Modelling Probe Wedge and Pipe Geometry as Critical Parameters in Pipe Girth Weld Ultrasonic Inspections Using Civa Simulation Software

Ed Ginzel [1]

[1] Materials Research Institute, Waterloo, Ontario, Canada
e-mail: eginzel@mri.on.ca

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Abstract

Attempts to standardise ultrasonic inspection of girth welds is made difficult due to the effects of pipe curvature on the beam. Although codes have allowed for some tolerances in the range of curvature and thickness that can be addressed from a single calibration standard, there seems to be no documented studies that rationalise these tolerances. This paper uses Civa simulation software to evaluate the variability in sensitivity due to changes in diameter, wall thickness and wedge-curvature matching.

Keywords: ultrasonic, CIVA, pipe, curvature, modelling

1. Introduction

Ultrasonic testing (UT) of butt welds has been commonplace for decades and many codes and standards are available to address the application [1,2,3,4,5,6,7,8]. Some of the standards simply address acceptance criteria and refer the inspection requirements to the generic non-destructive testing (NDT) codes that provide directions on how the inspections are to be carried out. The more generic codes [7,8] often group the UT of plate and pipe into a single category and make provision in the wording for probe-wedges to be contoured to improve coupling efficiency and reduce rocking.

ISO 17640 makes no reference to special considerations for reference blocks relating to pipe. ISO 13588 makes a recommendation for thickness of the reference blocks to be between 0.8 and 1.5 times the thickness of the test object with a maximum difference in thickness of 20 mm compared to the test object. ISO 13588 also makes provision for diameter tolerances such that reference blocks shall have diameters from 0.9 to 1.5 times the test object diameter. However, the ISO 13588 provision for diameter variation is only applicable to inspection of longitudinal weld seams and no such provision is made for girth welds.

ASME V, Art. 4 addresses calibration block requirements separately for plate and curved surfaces. For curved surfaces a single curved basic calibration block may be used for examinations in the range of curvature from 0.9 to 1.5 times the basic calibration block diameter. ASME also provides a tolerance on the thickness range applicable allowing the calibration block to be ±25% of the nominal thickness of the component to be examined.

The range of tolerances allowed in the codes can, in some cases, be wide and significantly different from one to the other. Although the diameter variation in ISO 13588 and ASME V Art. 4 indicate the same range, 0.9-1.5 times the calibration block diameter, the ISO document indicates that this is only relevant for longitudinal welds whereas the ASME requirement is for all curved surfaces. The thickness differences in ISO 13588 being from 0.8 and 1.5 times the thickness of the test object is close to the ±25% of the nominal thickness in ASME for the lower end but significantly larger at the upper end. However, ISO 13588 places a maximum limit of 20mm on the thickness difference and ASME has no upper limit apart from +25%.

Some compensation for differences between calibration blocks and test pieces may be achieved using a pitch-catch transfer technique; however, the effect of curvature variation may make this much more complicated than the simple two-line plot indicated in ISO 16811 [9].

Divergence refraction of the beam entering a curved surface can be addressed by curved elements [10,11], but these too will be affected by the reflection off the inside surface of the pipe, thereby reducing the forward scattered pressure.

Perhaps the most significant effect on the beam occurs as a result of reflection at each interface on the beam path including the transmission from wedge to pipe. Figure 1 illustrates how the divergence process is accelerated at the entry to the pipe and upon reflection from the inside surface of the pipe.

Figure 1 uses a simulation of a 9.6x10mm element on a 60° refracting wedge contoured to fit a NPS4 (Nominal Pipe Size 4") pipe with 18mm wall thickness. Rays simulate a plane wavefront emitted from the element. Lateral divergence is seen due to the curvature of the wedge/pipe interface with a slight delay in the wavefront at the outer edges due to the longer path in the slower wedge material. Upon reflection from the inside surface the rate of lateral divergence increases. However, on the next surface reflection the curvature of the pipe can actually provide some focussing effect and the divergence narrows.
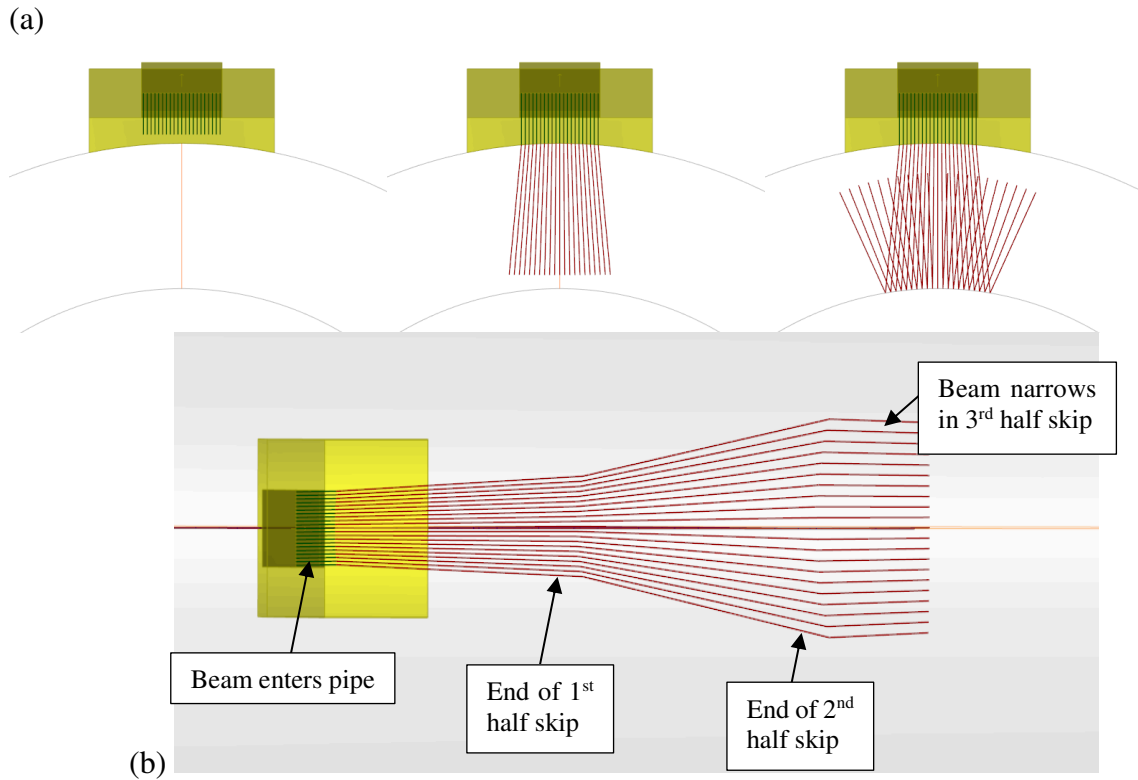
(a)

(b)

Figure 1   (a) Ray tracing illustrating divergence due to refraction upon entry into the pipe and at the reflection from the inside surface. (b) Note, a small focussing effect can be seen in the 3rd half-skip upon reflection from the outside curvature.

At the time of writing this paper, there is a draft ISO document being prepared (ISO 20601 Non-destructive testing of welds -- Ultrasonic testing -- Use of automated phased array technology for thin-walled steel components) that attempts to address several of the concerns associated with small diameter thin wall UT weld inspections. Because it limits the thickness in the scope to "semi- or fully automated ultrasonic testing of fusion welded joints in steel parts with thickness values between 3.2 mm and 8mm", the variation between calibration and test piece sensitivities is likely to be small. Provision is made to inspect wall less than 3.2mm but it is considered a "Special Application".

2. Civa Modelling Parameters

The combination of pipe diameters, wall thicknesses, element frequencies and apertures and wedge geometries have the potential to generate an unwieldy matrix of data. A limited matrix of pipe and probe parameters was used to assemble an initial set of modelled data. Pipe parameters considered are listed in Table 1.

Table 1   Pipe Parameters

Nominal	Diameter (mm)	Wall Thicknesses (mm)
NPS2	60.3	6,9,12
NPS3	88.9	6,9,12,15
NPS4	114.3	6,9,12,15,18
NPS6	168.3	6,9,12,15,18
NPS8	219.1	6-24 (in 3mm increments)
NPS10	273.1	6-30 (in 3mm increments)
NPS12	323.9	6-33 (in 3mm increments)
NPS14	355.6	6-36 (in 3mm increments)

In North America, pipe sizes are indicated using the terminology NPS (nominal pipe size) followed by a number that approximates an inch value; e.g. NPS 4 is considered a 4-inch pipe and all NPS 4 pipe have the same outside diameter (OD). But the OD is not exactly 4 inches (it is in fact it is 4.500" or 114.3mm). A similar metric system exists abbreviated DN (diamètre nominal/nominal diameter/Durchmesser nach Norm). Pipe wall thicknesses are also given as a dimensionless parameter called Schedule. When NPS and Schedules are combined, the matrix of geometries available can be large (for more details and tables on sizes see https://en.wikipedia.org/wiki/Nominal_Pipe_Size).

Tolerances on the accuracy of pipe wall thickness is typically on the order of ±12%. As a result, no attempt was made, in the matrix assembled for this study, to adhere to exact schedule thicknesses. 3mm increments were considered adequate to evaluate the effect of the thickness variations.

Additionally, several variations on the probe parameters were made including element aperture size and wedge geometries.

1. Three element apertures for a 5MHz nominal frequency
2. Wedge geometries (flat, curved/contoured, 2 widths and 3 refracting angles)

An initial set of modelled data was obtained using 3 element sizes at 5MHz; 6mm diameter 12.5mm diameter and a rectangular aperture 9.6mm long by 10mm wide (this is similar to the typical phased-array aperture used for general applications).

Each element was modelled on typical wedge dimensions used in manual UT. The wedges consisted of refracting wedges for 45°, 60° and 70°. For the 6mm diameter element the refracting wedge was 13mm wide and for the 12.5mm diameter element and the 9.6x10mm element the wedge was modelled as 23mm wide.

A critical variable in the assessment of relative sensitivity is the effect on coupling that contouring the wedge to the test piece has. To assess the coupling effect all the wedges were modelled with a flat contact surface and also a contoured contact surface. Civa provides a modelling condition for a wedge with a flat contact surface on a curved surface that uses the coupling fluid to fill the gap between the test piece and the wedge. In this modelling analysis water was used as the couplant.

Wedge contouring can be made to the test piece or calibration piece by assigning a cylindrical concave curvature parallel to the axis of scanning. For example, in Figure 2 the Civa interface is illustrated for the wedge being curved to an 84.15mm radius of curvature. This would match the 168.3mm diameter surface of the NPS6 pipe.
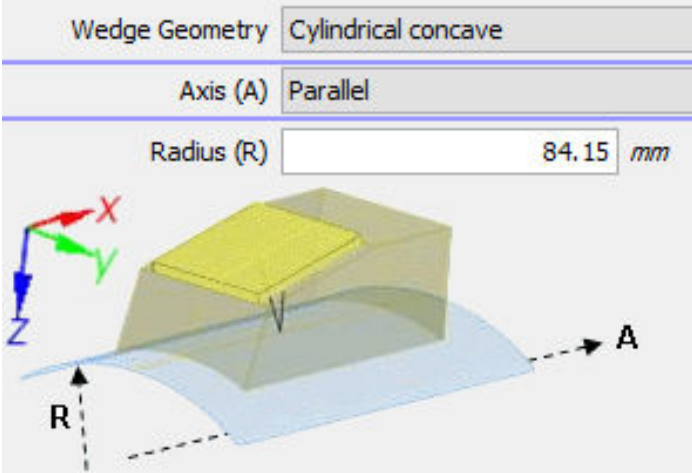

Figure 2   Preparing a contoured wedge condition

Note, it is possible, and sometimes useful, to prepare a wedge with a curvature that matches the test piece being scanned and then also use the same wedge on a slightly smaller diameter surface that could be used as the calibration standard. Such an example is illustrated in Figure 3 showing the 6mm diameter element on a 13mm wide wedge contoured to 168.3mm diameter (NPS6). When placed on a smaller diameter (NPS4 = 114.3m diameter) a small 0.19mm gap is present at the corner of the wedge.
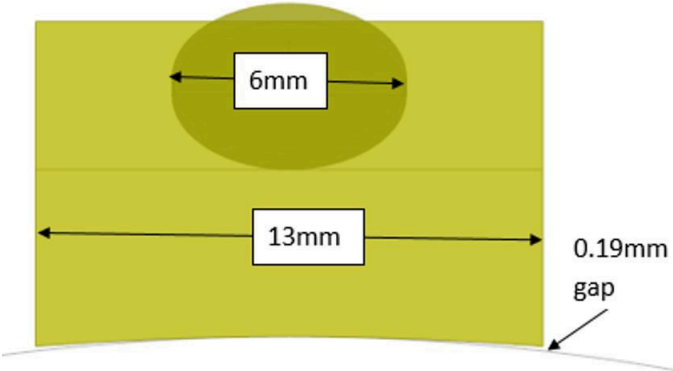

Figure 3   Wedge contouring effect (wedge contoured for 6NPS placed on 4NPS surface)

Material parameters for the pipe used standard steel values (Density 7.8 g/cm^3, V-long 5900m/s, V-shear 3230m/s).

Sensitivity comparisons were made using 2mm diameter SDHs. In thinner wall a single SDH was placed at the midwall depth and for thicker sections the SDHs were placed at 25% and 75% of the wall thickness. Figure 4 illustrates the target placement for a 6mm wall and 21mm wall sample.
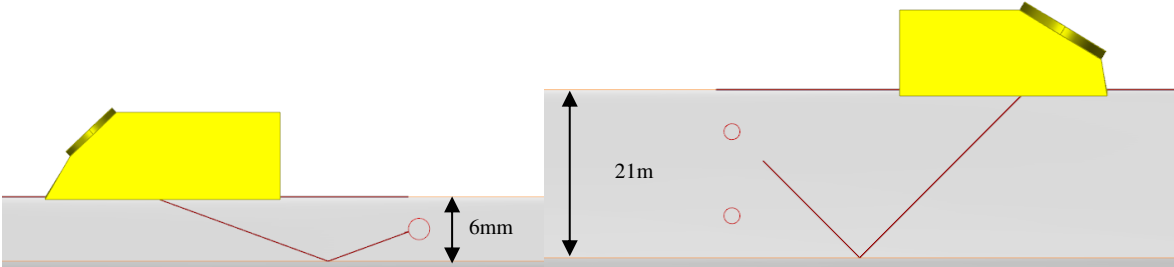

Figure 4   2mmm diameter SDH targets for 6mm and 21mm wall thicknesses

In addition to the simulated pipe samples with SDH targets, a series of cylinders were modelled to assess the effect of wedge gap when using a flat wedge. This was done to ascertain why codes have stressed that the maximum wedge dimension be a function of the part diameter.

ISO 17640 [7] states that a maximum gap between the bottom of the probe shoe (wedge) shall not be greater than 0.5mm. It then suggests that this requirement can be checked with Equation

$$g = \frac{a^2}{4D}$$

where
a is the dimension, in millimetres, of the probe shoe in the direction of testing;
D is the diameter, in millimetres, of the component

Earlier versions of the European standards provided different guidance and simply related the wedge dimension as a ratio of the diameter of the tested component. EN 1714 (1997) [12] used the "guidance' statement that the requirement for a 0.5mm gap will normally be met when $D \geq 15a$. Compared to the actual 0.5mm gap limit, this guidance statement is overly conservative.

A similar "guidance" was stated in the old EN 583-2 (2001) [13]. There the guidance suggested that the probe face shall be contoured when the diameter of the test object is less than ten times the wedge dimension. For typically small (<20mm wide) wedges this rule of thumb comes close to the requirement for a 0.5mm gap; however, it results in gaps more than 0.5mm for wedges with widths much more than about 20mm wide.

The 2017 edition of ASME Section V does not have the user calculate gap. Instead, it merely imposes a condition. There you solve for the dimeter of the component that a flat wedge may be used on, rather than attempt to solve for the gap. However, since no specific gap value is imposed it is difficult to infer how to address the condition of a curved wedge when placed on a curved surface (although a range is provided in tables).

The ASME equation states:

$$D \leq \frac{A \times A}{2.87mm}$$

where
A = length of search unit footprint during circumferential scanning or the width when scanning in the axial direction
D = the component diameter at inspection surface (I.D./O.D.)

Solving the geometric value for gap at the edge of the wedge using the ASME approach provides a consistent value of 0.72mm as the maximum gap produced.

To observe the effect of gap with respect to wedge width and part curvature, several simulations were made using probes with a flat wedge scanning a 2mm diameter SDH at a fixed depth (35mm). Scans were made on a series of curvatures ranging from 50mm diameter to 500mm diameter.

3. Simulated Scanning and Analysis

Simulated scanning of the SDHs in the pipe models allows several analysis options.

1. Comparing the sensitivities at different thicknesses for the same probe and diameter pipe (this is important due to the fact that a reflection off curved surfaces, both inside and outside surfaces, scatter and then focus the beam at different sound paths)
2. Comparing sensitivities for the same thickness but on different diameters (assesses the effect of curvature)
3. Comparing the combined effect of thickness and curvature variations (this is relevant where a calibration block is made from a pipe of one diameter and thickness and then a component is tested with a different diameter and thickness, within an allowed tolerance)
4. Analysis of transfer value determination as a means of determining suitability of tolerances for diameter and thickness differences between calibration and test components
5. Comparing the sensitivity effects of curvature matching to flat wedges and wedges with perfectly matched curvatures to wedges with slightly larger curvatures
6. Comparing attenuation effects due to curved contact surfaces under a flat wedge
7. The effect of element size on curved surfaces using flat wedges
8. The effect of wedge rocking

In addition to the comparisons made on simulated pipe sections, simulations were carried out on a fixed target scanned from varying curvatures using a flat wedge. This setup was further reviewed using the same size element on wedges of different widths to assess the effect of gap as described in codes.

4. Observations

4.1 DACs on Varying Wall Thickness and Same Diameter

Compare 45° Contoured wedges with 9.6x10mm 5MHz aperture on NPS8 DACs

Three thicknesses for the NPS8 pipe are compared in Figure 5. The black line is the echo-dynamic curve for the 24mm thickness, the blue line is the echo-dynamic curve for the 21mm wall thickness and the red line is the echo-dynamic curve for the 18mm thickness.

The bracket labelled "1" indicates the responses from the t/4 SDH. It is seen as a double peak for all 3 thicknesses as a result of being in the near zone. The bracket labelled "2" indicates the responses from the 3t/4 SDH. The bracket labelled "3" indicates the responses from the 3t/4 SDH seen after a reflection from the inside surface of the pipe.
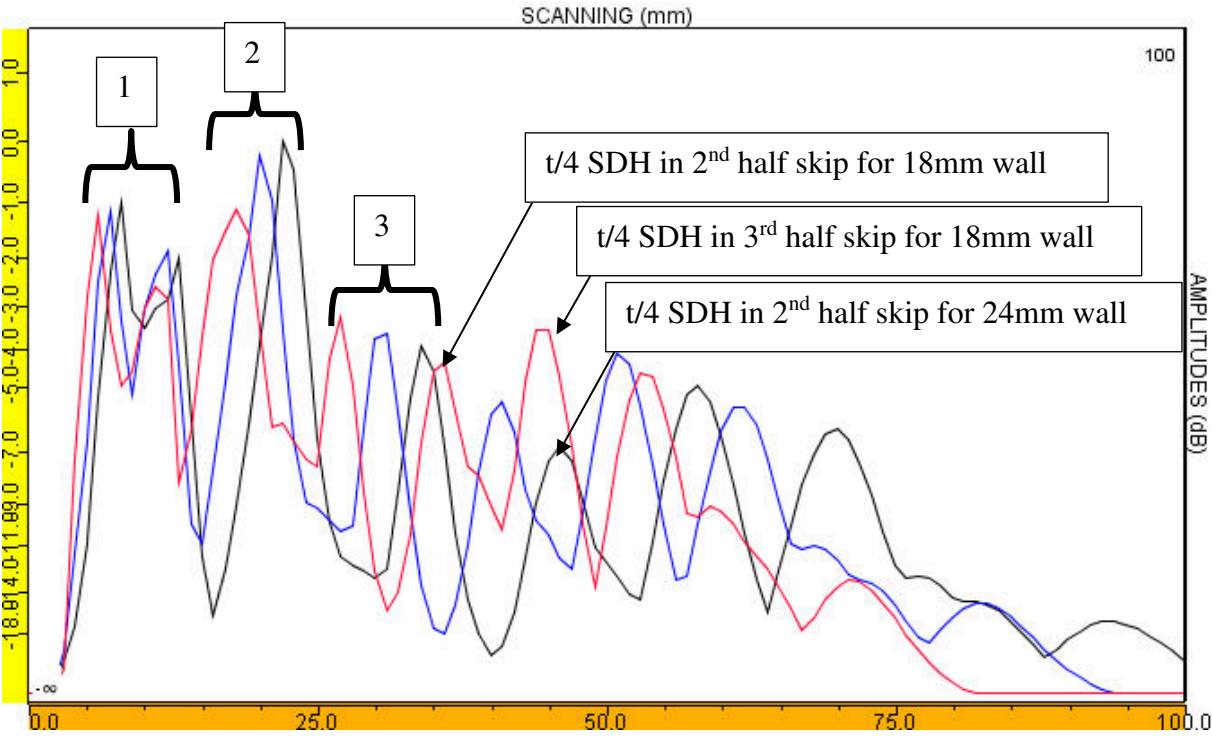
Figure 5 **Echo-dynamic curves for 18mm (red), 21mm (blue) and 24mm (black) wall thicknesses on 8NPS pipe with 45° 9.6x10mm 5MHz probe with contoured wedges to match curvature**

A focussing effect can be seen for the SDHs detected in the 3rd half skip. The t/4 SDH response in the 18mm wall thickness in the 2nd half skip is approximately 1dB lower than the t/4 SDH response in the 3rd half skip (red curve). However, it should be noted that the travel time to the t/4 SDH in the 2nd half skip for the 24mm wall is only 1µs longer than the travel time to the t/4 SDH response in the 3rd half skip, yet for that point the amplitude difference is 3.5dB (the 24mm wall being lower amplitude).

The effect of the curved reflecting surface can clearly have a pronounced effect on the relative amplitudes of DAC points for the same travel times.

Figure 6 illustrates a similar pattern using a NPS4 pipe with 6mm, 9mm and 12mm wall thicknesses, again with a wedge that is contoured to match the NPS4 curvature. The increase in amplitude seen in the 3rd half skip in Figure 5 is not seen for the NPS4 DAC in Figure 6.
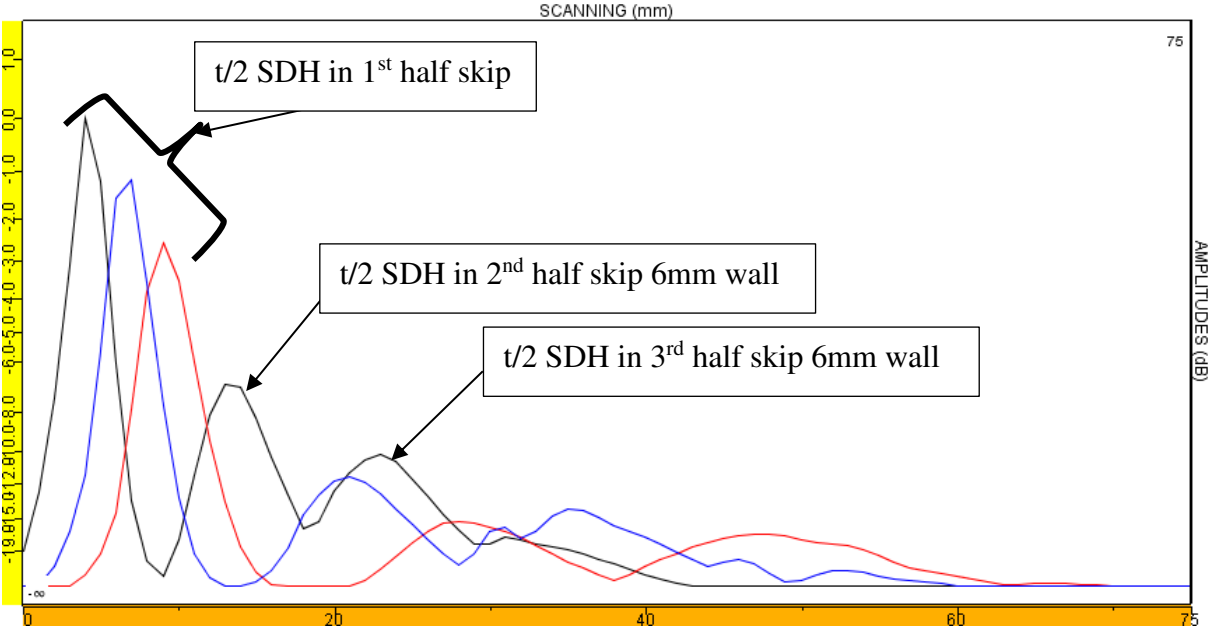

Figure 6   Echo-dynamic curves for 12mm (red), 9mm (blue) and 6mm (black) wall thicknesses on 4NPS pipe with 60° 6mm diameter 5MHz probe with contoured wedges to match curvature

4.2 DACs on Same Wall Thickness and Varying Diameter

To assess the effect of curvature on the sensitivity we can compare the echo-dynamic curves for the same probe contoured to match the pipe diameter over a range of diameters.

Starting with a flat 60° refracting wedge on a flat plate for a probe 6mm diameter and 5MHz, the response from the SDH is plotted as the scan distance increases. On the direct path (i.e. 1st half skip) the contoured wedges result in very closely matching the flat plate condition. Figure 7 illustrates the wedge and target conditions for the 6mm wall thickness on plate and curved contact surfaces.
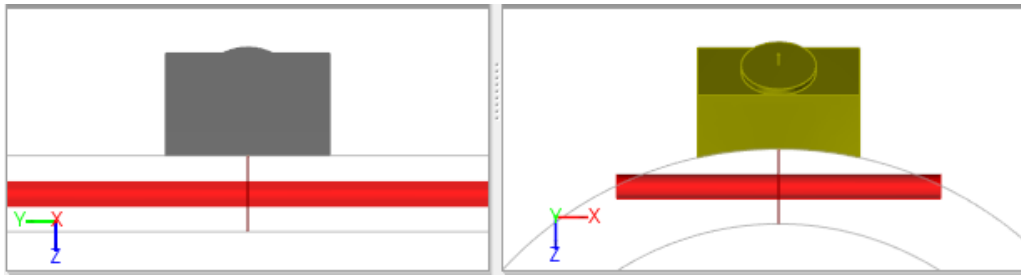
Figure 7 **Simulation condition to compare echo-dynamic curves for 6mm wall in plate and curved surfaces for wedges with matched curvatures**

Figure 8 is a comparison of the echo-dynamic plots for the range of curvatures from flat plate to NPS2 pipe.
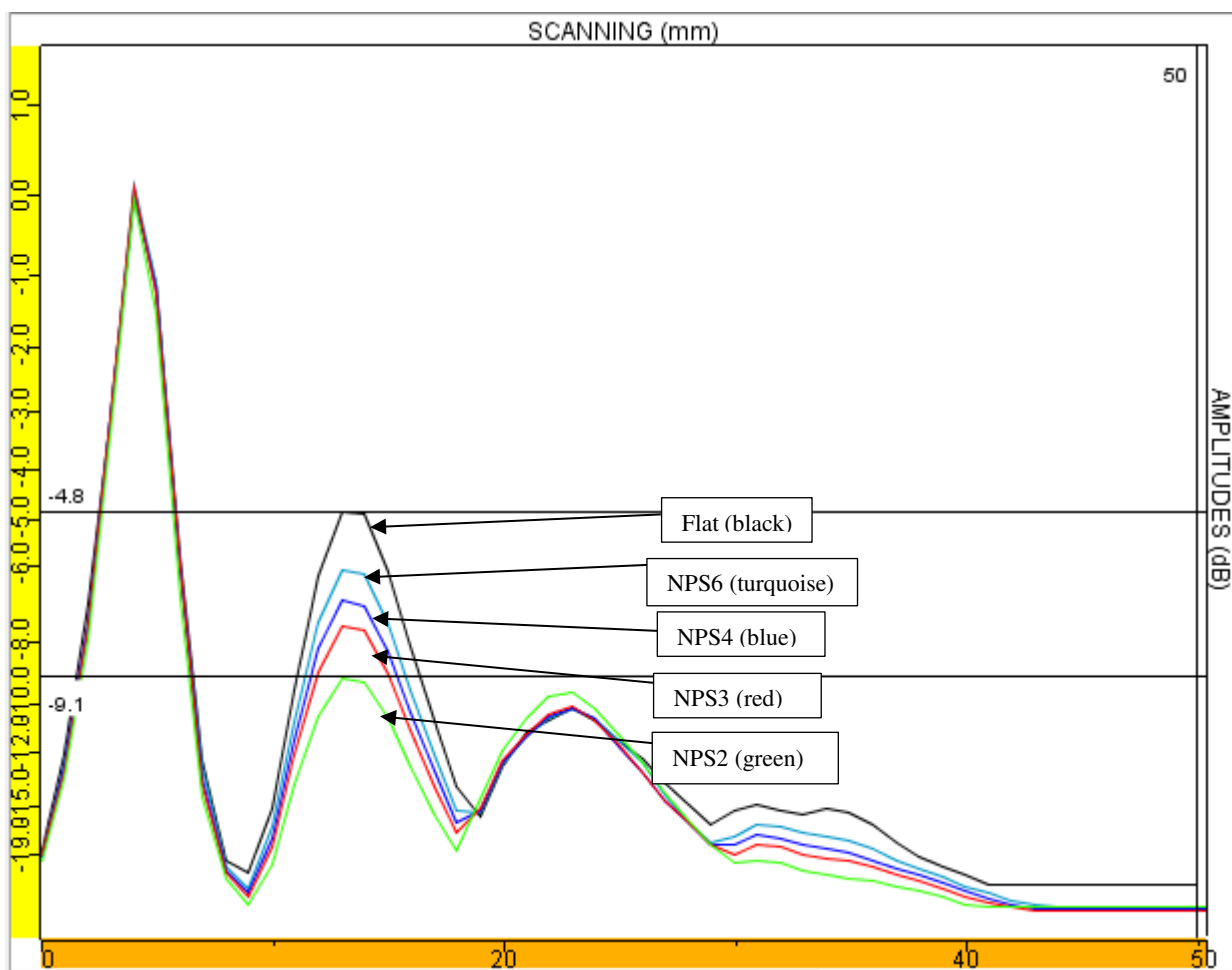

Figure 8 **Comparison of echo-dynamic curves for matched wedge curvatures from flat plate to NPS2 pipe using 60° wedge with 6mm diameter 5MHz probe.**

Figure 8 shows how the matched wedges provide essentially the same coupling as a flat wedge on a plate in the first half skip (i.e. the direct path to the SDH). However, the effect of the reflection off the pipe inside surface causes the beam to diverge by specular reflection with a

difference of 4.3dB between flat plate and 2NPS conditions for the SDH response in the second half-skip. This is significantly less loss compared to the flat wedges where the same target varied by about 9dB.

Note too that for the 3rd half-skip there is a focussing effect with the responses all being similar when using a contoured wedge (Civa predicts a slight increase in response for the 3rd half skip response on the NPS2 pipe).

4.3 Combined Wall Thickness and Diameter Variations

The effect of combining variations in wall thickness and diameter is of special concern to conformance to some codes and standards. ASME Section V [4] makes provision for weld inspections in piping to use calibration blocks that are within ±25 of the thickness of the tested component. It also makes provision that tested components may be between 0.9 and 1.5 times the diameter of the calibration block.

To gauge the degree of sensitivity difference allowed with these tolerances we can select some of the simulations in the matrix and analyse the variation that might result.

When considering the combined variation in light of code provisions, one should also be aware of practical conditions applying the tests. It is not possible to make a correct calibration of range and wedge delay when using a wedge that is contoured for a specific curvature on a calibration block and then use it on a test surface with a larger diameter. This results in a gap between the wedge and test surface at the middle of the wedge. This can alter the assessed distance to a target. There is also the concern that there may be difficulties maintaining the couplant in that gap and gap multiples may result that can degrade signal resolution.

Figure 9 indicates the problem quantitatively. The free utility programme, ESWedgeGap from the Eclipse Scientific website, allows us to visualise the gap that results for combinations of probe/wedge and contact surfaces.
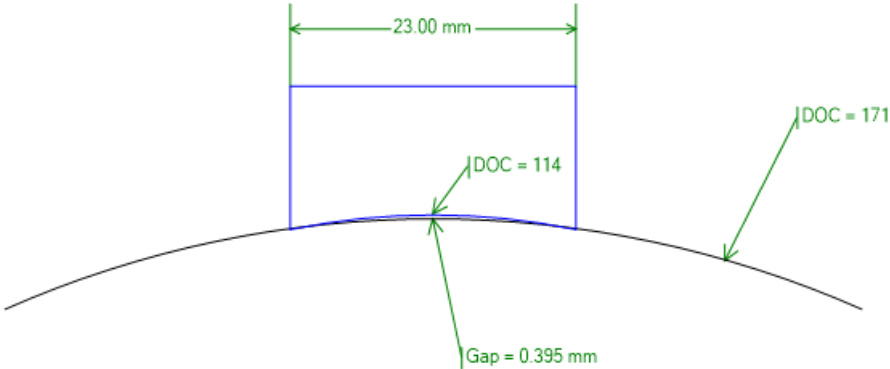

Figure 9 **Gap for wedge contoured for a NPS4 calibration pipe placed on a surface with the maximum allowed tolerance (1.5 times the calibration block diameter)**

The 0.4mm gap indicated seems to be small; however, several issues arise under these conditions.

1. Coupling efficiency may be irregular as the gap fills and empties during scanning
2. An added delay on the order of 1μs in water couplant occurs that is not compensated for during wedge-delay calibration
3. A series of multiples occurs in the tested component as the pulse echoes between the test piece and wedge in the gap, thereby deteriorating temporal resolution
4. The gap may work out to be close to that required to produce a half-wave layer and this could reduce the transferred pressure by as much as 6dB compared to the zero gap that was used for calibration

The increments of diameter in the matrix used in this study have no diameters that meet the 0.9-time criterion when compared one to another; however, several could meet the 1.5-time criterion.

For example, a NPS6 pipe has a diameter of 168.3mm. If it was used as a calibration block the 0.9 lower limit would indicate that the smallest diameter that could be tested after calibrating on the NPS6 reference would be 151.5mm and the 1.5 upper limit would be 252.5mm. The NPS8 pipe at 219.1mm meets the upper limit criterion but the NPS4 at 114.3mm diameter is less than the 151.5mm allowed.

Similarly using a NPS4 pipe as the reference standard allows scanning on pipe with a diameter in the range of 102.9mm to 171.5mm. The NPS6 pipe meets the 1.5 criterion but the NPS3 at 88.9mm is too small to be tested using a NPS4 reference block.

To consider the suitability of the ASME tolerances the matrix was used to select a pipe that could be used as a sensitivity calibration reference and then the matrix was used to select the specimens that would have diameter and thickness values in the range of the allowed limits.

Using the NPS4 pipe with 12mm wall thickness as a reference calibration, ASME would permit scanning on a test piece up to 171mm diameter and the thickness of the tested component could be ±25% of 12mm, or 9mm to 15mm. The range of diameters and thicknesses allowed using pipe NPS4 with 12mm nominal wall thickness is seen in Figure 10.
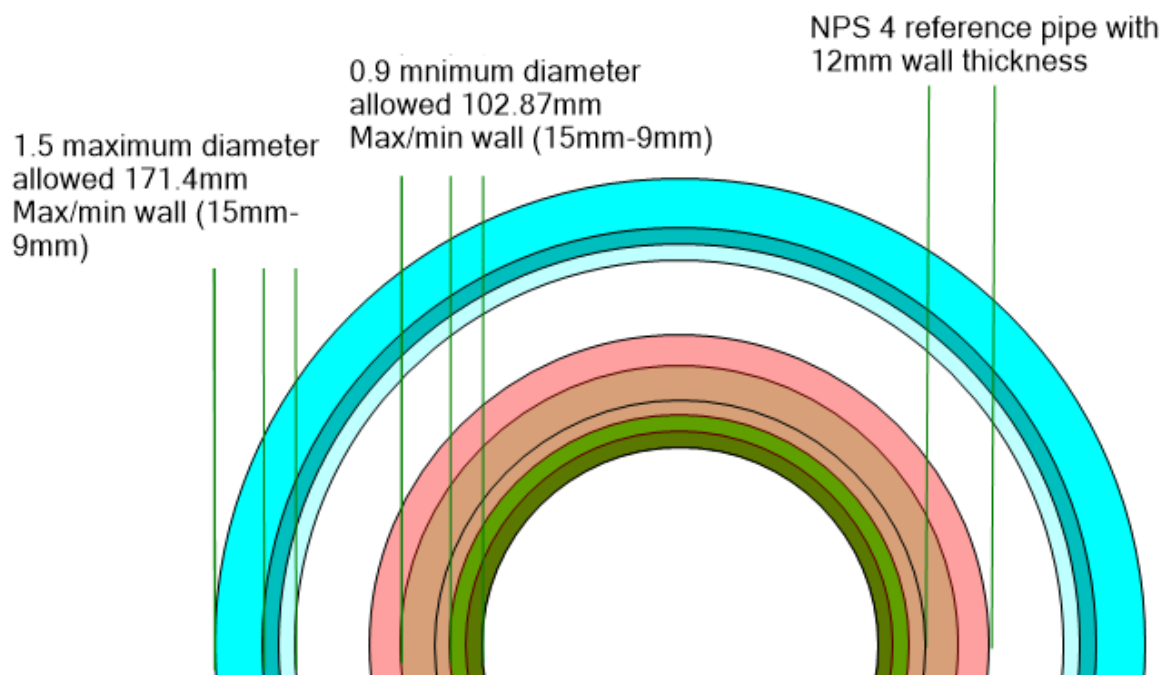
Figure 10   Example of diameter and thickness range allowed tested by ASME using a nominal NPS4 pipe with 12mm wall thickness

Using the proviso that we described here, that a wedge should not be contoured to a diameter less than the surface it is to be used on, it was therefore deemed practical to contour the wedge to the test on the NPS6 pipe for both the sensitivity calibration on the NPS4 sample and for the test scanning on the NPS6 sample.

Figure 11 is a superposition of the echo-dynamic curves for the four conditions being compared.

The black curve is the reference sensitivity established on the NPS4 on 12mm wall using a 60° wedge with the 6mm diameter 5MHz probe. The wedge is contoured for a 168.3mm diameter surface (i.e. to match the NPS6 pipe).

The red curve is from the NPS6 on 12mm wall. It is seen to be a higher response than the calibration because the wedge is perfectly contoured for the NPS6 pipe.
The green curve is from the scan on the SDHs in the NPS6 with 9mm wall thickness.
The blue curve is from the scan on the SDHs in the NPS6 with 15mm wall thickness.
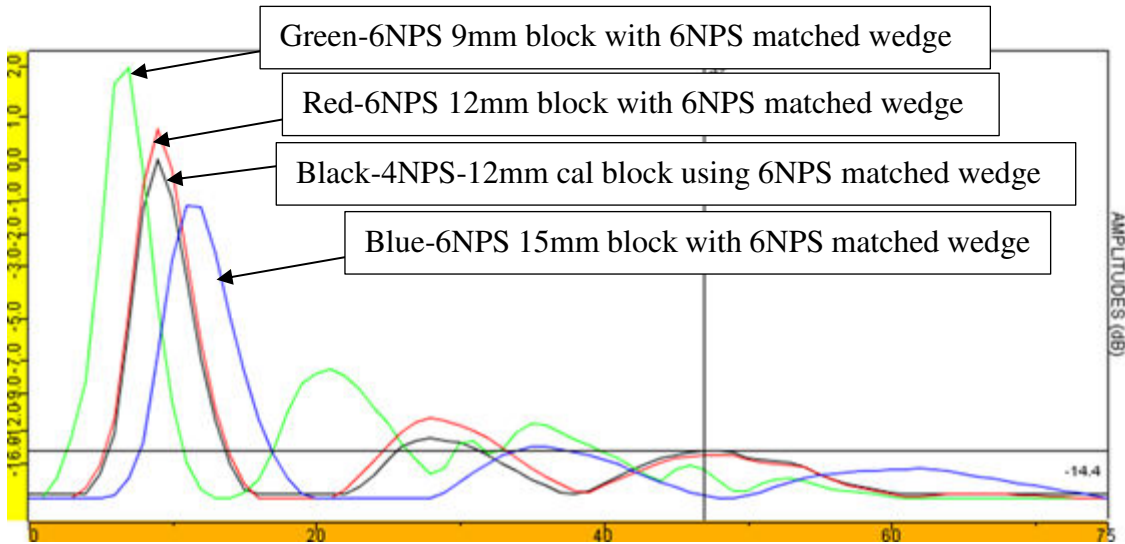
Figure 11   **Comparing 60° beam sensitivities for diameter and wall thickness variations in allowed tolerance range (4NPS calibration used on 6NPS test components)**

The peak amplitude values seen in Figure 11 are based on scan position. If we extract the time of arrival for the peak amplitude we can convert the 3 peak points to a DAC-like curve in Excel. This is presented in Figure 12 where we see that at 21µs the responses from the three NPS6 options are all more sensitive than the reference DAC. This follows due to the improved coupling that the matched curvature provides.

Placing ±2dB tolerance bars on the NPS4 pipe used as a reference DAC (blue curve in Figure 12) it suggests that at 21µs the calibration using the tolerance guidelines in ASME provides sensitivities that are slightly more than 3dB different for the allowed maximum diameter and 25% thicknesses. Most other points are less than 2dB off the reference DAC.
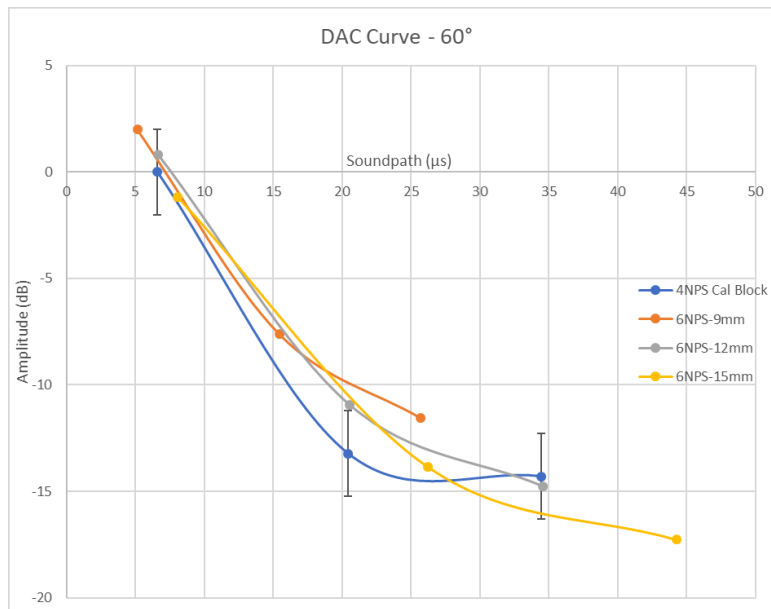

Figure 12   **Simulated DAC curves based on peak amplitudes and arrival times (NPS4 and NPS6)**

The comparison was repeated using a 12mm thick NPS6 pipe as the reference calibration with a 70° wedge and 12mm diameter 5MHz probe on a curved wedge to match NPS8 pipe. The SDHs in the 9mm, 12mm and 15mm thickness NPS8 pipe were scanned for comparison. The superimposed echo-dynamic plots are seen in Figure 13.
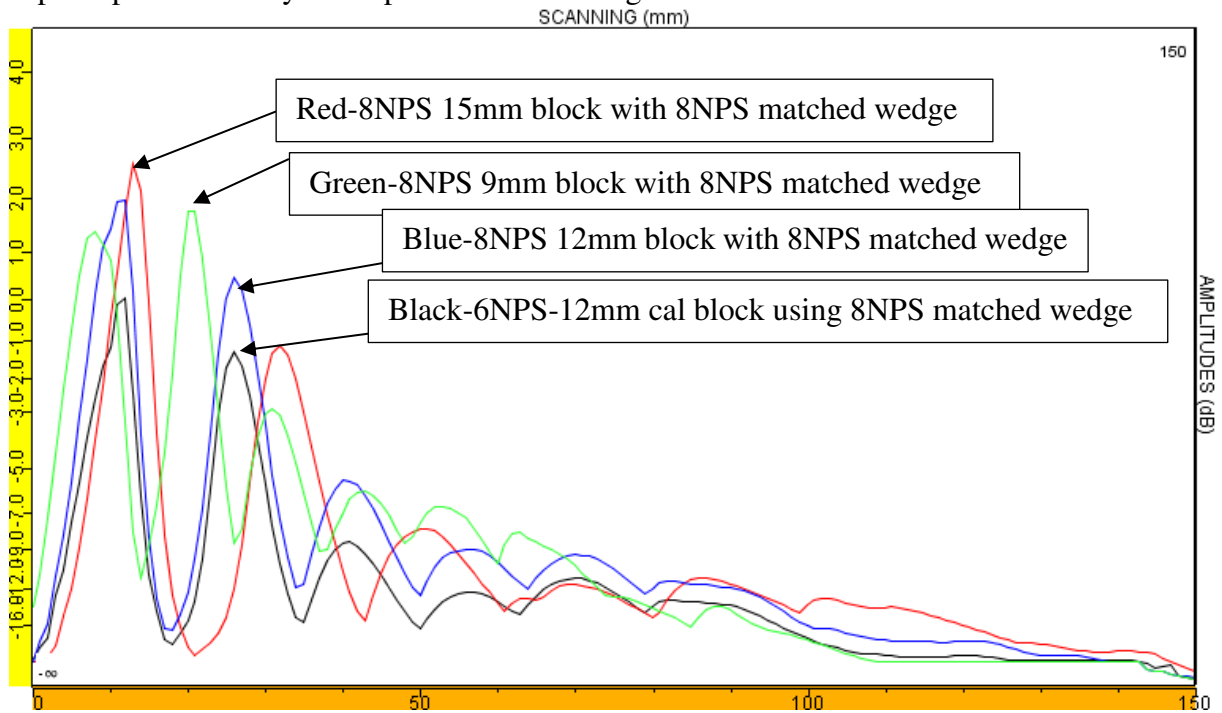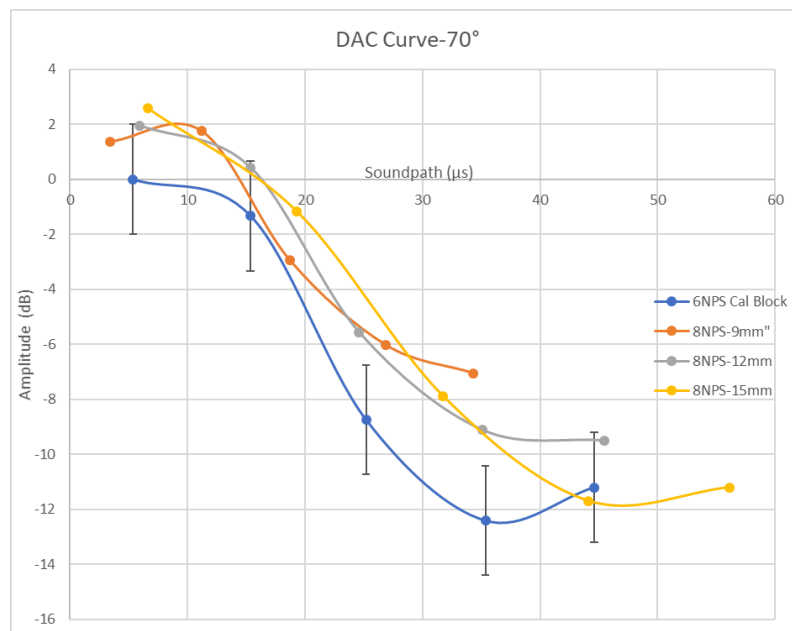

Figure 13   Comparing 70° beam sensitivities for diameter and wall thickness variations in allowed tolerance range (NPS6 calibration used on NPS8 test components)

Figure 14   Simulated DAC curves based on peak amplitudes and arrival times (NPS6 and NPS8)

The 2dB tolerance bars in Figure 14 indicate that the deviation of sensitivity from the reference calibration using the NPS6 reference block may result in up to 4dB to 6dB difference when applied to the allowed thickness variations on the NPS8 pipe.

4.4 Transfer Value Results

Codes have made provision to allow calibration on one thickness and diameter of pipe and then inspecting another within a range of tolerance for the diameters and thicknesses. A common method of compensating for differences between calibration and inspection conditions is the use of "transfer value". Several methods have been used. One involves constructing a DAC curve on the calibration block and then using a pair of probes in pitch-catch mode to bring the signal from the V path on the calibration block to the DAC and the gain setting noted. The probes are then positioned on the component to be tested and the gain required to bring the signal from the V path to the DAC is again noted. If more gain is required to bring the V-path signal to the DAC for the component to be tested, it is added to the calibration sensitivity. The use of the DAC is a means of compensating the process for any differences in thickness between the calibration piece and tested component.

ISO 16811 describes a method that has the amplitudes of the V path and W path peaked on the reference block and a line is drawn connecting them using the gain to bring the signal to the same screen height as the vertical value and the sound path as the horizontal value. V and W paths are then maximised on the test piece and a line drawn connecting them. The difference between the two lines indicates the transfer value.

A technique similar to that described in ISO 16811 was adapted using a Civa simulation. A pair of probes was configured with the same wedge geometries and positioned in a pitch-catch arrangement. A series of Civa scenarios was used that increased the probe-centre spacings with the probes placed on the pipe considered a "calibration" block and then on pipe considered the test pieces. The A-scans that corresponded to the maximum response from the V and W paths were used to identify the applicable soundpath and amplitudes. Similarly, the PCS was adjusted to locate the V and W path maxima for the values on the components with larger diameters and wall thicknesses in the range allowed by codes.

Figure 15 is a plot provided by the Civa scenario feature that indicates the pitch-catch amplitude as a function of the probe centre spacing (PCS).
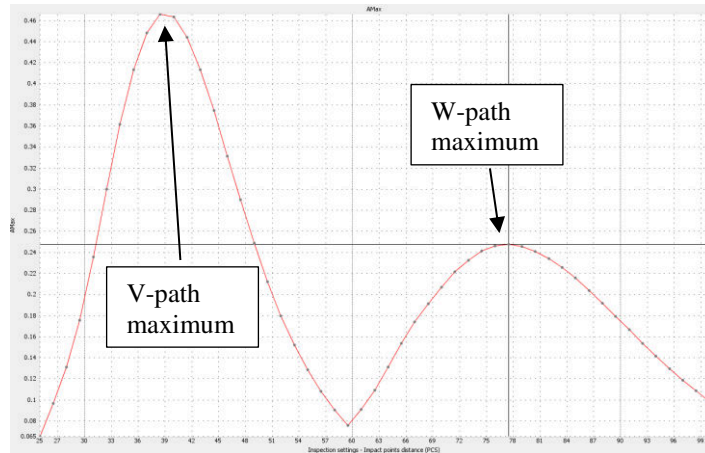
Figure 15 **V and W amplitudes resulting from increasing PCS for TV determination**

In the samples used for the TV assessment, the wedges were contoured to match the larger diameter test pieces so a slightly reduced coupling resulted when placed on the calibration block with smaller diameter. The reduced coupling on the calibration blocks is seen by the response from the calibration TV plotted in Figure 16 being lower than the TV obtained from the test pieces.
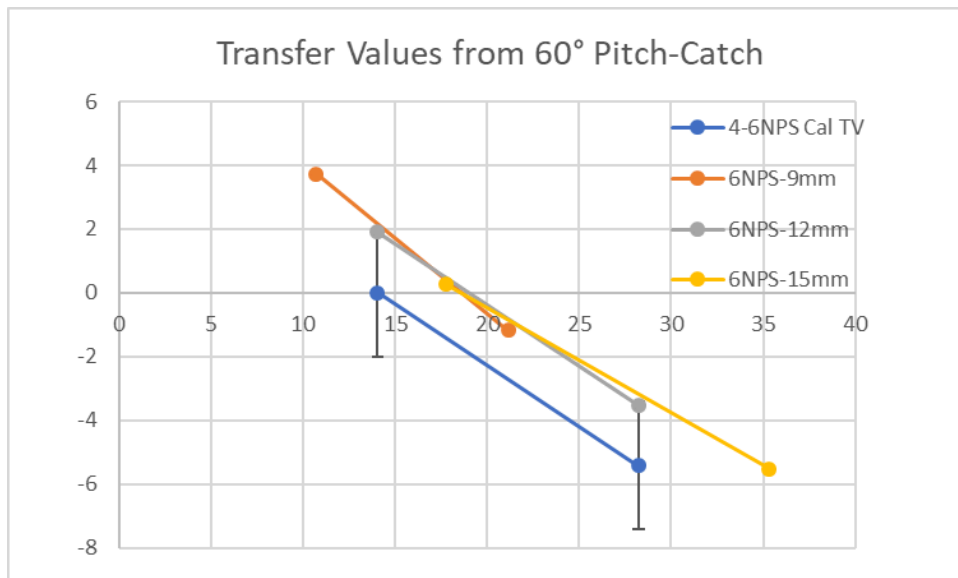

Figure 16 **TV determination for 6mm element on 60° wedge**

The TV simulation process was repeated using a 70° wedge with the 12.5mm diameter probe using a 12mm thick NPS6 pipe as the referenfce block and comparing the results with the NPS8 pipe having thicknesses of 9mm, 12mm and 15mm. The TV plot is seen in Figure 17.
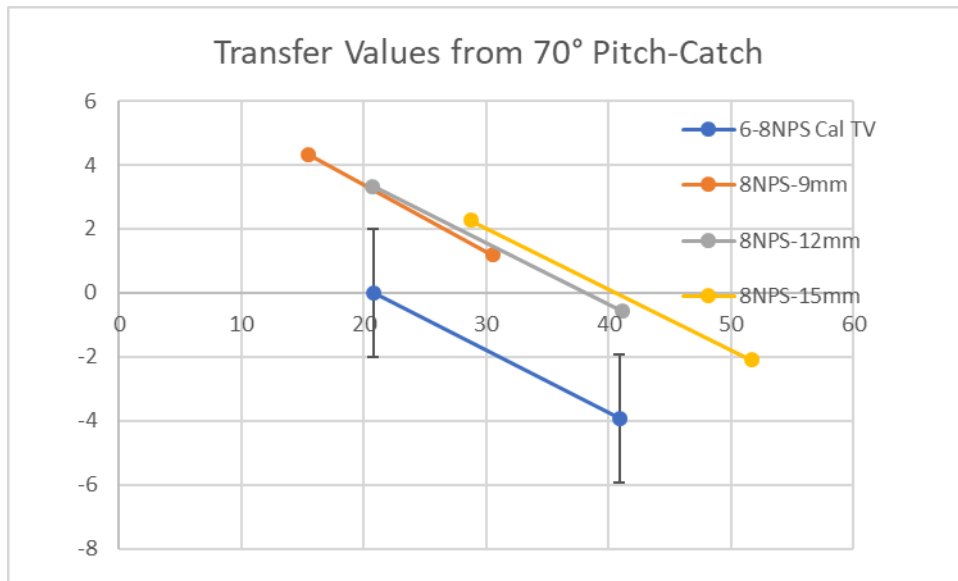
Figure 17   TV determination for 12.5mm element on 70° wedge

Most procedures would have the operator not apply any TV in this case. This means that if the sensitivity on the test piece is greater than on the calibration block no TV correction is made. For the TV examples obtained by the Civa analysis the test suggests that improved coupling results on the test component compared to the calibration block.

The effect of attenuation losses between the small diameter calibration block and the test pieces would be easiest to see if it was possible to have calibration targets in the same size pipe as those being tested (i.e. have a calibration block for every diameter and thickness tested). In real life this is not so convenient and is the reason why diameter and thickness tolerances are permitted. However, in Civa we can simulate the situation. To do so, the 2mm diameter SDHs were placed in the modeled specimens, both those used as calibration pieces and those used as tested components. Differences between the responses allowed a construction of a DAC for each condition.

The two conditions modelled to illustrate the effect are seen in Figures 12 and 14. Note that Figure 12 uses a 6mm diameter element with a 60° 13mm wide wedge contoured to match the NPS4 pipe whereas Figure 14 uses a 12.5mm diameter element on a 23mm wide wedge contoured to fit the NPS8 pipe. The 2dB tolerance bars in the TV plots for Figures 16 and 17 appear to provide a reasonable estimate of the degree of attenuation difference that would be seen had a DAC been constructed using calibration blocks of the same size as each pipe tested.

4.5 Closely Matched Curvature Effects

It has been noted that a wedge may be contoured to calibrate on a pipe of one diameter but then scan pipe of a different diameter. The practical concerns for the gap at the centre of the wedge make it ill advised to use the curved wedge on any pipe with a diameter greater than the wedge has been contoured for.

Restrictions on the allowed gap when using a curved wedge on a curved surface is generally more difficult to calculate.

To assess the effect of closely matched curvatures a Civa scenario simulation was run using a cylinder with a curvature equal to the NPS2 pipe (60.3 mm diameter) and varying the curvature of the wedge from fully matched to 800mm diameter. A 2mm diameter SDH at a fixed 35mm depth was used to monitor the amplitude change so as to gauge the effect of gap. This can provide an indication of the importance of the allowed gaps (0.5mm ISO or 0.71mm ASME).

Scenarios were configured for the three probe sizes used in this study. 45° refracting wedges were then modelled with wedge widths at 13mm for the 6mm diameter element and 23mm for the 12.5mm diameter probe and 23mm for the 9.6x10mm rectangular element probe. The scenario consisted of increasing the curvature of the wedge contour and comparing the resulting maximum amplitude from the SDH.

Figures 18, 19 and 20 illustrate the effect of reduced contact as the wedge curvature increases. These figures present the change in amplitude of the response from the SDH to the increasing radius of curvature of the wedge. Overlaid on the Civa plots are plots showing the amount of gap as the radius of the wedge increases and the amplitude drop as the gap between the wedge and pipe increases.
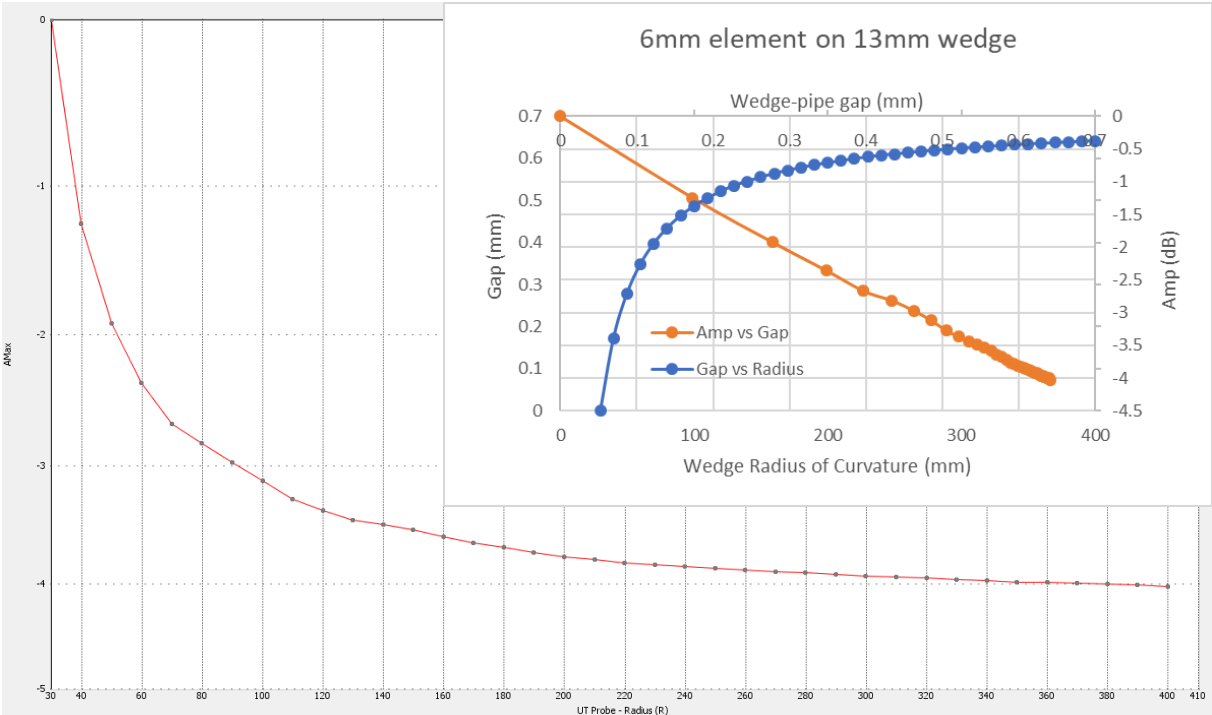

Figure 18   6mm diameter probe on a 13mm wide wedge contoured from 30 to400mm radius (maximum amplitude drop is 4dB)
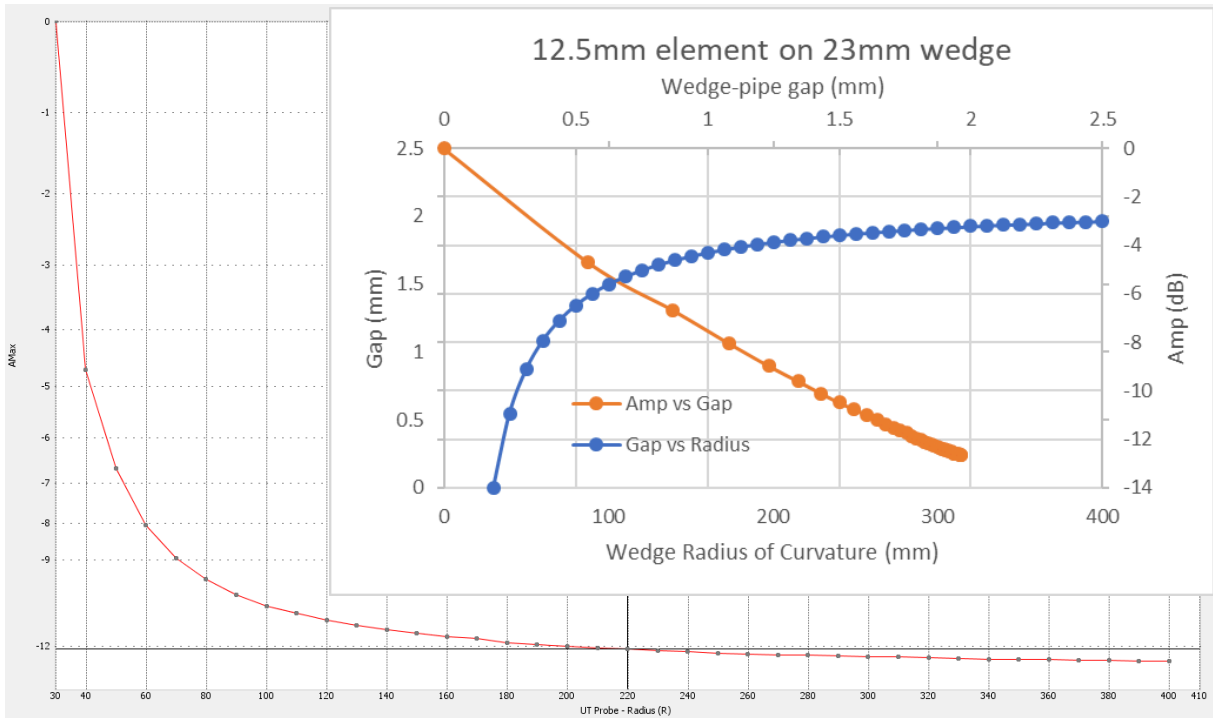
Figure 19 **12.5mm diameter probe on a 23mm wide wedge contoured from 30 to 400mm radius (maximum amplitude drop is 12dB)**
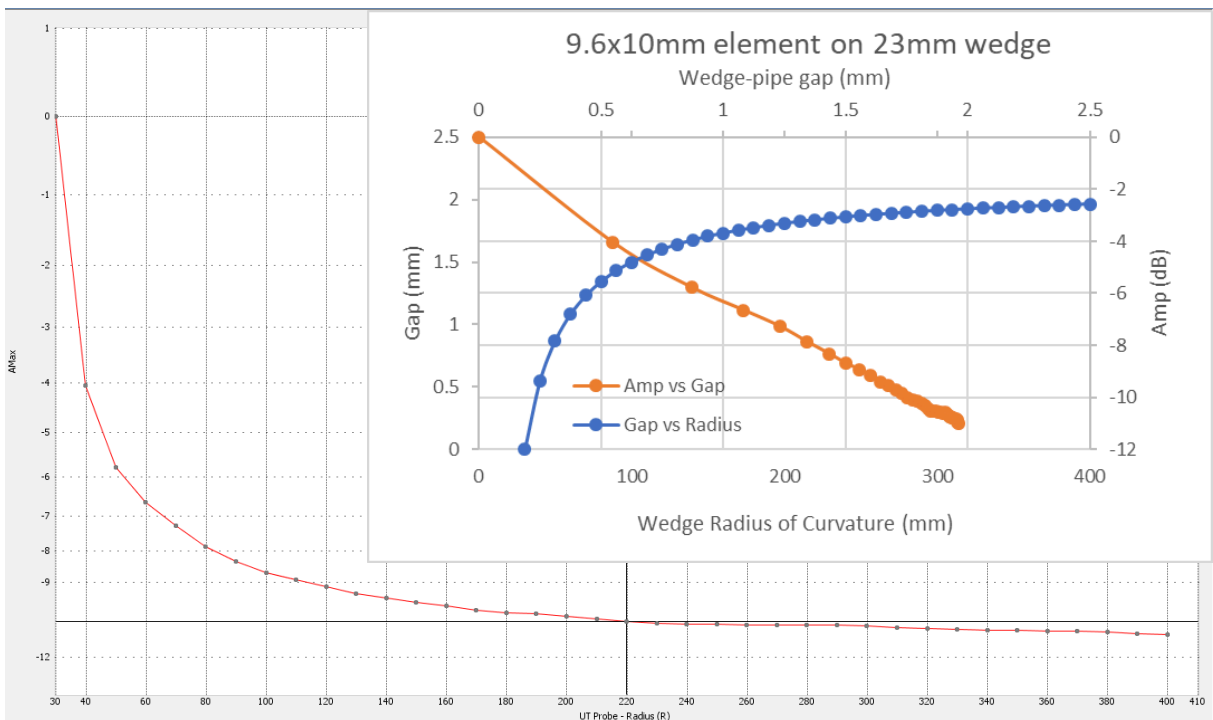

Figure 20 **9.6x10mm probe on a 23mm wide wedge contoured from 30 to 400mm radius (maximum amplitude drop is 11dB)**

Using the ESWedgeGap utility as shown in Figure 21, we can see that a wedge 13mm wide contoured for a 400mm diameter curved surface results in a gap at the edge of the wedge of 0.589mm when placed on the NPS2 pipe surface. This is greater than allowed by the ISO standards. But even a flat wedge 13mm wide will not exceed 0.695mm gap at its wedge, so it will always conform to the ASME code requirements.
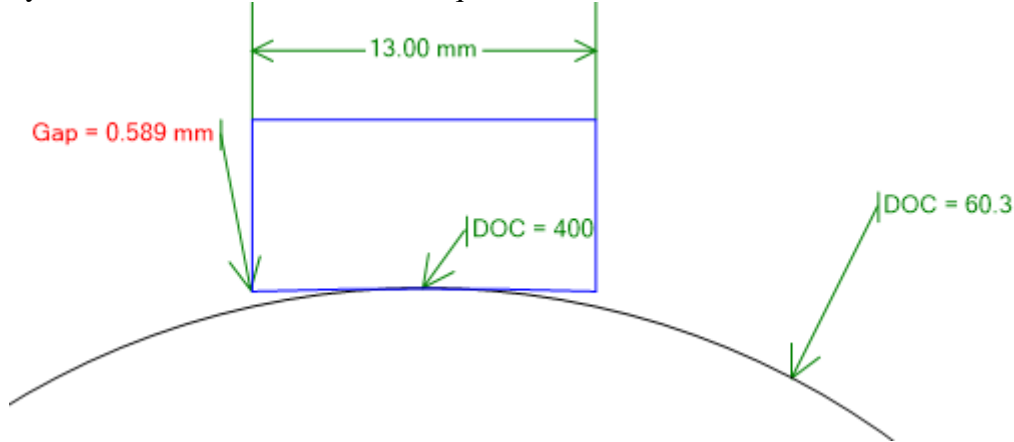

Figure 21   Gap at edge of wedge for wedge contoured at 400mm diameter when placed on curved surface 60.3mm diameter

4.6 Attenuation Effects Due Solely to Curvature Under a Flat Wedge

A variation on the scenario whereby the wedge curvature was increased was made comparing just the effect of gap when the probe was used on a flat wedge and the diameter of the test surface varied. On a flat surface the gap is zero millimetres. For most codes the assumption is made that a surface larger than about 500mm diameter is sufficiently close to a flat surface that no probe wedge adaptation is required and the wedge may remain flat.

Simulations were run using the 6mm diameter and 12.5mm diameter elements on a flat 45° refracting wedge. However, in this case, both probes were placed on wedges 23mm wide. Gap at the edge of the wedge was calculated using the ESWedgeGap utility and Civa simulations were run for a series of test surface curvatures from the flat condition and then from 50mm diameter up to 500mm diameter.

For each of the two probes, the amplitude response to the 2mm diameter SDH was normalised to its amplitude on the flat surface. Amplitude was then plotted against gap and the range of the diameters in the scenario. The results of the comparison are seen in Figure 22.

Amplitude Relative to Wedge gap and Test Surface Diameter
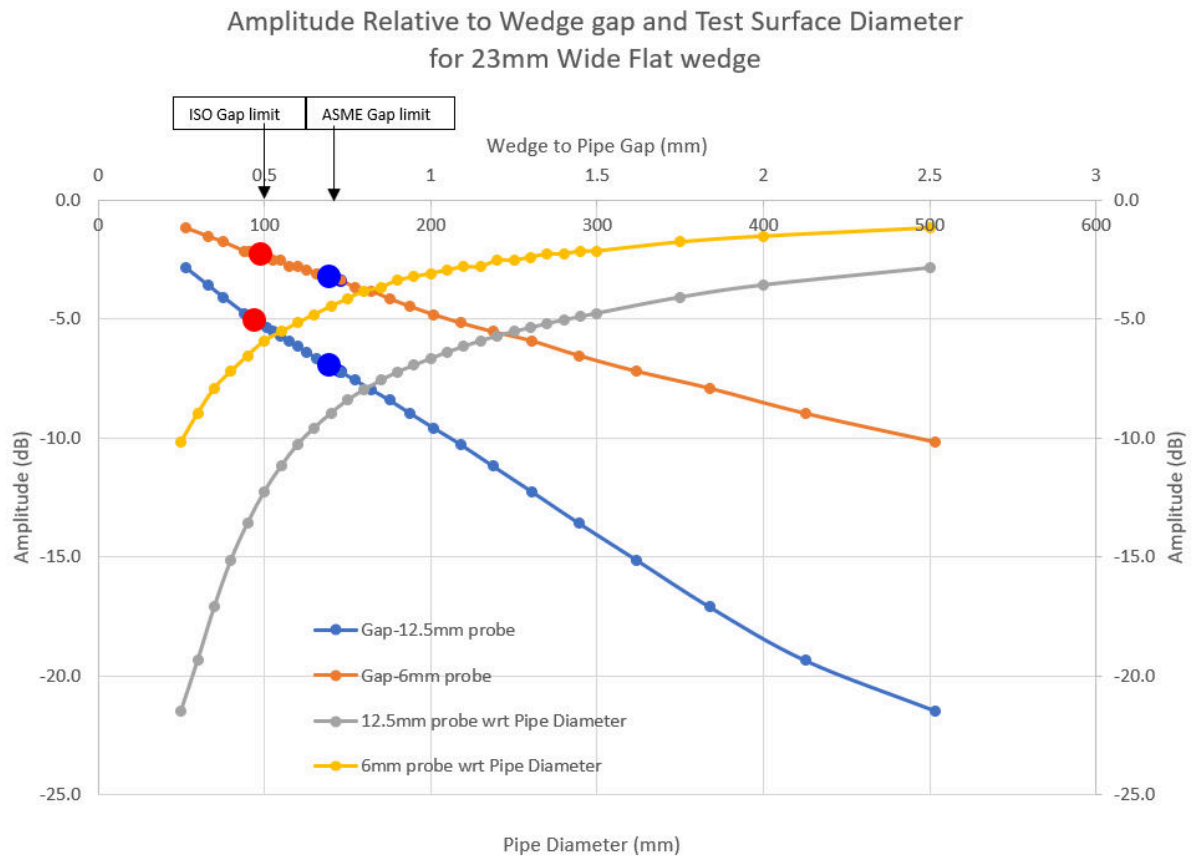for 23mm Wide Flat wedge

Figure 22   Amplitude versus Gap and Amplitude versus pipe diameter for 6mm diameter and 12.5mm diameter 5Mhz elements on 23mm wide 45° flat refracting wedge

In spite of the gap at the edge of the wedge being the same (since the same width of wedge is used for both elements), the plot in Figure 22 shows that the rate of amplitude decrease is greater for the larger diameter element and there is a nearly linear relationship between that gap and the amplitude.   The curves made for the gap versus pipe diameter show a logarithmic relationship with amplitude increasing as pipe diameter increases.

Red dots on the Gap versus Amplitude curves indicate the maximum gap allowed for ISO applications and the blue dots indicate the maximum gap allowed for ASME applications. In both cases (ISO and ASME) larger sized probes will suffer greater attenuation due to curvature effects even though both may be placed on wedges having the same gap at their edge.

4.7 Flat Wedge-Width versus Element Size on Curved Surfaces

Looking at Figure 22 it can be seen that in spite of the same gap at the edge of the wedge, the difference in rate of amplitude drop is greater for the larger diameter element.

This suggests that it is not the gap that at the edge of the wedge that is the factor of concern, but rather the gap relative to the projected dimension of the element.

To test this idea, another scenario is run that uses the wedge width as the variable parameter. Three scenarios were run; one each for the 6mm, 12.5mm and 9.6x10mm elements. Each element was placed on a 45° refracting wedge on a nominal NPS6 pipe (168.3mm diameter) with 21mm wall thickness. The 2mm diameter SDH targets were scanned with sufficient scan length to detect the first 4 responses (up to the t/4 target near the end of the second half-skip). See Figure 23 for the targets scanned for wedge width assessment.
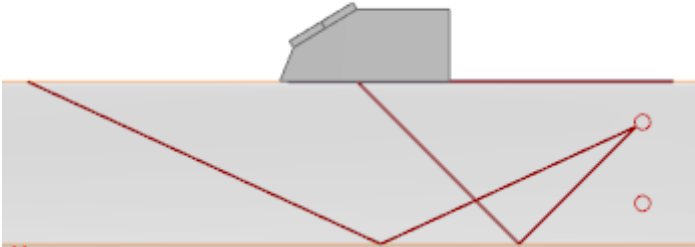

Figure 23   Targets compared for wedge width variations on 6NPS 21mm wall thickness

The wedge width was varied in each case from 11mm up to 31mm in 5mm steps. At 11mm width the wedge is in fact smaller dimensioned than the 12.5mm diameter element as seen in Figure 24.
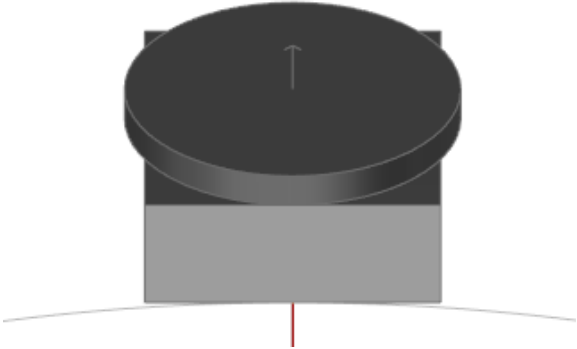

Figure 24   Extreme case of wedge width relative to element width with 12.5mm diameter element on 11mm wide wedge (on NPS6 pipe surface)

By superimposing the responses from the 4 targets scanned for each of the wedge widths, the effect on amplitude can be gauged for varying the wedge width, which also varies the wedge-gap width as implied by the codes. The comparison of responses can be seen in Figures 25, 26 and 27.

These plots demonstrate that the wedge gap at the edge of the wedge is not a significant concern. The real concern for gap, as it affects attenuation due to gap geometry, is therefore the projected dimension of the element on the surface of the test piece.

The only practical rationale for concern of the wedge gap at the edges of the wedge will be for mechanical rocking.
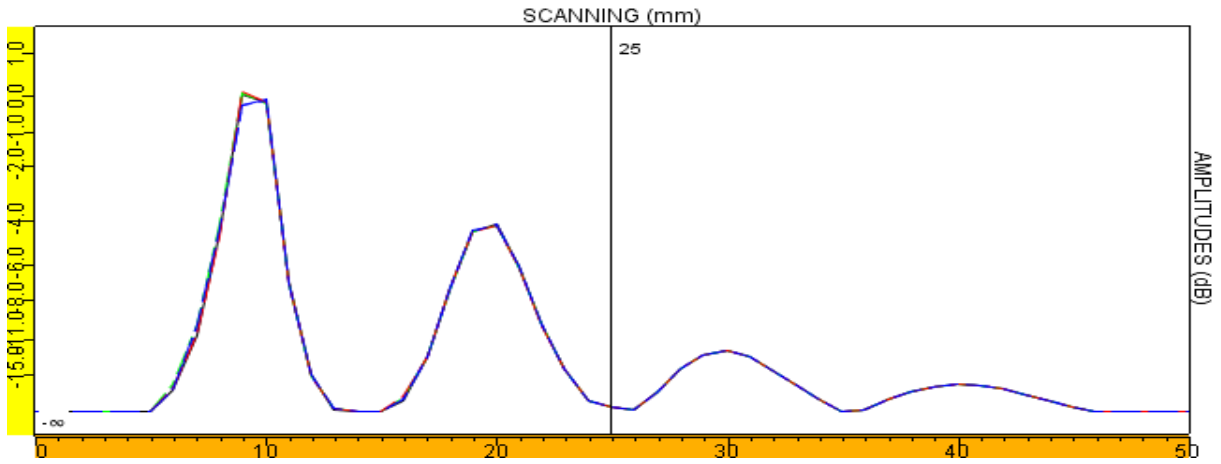
Figure 25 6mm diameter 45° probe wedge width from 11mm to 31mm in 5 steps has less than 0.3dB maximum variation
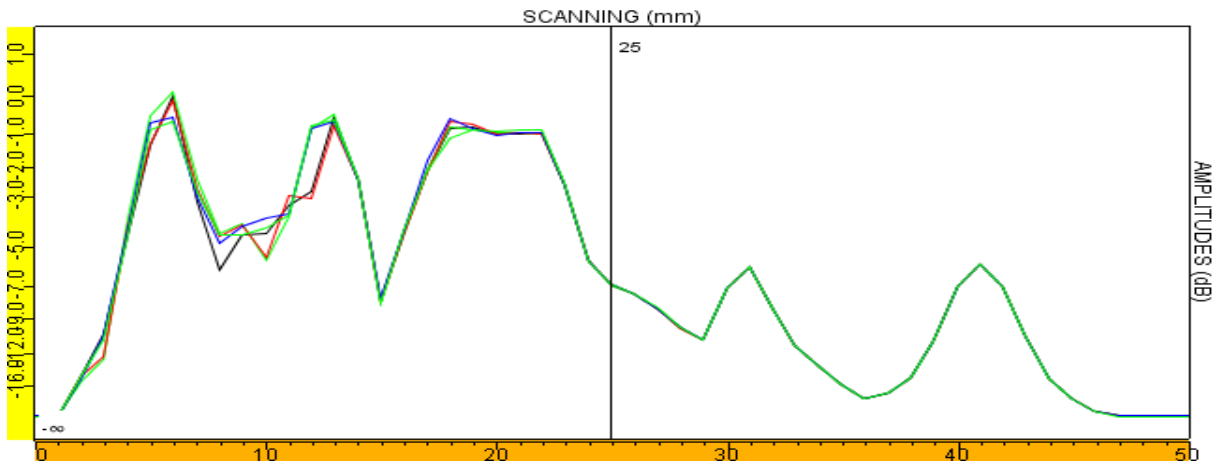

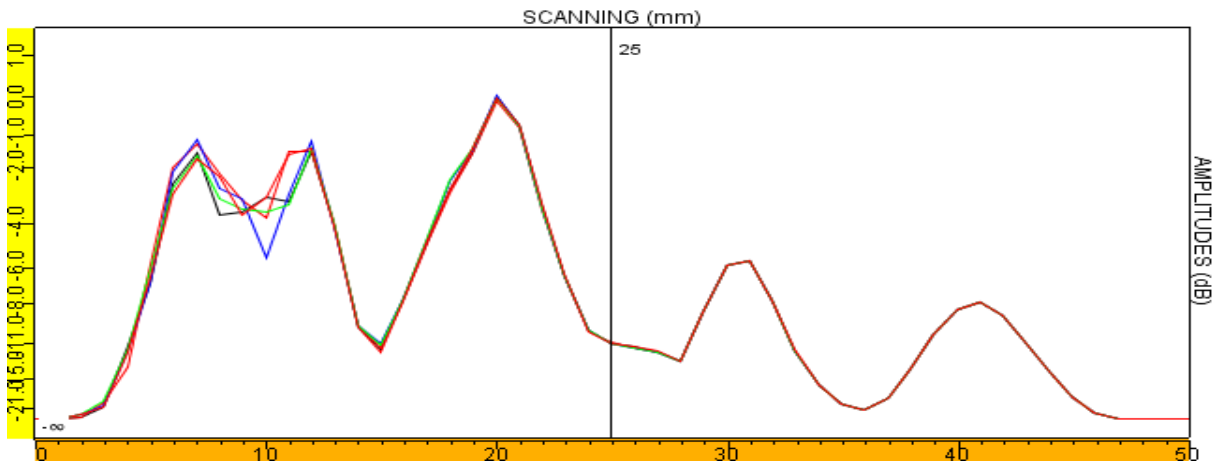**Figure 26** 12mm diameter 45° probe pedge width from 11mm to 31mm in 5 steps has less than 0.8dB variation

Figure 27 9.6x10 mm 45° probe wedge width from 11mm to 31mm in 5 steps has less than 0.3dB variation

4.8 Flat Wedge Rocking effect on Curved Surfaces

Even the relatively small 13mm wide wedge can quickly skew the beam away by simple rocking of the wedge on the test surface.

Figure 28 presents the conditions for a 13mm wide flat wedge on the NPS2 (60.3mm diameter) pipe surface. The half-width of the wedge when made to follow the pipe surface will have the edge of the wedge meet the pipe 6.5mm along the circumference, representing about 12.3° of tilt.
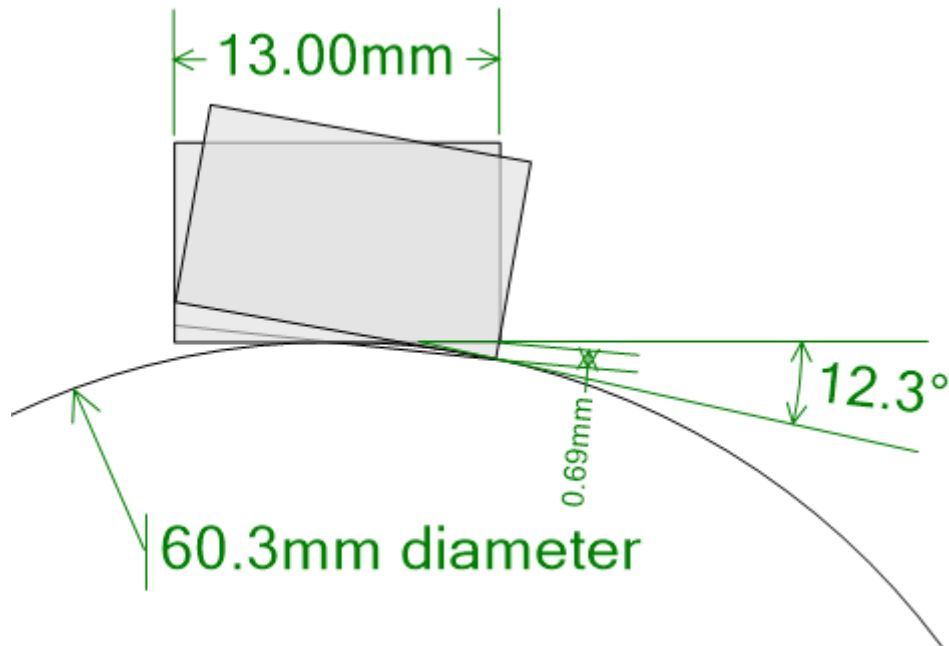

Figure 28   Tilt available with 13mm wide wedge on 60.3mm diameter pipe surface

This 12.3° is far more than required to eliminate any practical contact of the projected element at the pipe surface of an NPS2 pipe.

To simulate the degree of signal change that might result due to the tilt for a rocking motion, a Civa model was made using a 3D (iges file format) solid model of a cylinder and another with a 45° refracting wedge placed to detect a 2mm diameter SDH at a peak amplitude for 0° inclination (i.e. no rocking condition).

The wedge was then positioned as it would if rocked in 1° steps up to 6°. See Figure 29. Amplitude values for the SDH signal were then plotted against tilt angle.
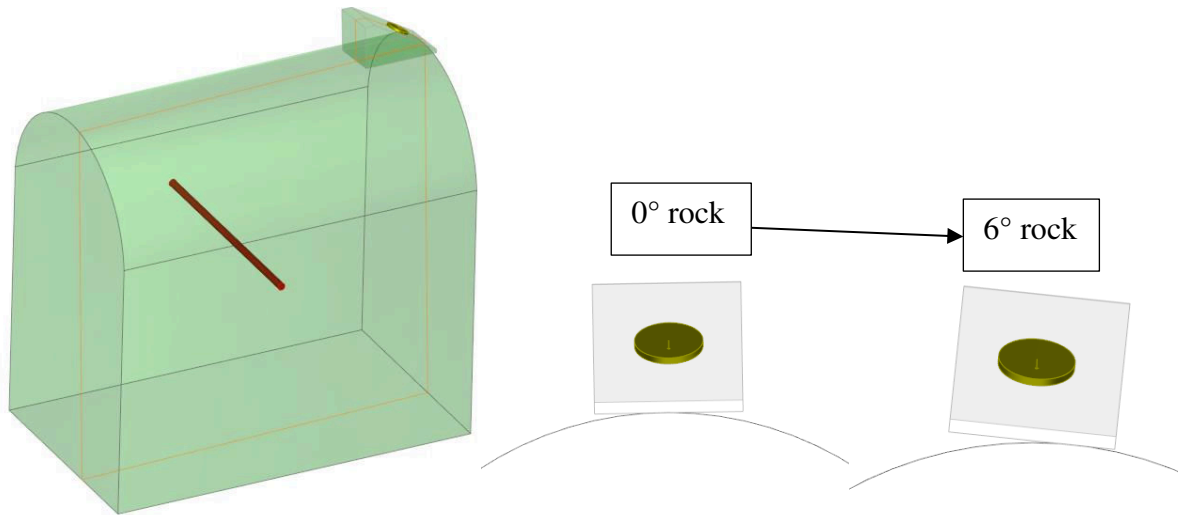
Figure 29   Rocking setup to assess 6° of wedge-rock

The plot of amplitude versus tilt angle in Figure 30 suggests that the change from good to poor coupling occurs in a relatively quick transition. Not only does coupling efficiency drop off as the centre of beam leaves contact with the pipe, there is a secondary angle of refraction that redirects the beam away from perpendicular incidence with the SDH.

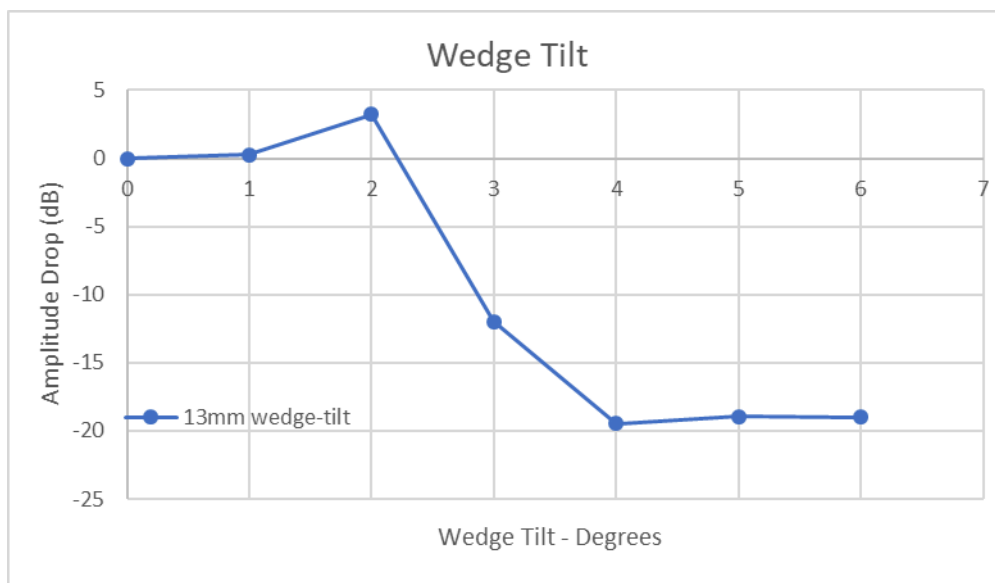
Figure 30   Effect of wedge rocking on relative sensitivity

When the effect of rocking is considered, even the 0.5mm gap provision may not be adequately conservative to maintain a small tolerance in sensitivity deviation from the ideal.

5. Discussion

Generally, NDT codes and standards exist to ensure that a consistent minimum quality is achieved by a product being inspected. For a given NDT method, the inspection standard typically indicates equipment requirements and how the test sensitivity is established. When using ultrasonic workmanship acceptance criteria, the standard establishes a reference sensitivity. This is then used as the reference to compare flaw responses to. When acceptance criteria are based on amplitude-response thresholds, and as little as 4dB separates one Acceptance Level from another, there is an underlying assumption by users that accurate sensitivities are critical. In fact, during inspections, ASME and ISO codes require periodic confirmations of reference sensitivities and any deviation greater than 2dB requires correction.

With the underlying assumptions that consistent quality using workmanship acceptance criteria requires accurate and consistent sensitivity settings, the implication exists that the codes and standards are written to ensure that the reference sensitivity is repeatable and identical regardless of the equipment used. The inference is made that inspections following the requirements of a Code will produce consistent results within 2dB regardless of operator or equipment used.

This assumption is of course not true. Ultrasonic inspection Codes have tolerances written into them. Variations are allowed in element sizes, refracted angles, nominal frequencies, couplant, instrumentation bandwidth, etc. In the preparation of this project we have seen how part geometry adds to the variability of sensitivity results. Wedge contour affects wedge-to-pipe contact. The diameter of a pipe and its thickness will vary the sound path to the reflecting surfaces which may result in more or less divergence or focussing at different points along the sound path.

ASME and ISO codes have made provision for parameters relating to pipe inspections such that a range of geometries (diameters and thickness) may be inspected using a single geometry as a reference block. However, when the same codes require tight control on amplitude stability (<2dB deviation from initial calibration) and have relatively small variations between workmanship acceptance levels, it should be of some concern that the tolerances allowed for differences between reference and inspection conditions assure similar narrow sensitivity tolerances. No guidance exists in these standards with regard to sensitivity tolerances when the geometric tolerances are taken into account.

Results of Civa modelling using the allowed geometric tolerances seem to suggest that the stated tolerances for pipe diameter and thickness may result in sensitivity deviations significantly larger than the 2dB permitted as instrument stability or the 4dB separating some acceptance levels. When the effects of wedge contouring are added to the variables, along with the effect of projected element dimension relative to the pipe curvature, it is apparent that quality assessment of a pipe weld using workmanship acceptance criteria may vary widely from one operator's setup to another. As a result, any sense of "standardisation" is diminished. ASME makes provision that alternative targets be used provided sensitivity is equal to or greater than that from the basic targets. This seems to be contrary to the implied idea that codes are attempting to provide a "consistent" level of sensitivity when using workmanship acceptance criteria; unless this is interpreted to mean a "consistent minimum level" and higher levels are allowed and unrestricted.

Civa modelling can provide a convenient method of determining the degree of sensitivity variation from the base levels described in codes and standards.

6. Conclusions

Civa has proven to be an effective method of evaluating variables relating to relative sensitivities in pipe girth-weld inspections. It is our opinion that the use of Civa modelling could provide writers of codes and standards an effective means of validating parameter tolerances.

The observations in this analysis may be considered representative of the issues that may be encountered in the field rather than indicating the quantitative values for specific probes, wedges, pipe and steels.

Guidance provided in standards for wedge gap seems to be incorrectly implying that the critical sensitivity concerns relate to the gap formed between the edge of the wedge and the pipe surface. Instead, the main factor relating to sensitivity concerns for wedge gap at the pipe surface relates to the projected element width.

A significant factor relating to sensitivity is the effect that a maximum gap has on probe rocking. As the wedge-gap increases, the degree of tilt can affect both the quality of coupling and a skewing refraction of the beam which results in directing the beam away from the intended axial direction. The combined effect of reduced coupling and non-perpendicular incidence on planar flaws can significantly reduce ideal sensitivity and detection capabilities. Some manufacturers have addressed this by using a chamfered edge to reduce the contact width of the wedge on the pipe.

Code guidance on wedge gap may be overly conservative if the wedge dimension is only considered with regard to coupling effects. It is more likely that a greater issue will be related to the rocking (tilt) if the wedge gap is excessive.

Codes allow for some tolerance between calibration and tested component thickness and curvatures. The tolerances recommended appear to provide no guidance on the expected range of deviation from sensitivities that would result if no tolerance was allowed; i.e. if calibration blocks had to be made using the exact same diameter and wall thickness as that being tested.

When different thicknesses and diameters are used for calibration sensitivity and scanning surfaces, some degree of compensation for the effects of sensitivity variation may be achieved using the traditional pitch-catch transfer value techniques.

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