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Inspection Development for Large-Diameter Titanium Billet—Engine Titanium Consortium Phase II

May 2007

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Inspection Development for Large-Diameter Titanium Billet—Engine Titanium Consortium Phase II

May 2007

Final Report

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16. Abstract

The Engine Titanium Consortium Phase I program comprised of Iowa State University; General Electric; Honeywell Engines, Systems & Services; and Pratt & Whitney began in 1993 with a focus on improved inspection of titanium billet used in the production of jet engines. The Phase II program began in 1999 and focused on further sensitivity improvements to titanium billet using the multizone approach. The goal of the Phase II effort was to achieve a #1 flat-bottom hole sensitivity for a 10″ diameter billet and assess the impact of attenuation compensation procedures. A supplemental task was later added to the Phase II effort that focused on titanium billet larger than 10″ in diameter. This report documents the results for 13″ and 14″ diameter billets in laboratory and factory settings.

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LIST OF ACRONYMS

AMS	Aerospace Material Specification
DAC	Distance-amplitude correction
ETC	Engine Titanium Consortium
FAA	Federal Aviation Administration
FBH	Flat bottom hole
FFT	fast Fourier transform
FSH	Full-screen height
GE QTC	General Electric Quality Technology Center
ISU	Iowa State University
MZ	Multizone
P&W	Pratt & Whitney
SNR	Signal-to-noise ratio
Ti	Titanium

EXECUTIVE SUMMARY

An extended study focusing on the inspection of large-diameter billet (>10-inch diameter) was added to the Inspection Development for Titanium Billet Study of the Engine Titanium Consortium Phase II program. The objective of the study was to assess the production capability of conventional and multizone (MZ) ultrasonic inspection systems for large-diameter (13″ and 14″), rotor-grade titanium billets using current state-of-the-art inspection technology. It included production of full-round dynamic standards in 13″ and 14″ diameters. Evaluations were made using standard MZ practices with improved technology that is available in current transducer fabrication. While this assessment does not represent the detailed analysis of a full probability of detection study, it demonstrates that the results can be achieved in a laboratory setting and provide a limited survey of factory capability.

Highlights of the results follow with full details in the report.

- Full-round calibration standards for 13″ and 14″ diameter billet were designed and manufactured following recommendations from the ETC Phase II Billet Attenuation Compensation Study. The standards contain both #2 and #3 flat-bottom holes (FBH) placed in the highest attenuation areas and in accordance with the MZ zoning scheme. With this design, all calibrations of the conventional and MZ systems yielded a conservative inspection result.

- MZ transducers were designed and built for both billet diameters following the established practices for fabrication of production transducers. Advances in transducer fabrication technology eliminated the need to limit the diameters to the previous (early 1990s) maximum of 2.35″, enabling F/10 focusing in all zones. All acquired transducers were characterized following the acceptance tests for production MZ probes.

- Laboratory assessments of MZ and conventional inspections using the ETC standards were performed at Pratt & Whitney and General Electric. The results of these inspections were presented in the form of sensitivity curves using the 3 dB signal-to-peak noise criteria as defined in earlier ETC programs. A quantitative summary for each billet size is provided below for the nearest and deepest zones for MZ and for the conventional inspection.

  <u>13″ Diameter Laboratory Results:</u>

  #1.5 FBH sensitivity at 1″ depth, MZ zone 1
  #2.2 FBH sensitivity at 7″ depth, MZ zone 7

  <u>14″ Diameter Laboratory Results:</u>

  #1.2 FBH sensitivity at 1″ depth, MZ zone 1
  #2.4 FBH minimum sensitivity at 7.5″ depth, MZ zone 7
  #3.3 FBH sensitivity, Conventional 0.6″ to 7.5″ depth

- Several factory evaluations were conducted using the new MZ transducers and conventional transducers that differed from the one used for the 14″ diameter laboratory evaluations. A total of four heats (32,000 lb) of rotor-grade 14″ diameter billet material were inspected using MZ and conventional inspection procedures at two different billet suppliers. Four heats (42,000 lb) of rotor-grade 13″ diameter billet material were inspected at one billet supplier using both existing and newly built zones 6 and 7 MZ transducers. The factory results for multizone of both 13″ and 14″ billets were conducted using the ETC calibration standard. The conventional evaluations of 14″ diameter billets were conducted using the production chord block calibration standards. A quantitative summary for each billet size is provided below for the nearest and deepest zones for MZ and for the conventional inspection.

  <u>13″ Diameter Factory Results:</u>

  #2.0 FBH sensitivity at 7″ depth, MZ zone 7 at supplier A (ETC Standard)
  #2.5 FBH sensitivity, Conventional 0.6″ to 7.0″ depth at supplier A (Supplier Standard)
  #3.9 FBH sensitivity, Conventional 0.6″ to 7.0″ depth at supplier A (ETC Standard estimated)

  <u>14″ Diameter Factory Results:</u>

  #1.7 FBH sensitivity at 1″ depth, MZ zone 1 at supplier A (ETC Standard)
  #1.4 FBH sensitivity at 1″ depth, MZ zone 1 at supplier B (ETC Standard)
  #2.4 FBH sensitivity at 7.5″ depth, MZ zone 7 at supplier A (ETC Standard)
  #2.9 FBH sensitivity at 7.5″ depth, MZ zone 7 at supplier B (ETC Standard)
  #2.7 FBH sensitivity, Conventional 0.6″ to 7.5″ depth at supplier A (Supplier Standard)
  #3.1 FBH sensitivity, Conventional 0.6″ to 7.5″ depth at supplier B (Supplier Standard)

As stated above, MZ and conventional inspections of 13″ and 14″ diameter billet were evaluated in the laboratory and at production suppliers. Both evaluations indicated that MZ inspection performed well in a production environment and these results represent improvements of about #1.7 FBH in the near zone to about #0.7 FBH in the center zone over the conventional inspection. The measured multizone improvement over conventional production facilities for 14″ diameter would likely be larger if both systems were calibrated using the same standard. The reason is, the ETC calibration standard was more attenuative than the conventional standards used by the suppliers. In other words**,** when comparing inspection system sensitivities using two different calibration standards, i.e., one with FBHs in higher attenuating regions (ETC standard), and one with FBH in lower attenuating regions (conventional supplier standards), the apparent sensitivity of the system calibrated using the ETC standard would appear lower than if calibrated using a supplier conventional standard.

1. INTRODUCTION.

1.1 PURPOSE.

Large-diameter (13″ and 14″) titanium (Ti) billets represent a particular inspection challenge because of the long metal travel paths involved. The purpose of this study was to assess current conventional and improved multizone (MZ) (fixed-focus) inspection capabilities for these large-diameter billets.

1.2 BACKGROUND.

Inspection development for Ti billet in the Engine Titanium Consortium (ETC) Phase II program primarily concentrated on ways to improve the inspection of 10″ diameter Ti billets. There was a smaller effort to assess the inspectability of the center zone of 14″ diameter billets. This work consisted of designing and building a pair of MZ transducers intended for inspection of the center zone of the billet. The transducers were evaluated on a chord block in a laboratory environment. The results showed an improvement in sensitivity over conventional inspection. The results also pointed out concerns for production implementation. It was observed that these transducers were sensitive to misalignment. Attenuation compensation studies conducted for Ti billets within the ETC Phase II program also pointed out that special care needs to be taken when deciding on the placement of the holes in calibration standards.

Currently, MZ inspection was not performed on the 14″ diameter production billet material. At the time of the development of MZ inspection for 13″ diameter billets, there was a limitation on the maximum probe diameter of 2.35″. This resulted in the transducers for the two deepest zones (zones 6 and 7) having F numbers larger than the intended value of F/10.

It was desired to extend the evaluation efforts for large-diameter billets to include building full-round standards and performing a limited production evaluation. This program was initiated in May 2003, per direction from the Federal Aviation Administration (FAA), and had a 12-month period.

1.3 PROGRAM OBJECTIVES.

To assess the production capability of conventional and MZ inspection systems for large-diameter (13″ and 14″), rotor-grade Ti billets using current, state-of-the-art inspection technology.

1.4 RELATED DOCUMENTS.

The ETC Phase I was established in 1993 and was comprised of Iowa State University (ISU); General Electric Aircraft Engines; Honeywell Engine, Systems & Services; and Pratt & Whitney in a partnership to perform research that contributes to improvements in flight safety. The Phase I program which was completed in 1998, led to improvements in production inspection of Ti billet [1], improved physics models for ultrasonics [2 and 3], and a feasibility study for phased array for ultrasonic inspection of billets [4]. In-service inspection efforts led to a commercially available portable scanner [5] and eddy-current probes [6], as well as improved probe designs [7]

and eddy-current probe design tools [8]. Considerable progress was also made in development of a new approach [9] to quantifying inspection performance, as reported in FAA report DOT/FAA/AR-01/96, "A Methodology for the Assessment of the Capability of Inspection Systems for Detection of Subsurface Flaws in Aircraft Turbine Engine Components" [10].

2. APPROACH.

The approach used for this research program included the following steps:

- Design and Manufacturing of Calibration Standards: The 13″ and 14″ calibration standards were made from typical rotor-grade Ti-6-4 billet material. Provisions were made to assess the effects of attenuation, and the billet material was prescanned to identify high- and low-attenuation regions for placement of the flat-bottom holes (FBH).

- Design of MZ Transducers: The transducers were designed following the practice for the design of MZ production transducers. Zones 1 through 6 transducers for MZ inspection of 14″ diameter billets and zones 6 and 7 for MZ inspection of 13″ diameter billets were manufactured.

- Characterization of MZ Transducers: Center frequency, bandwidth, and pulse duration for each of the delivered probes were measured. The transducer pulse volumes were also measured along with the water path required to achieve zone balance.

- Laboratory Assessment of Conventional and MZ Inspections: MZ and conventional inspections were calibrated using newly built calibration standards. Solid sections of the standards were scanned at these calibration settings. Noise statistics were recorded from generated C-scans, and peak noise values were used to generate sensitivity curves.

- Factory Evaluation: Upon completion of laboratory assessments, arrangements were made for factory inspection of rotor-grade 13″ and 14″ diameter Ti-6-4 billet material. Thirty-two thousand pounds of 14″ diameter material were inspected using conventional and MZ inspections with 20,000 lb being inspected at one supplier and the remaining 12,000 lb at other suppliers. Conventional inspection included both normal and oblique incidence inspections. The 13″ diameter billet evaluation consisted of inspecting 42,000 lb at one supplier.

3. DISCUSSION OF RESULTS.

3.1 CALIBRATION STANDARDS.

To calibrate the MZ inspections of 13″ and 14″ diameter billet, full-round calibration standards were designed and built with FBHs at the beginning, middle, and end of each zone. Current MZ production standards have only two holes, one at the beginning and end of each zone. The addition of the third center hole permitted the study of the variation in sensitivity across each zone and define the beam profile more accurately than the two-hole design.

A principal lesson learned from the ETC Phase II Billet Attenuation Compensation Study was that local attenuation variations in Ti billets will cause echoes from identical targets (at the same depth) to vary in amplitude. Such amplitude variations in the calibration standard and the billet under inspection can be significant and should be accounted for. One of the recommendations of the study was that when new calibration standards are fabricated, the FBH reflectors should be placed into high-attenuation bands (based on back-wall and grain-noise C-scans). It was decided to follow this recommendation when making the 13″ and 14″ diameter calibration standards for this study. The goal of attenuation compensation was to ensure that the FBH reflectors located anywhere in the test billet would have amplitudes near to or greater than some preset target level, which is typically 80% full-screen height (FSH). Since the FBHs in the new 13″ and 14″ diameter calibration standards were all placed into high-attenuation bands, higher gains were needed to boost their amplitudes to 80% FSH. This approach assures the intended sensitivity is achieved throughout the entire billet. This also tends to reduce any additional gain adjustments needed for attenuation compensation during the inspection of a test billet.

Rotor-grade Ti-6-4 billet material was identified and procured to manufacture these standards. Both 13″ and 14″ diameter pieces passed the conventional inspection and were characterized as typical by their supplier based on observed noise levels. Prior to FBH drilling, these billets were prescanned at General Electric Quality Technology Center (GE QTC) to identify high- and low-attenuation bands as well as check for any possible MZ indications.

For the 14″ diameter billet section, the billet was scanned with the full set of MZ transducers intended for the production inspection of 13″ diameter billet.

A calibration was performed using the GE master calibration standard for 13″ diameter billets that had #3 FBHs at the top and bottom of each of seven zones, as described in Aerospace Material Specification (AMS) 2628. The weakest response of the two holes in each zone was used to set the gain level to achieve 80% FSH. The 14″ diameter billet piece was scanned with this setup using seven scans (one per zone), as shown in figure 1. Also, the center zone of the billet and the back wall were scanned with the transducer designed and built previously in the Inspection Development for Titanium Billet Study for the inspection of this particular zone in 14″ diameter billets. This center zone probe for the 14″ billet is an elliptical element, bicylindrically focused, piezo-composite probe. Its characteristics are described in the Phase II Inspection Development for Ti Billet final report [11], and it is referred to as 14″ diameter center zone transducer 1 in that report. The scans obtained with this transducer are shown in figure 2. Note that the calibration had not been performed for this probe because of the lack of a 14″ diameter calibration standard. A water path of 2.675″ was selected for these measurements based on work performed previously in the Inspection Development for Titanium Billet Study with the chord block that was cut from a section of 14″ diameter billet. The center zone and back-wall scans of the GE master 13″ calibration standard that were performed with this probe as well, and the C-scans are shown in figure 2.

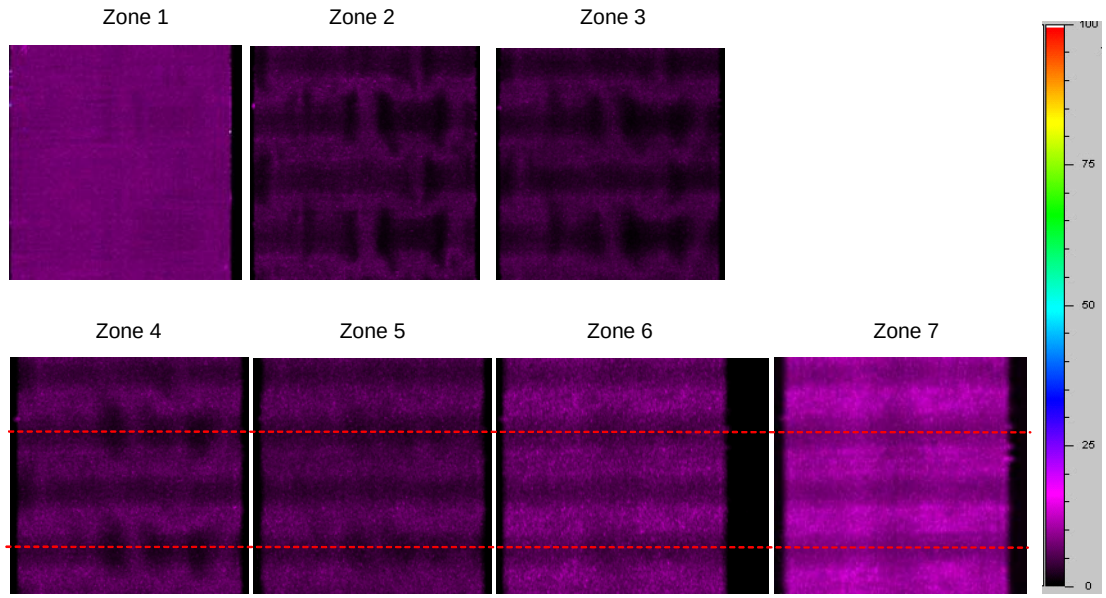


Figure 1. Evaluation of Billet Material Intended for the 14″ Calibration Standard Using the 13″ MZ Production Transducer Set

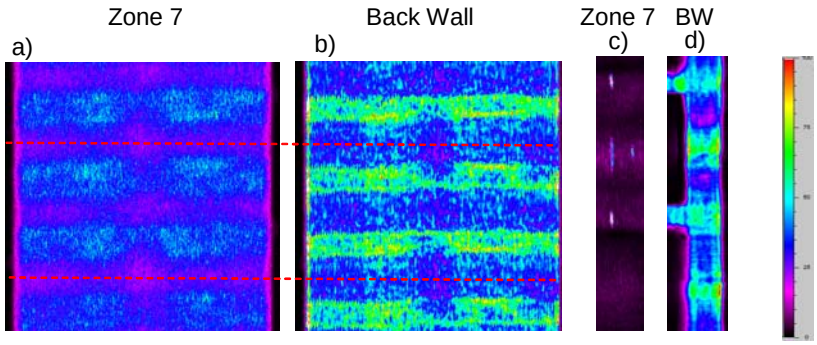


Figure 2. Evaluation of Billet Material Intended for the 14″ Calibration Standard (a and b) and the GE 13″ Master Calibration Standard (c and d) Using ETC Phase II 14″ Billet Center Zone Transducer

In figure 1, one can see that scans for all zones except zone 1 exhibit four bands of high and low attenuation. The zone 1 scan does not have this feature because of the front surface ring-down effect. The four-band, noise/attenuation structure is a result of the fact that the billets are made from rectangular bars, which have four corners. It is unclear whether the corners or the faces of the bar generate the high-attenuation bands. The red dotted lines on the scans in figures 1 and 2 identify the high-attenuation regions where the FBHs were located. Table 1 gives the noise statistics (peak, average, and standard deviation) for high- and low-attenuation regions for each of the scans of the regions of interest.

Table 1. Noise Statistics on the 14″ Diameter Ti Billet Selected to Make a Calibration Standard

	Peak Noise		Average Noise		Standard Deviation	
	Low Attenuation	High Attenuation	Low Attenuation	High Attenuation	Low Attenuation	High Attenuation
Zone 2 (MZ Production 13″ Probe)	11.3	5.9	4.4	1.5	1.3	0.9
Zone 3 (MZ Production 13″ Probe)	11.3	5.1	4.1	1.1	1.3	0.7
Zone 4 (MZ Production 13″ Probe)	14.1	8.2	5.8	2.6	1.5	0.8
Zone 5 (MZ Production 13″ Probe)	12.9	7.0	5.3	2.9	1.4	0.8
Zone 6 (MZ Production 13″ Probe)	14.8	9.4	7.9	4.7	1.7	1.0
Zone 7 (MZ Production 13″ Probe)	23.8	23.4	11.6	7.1	2.1	1.4
Zone 7 (ETC 14″ Center Zone Probe*)	76.1	40.6	34.8	24.6	5.5	3.9
Back Wall (ETC 14″ Center Zone Probe*)	91.0	47.3	55.6	29.5	11.3	4.4

* For evaluations with ETC probe calibration has not been performed
All values are in % FSH

The calibration block for 14″ diameter billet was designed to have #2 and #3 FBHs at the start (top), center, and end (bottom) of each zone. The zoning scheme for the 14″ billet is given in table 2. For all depths up to mid-thickness, #2 and #3 FBHs were placed 180 degrees apart in the attenuation areas of the billet. Cylindrical steps were machined off to accommodate this (see figure 3), and the width of each step is 1.25″. The holes were placed 0.75″ away from the edge of the neighboring step, and all holes were drilled 0.5″ deep. Step edges were tapered to avoid reflection from the sharp edge, which may interfere with FBH response. The holes for the depths of 6.95″ and 7.5″ were spaced 1.25″ apart and were put on the same side of the calibration standard, which happened to be the side (clock position) where the row of #2 FBHs were placed. For the 7.5″ depth, one #2 and two #3 FBHs was drilled.

Table 2. Zoning Scheme for MZ Inspection of 14″ Diameter Billets

Zoning Scheme for 14″ Diameter Billets			
Zone	Start	End	Center
1	0.2	1.0	0.60
2	1.0	2.0	1.50
3	2.0	3.1	2.55
4	3.1	4.2	3.65
5	4.2	5.3	4.75
6	5.3	6.4	5.85
7	6.4	7.5	6.95

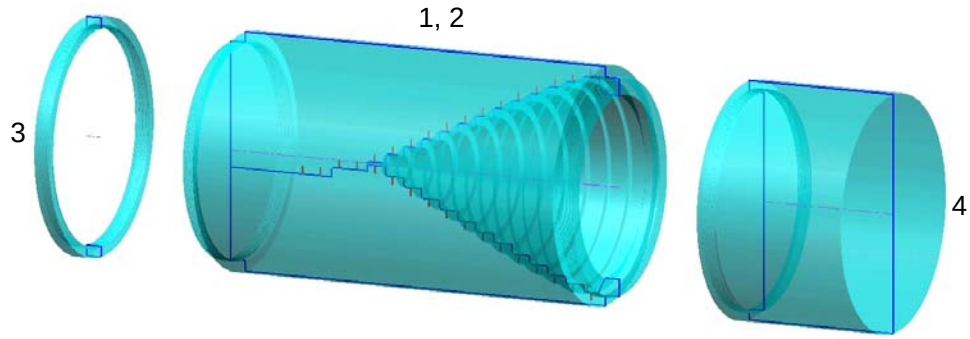


Figure 3. Different Pieces of the Calibration Standard

Figure 4 shows the schematic of the calibration standard. Note that all the above-mentioned FBHs are placed into the high-attenuation bands of the billet. These bands are marked with red dashed lines in figures 1 and 2. Also, it was decided to place #2 and #3 FBHs into a low-attenuation region of zone 5, and figure 5 shows the placement of these FBHs. The FBHs in the low-attenuation region were placed ±45 degrees from the line with #2 FBHs. There is a total of six additional holes: one #2 FBH and one #3 FBH at depths of 4.2″, 4.75″, and 5.3″. Also, the calibration standard has a 9″ long solid piece for attenuation compensation measurements as well as assessment of noise statistics. Overall, the calibration standard consists of four separate pieces: two main pieces with FBHs, an end section for attenuation compensation, and a retaining ring. A side-drilled hole of 0.020″ diameter and 0.5″ depth was placed at the edge of the solid piece, 4.67″ in from the outside diameter. This hole was intended for calibration of the angled conventional inspection.

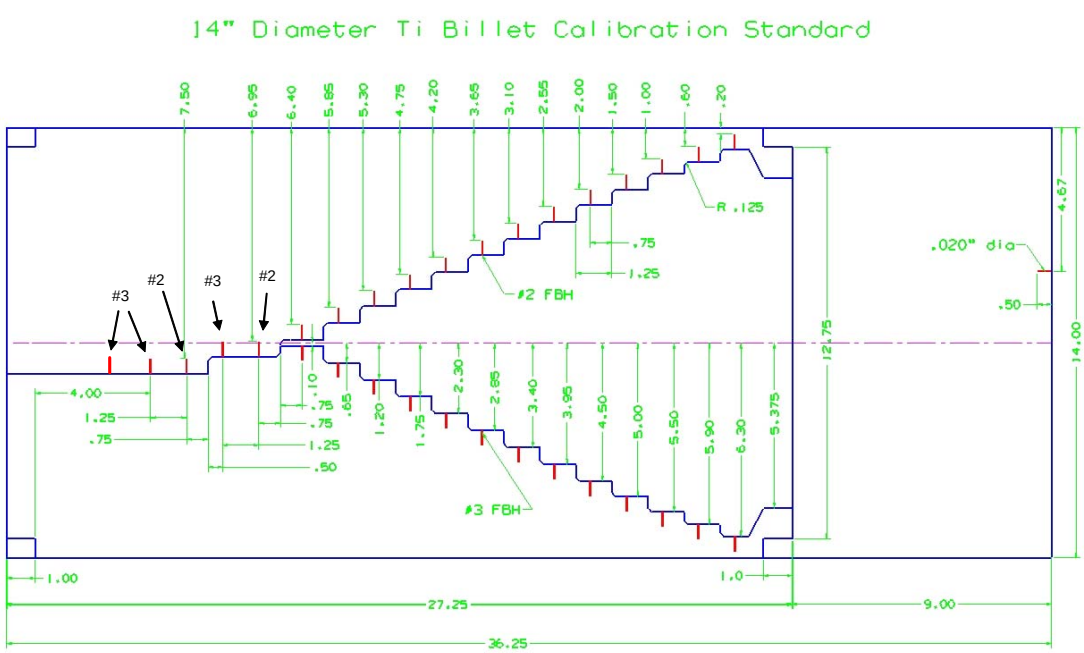


Figure 4. Layout for the 14″ Diameter Ti-6-4 Calibration Standard

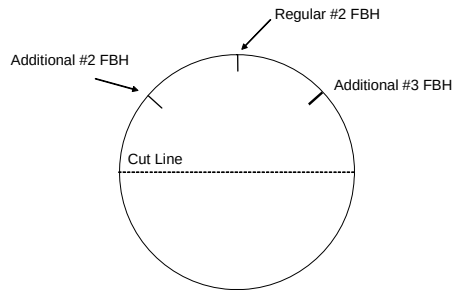


Figure 5. Additional Holes for Zone 5 in Low-Attenuation Regions
(Total six additional holes: #2 and #3 at depths 4.2″, 4.75″, and 5.3″.)

The surface finish of the billet used for the calibration standard was qualified as appropriate for both MZ and conventional inspection by the billet manufacturer.

The 13″ diameter calibration standard was machined following a review of the results of the 14″ calibration standard laboratory results. As with the 14″ billet, a prescan was conducted to assure that the standard billet material was typical of rotor-grade Ti and that it exhibited the noise banding usually seen in Ti billet with no rejectable indications. The billet was marked to identify areas of both high- and low-attenuation positions around the circumference but was not machined until a decision was reached regarding the placement of the FBHs. Following a review of the 14″ calibration standard results and with FAA approval, the 13″ calibration standard was designed to have three complete sets of reference FBHs machined. A set of #3 and a set of #2 FBHs were machined into areas identified as high attenuation and a third set of #2 FBHs machined in an area of low attenuation. Figure 6 shows the FBH positions in the high- and low-attenuation bands.

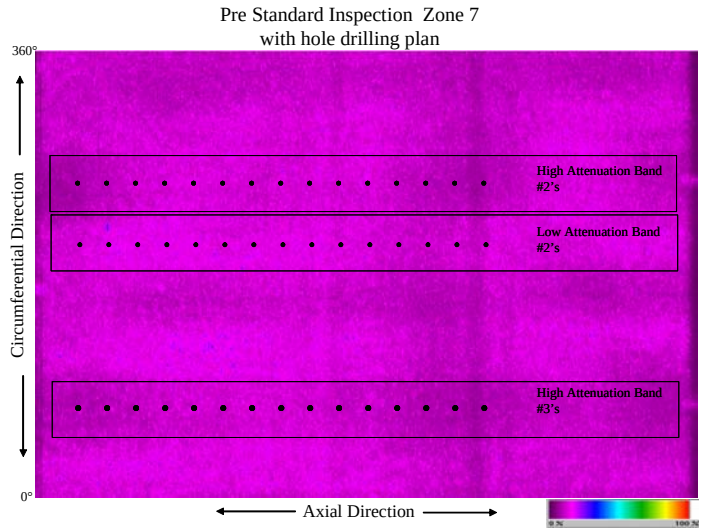
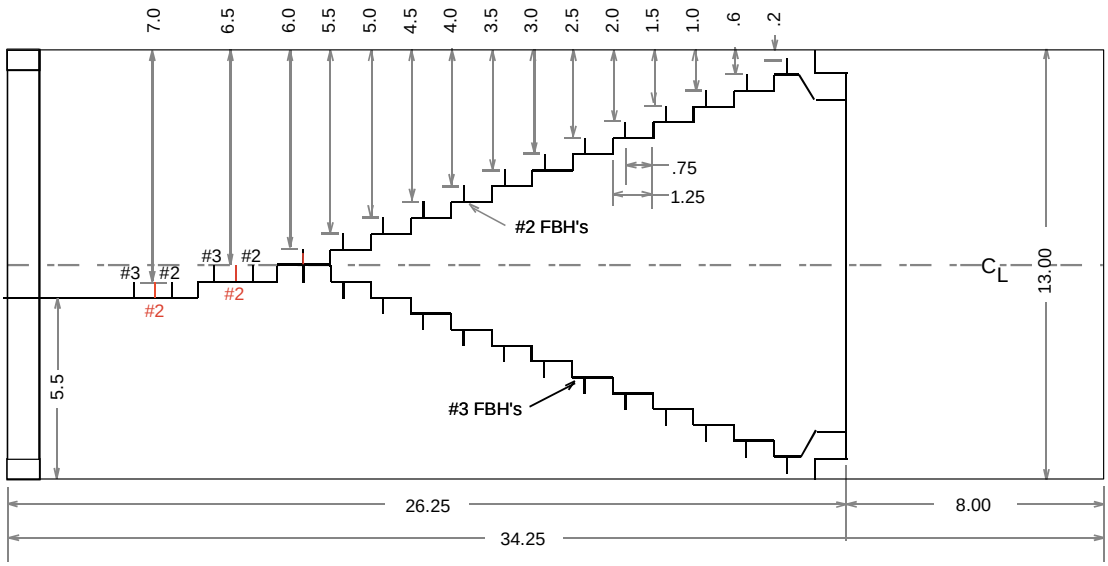


Figure 6. C-Scan of Pre-standard Billet Material Indicating Planned Position of the Calibration Targets With Respect to the Attenuation Bands

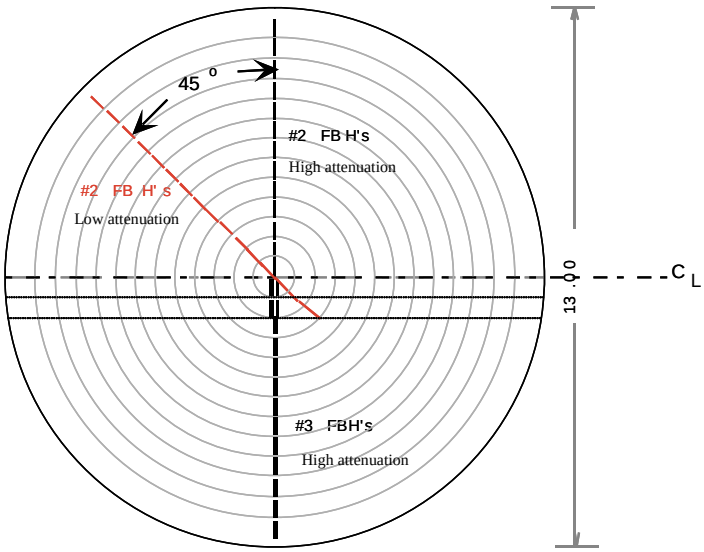
The complete design of the 13″ calibration standard is shown in figures 7 and 8. The #2 and #3 FBHs in the high attenuation were placed 180 degrees apart, while the #2 FBHs in the low attenuation were placed in a position 45 degrees from the #2 FBHs in high-attenuation areas.



Dimensions in inches

All FBH's .5 inches deep. 2/64" and 3/64" diameter

Figure 7. Side Diagram of the 13″ Ti-6-4 Calibration Standard With Hole Depths and Axial Spacing



Dimensions in inches

All FBH's .5 inches deep. 2/64" and 3/64" diameters

Figure 8. End View of the 13″ Ti-6-4 Calibration Standard With Hole Depths and Circumferential Spacing

During machining, the surface finish of the calibration standard remained unaltered from the original finish used for conventional inspection of the billet.

3.2 DESIGN OF MZ TRANSDUCERS.

The transducers for the 14″ billet MZ inspection were designed following the procedure used in the design of MZ production transducers. An overview of the procedure is given below.

The approach was to design circular element, bicylindrical focus, F/10 transducers that focus at the center of the zone for zones 2 through 7. Zones 2 through 7 transducers were designed to have a center frequency of 5 MHz and a bandwidth of 60%. The zone 1 transducer is a 7.5-MHz spherically focused transducer and was not designed using the procedure described here. Starting from an elliptical transducer design, a transducer is characterized by four parameters. There are two transducer dimensions: the diameter in the circumferential direction (D_x) and the diameter in the axial direction (D_y) and two geometrical focal lengths: circumferential (F_x) and axial (F_y).

Ray-tracing calculations are performed based on a bicylindrically focused transducer, which focused at depth F_1 in a billet of radius R made of material with longitudinal wave speed V_1.

Geometrical focal lengths are defined by the following formulae:

$$Fx = wp + F_1 \frac{V_1}{V_0}$$

$$Fy = wp + \frac{F_1}{\frac{F_1}{R} - \frac{V_0}{V_1}\left(1 - \frac{F_1}{R}\right)}$$

where wp is the desired water path and V_0 is the wave speed in water. Transducer dimensions are given by the formulas:

$$D_x = 2\theta_1\left(wp\frac{V_0}{V_1} + F_1\right)$$

$$D_y = 2\theta_1\left[wp\left(\frac{F_1}{R} + \frac{V_1}{V_0}\left(1 - \frac{F_1}{R}\right)\right) + F_1\right]$$

where

$$\theta_1 = \tan^{-1}\left(\frac{0.5}{\frac{F}{D}\frac{V_0}{V_1}}\right)$$

$\frac{F}{D}$ is called F-number of the transducer. It defines the size of the beam at focus, as well as the depth of the field as follows:

$$\text{Beam Diameter} = 1.03\frac{F}{D}\frac{V_0}{f}$$

$$\text{Depth of Field} = 4\frac{V_0}{f}\left(\frac{F}{D}\frac{V_0}{V_1}\right)$$

In this case, $\frac{F}{D} = 10$, R = 7″ for 14″ diameter billet, and F_1 = 1.50″, 2.55″, 3.65″, 4.75″, 5.85″, and 7.00″ for zones 2 through 7, respectively. The resulting geometrical focal lengths are given in columns 5 and 6 of table 3. The resulting probe dimensions are given in columns 9 and 10 of the same table.

Table 3. Design Results of MZ Transducers Intended for the Inspection of 14″ Diameter Ti Billet Material

Zone No.	Zone Start	Zone End	Focus	Nominal		Optimal		Diameter x Ellipse Dimension Circumferential	Diameter y Ellipse Dimension Axial	Effective Diameter of Circular Element	Beam Area (in.^{2})	Equivalent Beam Diameter (in.)
				GFLx* Curvature Circumferential	GFLx Curvature Axial	GFLx	GFLy					
1	0.2	1.0	0.60	6.00	6.00	6.00	6.00	0.625	0.625	0.625	0.013564	0.131
2	1.0	2.0	1.50	6.72	9.25	8.03	12.95	1.12	0.91	1.01	0.016708	0.146
3	2.0	3.1	2.55	7.93	13.63	8.38	15.81	1.69	1.35	1.51	0.015834	0.142
4	3.1	4.2	3.65	8.74	18.21	9.07	20.64	2.29	1.80	2.03	0.015104	0.139
5	4.2	5.3	4.75	9.29	22.80	9.35	24.18	2.89	2.25	2.55	0.014888	0.138
6	5.3	6.4	5.85	9.68	27.38	9.73	28.66	3.49	2.71	3.07	0.014913	0.138
7	6.4	7.5	7.00	10.00	32.18	10.12	33.89	4.12	3.18	3.62	0.014397	0.135

All dimensions are in inches.
*GFL = geometrical focal lengths
Note: The design is based on the approach used to make production MZ transducers.

The elliptical probe dimensions are replaced with one circular dimension, so that it has the same area. It is called the effective diameter of the circular element, and it is marked in red in column 11, table 3. The probe diameter is now fixed. The last step of the design process is the minimization of the beam size within the zone by varying geometrical focal lengths:

$$\min_{F_x, F_y} \left[\text{Maximum beam diameter within the zone from beginning to end}\right]$$

A direct search complex algorithm is used to perform this minimization. The resulting optimal geometrical focal lengths are given in columns 7 and 8 of table 3. The designed probe parameters are marked in red in the table.

The zone 1 transducer does not use this design process. Its main objective is to resolve the near-surface FBH, which is 0.2″ deep. It has a 7.5-MHz center frequency, a 0.625″ diameter, and a spherical focus of 6″.

The zone 7 transducer was made earlier in the program, and it was designed using a similar process. The only difference was that the step of replacing the elliptical dimensions with a circular element design was not performed. Therefore, the zone 7 transducer was built with an elliptical shape.

The zone 1 through 6 transducers were ordered with a circular element design and an operating water path of 3″. This water path differs from the 4″ water path prescribed by the AMS specification and was done to match the 3″ water path of the zone 7 transducer. The shorter operating water path permits smaller elements, however, it introduces a noninterfering water path multiple signal in the billet prior to the back-wall echo. The previously built zone 7 elliptical element transducer was added to the zone 1-6 transducers to form a complete MZ transducer set for the 14″ billet. The primary reason for using circular versus elliptical transducers was to make the alignment process easier and to increase the depth of field. The parameters of all seven transducers that were used in further evaluations are given in table 3.

The transducers used for the 13″ diameter billet study made use of the existing production transducers for zones 1 through 7. In addition, two zone 6 and 7 F/10 transducers were purchased for evaluation using the design procedure as described above. The transducer operating water path was 3.5″, as prescribed in the AMS, and the parameters for the 13″ development set are provided in table 4. The designed parameters are shown in red in the table.

Table 4. Design Results of F/10 Transducers Intended for the Inspection of 13″ Diameter Ti Billet Material

Zone No.	Zone Start	Zone End	Focus	Nominal		Optimal		Diameter x Ellipse Dimension Circumferential	Diameter y Ellipse Dimension Axial	Effective Diameter of Circular Element	Beam Area (in.^{2})	Equivalent Beam Diameter (in.)
				GFLx* Curvature Circumferential	GFLx Curvature Axial	GFLx	GFLy					
6	5.0	6.0	5.50	9.73	26.42	9.80	27.64	3.54	2.61	3.04	0.016879	0.147
7	6.0	7.0	6.50	10.00	30.59	10.04	31.80	4.12	3.02	3.53	0.012456	0.126

All dimensions are in inches.
*GFL = geometrical focal lengths
Note: The design is based on the approach used to make production MZ transducers.

A summary of the design parameters and the actual transducer characteristics used for the zone 6 and 7 evaluations are presented in table 5. It is apparent from the table that the F/10 element diameters (shown in blue) differ from the actual AMS (shown in red) that were a result of earlier manufacturing limitations. The element diameters were, at the time, manufactured in coarser fractional increments.

Table 5. Design Summary of MZ Transducer Set for the 13″ Diameter Ti Billet Evaluation

Zone No.	Zone Start	Zone End	Focus	Diameter x Ellipse Dimension Circumferential	Diameter y Ellipse Dimension Axial	Effective Diameter of Circular Element	AMS 2628 Diameter (Production)
1	0.2	1.0	0.60	0.625	0.625	0.625	0.75
2	1.0	2.0	1.50	1.22	0.96	1.08	1
3	2.0	3.0	2.50	1.80	1.38	1.57	1.375
4	3.0	4.0	3.50	2.38	1.79	2.06	1.75
5	4.0	5.0	4.50	2.96	2.20	2.55	2.35
6	5.0	6.0	5.50	3.54	2.61	3.04	2.35
7	6.0	7.0	6.50	4.12	3.02	3.53	2.35

All dimensions are in inches.

3.2.1 Transducer Characterization—14″ Diameter Billets.

The full set of MZ transducers for 14″ diameter billets is shown in figure 9. Upon transducer delivery, a functional test was performed on the zone balance, and a frequency content was completed. This test is typical of previous MZ transducer evaluations that were routinely performed for production applications.

Figure 9. Multizone Transducer Set for 14″ Diameter Ti Billet

Figure 10 shows a typical waveform and its spectrum for the zone 4 transducer. Waveforms were collected from #2 FBHs at the center of each zone using a nominal water path of 3″. The transducer zone balance of 3 dB was also checked to verify that it could be achieved by varying the water path within 0.5″ from the nominal value.

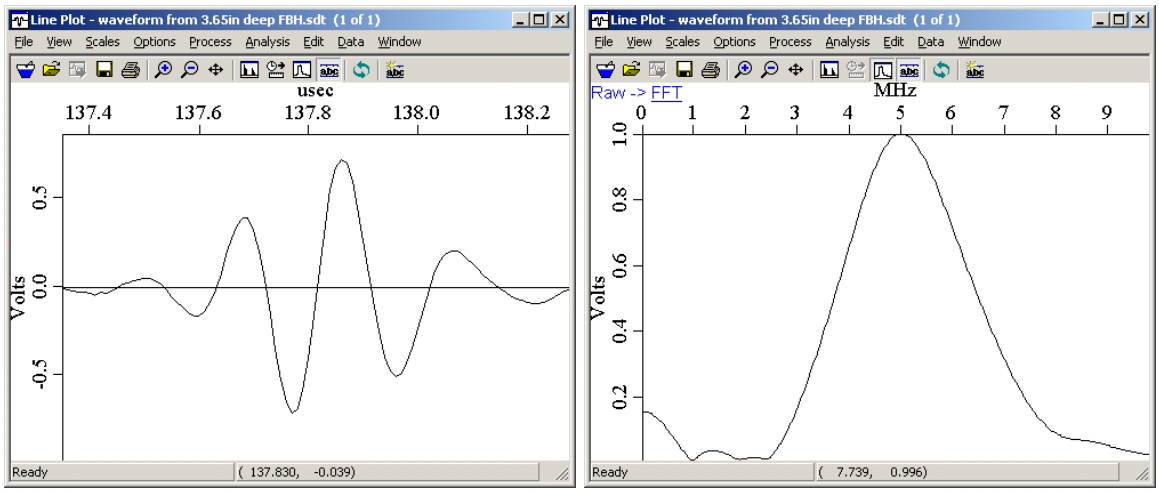


Figure 10. Zone 4 Transducer Evaluation on a 3.65″ Deep #2 FBH, 3″ Water Path

The results of these characterizations are summarized in table 6. All the transducers passed the functional test, with the exception of the zone 6 transducer. The 4.3-MHz center frequency of this transducer was slightly less than the intended minimum of 4.5 MHz. Because the deviation was small, the zone 6 transducer was accepted.

Table 6. Characterization of MZ Transducer Set for 14″ Diameter Ti Billets

Zone No.	Amplitude, % FSH		Balance (dB)	Water Path (in.)	From Middle Hole		
	Shallow Hole	Deep Hole			Center Frequency (MHz)	Bandwidth (%)	Pulse Width (μsec)
1	31*	45		3.0	7.6	57	0.14
2	72	81	-1.0	3.5	5.7	49	0.21
3	50	63	-2.0	3.0	4.9	53	0.28
4	77	64	1.6	3.5	4.9	55	0.33
5	74	96	-2.3	2.5	4.8	55	0.40
6	38	50	-2.4	2.5	4.3	52	0.42
7	77	62	1.9	2.6	5.0	55	0.31

*This hole was not completely immersed in water.

3.2.2 Transducer Characterization—13″ Diameter Billets.

Figure 11 shows the 13″ transducer set containing the newly designed zone 6 and 7 transducers. Upon delivery, the full set of production transducers were characterized using the 13″ diameter calibration standard for frequency, bandwidth, and zone balance. The reflection from the center target hole in each zone was used to capture the waveform of each transducer. A fast Fourier transform (FFT) was then obtained along with bandwidth measurements. Figure 12 shows a typical waveform captured and the resultant FFT.

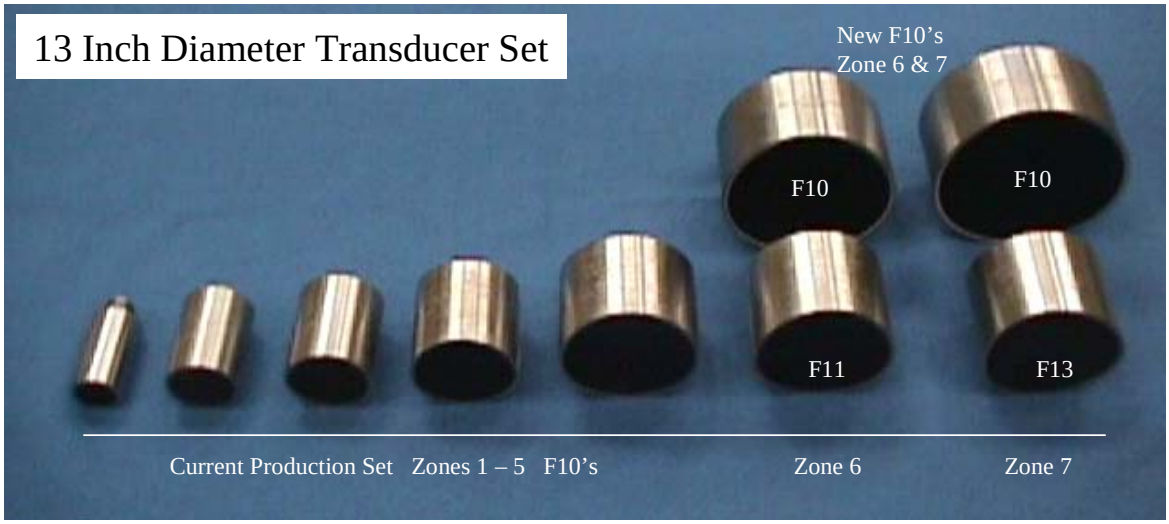


Figure 11. Conventional 13″ Transducer Set With Two Development F/10 Designs

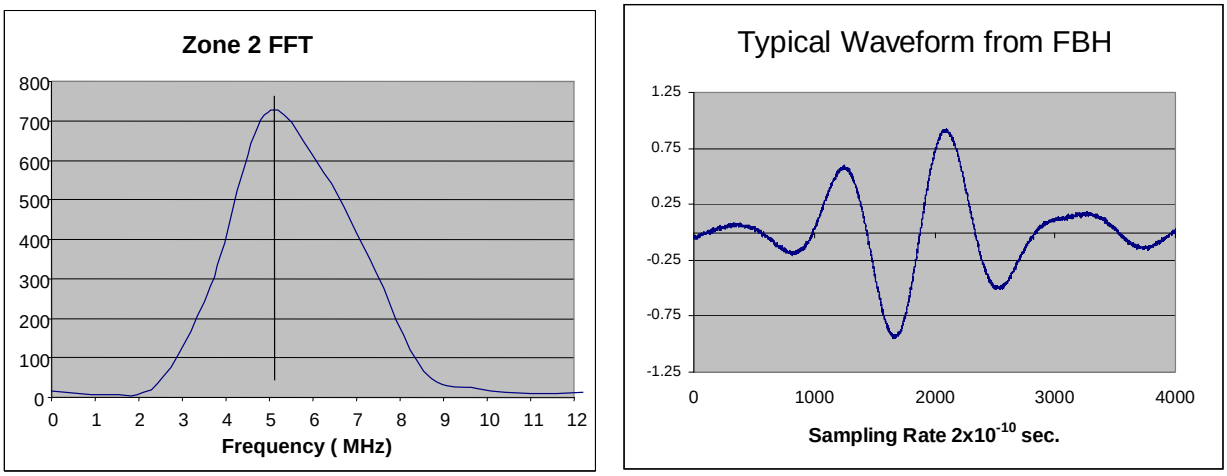


Figure 12. Typical Waveform From Center Hole in a Zone From Which the FFT Was Obtained

The full details of each transducer characterization are contained in table 7.

Table 7. Characterization of MZ Transducer Set for 13″ Diameter Ti Billets

Zone	Amplitude, % FSH		Balance (dB)	Water Path (in.)	From Middle Hole		
	Shallow Hole	Deep Hole			Center Frequency (MHz)	Bandwidth (%)	Pulse Width (μsec)
1	64	60	0.6	2.7	6.1	65	0.25
2	93	83	1.0	2.8	5.1	65	0.28
3	81	84	-0.3	3.1	5.8	50	0.35
4	74	75	-0.1	3.5	5.0	51	0.38
5	82	81	0.1	3.0	4.9	53	0.40
6	88	71	1.9	3.0	4.9	44	0.41
6 (F/10)	86	71	1.7	3.2	4.7	62	0.35
7	83	62	2.5	3.5	4.9	57	0.34
7 (F/10)	63	69	-0.8	3.1	4.0	64	0.39

3.2.3 Pulse Volume Characterization for 13″ and 14″ Transducers.

The 13″ and 14″ transducers were characterized to provide information regarding the pulse volumes. The importance of this characteristic was demonstrated on the 10″ diameter billet and is a useful tool in predicting inspection capability. The pulse volume more fully defines the beam characteristics compared to bandwidth alone because bandwidth does not take into account the beam area. This transducer characteristic is closely related to material noise. In general, the larger the pulse volume, the greater the material noise. The grain size gradient existing across the billet radius is the other component of the total noise picture. The 3 and 6 dB beam dimensions were measured for all three holes in the zone. Using the waveform captured from the center hole in each zone, a 6 dB pulse length was calculated. The pulse length, along with the largest beam area from the three FBHs, provided the data for the pulse volume calculations for each transducer. A Hilbert transformation and envelope were calculated for all the waveforms because they established a consistent means of arriving at ultrasonic pulse length.

Figure 13 shows an example of the Hilbert envelope for one of the zones. The light blue horizontal line is the -6 dB amplitude established from the peak value in the yellow envelope curve. The two intersections of the light blue line with the Hilbert envelope establishes the time duration of the pulse length. Using the 6 dB pulse length, converted to distance in the material, along with the largest area from all three holes of the zone, the pulse volumes (as shown in green) were calculated and are summarized in table 8.

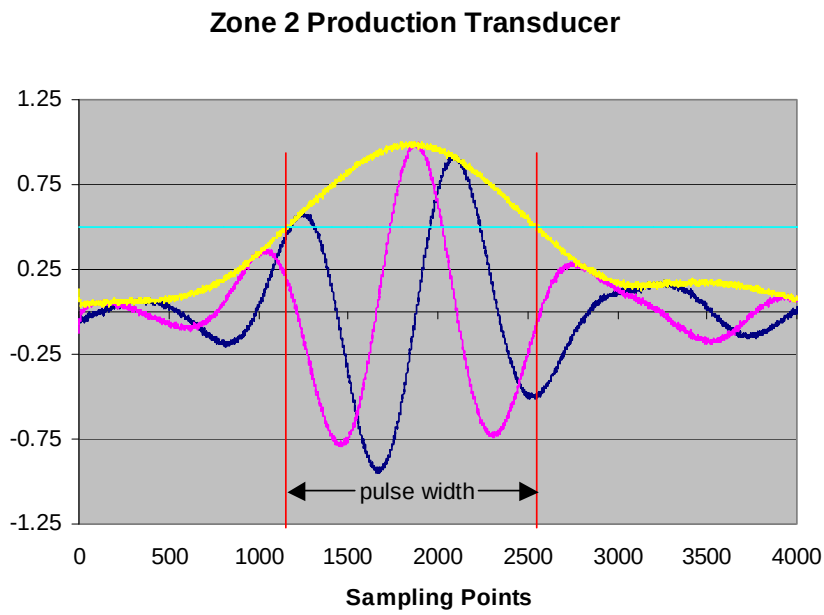


Figure 13. Example of the Hilbert Transformation With Envelope for One of the FBH Signals (The blue line is -6 dB level for the envelope and determines the pulse length in microseconds.)

Table 8. Pulse Volume Calculations

Zone	13″ Transducer Set				14″ Transducer Set			
	Largest Beam Area (in.^{2})	Pulse Length (in.)	Pulse Volume (mils^3)	(Pulse Volume)$^{0.5}$	Largest Beam Area (in.^{2})	Pulse Length (in.)	Pulse Volume (mils^3)	(Pulse Volume)$^{0.5}$
1	0.027	0.061	1663712	1290	0.0024	0.034	80778	284
2	0.015	0.068	993677	997	0.0038	0.052	199942	447
3	0.012	0.085	1048678	1024	0.0102	0.069	700794	937
4	0.018	0.094	1713714	1309	0.0128	0.079	1013598	1007
5	0.020	0.099	2018119	1421	0.0112	0.097	1088987	1044
6	0.027	0.101	2762047	1662	0.0128	0.104	1330087	1153
7	0.041	0.084	3414600	1848	0.0212	0.076	1613475	1270
6 (F/10)	0.013	0.084	1119251	1058				
7 (F/10)	0.017	0.095	1646975	1293				

The graphs in figure 14 summarize the relationships between the square root pulse volumes and the peak noise values on a zone-by-zone basis. In regard to the values used for the 14″ evaluation, the peak noise associated with the 14″ billet was the noise when calibrated to a #2 FBH. These values were normalized to a #3 FBH by dividing the values by 2.25″ so that the noise would be on the same scale as the 13″ billet.

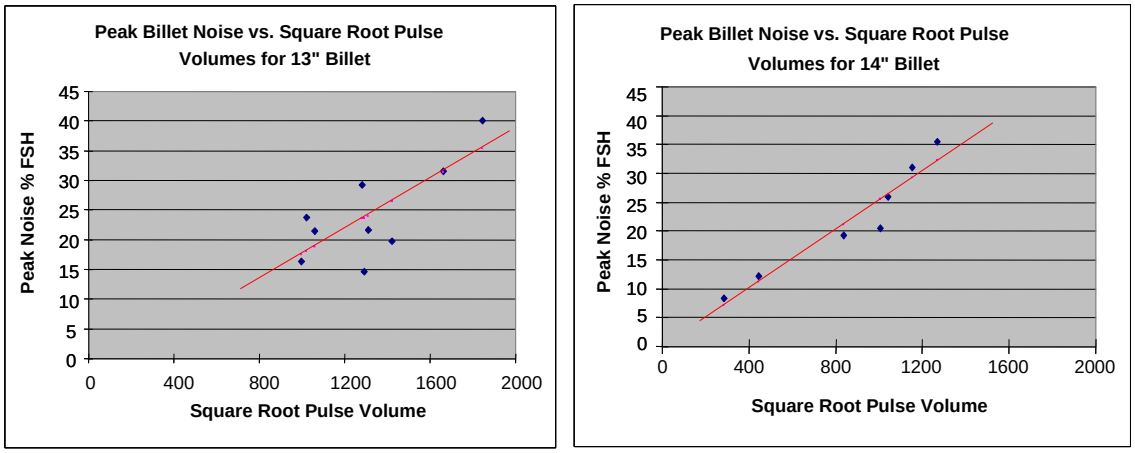


Figure 14. Relationship Between Transducer Pulse Volume and Billet Peak Noise for 13″ and 14″ Transducer Sets

3.3 LABORATORY ASSESSMENT OF CONVENTIONAL AND MZ INSPECTIONS—14″ CALIBRATION STANDARD.

The conventional transducer that was used for the laboratory assessment, a 3/4″ by 1″ cylindrical focus at 7″, 5 MHz, was assumed to be of the same design used by all the suppliers for evaluation of Ti billet.

To make sure that the conventional transducer that was chosen for the evaluation was representative of an industry acceptable transducer, it was sent to a supplier for comparison to their stock of three such transducers. Comparison of gain required to place FBHs at three depths to 80% FSH showed that the Pratt & Whitney (P&W) conventional transducer was equivalent to the average of the three stock transducers. This comparison gave confidence that an inappropriate transducer was not accidentally chosen.

However, when the factory evaluation was performed at this supplier, a newer design for the conventional probe was implemented. The transducer that was used for conventional inspection of pilot plot was a Megasonics 5 MHz 0.75″ element size, 10″ cylindrical focus. It gives better performance for inspection near the center line of the 14″ billet compared to 0.750″ x 1.00″ element size, 7″ cylindrical focus, that was used in the laboratory evaluation. Thus, the laboratory evaluation was not quite equivalent to the factory evaluation for the conventional inspection. The newer probe design used a longer focus and a larger element.

Data was first collected for the 14″ calibration standard with the MZ transducers in the P&W East Hartford immersion tank to evaluate laboratory sensitivity. However, because the depth of the tank was inadequate by 1/2″, one zone could not be completely investigated with the large-diameter transducers using a single setup. Therefore, the calibration standard was sent to GE QTC to facilitate the sensitivity evaluation. After the evaluation data was collected at GE, the standard was returned to the machining vendor to have the mistaken #2 FBHs redrilled to #3 FBHs. The standard was then returned to P&W to perform the sensitivity evaluation with the conventional transducer.

The data produced at GE with the MZ transducers on the 14″ calibration standard was nearly identical to the data for the six zones that could be collected at P&W. Table 9 shows the comparison of the resulting sensitivity values for the data collected at P&W and GE. P&W personnel were involved in data collection at both facilities. The data at GE was analyzed in two fashions: (1) using the setup with the #2 FBHs in the same fashion as the data analysis at P&W and (2) using the #3 FBHs and making the appropriate gain adjustment for a #2 FBH sensitivity inspection. As the values in table 9 show, there is not a systematic difference in the resulting sensitivity values. The sensitivity values were calculated by setting the inspection sensitivity using the FBHs and then performing a scan to find the peak noise value. The sensitivity value is the equivalent FBH size of a signal that is 3 dB above the noise value.

Table 9. Sensitivity Values Determined at GE and P&W for MZ Setup

Zone	Data From GE Using #2 FBHs	Data From GE Using #3 FBHs	Data From P&W Using #2 FBHs
1	1.2	1.1	
2	1.4	1.6	1.6
3	1.8	1.6	2.1
4	1.8	2.0	1.8
5, high attenuation	2.0	1.9	2.1
5, low attenuation	1.6	1.6	1.8
6	2.2	2.3	2.4
7	2.4	2.2	2.4

Note: The zone 1 value for the P&W data is not reported because the transducer could not be completely submerged.

As previously reported, the calibration standard was prepared with the #2 and #3 FBHs placed in the high-attenuation bands of the billet section. The resulting sensitivity values were lower than if the calibration holes were placed in the low-attenuation regions of the billet, i.e., less gain would have been required to bring the FBHs to 80% FSH and the noise values would have been correspondingly lower. However, using calibration holes in the low-attenuation region would result in not having sufficient gain to achieve the desired sensitivity in the high-attenuation regions of a billet causing the potential for underinspection in these areas. For comparative purposes, an extra set of FBHs was placed in the low-attenuation region of the calibration standard for zone 5. An extra sensitivity value was calculated for zone 5 that assumes setup on the calibration holes in the low-attenuation region.

The data that is presented in table 9 and plotted in figure 15 are representative of the sensitivity that can be achieved in a laboratory setting. The setups were made on the FBHs and then scans made on the same sample to determine sensitivity. This condition differs from a factory setup where the transducers are aligned on a calibration sample and then the inspection is performed on a long billet with all its imperfections. The primary problem in such factory evaluations is misalignment of the probes on the billet, which is a concern for both conventional and MZ approaches. As reported in the ETC Open Forum in November 1997 relating the Rolls-Royce study to the Contaminated Billet Study (CBS) billet, probe alignment was identified as the

primary source of error for both conventional and MZ inspections. More recently, analysis performed at ISU on a 12″ billet with seeded defects showed that for highly focused beams, such as in MZ inspections, a sensitivity drop of 8 dB or greater occurs with a 1° misalignment of the probe for zones deeper than 4.5″ [1]. With the myriad of factors that can affect the sensitivity of billet inspection, it should be noted that this limited study may not capture all the factors that occur in a production setting.

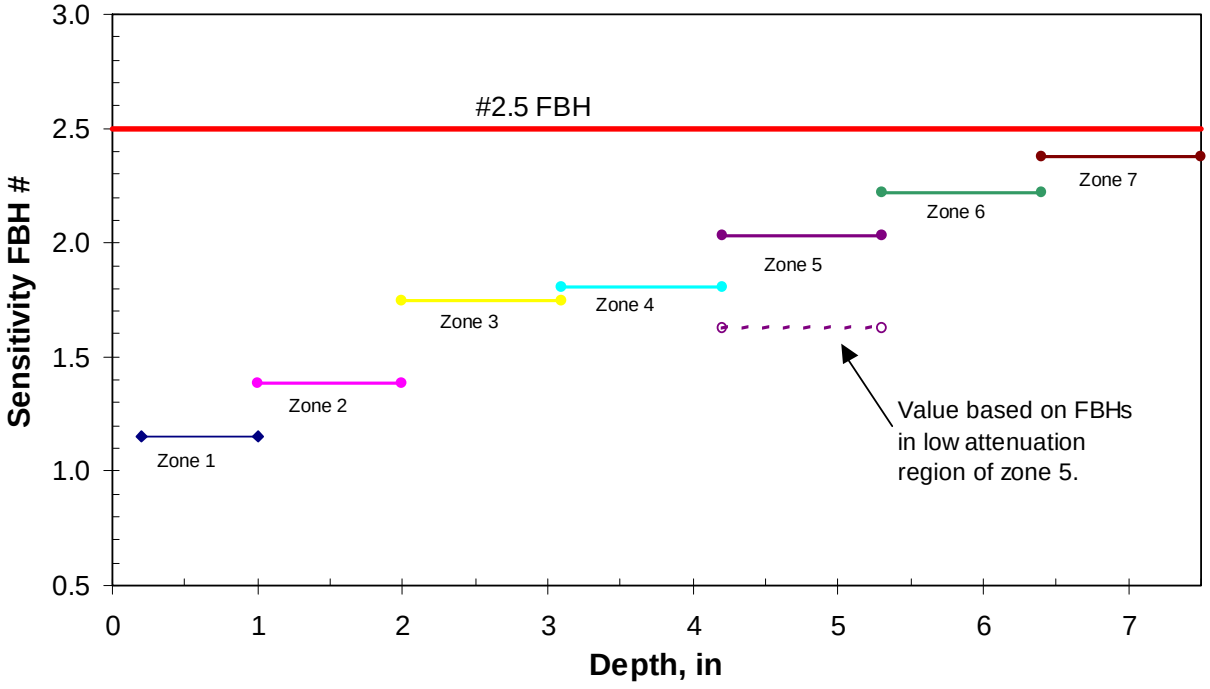


Figure 15. Multizone Transducers Laboratory Sensitivity Plot for a 14″ Billet

Figure 15 shows the laboratory sensitivity plot using the data collected at GE with #2 FBHs in the high-attenuation region of the calibration standard. The zone 5 results indicate that the sensitivity in the low-attenuation region is approximately 0.5 FBH higher than the high-attenuation sensitivity. The sensitivities were calculated using the 3 dB difference between peak noise and signal strength as agreed to previously by the ETC for sensitivity plots.

The C-scans in figures 16 and 17 show the results of scans where the gain values were set low enough to have all FBHs show as unsaturated features. These scans were used to determine the gain settings for the setup that used the #3 FBHs.

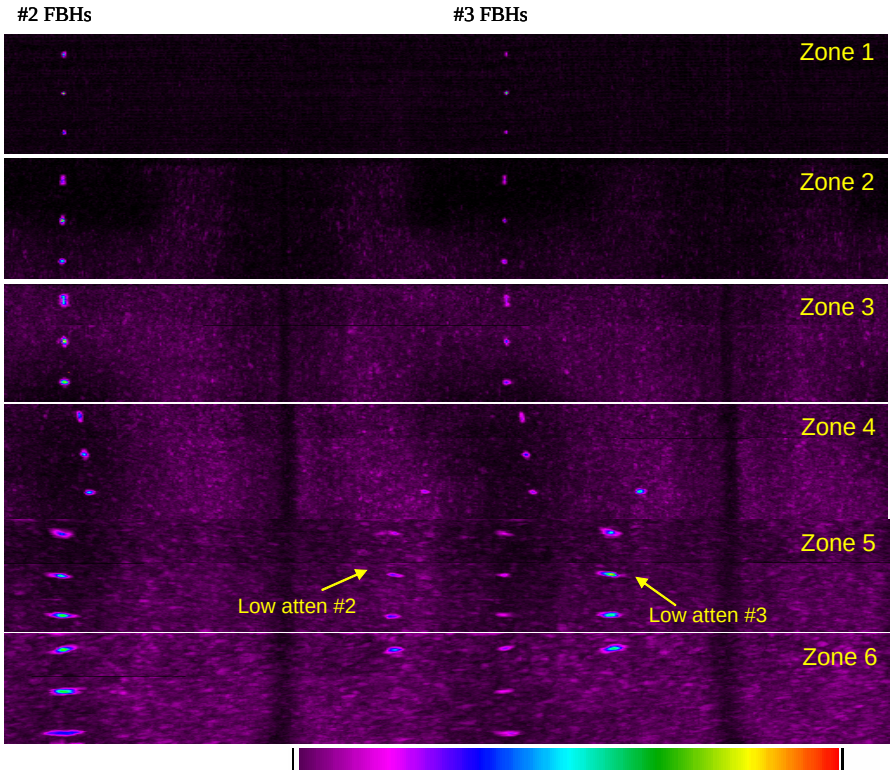


Figure 16. Multizone C-Scans for Zones 1 Through 6 With Gains Reduced to Show All Signals Unsaturated

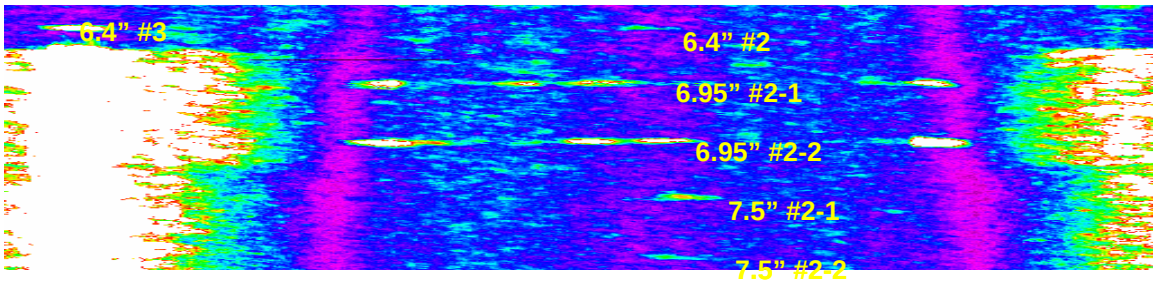


Figure 17. Multizone C-Scan for Zone 7
(The zone 7 scan is complicated by the reflections from the back walls resulting from fabrication of the standard. The holes identified as #2-2 were drilled as #2 FBHs rather than #3 FBHs.)

After the sample was returned from the supplier with the redrilled holes to enlarge the misdrilled #2 FBHs into #3 FBHs, the conventional evaluation was performed at P&W. As with the series of #2 FBHs, the #3 calibration FBHs were placed in the high-attenuation regions of the billet section so that the setup would reflect the required #3 FBH sensitivity in all regions of the billet. The conventional inspection used a distance amplitude correction (DAC) setup so the calibration holes at depths of 0.6″, 2.0″, 3.65″, 5.3″, and 7.5″ were made and the corresponding gain values for the DAC are 8.6, 3.8, 14.2, 24.0, and 28.6 dB, which places the calibration hole signals at 80% FSH. A typical conventional inspection does not use C-scan images, but rather sets an

alarm just above the noise level (but no higher than 70% FSH) with the reject level at 80% FSH. A signal-to-noise reject criteria also exists in the conventional inspection, whereby signals that are 3 dB above background are rejectable.

Both the MZ and conventional laboratory sensitivity levels were calculated using C-scan data so the peak noise value could be captured electronically rather than visually. The P&W conventional inspections require the alarm threshold to be 70% FSH, which is 1 dB below the reject level of 80% FSH. Hence, the sensitivity values in table 10, which are shown in figure 18, show both the 1 dB sensitivity, representing the allowable production practice, and the 3 dB sensitivities, shown for comparison to other plots. Also, instead of the standard production practice of a singe zone, three gates were used for the data collection to show the increase in noise with depth. The highest value for the scan of the full-round section was 1% of the screen height above 70% at the center of the billet. C-scans associated with the three gates were made from the solid, full-round section of the calibration standard are shown in figure 19.

Table 10. Sensitivity Values Based on #3 FBH Conventional Setup

Depth	1 dB Sensitivity (Production Requirement)	3 dB Sensitivity
0″ to 4″	2.2	2.5
4″ to 6″	2.9	3.3
6″ to 7.5″	3	3.4

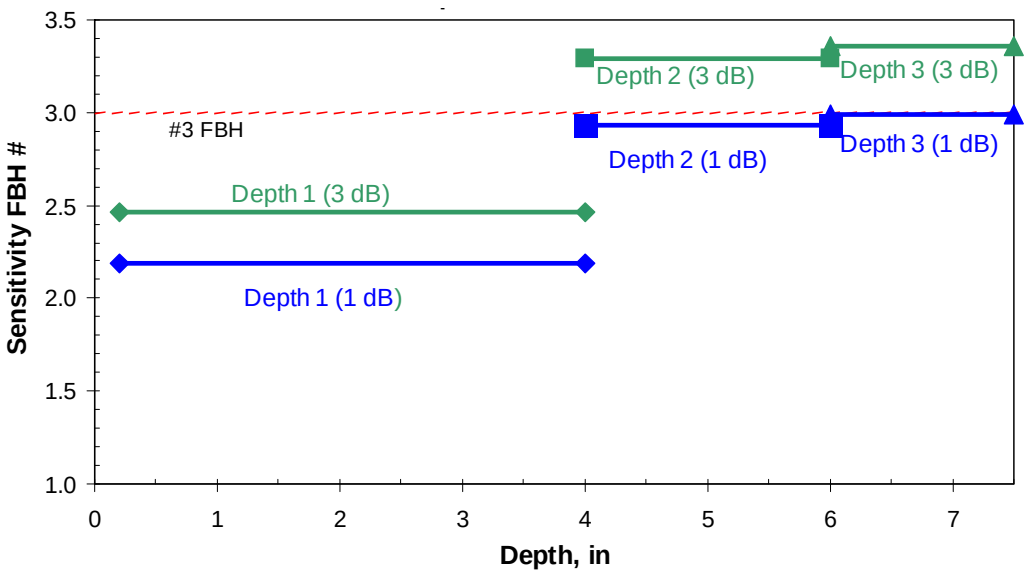


Figure 18. Laboratory Sensitivity Plot for the 14″ Billet With a Conventional Transducer (The 1 dB sensitivity requirement is plotted with blue and the 3 dB comparison is plotted with green.)

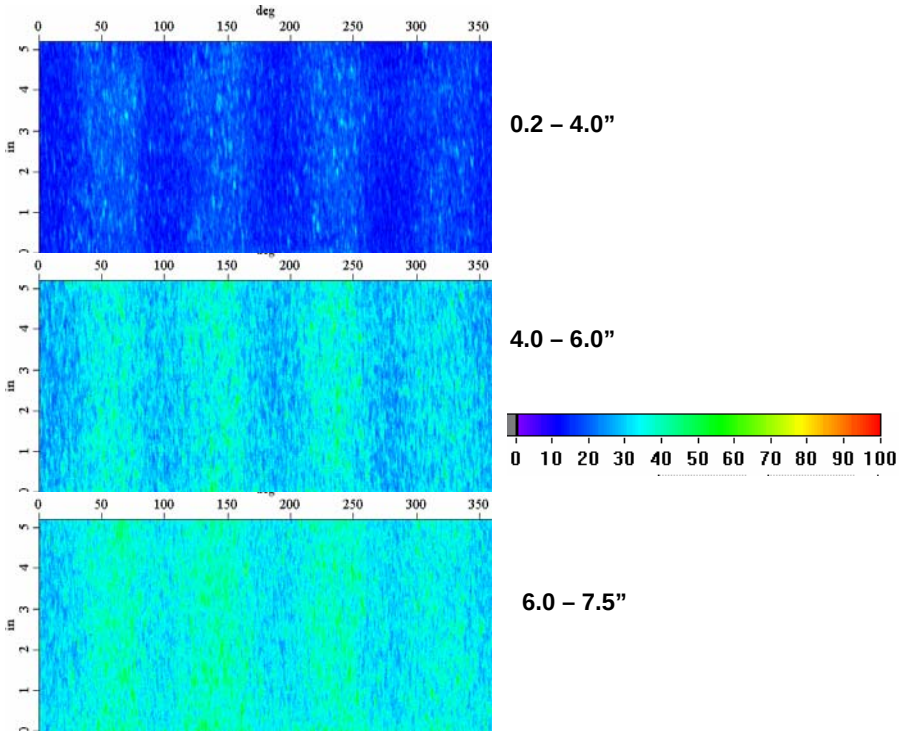


Figure 19. C-Scans Used to Collect the Laboratory Sensitivity Data for the 14″ Billet Section

An inspection of the solid section of the calibration standard was conducted using a conventional angle scan setup with a single gate. The resulting C-scan is shown in figure 20. The peak noise in the angle scan was slightly less than the deep region of the normal incidence scan, indicating that, approximately, the sensitivity was achieved in both inspections.

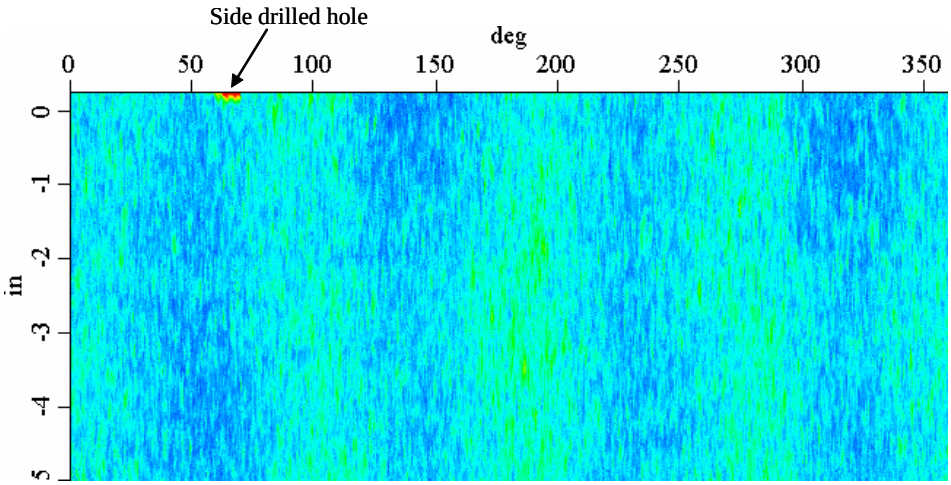


Figure 20. C-Scan With Refracted Longitudinal Setup and Conventional Probe

Figure 21 shows a comparison of the laboratory measurements on the 14″ calibration samples using the MZ probes and the conventional probe. Both the conventional data and the MZ data are plotted to show sensitivity at 3 dB above noise. The conventional inspections performed at the suppliers require 1 dB or greater signal to noise, which is plotted in figure 18 along with the 3 dB sensitivity. Figure 21 also shows the data as if it were collected in three different time gates to illustrate the increase in noise with depth using the conventional probe. For conventional inspections performed at the suppliers, one gate is used from the surface to 0.5″ beyond billet center.

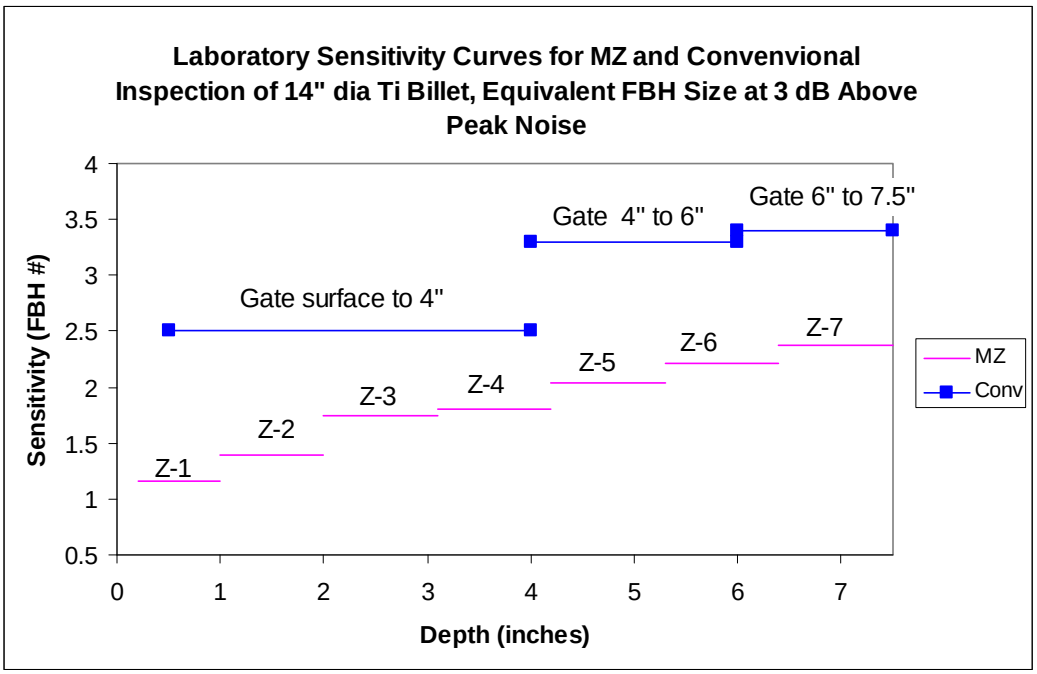


Figure 21. Comparison Plot of MZ and Conventional Laboratory Evaluations at 3 dB Above Peak Noise

3.4 LABORATORY ASSESSMENT OF MZ INSPECTIONS—13″ CALIBRATION STANDARD.

The evaluation plan consisted of calibrating all zones of the production transducers on the #3 FBHs in the ETC calibration standard according to established procedures. The water path was adjusted from the designed 3.5″ operation to achieve the best balance response between the extreme holes for each zone at around 80% FSH. The normal ±0.5″ tolerance in water path from design was not achieved in all cases. A deviation from the normal calibration procedure was to then check the center hole to make sure it was not saturated and the gain adjusted accordingly. The same procedure was followed for calibrating the two F/10 development transducers for zones 6 and 7.

After each zone was calibrated, a C-scan was produced for all the holes in the zone at a 15-mil index. The use of a fine 15-mil index instead of the normal 40-mil index captures as close to the maximum response from the targets as possible so that one could reasonably rely on the C-scans

values in calculating the sensitivity for each zone. The gate had to be shortened and adjusted during these scans to prevent back-wall echoes from obscuring the holes. Finally, the full zone was gated and a C-scan produced for the solid section of the calibration standard. This scan provided the peak noise values used in generating the sensitivity graphs. In addition to the #3 calibration FBHs being imaged, the #2 FBHs were also imaged in the scans.

Figures 22 through 26 show the results of these scans. Each figure is labeled with the maximum noise value obtained from the full-gated section.

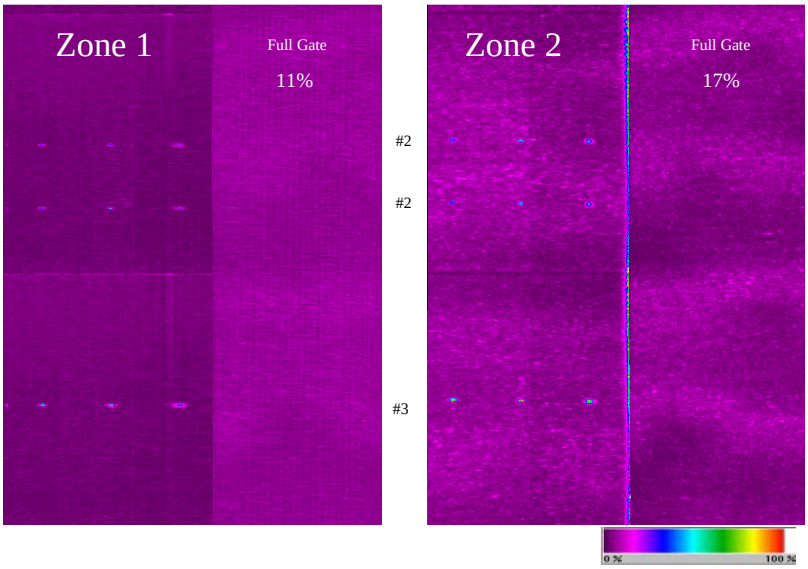


Figure 22. The 13″ ETC Calibration Standard Zones 1 and 2

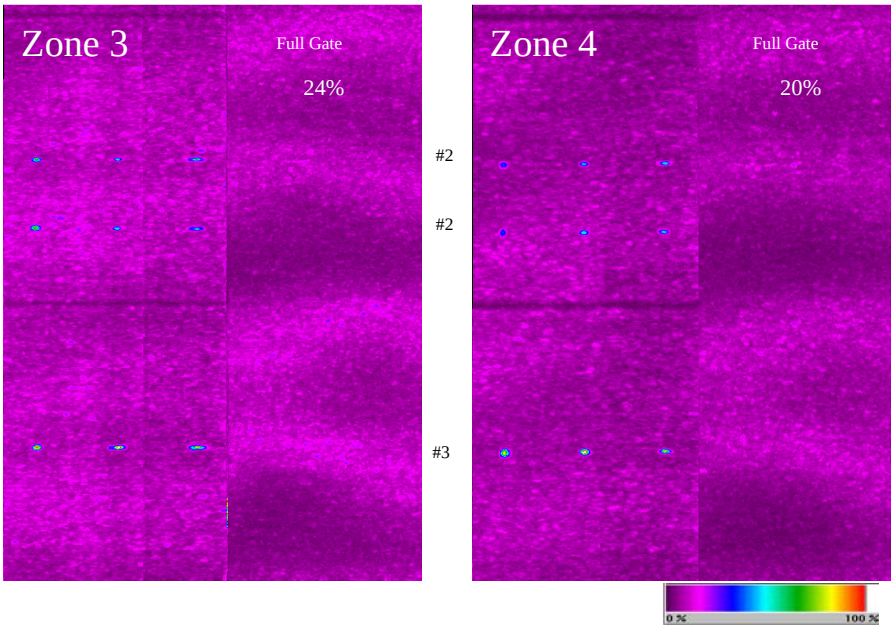


Figure 23. The 13″ ETC Calibration Standard Zones 3 and 4

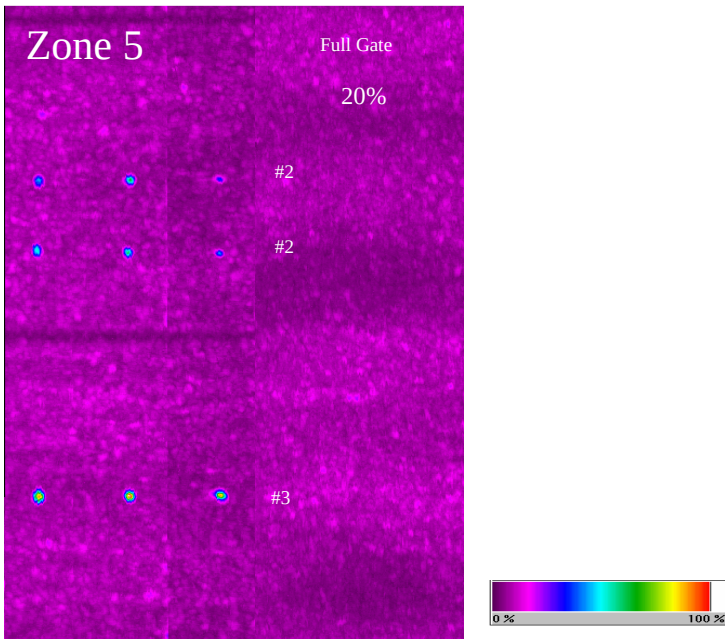


Figure 24. The 13″ ETC Calibration Standard Zone 5

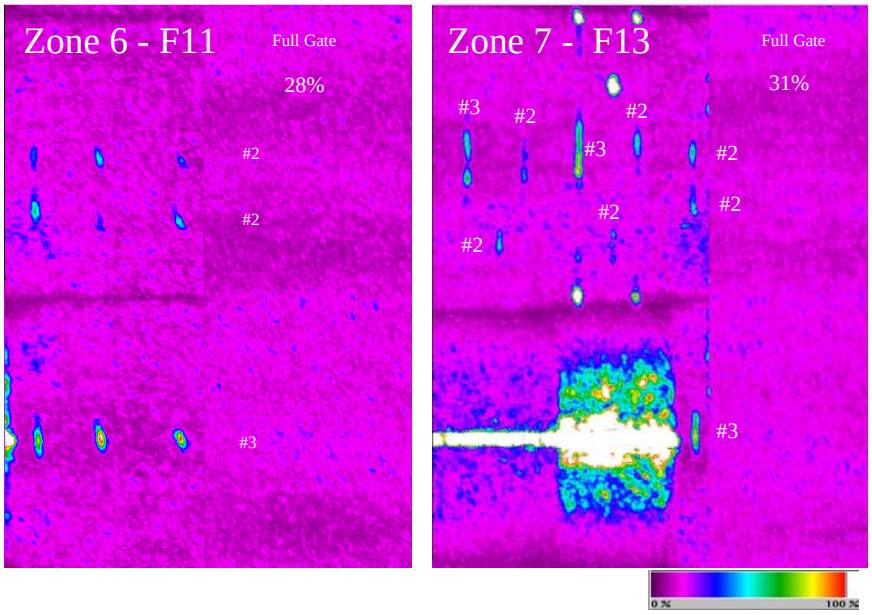


Figure 25. The 13″ ETC Calibration Standard Zones 6 and 7 Production Transducers

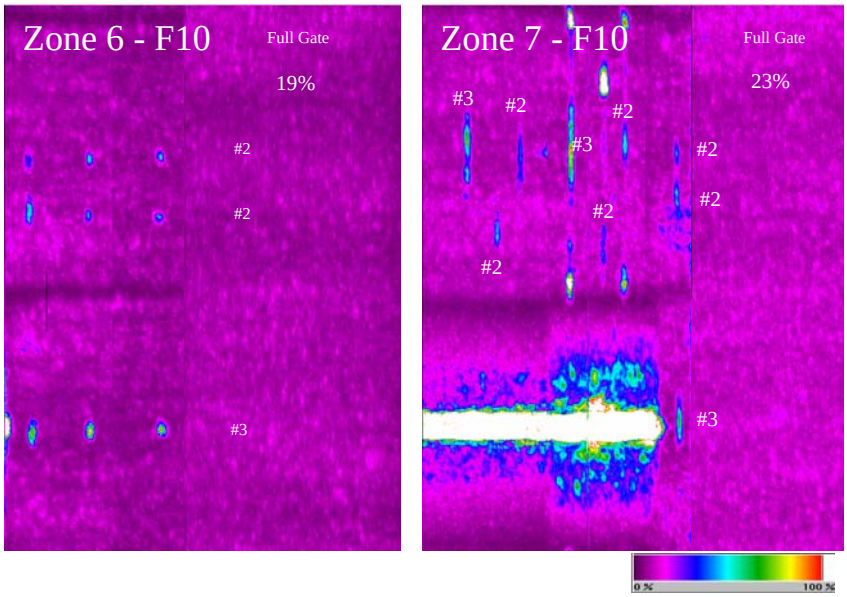


Figure 26. The 13″ ETC Calibration Standard Zones 6 and 7 Development F/10 Transducers

After the C-scans were produced for each zone, the amplitudes of the FBHs were measured from the image. Table 11 is a summary of all the amplitude responses (peak noise and mean noise are shown in green) measured from the C-scan image.

Table 11. Summary of Target Amplitudes for the 13″ Calibration Standard

Zone	#2 FBH High Attenuation			#2 FBH Low Attenuation			#3 FBH High Attenuation			Peak Noise	Mean Noise	Sensitivity FBH #		
	Shadow	Center	Deep	Shadow	Center	Deep	Shadow	Center	Deep			Using #2	#2 Low Att.	Using #3
1	30	44	29	35	47	33	64	86	60	11	6	1.46	1.37	1.53
2	38	56	52	37	59	55	93	85	83	17	5	1.59	1.61	1.61
3	57	51	64	47	49	68	81	93	84	24	8	1.63	1.70	1.94
4	50	42	35	47	48	33	74	97	75	20	7	1.80	1.85	1.85
5	33	56	40	39	53	47	82	91	81	20	7	1.82	1.70	1.77
6	40	48	36	51	33	56	88	95	71	28	12	2.10	2.19	2.24
7	58	56	40	58	47	46	83	84	62	31	13	2.09	1.95	2.52
6 (F/10)	47	50	33	45	41	54	86	94	71	19	7	1.80	1.62	1.84
7 (F/10)	41	53	36	46	36	46	63	90	69	23	10	1.90	1.90	2.15

In generating the sensitivity curves, the lowest amplitude #3 FBH target was then used to calculate the ETC-identified 3 dB sensitivity values for each zone. The 3 dB value was selected to facilitate the comparison of different inspection methods. A second set of sensitivity curves was also generated using the #2 FBHs located in the low-attenuation band of the calibration standard. The peak noise value was obtained from the C-scan of the solid section of the calibration standard, with full gate, and used in the calculation. The resultant sensitivity chart shown in figure 27 indicates the FBH number required to give a response, 3 dB above the peak noise value in each zone.

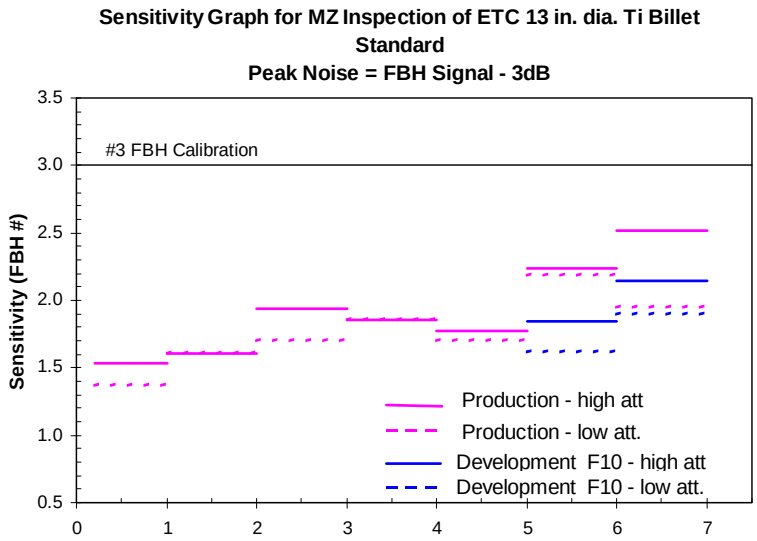


Figure 27. Sensitivity Graph for the 13″ Production and Development Transducer Set (The graph includes the sensitivity that was measured using the low-attenuation #2 FBH targets.)

These curves do show the sensitivity in each zone to be better than a #3 FBH and an indication that the new F/10 transducer provides a significant improvement over the current production units for zones 6 and 7. Figure 27 also indicates the effect on sensitivity caused by placing the FBH in high- and low-attenuation regions. This effect on the sensitivity curves was not unexpected and was documented earlier in the attenuation compensation.

3.5 SIGNAL-TO-NOISE RESULTS ON THE CALIBRATION STANDARDS.

An additional evaluation was made applying a signal-to-noise criteria for identification of the FBH targets. The signal-to-noise ratio (SNR) values were obtained using the amplitudes from the FBHs and the mean and peak noise values in table 12, according to the following formula.

$$SNR = (Amp_{FBH} - Noise_{Mean})/(Noise_{Peak} - Noise_{Mean})$$

Table 12 shows the improvement the F/10 transducer had o the SNR with cells highlighted in green showing SNR greater than values using the production transducer. Cells highlighted in pink are conventional transducers, and cells highlighted in blue are the new F/10 transducers.

It is important to note that the signal-to-noise calculations in table 12 use global peak noise rather than local values normally used in the automated calculations. Because the C-scan files were not large enough to run the automated calculations, the peak values were used. The results of using the maximum peak value in the C-scan will have the tendency to lower the SNR over what might be achieved by using the local values. Finally, the results of using the F/10 transducers designs do show an improvement in the number of FBH targets that would be rejected due to SNR alone.

Table 12. Summary of SNR Obtained From the FBH Targets

Signal-to-Noise Improvement Using F/10 Transducers on 13″ Diameter Billet										
Zone	F No.	#2 High Attenuation			#2 Low Attenuation			#3 High Attenuation		
		Shallow	Middle	Deep	Shallow	Middle	Deep	Shallow	Middle	Deep
1	F/10	4.80	7.60	4.60	5.80	8.20	5.40	11.60	16.00	10.80
2	F/10	2.75	4.25	3.92	2.67	4.50	4.17	7.33	6.67	6.50
3	F/10	3.06	2.69	3.50	2.44	2.56	3.75	4.56	5.31	4.75
4	F/10	3.31	2.69	2.15	3.08	3.15	2.00	5.15	6.92	5.23
5	F/10	2.00	3.77	2.54	2.46	3.54	3.08	5.77	6.46	5.69
6	**F/11**	1.75	2.25	1.50	2.44	1.31	2.75	4.75	5.19	3.69
7	**F/13**	2.50	2.39	1.50	2.50	1.89	1.83	3.89	3.94	2.72
6	**F/10**	**3.33**	**3.58**	**2.17**	**3.17**	**2.83**	**3.92**	**6.58**	**7.25**	**5.33**
7	**F/10**	2.38	**3.31**	**2.00**	**2.77**	**2.00**	**2.77**	**4.08**	**6.15**	**4.54**

FBHs showing increased signal to noise ratios over production F/11 and F/13 designs.

4. FACTORY EVALUATION.

Following the laboratory studies, factory evaluations were planned. This was to survey additional material beyond the small sample afforded by the calibration billets. This also provided an opportunity to compare sensitivities between suppliers and identify any unforeseen problems that might exist in a factory environment. One clear issue observed when making comparisons between conventional and MZ inspection sensitivities was that different standards were used. These differences will have an impact on the resultant sensitivity curves and should be carefully noted. Comparisons were made between the ETC and supplier standards when possible and the difference explained in the text.

4.1 FACTORY EVALUATION OF THE 14″ DIAMETER BILLET.

After completion of the MZ and conventional data collection on the 14″ diameter Ti calibration standard in laboratory conditions at P&W and GE, work was initiated to conduct a pilot lot MZ inspection at a supplier. Several suppliers indicated an interest to participate in the program. Because of low production volumes of this size billet material, the program experienced difficulties in identifying available material and scheduling of its MZ inspection. Ultimately, two heats (20,000 lb) were located at one of the suppliers and two additional heats of 12,000 lb were located at another supplier. The evaluations took place during the second quarter of 2004. The first supplier will be referred to as supplier A and the second as supplier B. All the material inspected in this study was rotor-grade, triple-melt Ti-6-4 billet material and all passed the conventional inspection. Because of the limited inspection opportunity window and the lack of readily available capabilities to collect electronic C-Scans for a conventional system, the decision was made to use the results from production conventional inspection to meet contractual requirements.

The 14″ calibration standard and the full set of MZ transducers designed for the inspection of 14″ diameter Ti billet were used for the MZ inspection evaluation. Conventional inspections were performed with transducers and calibration blocks used by the suppliers in their production conventional inspections. The supplier calibration standards were compared to the ETC calibration standard.

The Attenuation Compensation Study of ETC Phase II recommends that when deducing attenuation compensation values, one should compare zones of high attenuation in the calibration standard to high-attenuation zones in the test billet. This is not a standard MZ production inspection practice. In the standard production practice, the average back-wall signal from the test billet is compared to the average back-wall signal in the calibration standard to deduce the compensation value. It was decided to follow standard production procedure when performing pilot lot MZ evaluations for this study. This was dictated by a limited inspection opportunity window and the program guidelines to follow established production inspection practices.

The conventional inspection at supplier A was performed using a 5-MHz, 0.750″ x 1.250″ rectangular element with a 10″ cylindrical focus. It required 5 dB less gain to set the 7″ deep #3 FBH to 80% FSH in supplier A's calibration chord block compared to the gain needed to set the 5-MHz, 0.750″ x 1.000″, 7″ focus probe to the 7″ deep # 3 FBH in the ETC full-round calibration standard used for laboratory evaluations of conventional inspection at P&W. This is a conventional production inspection probe used by supplier A for the last year.

Table 13 represents peak noise values for eight billets from two heats used in the pilot lot at supplier A. Note that these values are visually estimated readings from the screen since electronic C-scans for conventional inspection were not produced.

Table 13. Peak Noise Values for Conventional Inspection at Supplier A

Peak Noise Values in % FSH for Conventional Inspection (#3 FBH = 80 % FSH)							
Heat 1				Heat 2			
Billet 1	Billet 2	Billet 3	Billet 4	Billet 1	Billet 2	Billet 3	Billet 4
45	45	45	45	40	40	40	40

For the MZ evaluation, the ETC calibration standard was used to select water paths to ensure zone balance, establish gains, gate delays, and lengths for each of the seven zones. The calibration procedure specified for production inspection of the 13″ diameter billets was used in this setup. Back-wall signal comparisons between the calibration standard and tested billets is shown in table 14. It is apparent that seven of the eight billets tested exhibited average attenuation values that were smaller than that of the calibration standard. The overall attenuation difference between the billets and the calibration standard is rather small, since it is measured over 28″ of metal travel. No indications were detected in the pilot lot billets using MZ dynamic threshold software. Peak noise values were recorded for each of the generated C-scans. These values were used to generate the inspection sensitivity curves shown in figure 28. In generating these curves, it was assumed that the signals from a #3 FBH placed within the zone would generate a signal with an amplitude equal to 80% FSH.

Table 14. Back Reflection Comparison Between Billets and Calibration Standard at Supplier A

Difference in dB Between Back Reflection in Billet and Calibration Standard							
Heat 1				Heat 2			
Billet 1	Billet 2	Billet 3	Billet 4	Billet 1	Billet 2	Billet 3	Billet 4
1.9	-1.3	3.6	1.9	3.4	2.1	0.6	4.9

Positive number means that back reflection in the standard is stronger than in calibration standard.

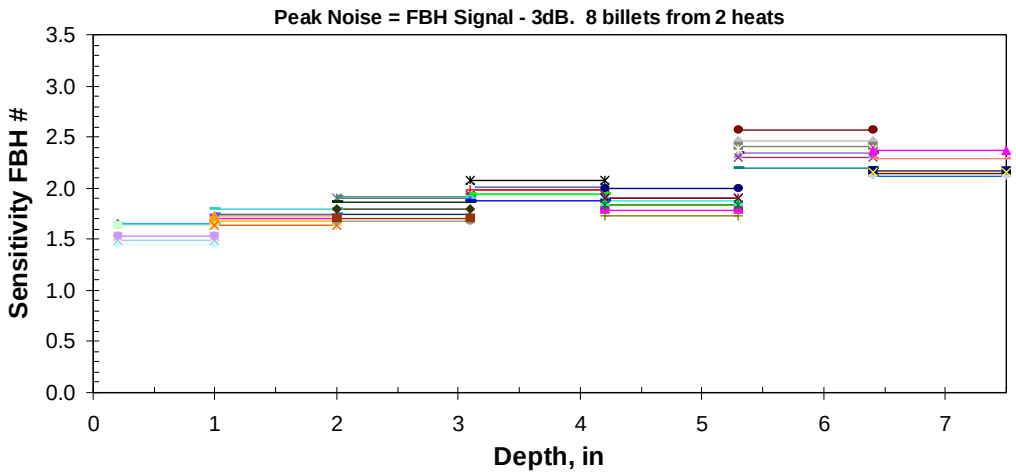


Figure 28. Sensitivity Curves for Pilot Lot MZ Inspection of 14″ Diameter Ti Billet Material at Supplier A

In comparing the sensitivity graphs for the laboratory and factory evaluations, it was noted that there was not total agreement in the resultant curves. This may in part be due to the FBH used for calibration. The laboratory sensitivity curves shown in figure 15 were generated using the values from the #2 FBHs. The factory evaluation was calibrated using the #3 FBHs. In an ideal world, the size of the FBH used for calibration would not have any effect on the sensitivity results. However, the actual responses from #2 to #3 FBHs can vary more than the theoretical 2.25 to 1. In the case of the #2 FBH calibration conducted in the laboratory, the imbalance between the holes was 1.1 dB. At this water path, the imbalance between the #3 FBHs was greater than 6 dB. If one assumes that one of the #3 FBHs was giving an unusually weak response, the calibration procedure would require that the transducer water path be adjusted to balance the targets to within 3 dB, consequently a higher calibration gain is required. For the laboratory evaluation, a water path was chosen to achieve the best balance between the #2 FBHs with the #3 FBHs, indicating as much as 6 dB variance in the balance between the holes. If the #3 FBH sensitivity values listed in table 9 were used, the resultant curves would show similar sensitivity pattern to the factory results.

Another potential cause for some of the differences in the sensitivity curve is the larger sample size involved in the factory evaluation. This presents the opportunity for greater noise indications relative to the very small sample size afforded by the calibration standard. However,

this potential for increased noise was not true in all cases; for some of the factories, deeper zones that showed improved sensitivity compared to the laboratory results.

A direct comparison of MZ and conventional sensitivity for the pilot lot evaluations at supplier A are shown in figure 29. All data was plotted with a 3 dB signal to noise for the eight billets. The MZ values for peak noise are taken from the C-scans and the conventional values for noise, as shown in table 13, were recorded on the inspection sheet by the operator.

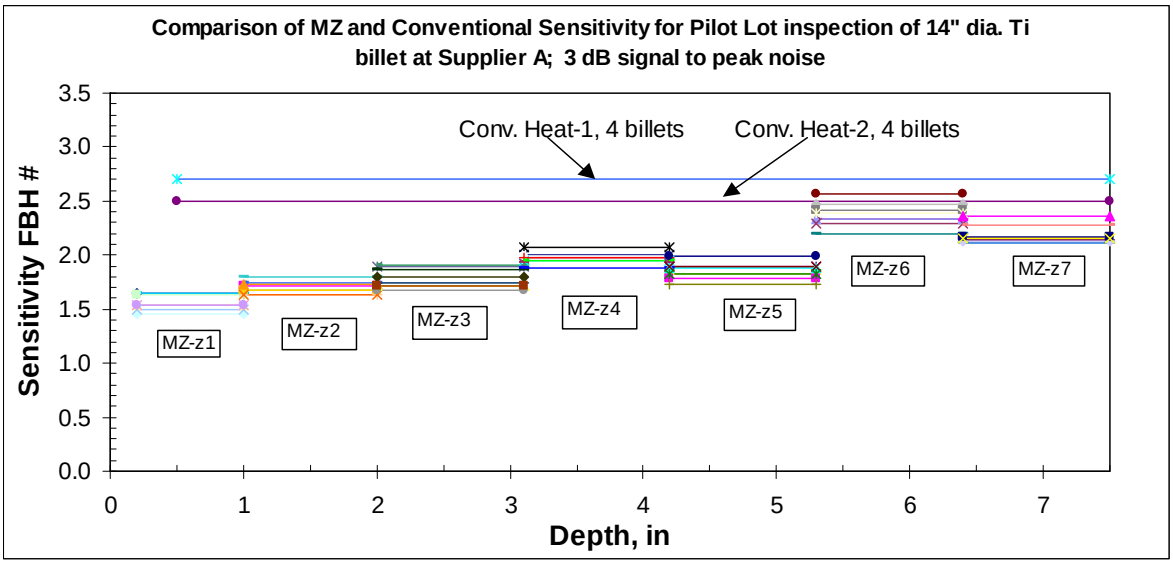


Figure 29. Comparison of MZ and Conventional Factory Evaluation Sensitivity for the Eight Billets Inspected at Supplier A

A comparison between the supplier A conventional standard and the ETC standard was also performed using the conventional inspection transducer. The results are given in table 15. One can see that the difference in response from 7.0″ deep holes is only 2.5 dB. This translates into an attenuation difference of 0.18 dB/in., with the ETC standard being only slightly more attenuative.

Table 15. Comparison of ETC and Supplier A 14″ Calibration Standards

ETC 14″ MZ Standard		Supplier A 14″ Block Set	
Hole Depth (in.)	Gain Required to Set #3 FBH to 80% FSH	Hole Depth (in.)	Gain Required to Set #3 FBH to 80% FSH
0.6	61.5 dB	0.5	63.9 dB
1.5	57.2 dB		
2.0	58.2 dB		
3.65	62.6 dB	3.5	65.2 dB
6.95	83.6 dB	7.0	81.1 dB

Conventional inspection at supplier B was performed using a 5-MHz, 0.750″ x 1.000″ rectangular element with 7″ cylindrical focus. This probe is very similar to the probe used for laboratory evaluations of conventional inspection at P&W. Table 16 shows the peak noise values for four billets from two heats used in the factory evaluation at supplier B. Note that these values are readings from the screen, since electronic C-scans for the conventional inspections were not produced.

Table 16. Peak Noise Values for Conventional Inspection at Supplier B

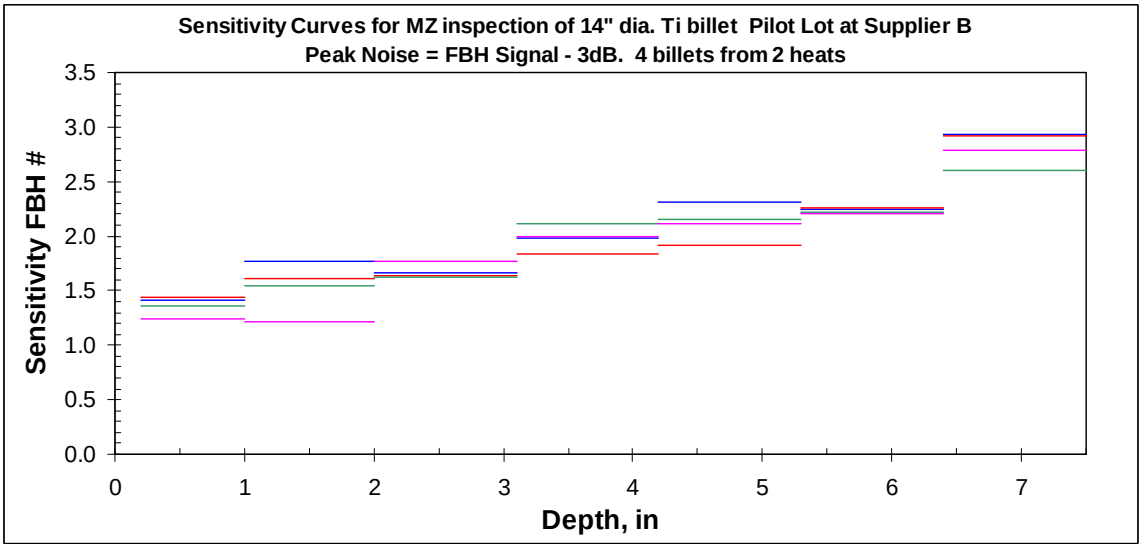
Peak Noise Values in % FSH for Conventional Inspection (#3 FBH = 80% FSH)			
Heat 1		Heat 2	
Billet 1	Billet 2	Billet 1	Billet 2
50	50	55	55

For the MZ evaluation, the ETC calibration standard was first used to select water paths that ensure zone balance, select gains, and establish gate delays and lengths for each of the seven zones. The established calibration procedure for production inspection of the 13″ diameter billets was used in this setup. A back-wall comparison of the calibration standard and tested billets is shown in table 17. One can see that all billets exhibit average attenuation values that were smaller than the calibration standard. Negative attenuation compensation was not applied prior to data collection. Negative attenuation was used, however, during data analysis to correct for attenuation differences between the calibration block and the inspected billet. No indications were detected in the pilot lot billets using MZ dynamic threshold software. Peak noise values were recorded for each of the generated C-scans and adjusted based on attenuation difference. These values were used to generate the inspection sensitivity curves shown in figure 30. These curves were generated such that the signals from a #3 FBH placed within the zone would generate a signal with an amplitude equal to 80% FSH.

Table 17. Back Reflection Comparison of Billets and Calibration Standard at Supplier B

Difference in dB Between Back Reflection in Billet and Calibration Standard			
Heat 1		Heat 2	
Billet 1	Billet 2	Billet 1	Billet 2
2.6	3.2	3.7	6.7

Positive number means that back reflection in billet is stronger than in calibration standard.



Results for each billet are presented with its own color

Figure 30. Sensitivity Curves for Factory Evaluation of MZ Inspection of 14″ Diameter Ti Billet Material at Supplier B

A direct comparison of MZ and conventional sensitivity for the pilot lot evaluations at supplier B are shown in figure 31. All data was plotted with a 3 dB signal to noise for the four billets. The MZ values for peak noise are taken from the C-scans and the conventional values for noise, as shown in table 16, were recorded on the inspection sheet by the operator.

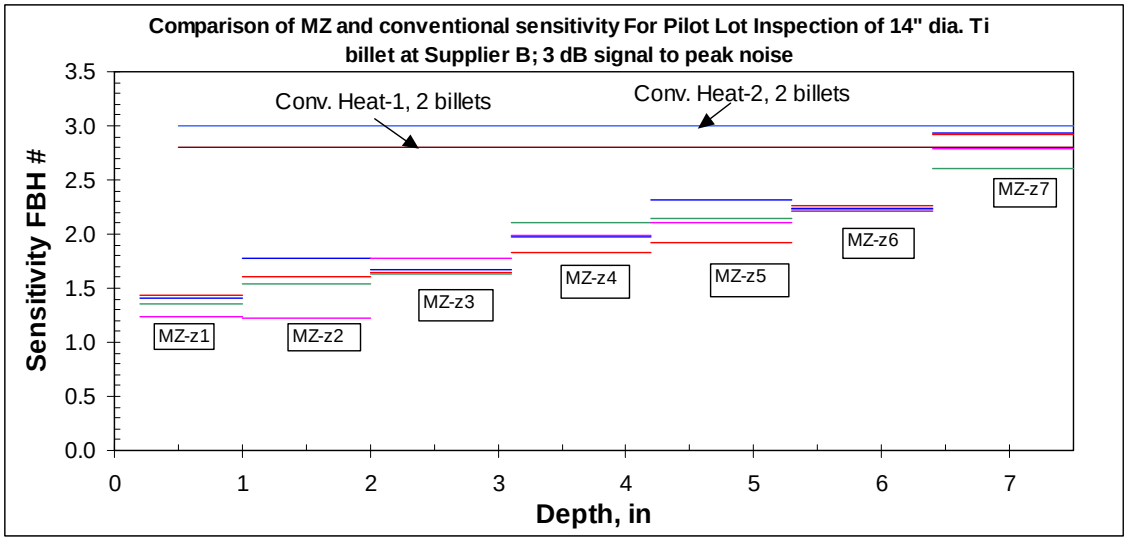


Figure 31. Comparison of MZ and Conventional Factory Evaluation Sensitivity for the Four Billets Inspected at Supplier B

During the factory evaluation it was observed that for both the 13″ and the 14″ MZ transducers, the larger diameters that were used did not allow a full set of transducers to fit on the existing billet followers. The followers that hold the transducers would have to be reconfigured to accommodate these larger transducers.

The evaluation of 12,000 lb of 14″ billet material at supplier B was performed in June 2004.

4.2 FACTORY EVALUATION OF THE 13″ DIAMETER BILLET.

The factory evaluation of the 13″ diameter billet took place at supplier A during the second quarter of 2004. Initially, one heat (10,000 lb) was identified for inspection. Several weeks later, an additional three heats were identified and inspected. This material was also inspected using a conventional inspection procedure. All the 13″ material inspected was Ti-6-4 triple-melt, rotor-grade material with surface finishes acceptable to MZ inspection.

The inspection evaluation consisted of using only the two deep zones (zones 6 and 7) of the MZ production alongside the two newly developed F/10 transducer designs. The following calibration procedure was followed for both transducer sets. Using the #3 FBHs in the 13″ ETC standard, the signal response from the top and bottom holes of each zone were balanced to within 3 dB by adjusting the transducer water path. The instrumentation gain was adjusted to bring the weakest response to 80% FSH.

Normal production attenuation compensation procedures were used by comparing the average back-wall response from the calibration standard to the average back-wall response from the billet under inspection. All the billets were less attenuative than the ETC standard, with the most extreme difference being 1.7 dB over 13″. Thus, no attenuation correction was required.

Conventional inspection of the 13″ diameter billet was performed in a similar manner to the 14″ diameter billet inspection using the same transducer and calibration standard. The 14″ diameter standard at supplier A is used for both 13″ and 14″ diameter product. Peak noise for the four heats were reported to be between 35% and 40% FSH at #3 FBH 80% calibration. A comparison of the 7″ deep #3 FBHs in the ETC standard and the suppliers calibration standard indicated 8 dB of additional gain was required to calibrate the ETC standard. If one assumes that most of the noise comes from the deepest regions of the billet, one can project what the peak noise would be for conventional inspection, if the ETC standard was used for calibration. At 8 dB, this noise value would project to be 100% FSH.

The sensitivity curves shown in figure 32 show the results of the factory evaluation on all the heats inspected and represent the capability improvement achieved by using the development F/10 transducers in place of the existing production transducers. The conventional results were also identified on the same graph for comparison. The sensitivity curves were calculated by using the peak noise value from all the billets inspected. Two sensitivity values were calculated for the zone 7 F/10 inspections that represented the results obtained from the first heat and heats 2-4. A look into the noise statistics between the two inspections indicate that the sensitivity difference is not likely a result of material processing variation but rather in the calibration of the zone 7 transducer.

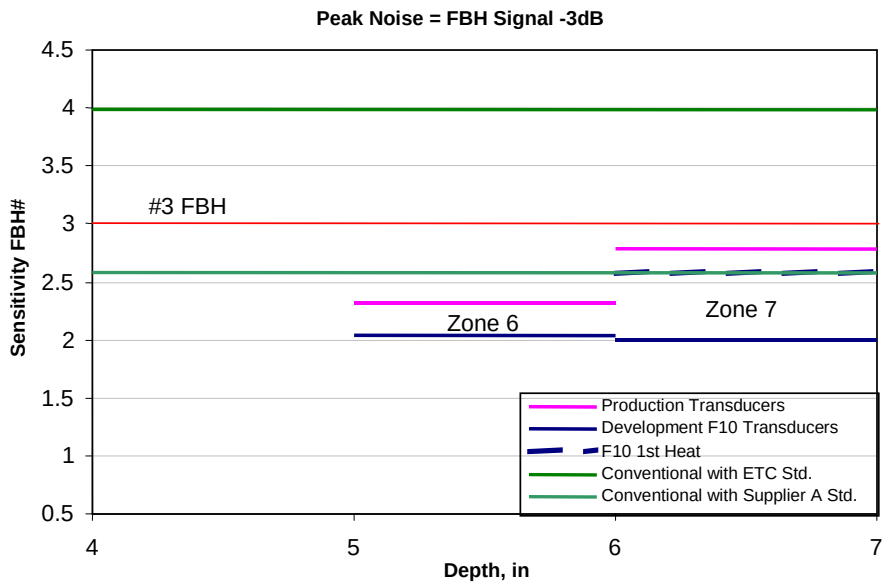


Figure 32. Sensitivity Curves for Factory Evaluation MZ and Conventional Inspections of the 13″ Diameter Ti Billet at Supplier A

A summary of the noise statistics for heats 1 through 4 is presented in table 18. The average and peak noise for three of the four transducers used indicated a reasonably consistent range of values. However, the zone 7 mean and peak noise is noticeably different between the first and second inspections. This behavior is more consistent with a variation in the calibration procedure.

Table 18. Noise Statistics for Billet Heats 1 Through 4 Identified per Zone

Mean and Peak Noise Statistics for Heats 1 through 4								
	Zone 6 F/11		Zone 6 F/10		Zone 7 F/13		Zone 7 F/10	
Heat	Mean	Peak	Mean	Peak	Mean	Peak	Mean	Peak
1	10.5	31.0	7.8	25.0	16.8	49.0	14.0	42.0
2	10.7	34.0	7.7	24.0	17.3	49.0	8.0	24.0
3	10.5	31.0	7.8	26.0	16.2	45.0	8.2	25.0
4	11.0	29.0	7.8	22.0	17.0	49.0	8.0	25.0

Of the four heats inspected, there was one reject indication found in zone 7, (6.0″ to 7.0″ deep) with the development F/10 transducer. This indication had an SNR of 2.51 and an amplitude of 32% FSH, as determined by the MZ-automated SNR software. A relocation of the indication days later gave an acceptable SNR of 1.6 but was still identifiable in the C-scan image. Figure 33 shows the indication as it appeared in the first and second inspections at supplier A. The ETC requested to purchase this indication for further study and a section of billet was delivered to GE. Several attempts were unsuccessful, and the billet was returned to the supplier.

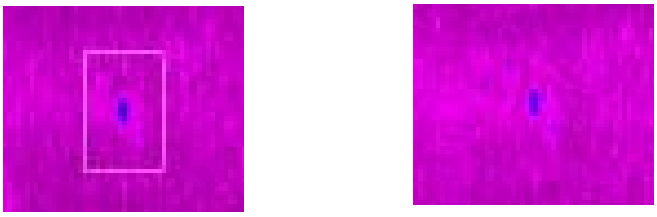


Figure 33. Zone 7 MZ Indication Found in 13″ Diameter Ti Billet

One benefit of the reduced material noise offered by the new F/10 transducer designs was the reduction in the number of signals requiring evaluation. Evaluation signals are signals exceeding a specific amplitude value based on the inspection index. For example: if a 3 dB beam index is used for scanning, all signals that are equal to or greater than 3 dB below the reject amplitude need to be evaluated by returning or stopping over the indication and peaking up to get the maximum response from the indication. The less often this evaluation occurs, the better for productivity. Of the four heats inspected, there were a total of 24 signal amplitudes exceeding the evaluation threshold using the old production zone 7 F/13 transducer, whereas there was only one amplitude exceeding the evaluation threshold using the new zone 7 F/10 design.

5. SUMMARY AND CONCLUSIONS.

All the program objectives for the large-diameter billets were achieved. Thirteen- and fourteen-inch Ti-6-4 calibration standards were designed and built containing calibration targets according to the AMS specification. Primary calibration flat-bottom holes (FBH) were placed into high-attenuation regions per recommendations from the Engine Titanium Consortium (ETC) Phase II Billet Attenuation Compensation Study. Additional targets were placed into low-attenuation regions to further study the effects of attenuation on inspection sensitivity. Two development F/10 transducers for 13″ billet and a full set for 14″ billet were designed and fabricated according to standard General Electric production transducer design practice.

Both laboratory and factory evaluations have demonstrated that by using the F/10 zoned inspection for all zones in 13″ diameter billet, #2.5 FBH sensitivity in the center two zones could be achieved during typical inspections, as shown below.

Sensitivity Summary		
	13″	14″
Laboratory results:		
MZ	# 1.5 to # 2.2	# 1.2 to # 2.4
Conventional *	no lab. conv.	# 3.3 *
Factory Results:	# 2.0	# 1.7 to # 2.6
MZ	no MZ at supplier B	# 2.9 (B)
Conventional	# 2.5	# 2.7
Conventional **	#3.9	#3.1

*Conventional inspection meets the inspection requirements of a #3 FBH when applying the current accepted signal to noise requirement.

**Estimated capability using ETC calibration standard.

This represents an improvement over both the conventional inspection and the current center zone multizone (MZ) inspection sensitivities. Based on the initial factory evaluation, the reduction in material noise achieved by the new F/10 transducers not only improved the inspection sensitivity by lowering the material noise, but also reduced the number of evaluation level indications and possibly the number of false calls. This would improve material quality levels while also enhancing inspection throughput. Provisions would have to be made for configuring the larger transducers on the followers on a site-by-site basis.

MZ inspection of 14″ diameter billet was conducted in the laboratory and demonstrated at two production suppliers. Both evaluations indicated the MZ inspection as having the capability to achieve sensitivities ranging from about a #1.2 FBH in the near-surface zone to about a #2.5 FBH at the center of the billet. These results represent an improvement over the current conventional inspection sensitivity. Factory evaluations also demonstrated that such an inspection could be implemented in a production environment.

The reported MZ and conventional sensitivity curves based on laboratory measurements of the ETC calibration standards are conservative due to the placement of all the calibration FBHs in high-attenuation areas.

Although the factory demonstrations were a good indicator of the inspection potential capability, they did not fully account for inspection and calibration variabilities present in all production inspections. For example, it was observed in the laboratory inspections that large-diameter transducers required to maintain F/10 focus at the center of large-diameter billets were sensitive to misalignment. To fully assess inspection sensitivity in a production environment, it is important to study this effect as well as variability in calibration standards, transducers, electronic noise, billet attenuation, and background noise levels. Although not yet quantifiable in terms of probability of detection, the production implementation of F/10 MZ inspection on 13″ and 14″ diameter billets offers improved sensitivity capability and should reduce the likelihood of melt-related defects from being missed during billet ultrasonic inspection.

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