The ability to measure coating weights above G235 (358 gsm/side) was also very important. CSI selected IRM gauges and once the installation was complete, several process and calibration challenges had to be met to improve the gauge accuracy. These challenges including air gap temperature compensation, strip pass line variability, initial gauge standards accuracy, and curve order fitting will be discussed in more detail below. Once these issues were addressed, the gauge performance met CSI's expectation.

2. Main features of the FVXR-1 coating weight gauge

2.1 Measurement principle

High performance zinc coating weight gauges are based on the X-ray fluorescence principle. The zinc coating layer is energized by an X-ray beam directed at its surface and the excited zinc atoms generate a secondary emission of photons (fluorescence) which are detected by a suitable detector - typically an ionization chamber (**figure 1).**

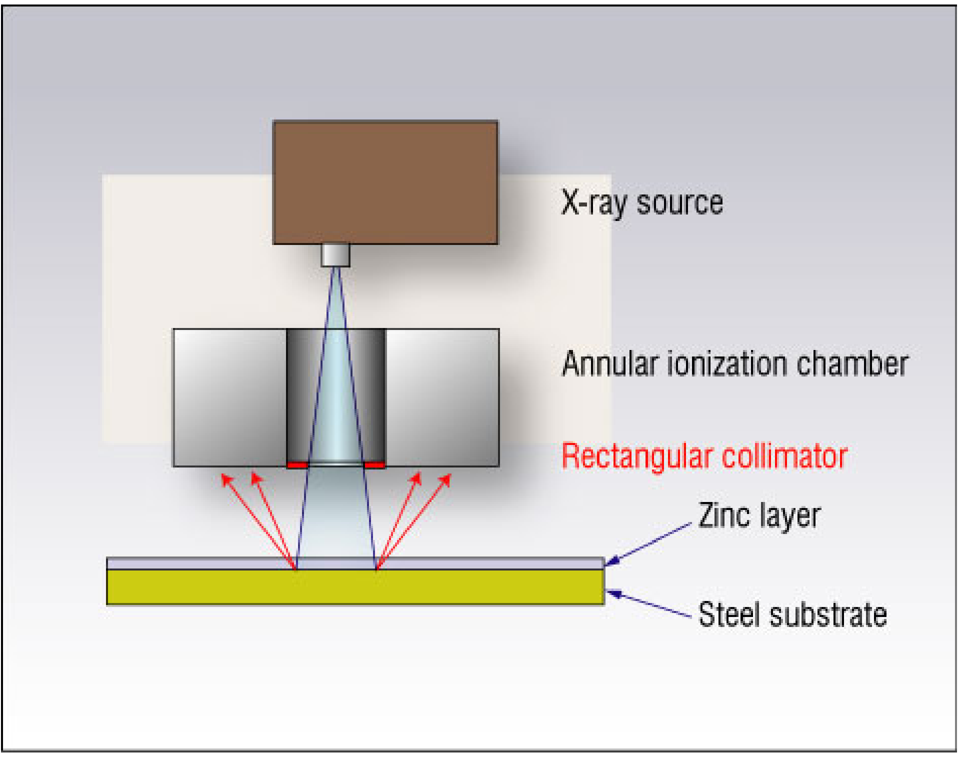

Figure 1: Zinc Coating Weight Gauge Principle

Such a measurement is characterized by a high noise/signal ratio. The quality of the measurement therefore strongly depends on the design of the entire measurement chain (X-ray source stability, high voltage generator stability, ionization chamber design, size of the measuring zone on the strip, preamplifier noise at high gain, signal data treatment, etc).

2.2 FVXR-1 gauge features

All these aspects have been optimized by IRM group engineers during the development of the FVXR-1 coating weight gauge. Consequently, the FVXR-1 is different in many aspects from other conventional gauges:

- a wide coating weight measuring range (up to 650 gsm/side for zinc coating),
- a representative measurement at the edges by using a rectangular X-ray beam, very accurate head positioning (edge detectors) and variable scanning speed,
- a high measurement response speed due mainly to proprietary ionization chamber design with very low time constant,
- a high scanning speed allowing more profile measurements of the strip coating weight and faster reaction of the air knives control.

As a result, the coating weight profiles measured by the gauge are highly reproducible regardless of the scanning speed and direction. Due to the sensor's high speed of response, there is no trailing effect which would otherwise dampen the gauge response to coating weight changes.

Figure 2 shows an example of this unique feature during the workshop acceptance test for one sensing head. Twenty-six successive coating profiles (13 forward and 13 backward) were measured on a static strip sample. Coating weight reproducibility between forward and backward profiles shows better than +/- 0.0013 oz/ft^2 (0.4 g/m²) at an average 0.20 oz/ft^2 (60 g/m²) coating weight (+/- 0.6 %).

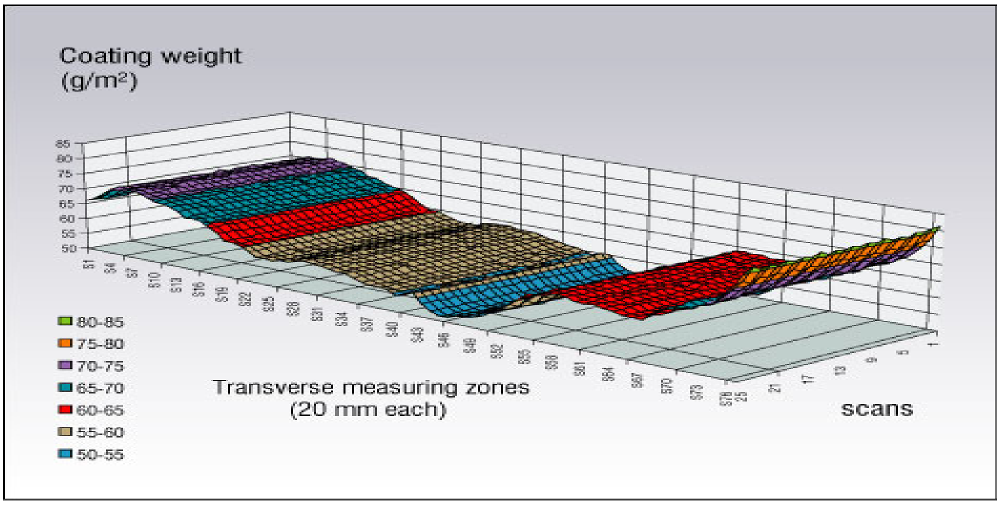

Figure 2: Reproducibility of Coating Weight Profile Measurements (26 profiles)

2.3 Critical Parameters for Heavy Coating Weight Applications

To meet product requirements and improve operation, California Steel expected the overall calibration accuracy to be better than +/- 1.0 % over the entire range G30 to G235 (30 to 405 gsm/side). This is essentially the same as the capability of the Weigh-Strip-Weigh method (ASTM standard A 90 / A 90M)[1] which was to provide the accuracy confirmation.

The FVXR-1 sensor is able to measure Zn coatings up to 2.15 oz/sqft/side (650 gsm/side). **Figure 3** shows the typical, exponential response curve of a fluorescence sensor.

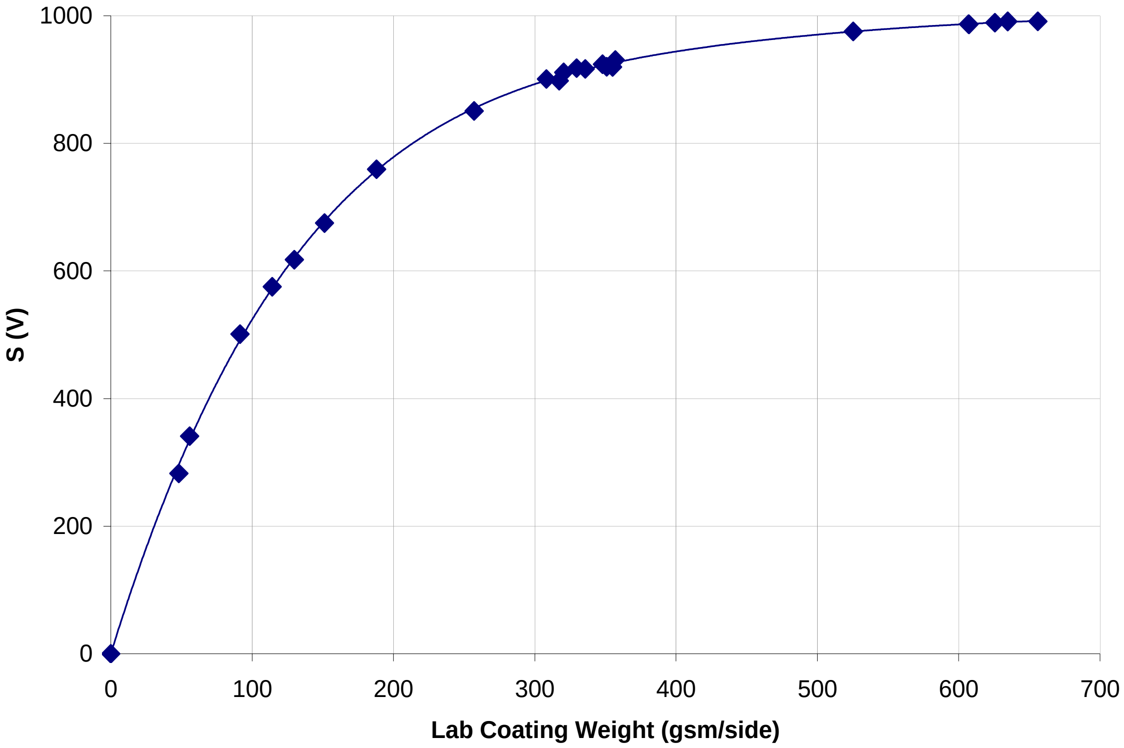

Figure 3: Sensor response curve for wide coating ranges

Due to the heavily non-linear relationship between the gauge signal and the coating weight, the accuracy of the measurement depends on several critical factors; some related to the sensor characteristics and others dependent on the quality of the calibration samples and the calibration methodology.

Sensor Characteristics:

- measurement resolution: with a 16 bits AD converter, 1 bit corresponds to 0.15 mV (for a 10 V signal range). The coating weight resolution thus gets worse as the coating weight increases as follows:

Coating weight (oz/sqft/side)	Resolution (oz/sqft/side)	Coating weight (gsm/side)	Resolution (gsm/side)
0.15	0.000007	45	0.002
0.50	0.000021	152	0.006
1.00	0.000070	305.2	0.020
1.35	0.000210	412	0.060
1.97	0.000630	600	0.180

As seen from the table, the resolution remains well below the level needed to reach a satisfactory accuracy. This is not a limitation of the system.

- measurement noise: the high level of noise related to the fluorescence principle is not a problem either because the high speed measurement produces approximately 20,000 measuring points per coating weight profile (width) divided into zones (typically 50 or 100 zones) across the width. Therefore, in each zone, there are sufficient measurements to ensure that the noise is averaged to acceptable levels.

- measurement stability: the sensors are selected for a +/- 0.10% stability over an 8 hour period. Regular standardizations at 4 hours intervals ensure that this limit is never reached.

- pass-line influence: Coating weight measurement average errors are less then 0.45% due to pass-line movement of +/- 1/8" (+/- 3 mm) for coating weights ranging from 0.15 to 1.40 oz/ft^2 (45 to 430 gsm/side) (**Figure 4**). This performance is achieved in part due to a hardware filter unique to the ion chamber. To ensure strip movement remains less than +/- 1/8" (+/- 3 mm), stabilizing rolls on each side of the gauge are used or a "split" frame system allows measurement on a bridle section.

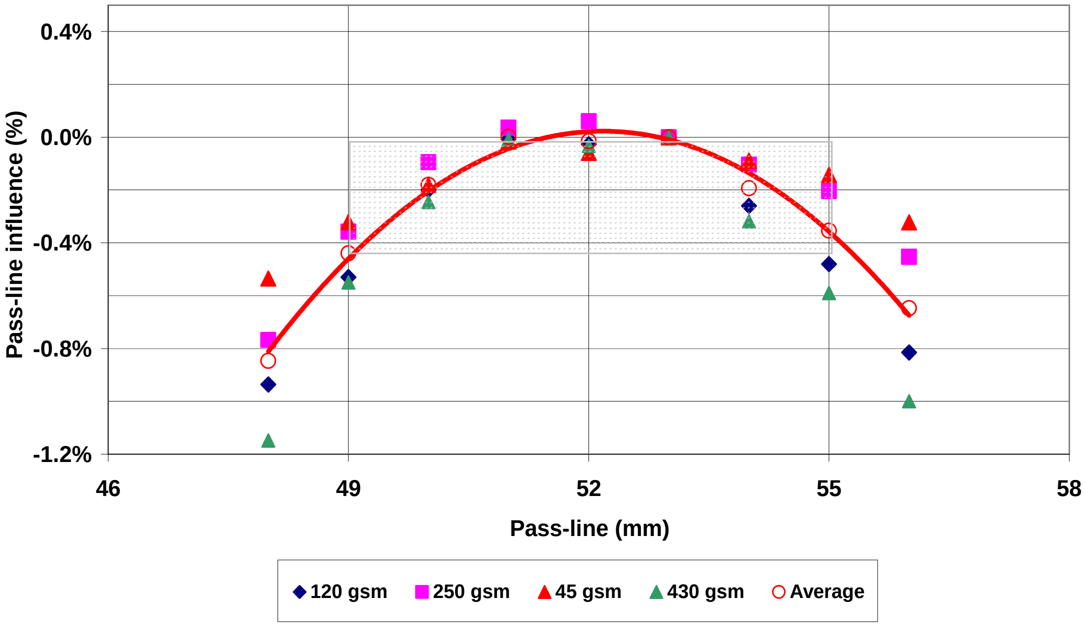

Figure 4: Pass-line Test Data.

- air gap temperature: For gauges installed in the cooling tower as at California Steel, the temperature on the measurement surface of the sensor heads facing the strip has been measured up to 212 °F (100 °C) during galvanneal runs. In this case the air gap temperature variations have an effect on the fluoresced X-Ray energy, therefore the sensor heads are equipped with air gap temperature sensors and the system includes a compensation algorithm to correct for temperature changes. The compensation was tuned to a default correction of -0.04%/F (-0.08%/C) during manufacture for a temperature range 68 to 140 °F (20 to 60 °C).

Combining these results, the overall expected accuracy of a standard FVXR-1 sensor for in line conditions can be estimated at +/- 0.6% (quadratic combination of the above mentioned residual errors).

Calibration Samples and Procedure:

The gauge was preliminarily calibrated and factory tested with an IRM group set of reference samples. However, final site calibration is always performed with customer samples to ensure the best possible correlation between the gauge and the plant laboratory which remains the final coating weight reference.

CSI had developed a set of galvanize and galvanneal standards for the coating ranges of G30 to G90 (45 to 137 gsm/side) and A40 to A60 (45 to 91 gsm/side) that was used for the old coating weight gauge. These standards were developed by using a linear regression comparison between the gauge reading and destructive WSW. This method, originally described in an ASM article[2], uses the coating weight gauge to measure the coating of approximately 40 samples of a specific coating weight. Once measured, a select few of the samples were set aside and the coating weights of the remaining samples were measured again using the WSW method. Once this data was accumulated, a linear regression between the gauge measurement data and the WSW data was computed to determine the coating weight of the samples that were set aside. This method worked very well as long as the coating weights measured were within the coating weight gauge measurement capability. Since the old gauge was not able to measure accurately above G90 (137 gsm/side) coatings, standards above G90 had to be developed by the traditional “perimeter” method.

The perimeter method essentially involves taking a large sample and dividing it into smaller zones with the central sample identified as the final calibration sample. All the external samples are measured by WSW, and the resulting average is assigned to the center calibration sample. This method relies heavily on homogenous coating distribution over the entire sample surface. Due to the coating process, homogeneity decreases as coating weight increases.

3. Commissioning and Initial Site Results

The gauge was calibrated with the existing California Steel samples (**Figure 5**) using a 7th order curve fit to the sample coating weights. The resulting on-line gauge measurements were then assessed during the next month by systematic comparison with the plant laboratory (**Figure 6**).

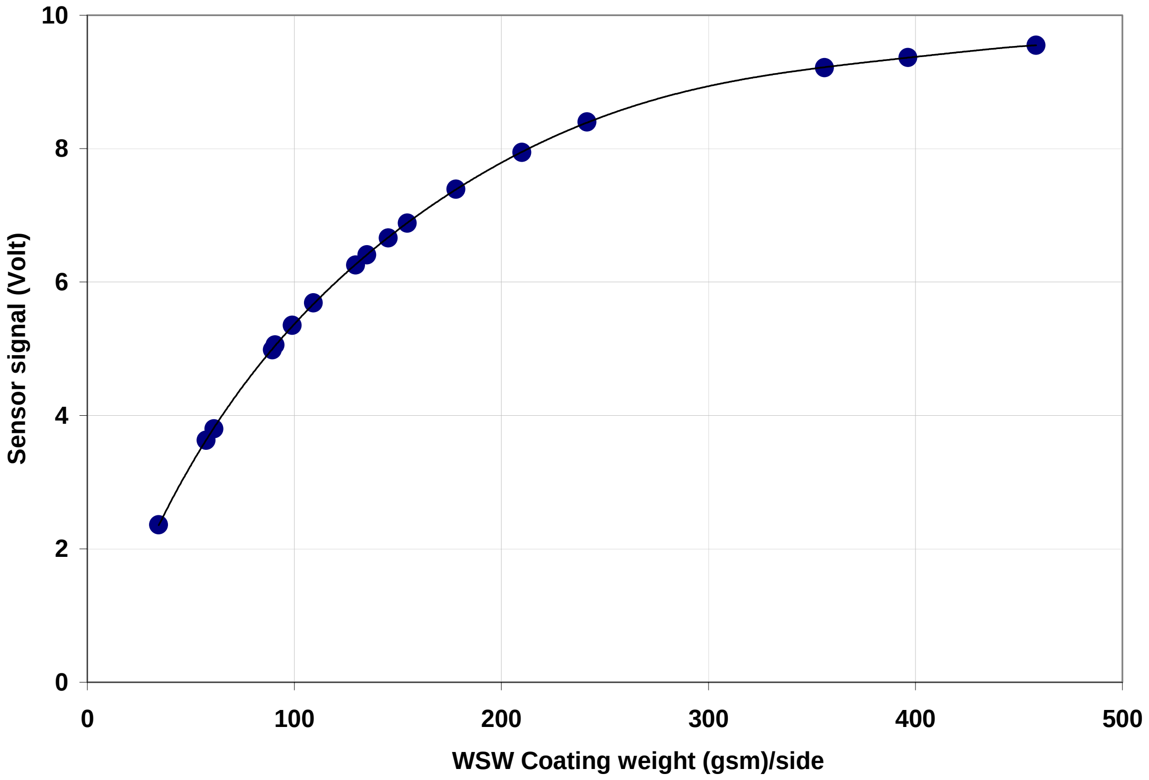

Figure 5: First Calibration On-Site (February 2008)

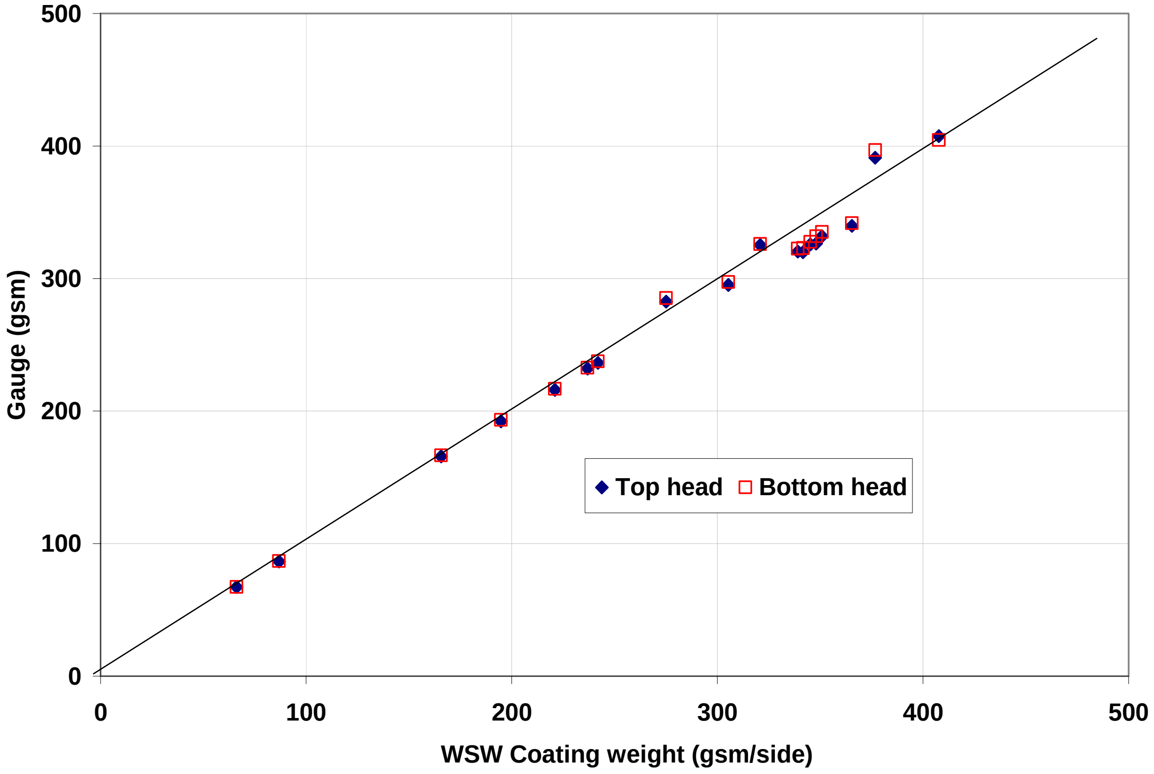

Figure 6: First Results On-Site (March 2008): Comparison between Gauge and Plant Laboratory

The comparison showed very good correlation up to G100 (152 gsm/side). For heavier coatings, errors up to +/-6% were recorded, consistent with the concern about the calibration samples used in this range.

Noticeably, however, top and bottom measurements were in excellent agreement. This confirmed the sensors expected capabilities and that improving the calibration procedure would without a doubt improve the accuracy.

4. Measurement Improvements

Following these results California Steel and IRM group worked together to identify areas of improvement influencing the measurement accuracy. The main improved items were:

Gauge and Process Improvements

- During initial galvanneal runs it was clear the default air gap temperature compensation was insufficient for the wide range of temperatures measured up to 212°F (100 °C). Using on-line sample measurements and the corresponding temperature readings gathered during each standardize, new compensation factors for each sensor were computed and entered. On average the new coefficients improved the coating weight measurement accuracy 2%.

- Pass-line variability – For the O-frame arrangement, pass line was originally established with two small pass line rolls on each side of the measuring heads. (**Figure 7**). A common configuration for the rolls was to pass the strip across the top of the two rolls closest on each side of the heads. A set of outer rolls were adjusted down from the top of the strip to create an intermesh that would insure the strip maintained the pass line established by the two inner rolls and eliminate any cross bow in the strip. This roll configuration worked well as long as the strip thickness was relatively thin. However, when heavier gauge material (> 2mm, .080 inches) was processed, it was found that the strip would bend or shift upwards exceeding the +/- 1/8" (+/-3 mm) pass line tolerance of the gauge. It was also determined that as the thickness of the material would increase, the distance from the bottom of the head would remain the same, however, the strip would move closer to the top head. At #1 CGL, when running heavy gauge, this distance would move over the 3 mm tolerance of pass line change. This coupled with the strip shift resulted in inaccurate gauge readings. To remedy this problem, the configuration of the pass line rolls was changed such that the entry inside roll was on the top surface and the exit inside roll was in contact with the bottom of the strip. The outer two rolls were positioned to create the proper intermesh to insure strip stability (**Figure 7**). The change resulted in canceling the effect of the strip shift and evenly distributed the thickness shift between the two heads keeping the strip distance to the heads within the gauge requirements. This change kept the pass-line to within the +/- 1/8" (+/- 3mm) and the resulting gauge errors within the original specification.

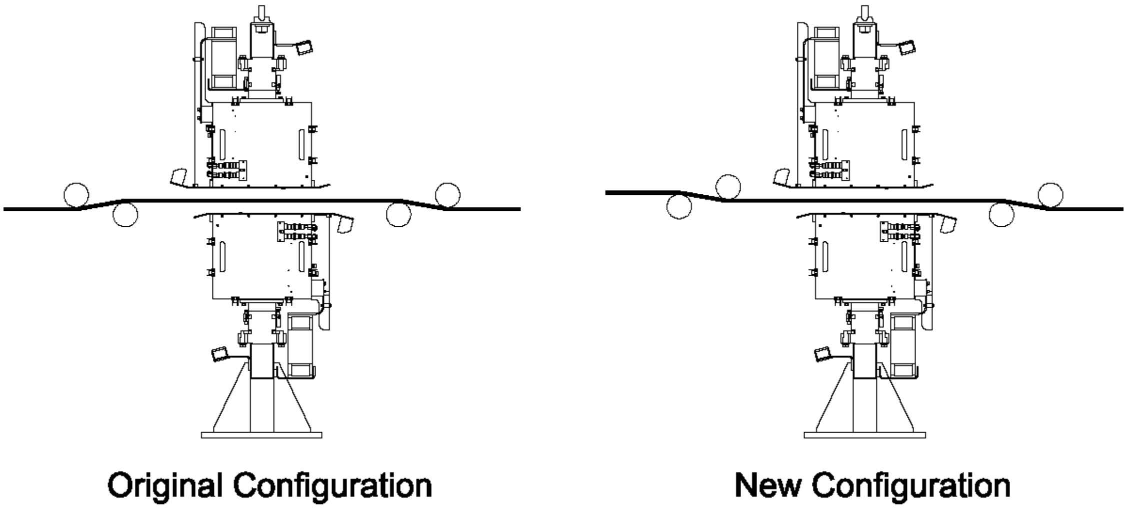

Figure 7. Pass-Line Roll Configuration

Calibration Sample and Procedure Changes

The final challenge and perhaps the most involved, was the sensor calibration for coatings G90 (137 gsm/side) and above. As referenced previously the existing standards were not adequate to provide a good calibration in this range. The calibration errors were further compounded by the 7th order calibration fitting to these standards. This technique amplified the calibration errors both within the range and proved unreliable beyond the last calibration sample.

The first change was to introduce a 1st order calibration curve that utilizes the pure logarithmic response of the IRM sensor design (mainly due to the proprietary ionization chamber), as proven in many previous projects. **Figure 8** shows the 1st order curve using the CSI standards. While the fit to existing samples is not as accurate as a 7th order, this curve proves very useful in confirming the validity of new samples, the WSW results and ensures proper measurement beyond the heaviest sample available.

This approach provides distinct advantages:

- the quality of a straight line fitting is intuitively easier to appreciate,
- the scatter of the points around the straight line is a direct indication of the quality of the reference samples.
- samples which deviate by a larger extent from the straight line can be considered as having a doubtful laboratory WSW measurement and should therefore be rejected (250 and 420 gsm samples for example in **Figure 8**).

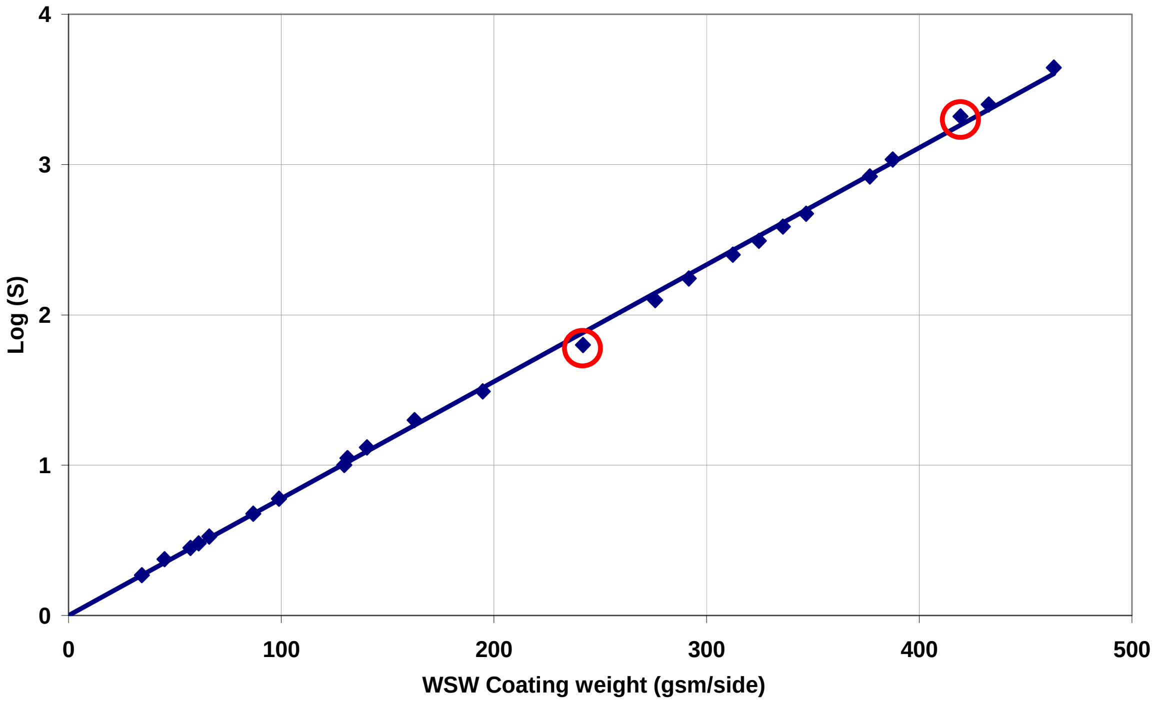

Figure 8: Sensor Logarithmic Response

New samples throughout the heavy coating weight range were measured by the gauge. To limit errors due to sample uniformity, especially with the heavier coated samples, each sample was read four times, rotated 90 degrees before each reading. Samples with large variability (> 1%) were discarded. The remaining samples were then measured by punching a 2.5" diameter coupon and using the WSW method to obtain the coating weight. These values were used to create the first order calibration. Additional samples through out the coating weight range were then measured in the gauge and again WSW to confirm and refine the calibration. Once satisfied the gauge calibration had reached the capability limit of the WSW, final standards were developed using the linear regression method described earlier.

In further discussions with California Steel, the ability to divide the calibration into multiple ranges was added to increase the calibration flexibility over the entire coating weight range (**Figure 9**). This feature allows the gauge to be calibrated up to G400 (610 gsm/side) taking into account different line and substrate effects for such an extreme range of product. The ability to adjust each calibration range to gauge/lab corresponding values was also added. This gives the user the ability to quickly tune the calibration to recent lab values by applying an offset or a slope adjustment as warranted by process data. This is helpful when a full calibration check is not possible within production requirements.

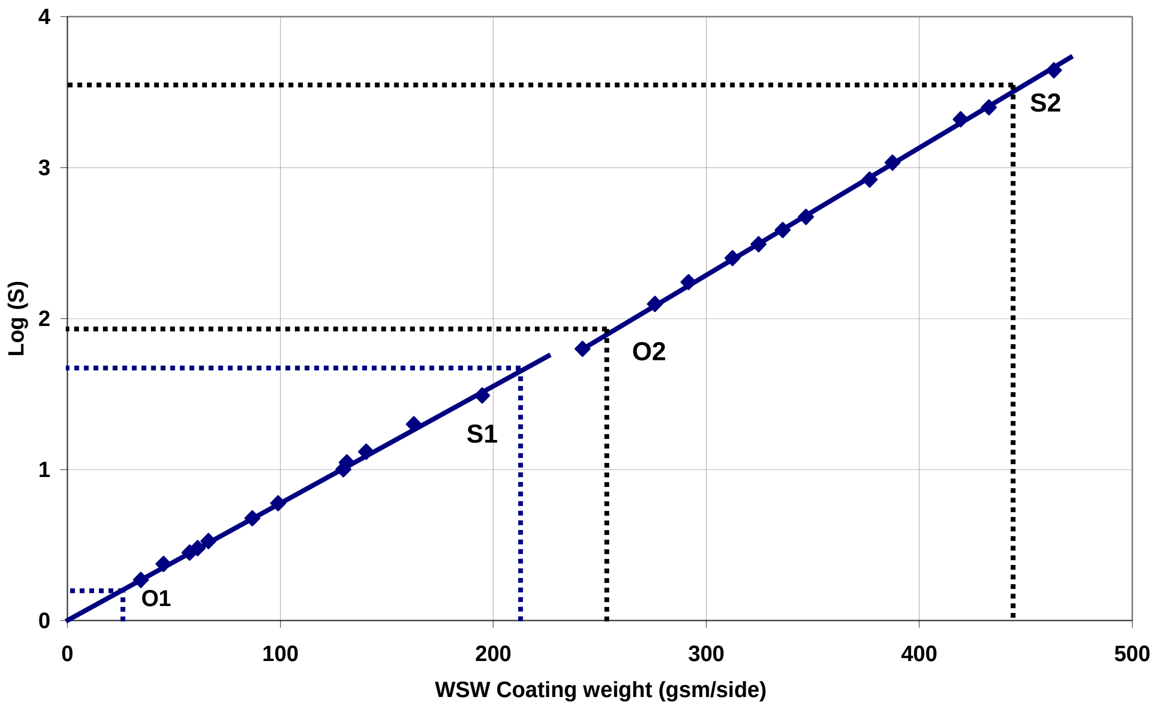

Figure 9: Multi-Curve Calibration

5. Operating results

The resulting calibration, pass-line and air gap temperature compensation improvements significantly improved the measurement accuracy above G90 (137 gsm/side). The on-line verification process results indicate errors through out the range that were originally +/- 6%, were reduced to less then +/- 1.0% for both sensors (**Figure 10**). This represents a significant improvement in calibration accuracy.

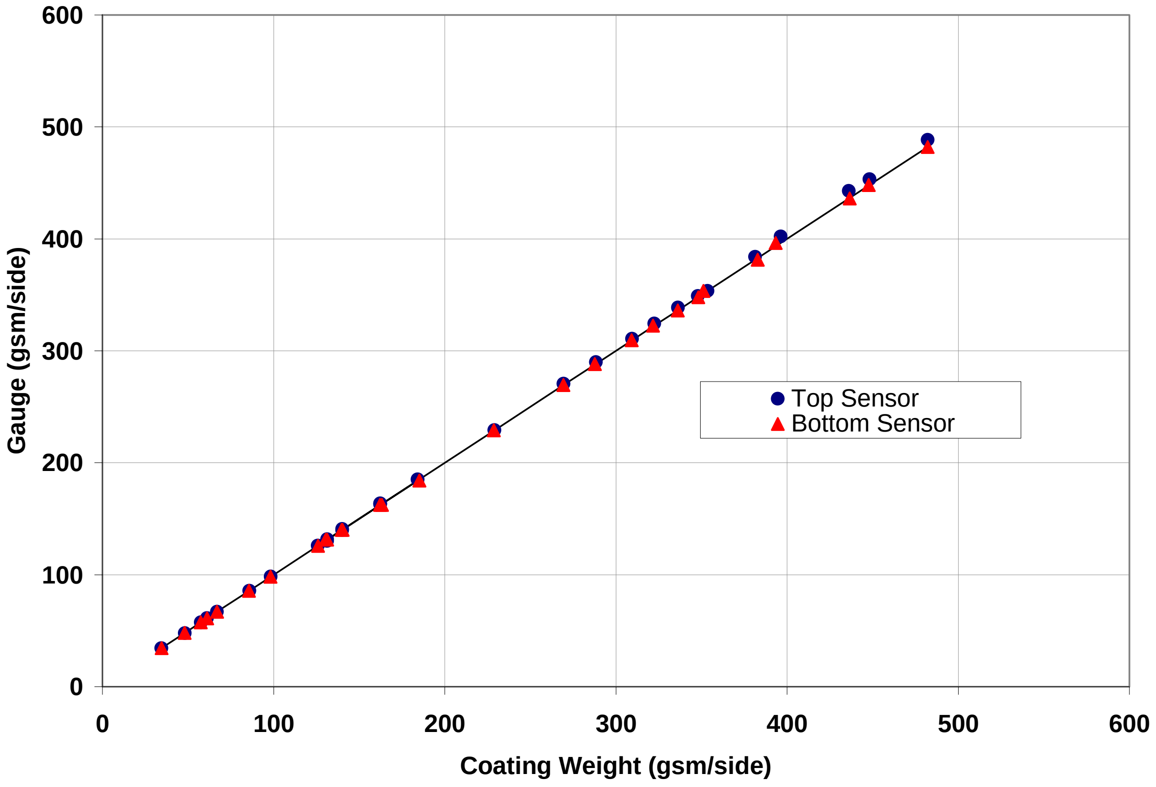

Figure 10. Final Verification Results

This created a much more reliable on-line measurement for heavy coatings. This was further enhanced by refined temperature compensation to the extreme air gap temperatures during galvanneal runs and the improved pass-line configuration that reduced shift movement, especially for heavy substrate and coating weight products. Consequently, with a more accurate and reliable on-line coating weight measurement, operations were able to use the existing closed-loop-control for a majority of the products.

6. Conclusions

California Steel Industries installed a standard IRM Group coating weight measurement system for warm locations in the tower of both #1 and #2 Continuous Galvanize Lines. While the gauges met all the standard measurement requirements for the lower coating weight range of G30 to G90, several improvements to the system at #1 CGL were necessary to provide acceptable measurement accuracy in the upper coating weight range of G90 to G235 (137 to 358 gsm/side)

Having the largest impact, new calibration samples were created using a simplified, single order calibration curve fit up to G235 (358 gsm/side). The inherent capability of the FVXR-1 sensor, especially for heavier coating weights, and the linear sample-to-gauge relationship allowed CSI to use the gauge to make more accurate coating weight standards through the entire range. As a result calibration errors through out the entire product range were reduced from as high as +/- 6.0% down to less than +/- 1.0%. The single order calibration curve fit also ensured valid gauge response to very heavy coatings beyond the heaviest known standard. The extended curve provided good coating weight measurement for the operators when extreme conditions existed such as transitions into the heaviest coating weights or large profile variations when processing G235 (358 gsm/side) coatings. In addition, implementing dual coating weight curves allowed CSI to best fit both lower and upper curves.

Other improvements to the system included fine tuning the air gap temperature compensation and modifying the pass-line stability rolls. The air gap temperature compensation required tuning due to the extreme temperatures that exist at the top of the cooling tower, especially during galvanneal production. Due to the large gauge range of product (0.015” to 0.165”), the pass-line stability rolls were reconfigured to minimize strip movement to +/- 1/8“ (+/- 3mm).

By improving the calibration standards, calibration technique, pass-line configuration and on-line temperature compensation, IRM Group and CSI were able to improve overall, on-line coating weight measurement for all products up to and including G235. As a result, operations are now able to use the closed-loop-control for a majority of the products produced on #1 CGL.

References:

1. Anon. ASTM Designation A90/A90M – Standard Test Method for Weight (Mass) of Coating on Iron and Steel Articles with Zinc or Zinc-Alloy Coatings, ASTM – Vol 01.06 Feb 2002, West Conshohocken, PA.
2. Larry F. Crawford, Theresa Simpson, and Fritz J Friedersdorf, Generation of Hot Dip Galvanized Coated Sheet Certified Reference Materials Using X-Ray Fluorescence and Gravimetry, Journal of Materials Engineering and Performance, Volume 12(5), October 2003. ASM International, Materials Park, OH.