
Assessment of Virtual Flaw Technology: An Approach Using Modify Virtual Mockup Software

September 2026

Prepared by:

Joel Harrison, Matthew Prowant, Richard E. Jacob

Pacific Northwest National Laboratory
Richland, Washington 99354

NRC Project Manager:

Chinthaka M. Silva
Materials Engineering Branch

**Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Rockville, MD 20852**

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Chinthaka Silva – NRC Contracting Officer Representative

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Richland, Washington 99354

Summary

The U.S. Nuclear Regulatory Commission (NRC) tasked Pacific Northwest National Laboratory (PNNL) to evaluate the feasibility of using digitally modified ultrasonic testing (UT) data—known as virtual flaws—for the training and qualification of nondestructive examination personnel. Since the 1977 introduction of American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC), Section XI, *Rules for Inservice Inspection of Nuclear Power Plant Components*, the requirements for UT personnel have expanded significantly. Appendix VII, *Qualification of Nondestructive Examination Personnel for UT*, and Appendix VIII, *Performance Demonstration for Ultrasonic Examination Systems*, published in 1989 and codified by the NRC in 2002 in Title 10 of the *Code of Federal Regulations* (10 CFR) Section 50.55a, mandated performance demonstrations using flawed specimens for the qualification of personnel, procedures, and equipment. This drove the demand for diverse flaw scenarios within physical mockups. However, such mockups are costly, time consuming to fabricate, and limited in availability. Indeed, the cost to invest in a full range of specimens is prohibitive for some licensees and inspection vendors.

The nuclear power industry is working to enhance and expand resources for training and qualifying inservice inspection personnel by addressing the challenges of limited access to mockups. Virtual flaw technology offers a potential solution by enabling the creation of realistic flaw signatures through software modification of empirical data. Virtual flaws are digitized UT flaw signatures with various modified flaw parameters, such as location, size, orientation, and amplitude. The resulting virtual flaws should ideally be indistinguishable from real flaws by a trained and qualified analyst. While the flaw modification process can take several hours depending on the complexity of the modification to be performed and the intended flaw characteristics, creating virtual flaws is much more rapid and cost-effective than fabricating real specimens containing flaws. The proper use of this technology can be a pathway to develop extensive datasets representative of real-world conditions for training and qualifying UT analysts and possibly even for training machine learning algorithms for automated or assisted data analysis.

PNNL collaborated with the Electric Power Research Institute (EPRI) under a memorandum of understanding with NRC to evaluate the effectiveness of EPRI's Modify Virtual Mockup (MVM) software for creating realistic virtual flaws. MVM evolved from UltraVision plugins to a MATLAB-based tool offering functions such as importing UT data files, creating configuration files for flaw modification, previewing and applying modifications, and exporting modified data for analysis in UltraVision. At the time of this study, PNNL was unaware of other available software to create virtual flaws.

PNNL sourced data from 17 specimens representing dissimilar metal welds (DMWs) and other configurations. Using MVM, PNNL created 27 virtual specimens consisting of different types of flaw modifications based on realistic flaw scenarios. Modifications included removing or relocating flaws, adjusting flaw amplitudes, adding or removing geometric responses, and combining multiple flaws into one dataset.

PNNL demonstrated that virtual flaws from empirical UT data can, when properly implemented, replicate real flaw characteristics. Through this work, PNNL has determined that expertise in UT analysis and UltraVision are essential for successfully modifying empirical flaws with MVM and any software employing a similar approach. The MVM software alone cannot ensure realism, and some anomalies require careful review and iterative adjustments. For instance, just an

operational knowledge of the modification software is not sufficient to determine if the result is acceptable. PNNL recommends personnel hold at least ASME Section XI Level II UT certification and receive ~24 hours of MVM-specific training.

Several challenges remain before virtual flaw technology should be used for qualification.

- (1) The essential parameters for the MVM software (or any comparable software package that might emerge) to produce valid results are unknown and need to be defined for consistent implementation.
- (2) Procedural guidance needs to be developed for flaw realism assessment.
- (3) Training and competency requirements for generating virtual flaws need to be defined.
- (4) Industry standards and ASME Code actions are needed to formalize the use of virtual flaws for training and qualification.
- (5) Regulatory guidelines need to be prepared for application acceptance.

Acronyms and Abbreviations

AI	artificial intelligence
ASME	American Society of Mechanical Engineers
BPVC	Boiler and Pressure Vessel Code
CASS	cast austenitic stainless steel
CEA	Commissariat Energie Atomique
CFR	<i>Code of Federal Regulations</i>
CS	carbon steel
DMW	dissimilar metal weld
EPRI	Electric Power Research Institute
IGSCC	intergranular stress corrosion cracking
ISI	inservice inspection
LOF	lack of fusion
MOU	memorandum of understanding
MVM	Modify Virtual Mockup
NPP	Nuclear Power Plant
NRC	U.S. Nuclear Regulatory Commission
OD	outer diameter
PDI	Performance Demonstration Initiative
PNNL	Pacific Northwest National Laboratory
RPV	reactor pressure vessel
SDK	software development kit
TFC	thermal fatigue crack
TIE	Technical Information Exchange
TRL	transmit–receive longitudinal
TW	through-wall
UT	ultrasound testing
UV	UltraVision data analysis software
WCL	weld centerline

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1.0 Introduction

The U.S. Nuclear Regulatory Commission (NRC) has tasked Pacific Northwest National Laboratory (PNNL) with evaluating the potential for virtual flaws, particularly digitally modified flaw signatures in ultrasonic testing (UT) data, to be used for training and qualification. The scope of the work mainly included evaluating the modification software for usability and determining the qualifications and experience that a user should possess to assure that the resulting virtual flaw signatures are indistinguishable from native signatures. The scope also included demonstrating the software performance on a variety of flaw modifications and evaluating the realism of the resulting flaw signatures.

Efforts have been initiated to improve and expand the resources available for personnel training and qualification in support of inservice inspection (ISI) of commercial nuclear power plants (NPPs). A key function of these personnel is data analysis, requiring the ability to recognize and characterize flaws and other indications in UT data acquired during plant examinations. In the early 1980s, intergranular stress corrosion cracking (IGSCC) (Mohanty et al. 2012) became a significant issue in boiling water reactor (BWR) recirculation systems. The detection of these flaws presented a substantial challenge to existing UT examination procedures, equipment, and personnel. To address the inspection challenges, the NRC mandated, in NRC Bulletin 83-02, a performance demonstration capability for IGSCC that required procedures and inspectors to pass a practical examination to become qualified. However, the most realistic flaws for such an examination are those in NPP components that have been removed from service. Usually, such components are metallurgically sectioned and examined to better understand the flaw mechanism or origin. Often the component is radioactive and requires special licensing for specimen storage, transportation, and access. Therefore, the number of specimens containing IGSCC is severely limited.

When the American Society of Mechanical Engineers (ASME) developed and published Boiler and Pressure Vessel Code (BPVC) Section XI, *Inservice Inspection of Nuclear Power Plant Components*, Appendix VII, *Qualification of Nondestructive Examination Personnel for UT*, and Appendix VIII, *Performance Demonstration for Ultrasonic Examination Systems*, in the 1989 Edition (later codified by the NRC in Title 10 of the *Code of Federal Regulations* [10 CFR] Section 50.55a¹ in November 2002), the need for relevant flawed specimens increased dramatically. The requirements are defined in nine different supplements of Appendix VIII for all Class 1 piping systems, reactor pressure vessel (RPV) welds, and RPV closure head bolting, as in the examples shown in Figure 1. The set of expanded specimens was not only required for Appendix VIII qualification, but also for an employer's certification and the annual practice requirements of UT inspectors. As a result, processes to create cracks that were then implanted into a welded component gained interest and popularity. This method can be used to fabricate mockups with realistic flaws, but it is time-consuming and expensive. Indeed, many such mockups have been fabricated; however, their supply is limited, and many are proprietary or reserved for blind performance demonstration testing. Although mockup fabrication has increased the supply of flawed specimens, the cost to invest in a full range of specimens was prohibitive for some licensees and inspection vendors.

¹ Title 10 of the *U.S. Code of Federal Regulations* Part 50, "Domestic Licensing of Production and Utilization Facilities," Section 55a, "Codes and Standards."

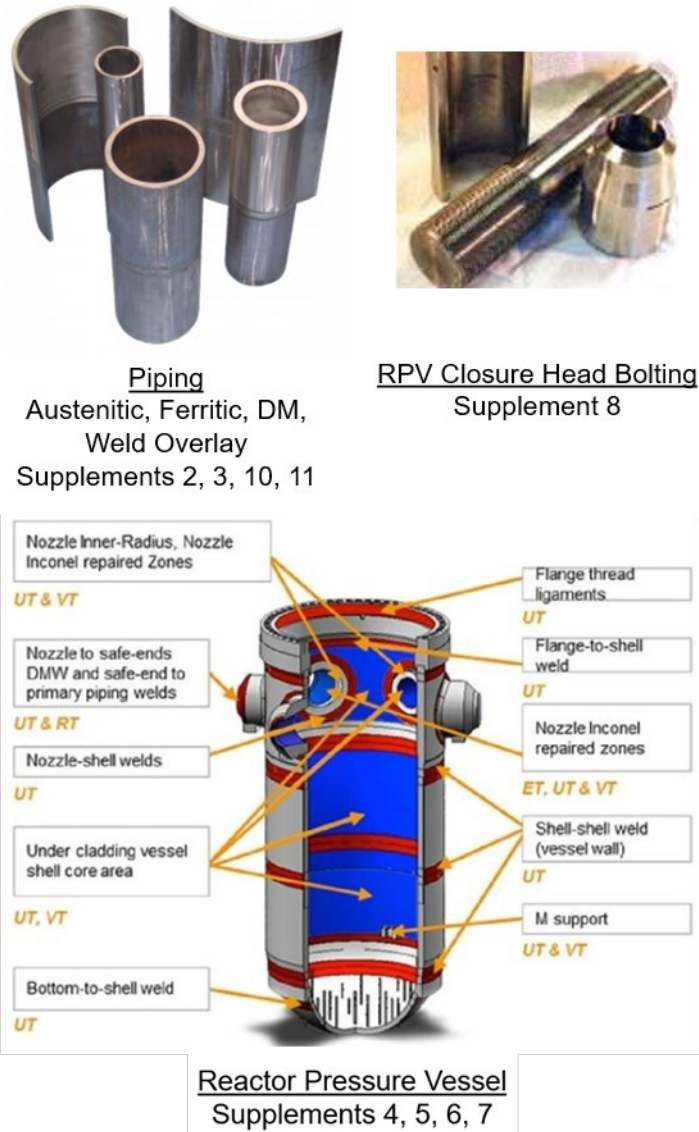


Figure 1. Examples of an RPV and Class 1 piping systems and materials with references to the respective Appendix VIII supplements. 'DM' denotes dissimilar metal.

Around 2010, the industry recognized the need for new flawed specimens for training and performance demonstration purposes. The Electric Power Research Institute (EPRI) was engaged to initiate a research project to investigate electronically altering encoded UT data to create new "specimens" and flaw scenarios. The idea was to create new "virtual" flaws from data files acquired in the laboratory or the field; this was seen as a path to improve training by augmenting training datasets and broadening the number and types of flaw signatures that analysts are exposed to (Svahn et al. 2018). The result of this effort was EPRI's Modify Virtual Mockup (MVM) software. A successful use of the approach can be a diverse and essentially unlimited database that contains realistic flaw signatures obtained by manipulating any combination of properties such as signal amplitudes, noise backgrounds, flaw positions, flaw orientations, and flaw sizes.

Two new types of flaws were defined:

- Virtual Flaw – a digitized ultrasonic flaw signature that has been computationally modified by changing some aspect of the precursor flaw signature, including the location, size, orientation, and signal intensity
- Synthetic Flaw – a digitized flaw signature that has been created from modeling and simulation software. Note that synthetic flaw generation was beyond the scope of the current study.

A virtual flaw may be created from empirical or synthetic flaw data. In either case, an ideal virtual flaw signature will be indistinguishable from that of an empirical flaw. Note that TrueFlaw, Ltd. (Espoo, Finland) has independently developed their own approach to ultrasonic virtual flaws (Virkkunen et al. 2021a), and the French Commissariat Energie Atomique (CEA) has worked on synthetic flaws for both ultrasonic and radiographic applications (Touron et al. 2025).

In recent years, EPRI has promoted virtual flaw technology during their annual June “NDE Technology Week” and during the annual NRC-Industry Technical Information Exchange (TIE). During the ASME Code Week meeting in November 2025, PNNL convened a group of licensee and vendor representatives to determine the industry’s plans for virtual flaws. It was informative to learn that, although interest was quite high five to six years ago, there were not any immediate plans to implement virtual flaws. However, during the more recent 2026 NRC-Industry TIE, there was increased interest in virtual flaw technology. Based on feedback from industry collaborators, recent additions to the MVM software suite have improved the appearance of simulation-generated synthetic flaws to produce more realistic results, and the ability to reduce the general background noise in UltraVision (UV, Eddyfi Technologies) data files has been added to better enhance a flaw response (EPRI 2025). While this work appears promising, it still requires evaluation outside of the industry collaboration (e.g., independent organizations, independent analysts, or broader stakeholder groups). Additionally, EPRI presented a “Qualification Roadmap” with a timeline from 2026 through 2029 with a plan to assemble and complete a virtual flaw library by the end of 2026, with planned qualification field trials through the end of 2029 supporting core barrel UT, UT in lieu of radiographic testing, personnel qualification, and procedure qualification. Industry’s first presentation to the NRC outlining the use of virtual flaws for qualification purposes is anticipated in 2027.

In addition to the need for data for training personnel, there is an emerging need for data for training artificial intelligence (AI) models. The nuclear industry is increasingly looking to AI as a tool for assisted data analysis. AI models require large amounts of data for thorough training, and the requirements cannot be adequately met by the current supply of physical mockups. Therefore, virtual flaws may be used to fill this gap (Koskinen et al. 2021; Virkkunen et al. 2021b).

2.0 Collaboration with EPRI

The MVM software is not commercially available; therefore, PNNL established a collaboration with EPRI via a memorandum of understanding (MOU) between the NRC and EPRI. Through the MOU, PNNL and EPRI are able to share software, data, information, and results without violating any organizational conflicts of interest. However, PNNL and EPRI maintain independent research and do not share authorship on publications or presentations.

In December 2022, PNNL sent four representative UV data files to EPRI for modification testing. UV is a software package commonly used in the nuclear industry for UT data acquisition and analysis. These data were modified, and the MVM software and modification configuration files (which define the specific modification parameters) were then provided to PNNL to become familiar with the workflow process and begin modifying PNNL's in-house data files.

In August 2023, PNNL and EPRI staff met for an in-person workshop at the EPRI NDE Center to review the progress to date by both organizations, exchange information and experience with MVM, and explore additional features of MVM, including the application to synthetic flaws produced from modeling and simulation software such as CIVA (Extende, Inc.). Discussions were also held with EPRI project managers about the nuclear industry's objectives for virtual flaws.

During the workshop, EPRI staff provided the PNNL team with a walk-through of the software functions and configuration examples for various types of modifications. Examples of completed flaw modifications were shown using both empirical and synthetic flaws. The PNNL team was then given the opportunity for "hands-on" experience to become familiar with the workflow from building a configuration file to executing and assessing a modification.

Some time was also dedicated to a discussion and evaluation of the modification process using synthetic flaws. An EPRI-developed method for transferring the data from CIVA to UV was described. The synthetic flaws in the demonstration were found to be too "perfect," with unrealistically smooth, consistent boundaries and amplitudes.

Since 2023, EPRI has continued to work on updating and improving the software while providing PNNL with technical support and software updates. PNNL has provided EPRI with information about bugs or technical issues so that they could be fixed in subsequent versions. For example, PNNL found that an early version of the software ran into problems with insufficient memory when run on typical desktop computers. This was important because typical users are not expected to have high-performance workstations for flaw modifications. The issue was brought to the attention of the EPRI software engineer, and the software was revised to reduce RAM requirements. After the fix, PNNL was provided with the revised version of MVM and was able to process 10 files, each in excess of 6 GB, on a computer with 32 GB of RAM. UT data files of this size are common, particularly with phased-array inspections that incorporate a sweep of angles at relatively small angular steps ($\sim 5^\circ$). The modification process was completed on all files, with the largest file taking approximately 30 minutes.

3.0 Modify Virtual Mockup (MVM) Software

As of this writing, the only standalone ultrasonic flaw modification software available is the MVM program developed by EPRI. While some limited data file modification is possible in UV, it requires additional application support for processing, as this is not UV's primary function.

The initial work performed by EPRI utilized UV to develop four basic plugins within the UV framework for data file modification. This was accomplished utilizing the UV software development kit (SDK) that allows users to create a dynamic link library (dll file) to interface with the UV graphical user interface to perform custom operations. The result of this initial effort is documented in an EPRI technical report (EPRI 2018).

3.1 MVM Software Development

In 2014, EPRI converted the UV tools to the MATLAB (The MathWorks, Inc.) environment. UV was still used for data acquisition, import, and export; however, all technical processes in between are now handled in a series of MATLAB scripts. The MATLAB tool continues to provide the same modification options available with the UV plugins, in addition to the following:

- allow copying data from a source file to itself or a different file
- stretch or compress the range of the data
- present the copied data along any axis (circumferential, axial, or skewed).

EPRI's current work on the MVM software, beginning in 2023, is driven by feedback from external collaborators and members of a focus group organized by EPRI. MVM has gone through six revisions since PNNL began reviewing the software¹. The revisions, with one exception, were to streamline the workflow process and address excessive RAM demands during a UV data import process. The workflow is explained in more detail in Section 3.2. Note that MVM is a work in progress, and software updates have been made since the initial writing of this report.

3.2 MVM Software Functions

The MVM software program includes five functions for performing flaw modifications. The functions include:

- Draw
- Load Configuration
- Preview Modification
- Apply Modification
- Export to UVData.

The MVM console window (Figure 2) shows these functions and their location in two MVM console subsections, "UVData File Selection" and "Config File Selection." Note that, in subsequent updates to MVM, some of the function names have been changed, but the functionality is essentially the same.

¹ MVM is up to version 1.6, but most of this work was performed in versions 1.1 and 1.2.

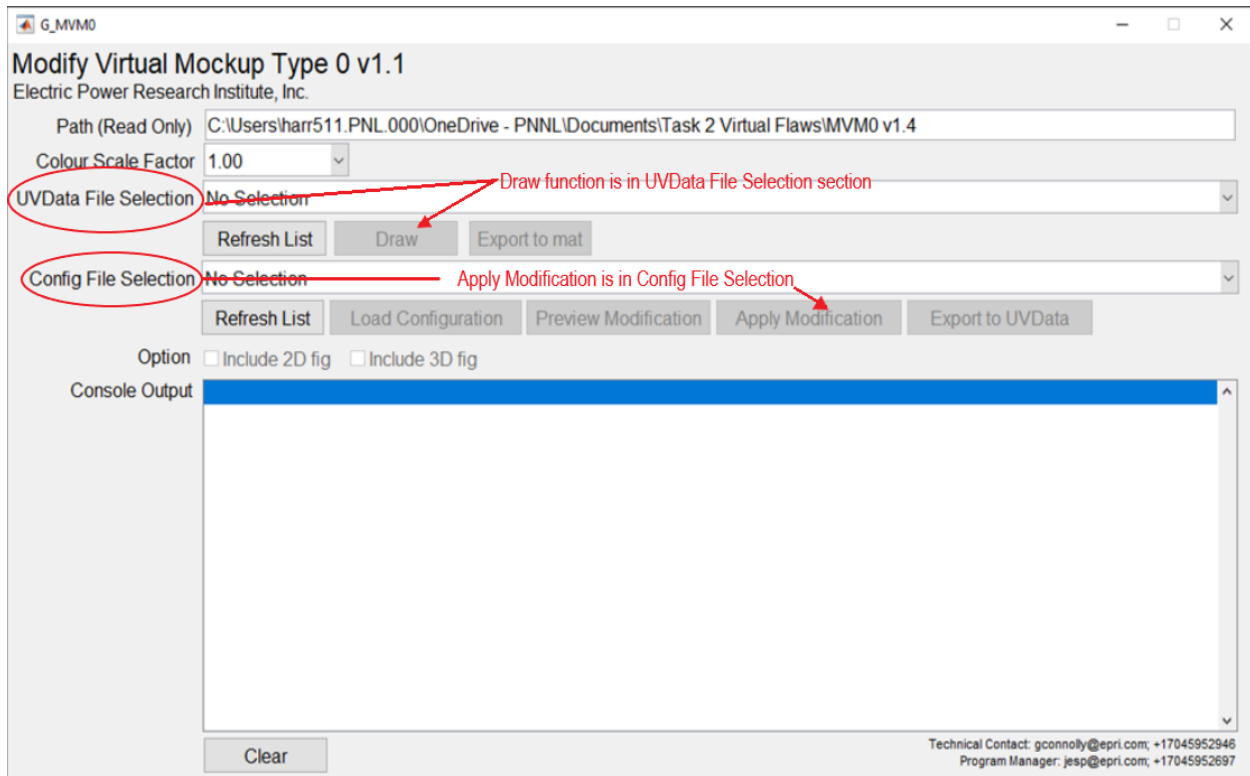


Figure 2. MVM main window showing two subsections.

3.2.1 The Draw Function

The Draw function is located in the “UVData File Selection” section of the MVM console window, shown in Figure 2. The use of the word “Draw” to describe a data import process could be somewhat confusing when working with image files such as those from UV. It does not mean that users can draw or sketch an image; rather, its purpose is to extract or source data from an existing UV file.

To begin a modification, the first step is to draw a UVData file into the MVM program. The UV files must be in a directory with a name fixed by MVM (e.g., MVM0 v1.4/uv) to be recognized by the software. Once the data file has been copied into this directory, the file appears in a drop-down box for selection, as shown in Figure 3.

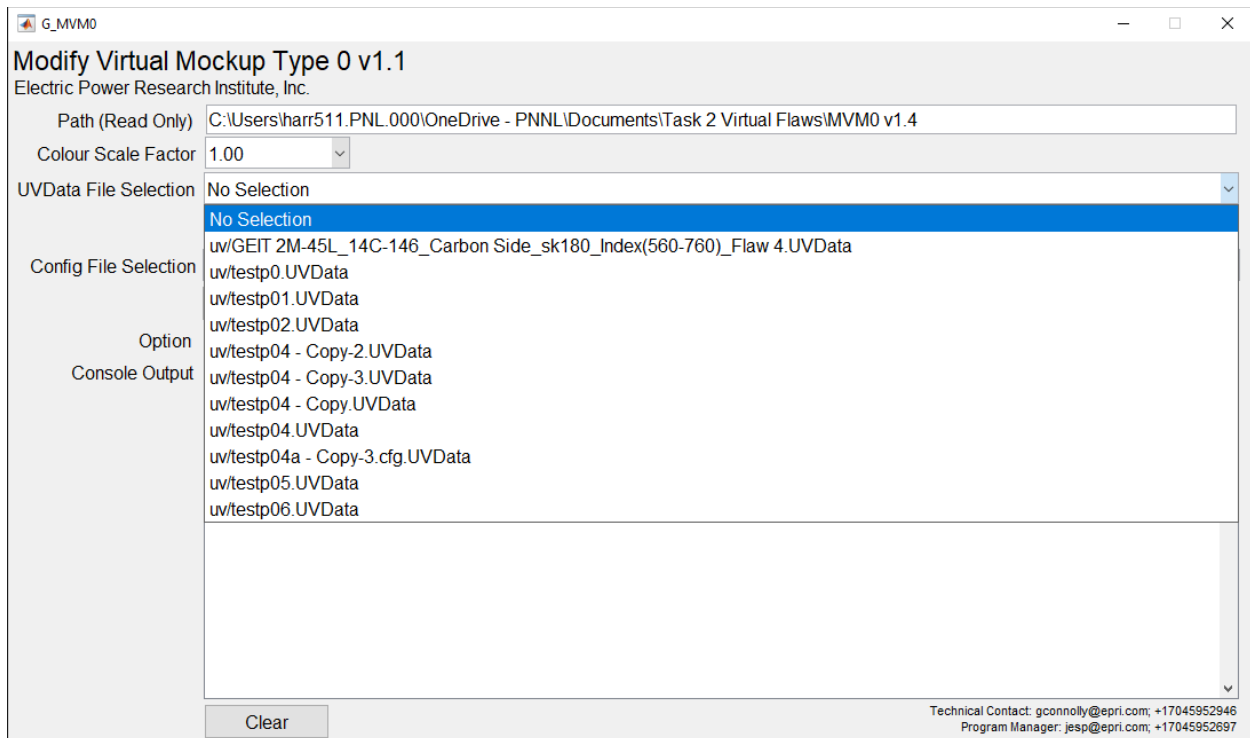


Figure 3. Filenames appearing in the MVM subfolder to be imported into MVM.

Once a file is selected from the drop-down box, the user may select “Draw” to import the data into MVM, as shown in Figure 4.

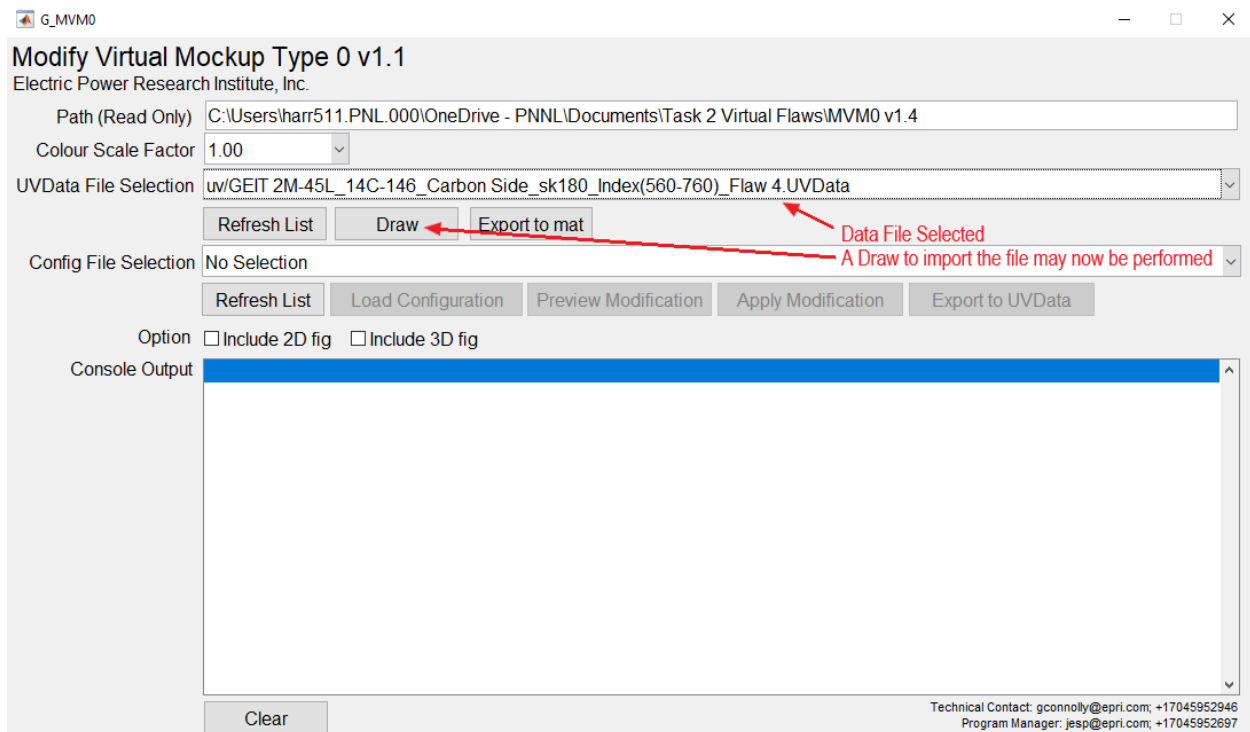


Figure 4. Depiction to initiate a Draw process.

After this task is executed, the draw progress is displayed in the “Console Output” window, as shown in Figure 5.

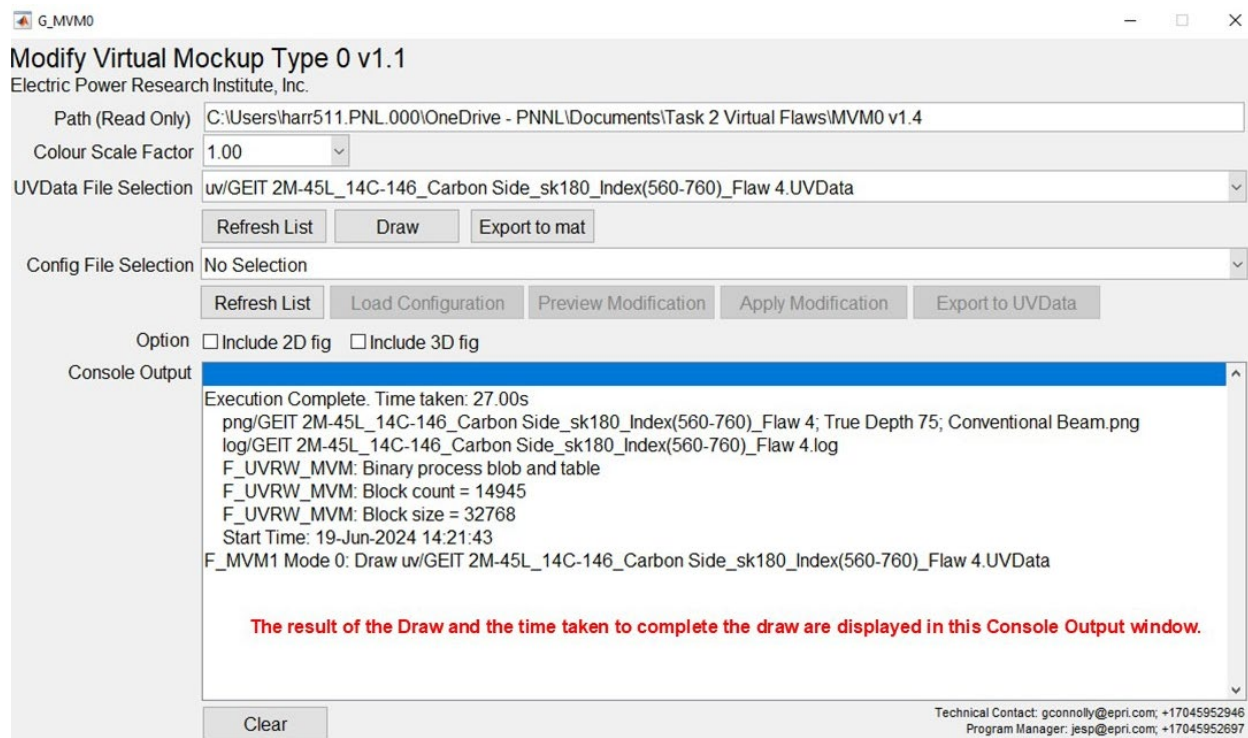


Figure 5. Result of the “Draw” task displayed in the Console Output window.

When the Draw function has completed, two files are created in MVM, a log file (in txt format) and an image file (in png format). As shown in Figure 6, the log file displays information about the UV data file: the number of channels, channel name, number of beam angles, and type of beam angle. Separate UV data “channels” may be used during scanning to simultaneously acquire data with different beam angles, gain settings, or other settings.

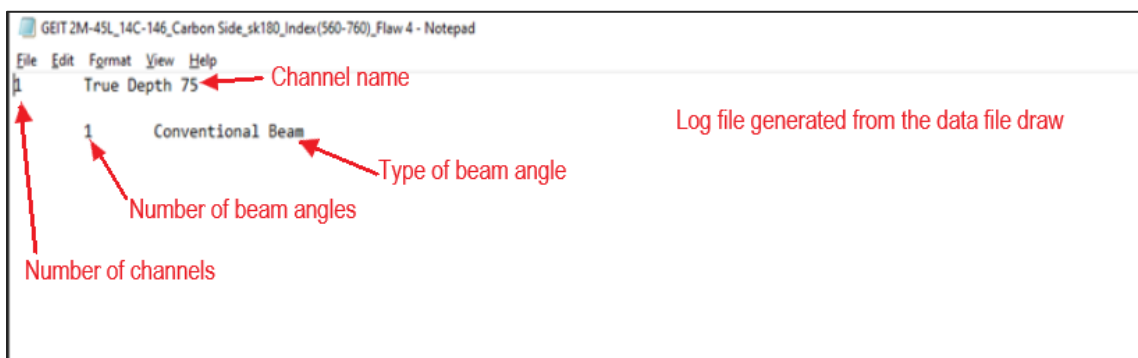


Figure 6. Log containing details of the imported UV data file.

The png file displays an image of the UT data, as shown in Figure 7, and defines the Index, Scan, and Depth dimensions of the data in millimeters. The Index is the circumferential distance along the weld, the Scan is the axial distance on either side of the weld centerline, and the Depth is the distance from the outer and inner surfaces of the component. A specific region

within the image will be selected, based on these dimensions, as the region to be sourced, modified, and then placed into the target file. Figure 8 displays the top and end views from a png graphic of the extracted file and shows the Index, Scan, and Depth axes as green, blue, and purple, respectively.

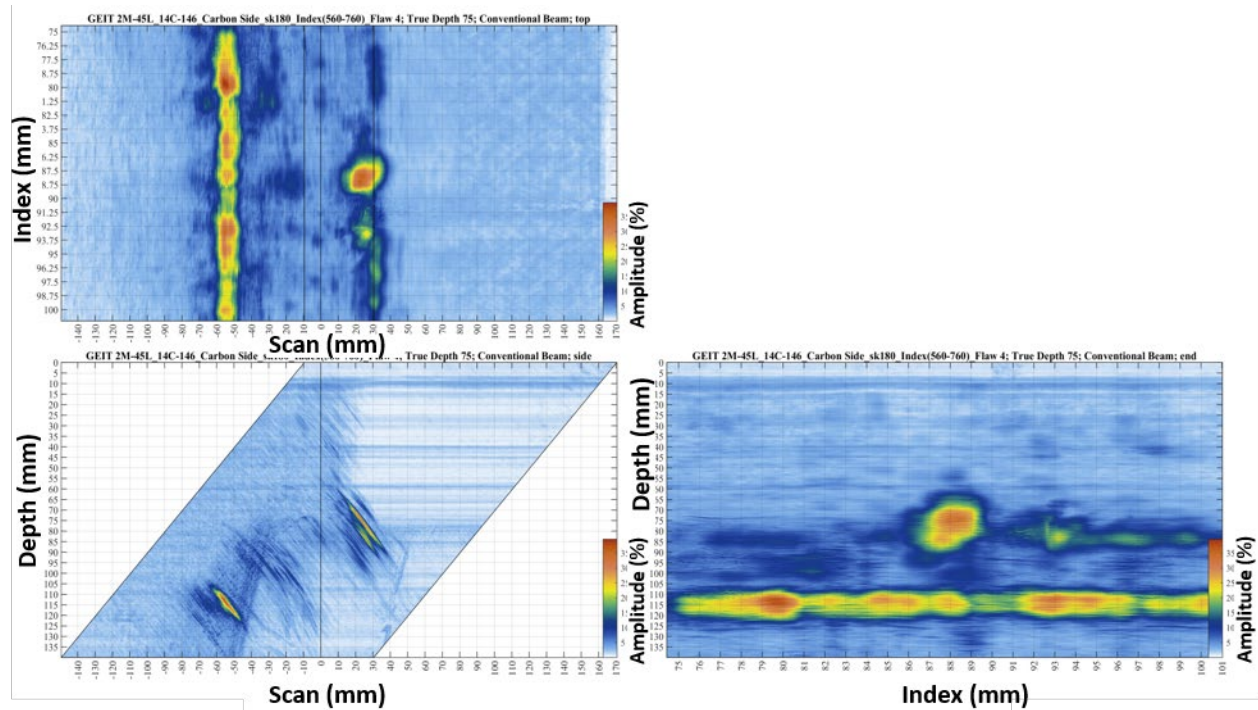


Figure 7. Graphical displays of UT data from the extracted file. Top-left is a C-scan (top view), bottom-left is a B-scan (end view), and bottom-right is a D-scan (side view).

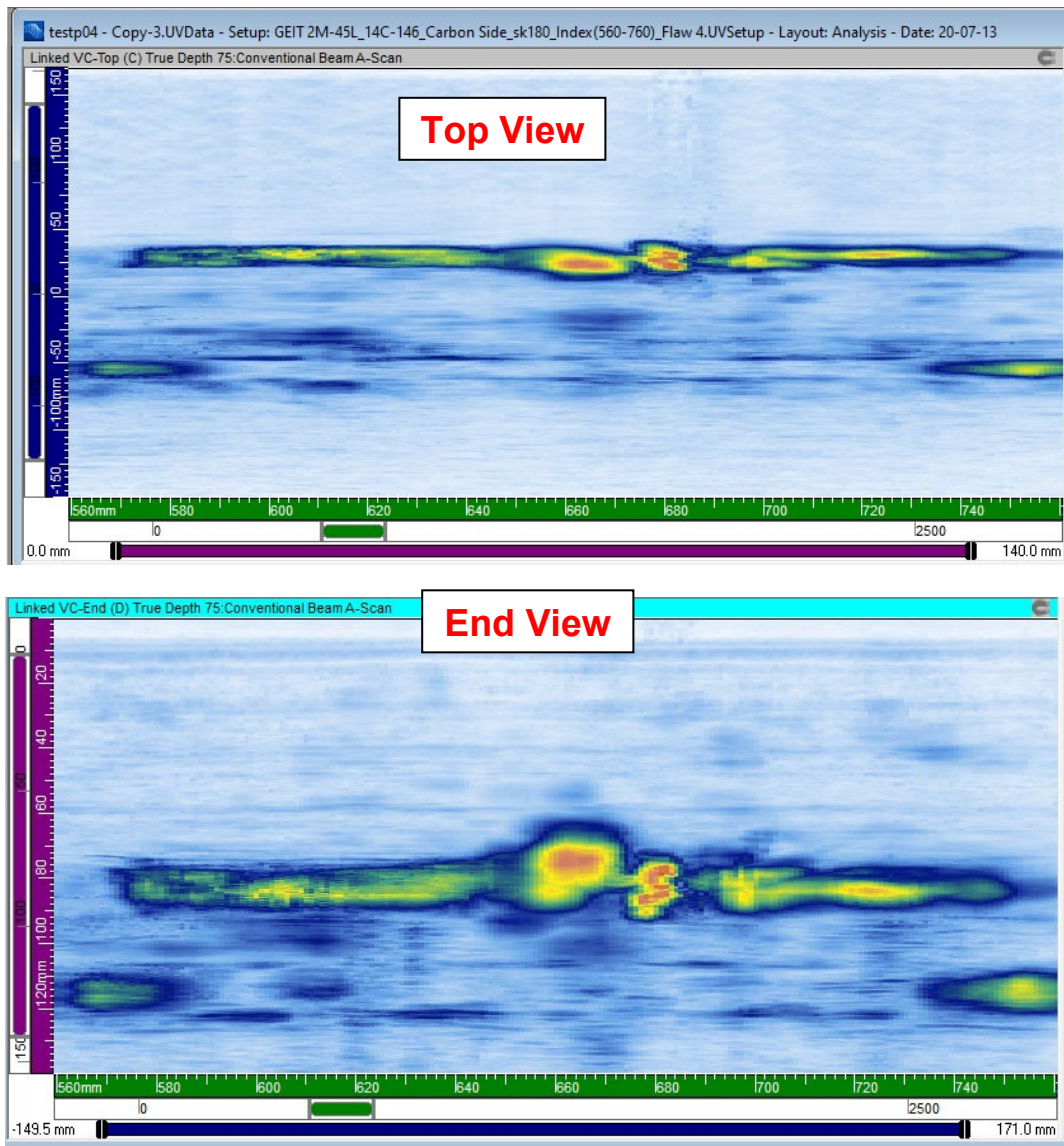


Figure 8. Top and end view displays of a UT data file showing the Index, Scan, and Depth axes as green, blue, and purple, respectively.

3.2.2 The Configuration File

Once a Draw has been completed, a configuration file must be created that defines the region and parameters of the actual modification. The configuration file is in a tab-delimited format and can be edited in Excel or a text editor.

Each column defines a separate modification process. Column A is reserved for the configuration “keys” that identify the parameters of the configuration. The rows define the source and target locations of the region to be modified and three “Factor” parameters: sourceFactor, targetFactor, and ampFactor. The two most commonly used functions are sourceFactor and targetFactor, which control the relative strength of the source and target regions at recombination for a modification. The amplitude factor (ampFactor) works in conjunction with sourceFactor and targetFactor. A zero ampFactor linearly sums the source data and target data.

Typically, the source and target factors are numbers between zero and one, so adjustment of these factors can be sensitive. Specific attention must be placed on the modification result to ensure that the background noise of the modified target area blends with the unmodified area and does not create an anomaly that would be identifiable by a data analyst as an unrealistic representation of background noise.

Figure 9 shows an example configuration file that defines two simple modification processes: the flaw is erased from its original location and moved to a new location in the same data file with no other changes made to the flaw appearance. The first process is defined in column B. Row 1 identifies the source file, and rows 4 through 10 define the start and stop coordinates of the Scan, Index, and Depth axes of the flaw to be modified. Row 12 is the name of the file to which the modified data will be written, and rows 16 through 22 define the modification (in this case, the target location for the new flaw).

Column C defines the second modification to be performed on this file. This modification “cleans” or erases the source flaw from its original location so it will no longer be visible. In row 1, the source file must be identified again, since column C is a separate function to be configured. The rows again define the specific location of the source data and define the target data modification. In row 12, the target file does not require a separate filename as in row 1 because each modification configuration is being written to the same target file. By not defining a second target file, this allows two separate flaws to be sourced from two separate files then written to only one new file. In this example, the targetindex0 and targetindex1 dimensions in column C are larger than the corresponding source dimensions. It was necessary to expand the target area for proper blending and removal of the cleaned area of the target location. The configuration file is then saved with a cfg file extension in a “cfg” folder within the MVM main folder.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	sourceFile	GEIT 2M-4	GEIT 2M-45L_14C-146_Carbon Side_sk180_Index(560-760)_Flaw 4																		
2	sourceChannel																				
3	sourceBeam																				
4	sourceScan0		-5	-5																	
5	sourceScan1		50	50																	
6	sourceIndex0		85	74																	
7	sourceIndex1		92	81																	
8	sourceDepth0		60	60																	
9	sourceDepth1		95	95																	
10	sourceFactor		1	0.8																	
11																					
12	targetFile	GEIT 2M-45L_14C-146_Carbon Side_sk180_Index(560-760)_Flaw 4																			
13																					
14	targetChannel																				
15	targetBeam																				
16	targetScan0		0	50																	
17	targetScan1		55	-5																	
18	targetIndex0		94	85																	
19	targetIndex1		101	92																	
20	targetDepth0		35	95																	
21	targetDepth1		70	60																	
22	targetFactor		1	0.2																	
23																					
24																					
25																					
26																					
27																					
28																					

Figure 9. Configuration file indicating two modification processes.

Once the configuration file has been written and saved, it may then be selected from the “Config File Selection” drop box, and a “Load Configuration” process can be initiated. The “Apply Modification” button can now be selected. Figure 10 displays the beginning of the modification process.

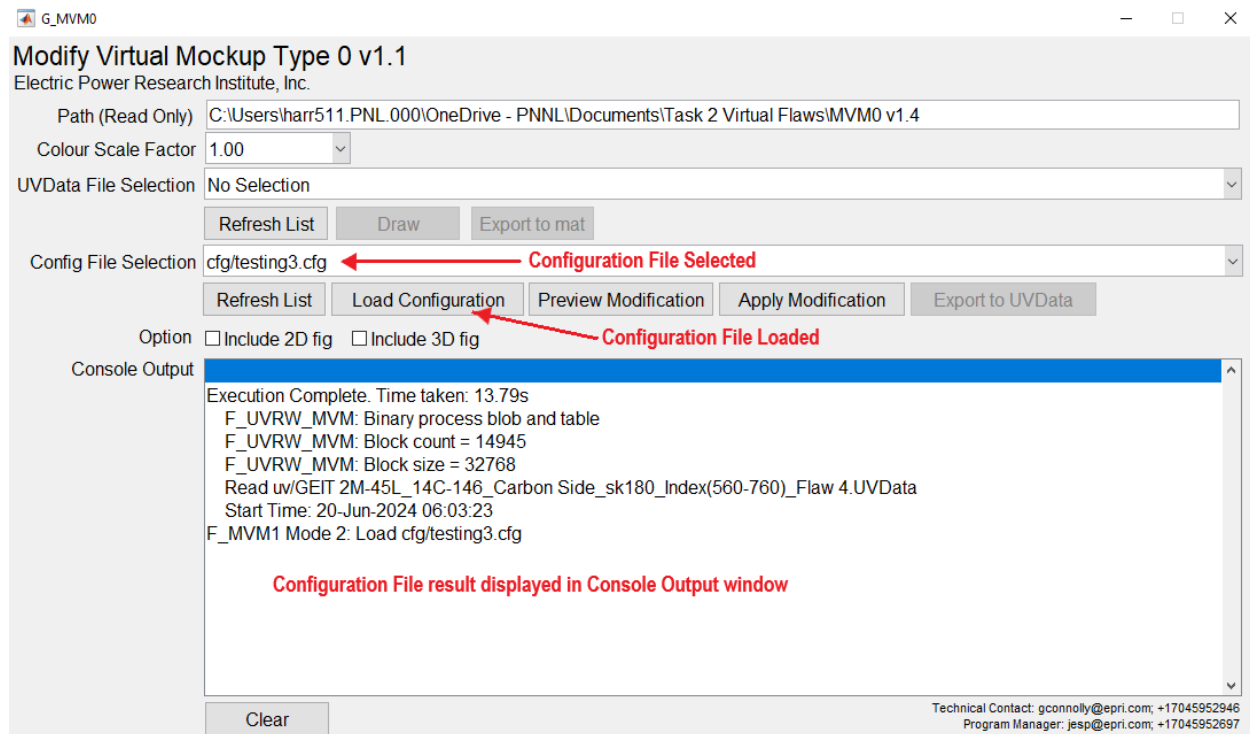


Figure 10. Modification file selected and processed.

If an error has been made in the configuration file, the process will not be completed. As shown in Figure 11, the errors are identified in the Console Output window of MVM. Otherwise, the window shows the status of the execution, such as that shown in Figure 12.

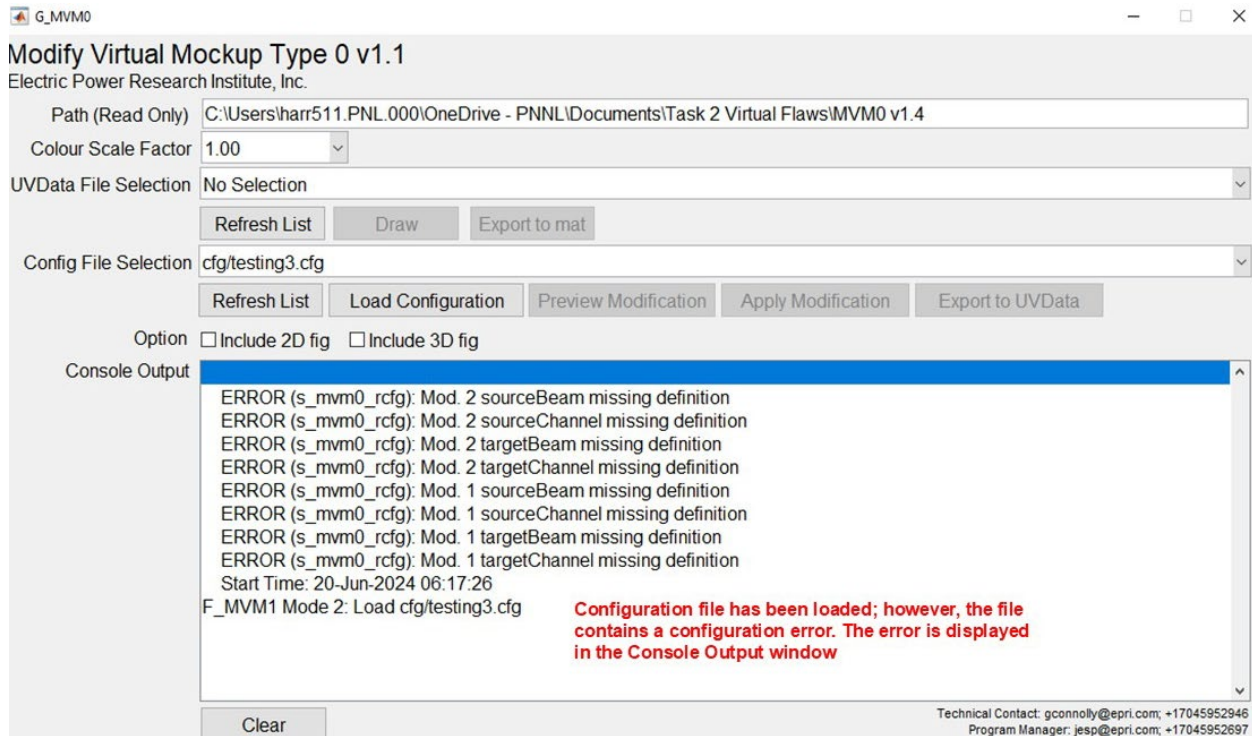


Figure 11. Example of a configuration file error displayed in the Console Output window.

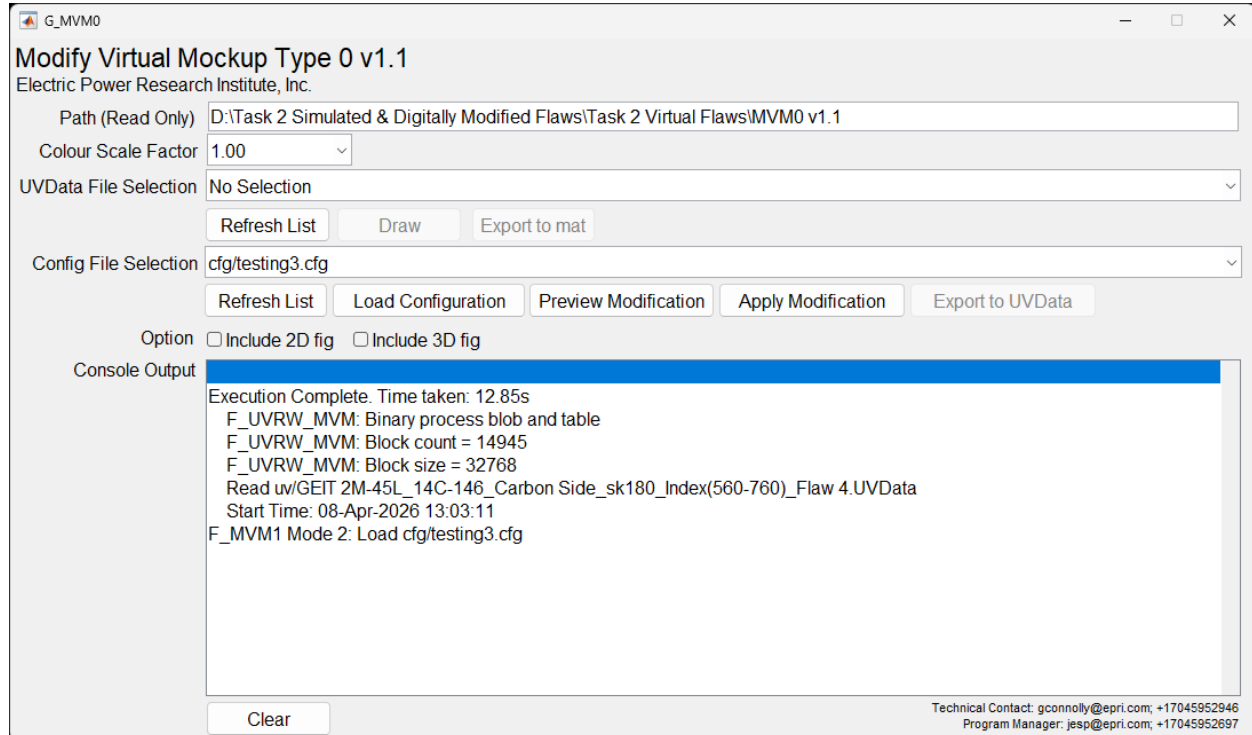


Figure 12. Successful execution of the modification mode for a configuration file.

Once the configuration file has been loaded and processed successfully, the user may preview the modification to determine if the result is correct. This process creates a png file, as shown in Figure 13.

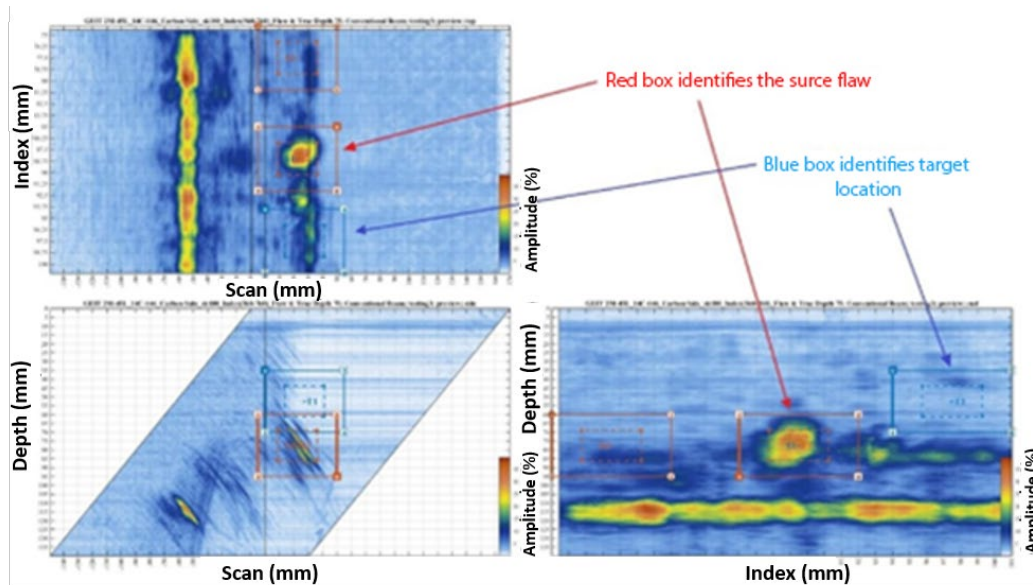


Figure 13. Preview of the processed modification file.

3.2.3 Apply the Modification

If the preview looks correct, then the modification can be performed. The Apply Modification function (Figure 2) tells the MVM program to execute the configuration, and the progress is shown in the console window along with any errors in the configuration file or errors that occur during the process. Note that MVM does not analyze or assess the quality of the resulting modification; that must be determined by a qualified data analyst. When the modification is complete, a png file of the resulting image is generated, as shown in Figure 14. If the results are found to be unsatisfactory, then the configuration file would need to be edited and the modification process repeated.

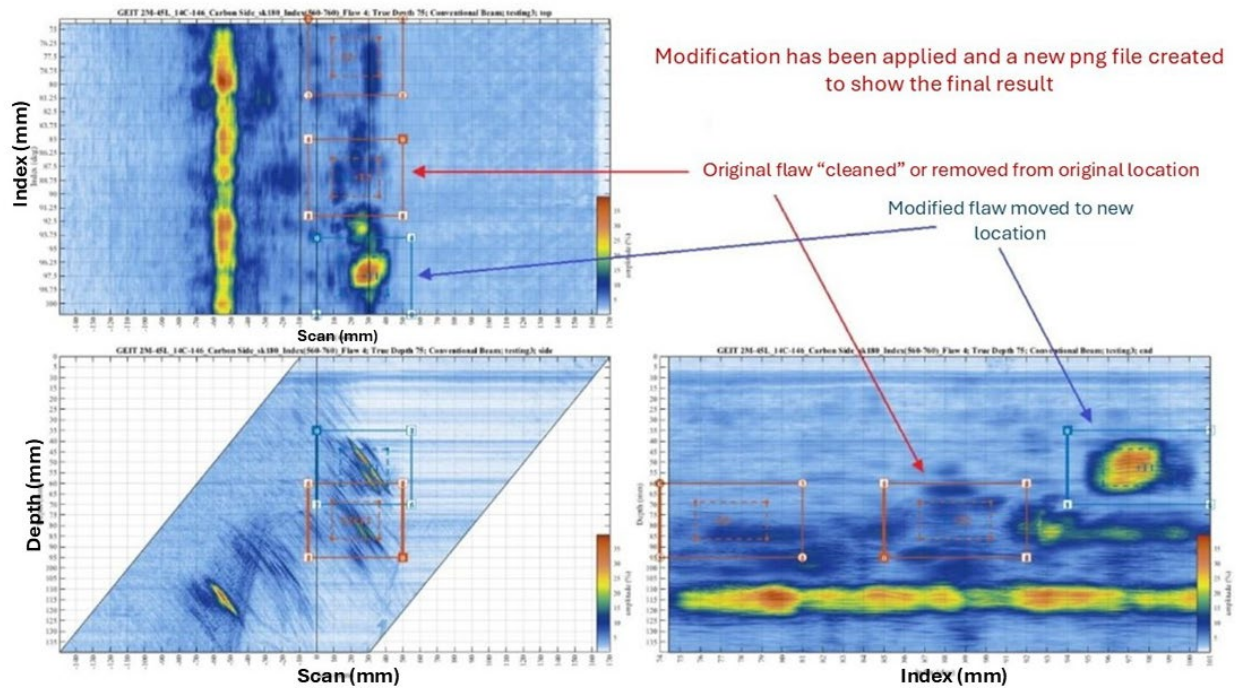


Figure 14. Depiction of final modification result.

3.2.4 Export and Assess the Modification

Once the configuration file has been processed successfully, the modified data file can be exported into a UVData file and viewed in UV. The resulting modification must then be thoroughly evaluated by an experienced and qualified data analyst to verify that the characteristics of the UT responses are realistic. If additional refinement of the modification is required, then the configuration file must be revised, and the modification process is initiated again.

One important area to evaluate is the appearance of the resulting A-scan signals. While modifying an image is relatively straightforward, the ability to maintain realistic amplitude and time characteristics of the A-scan response from a modified flaw is imperative. Realistic movement of the echo along the face of the flaw must be maintained as the transducer moves closer to the flaw, often referred to as echo “walk.” An example is illustrated below.

During a flaw modification, an original sourced flaw, shown in Figure 15, was extracted, modified with a different appearance, and placed adjacent to the original flaw in the modified data file. The original flaw was left “as is” in the new image, as shown in Figure 16. The image data and the A-scan data of the modified file were evaluated and determined to appear realistic with no identifiable characteristics that would indicate that this was a modified data file.

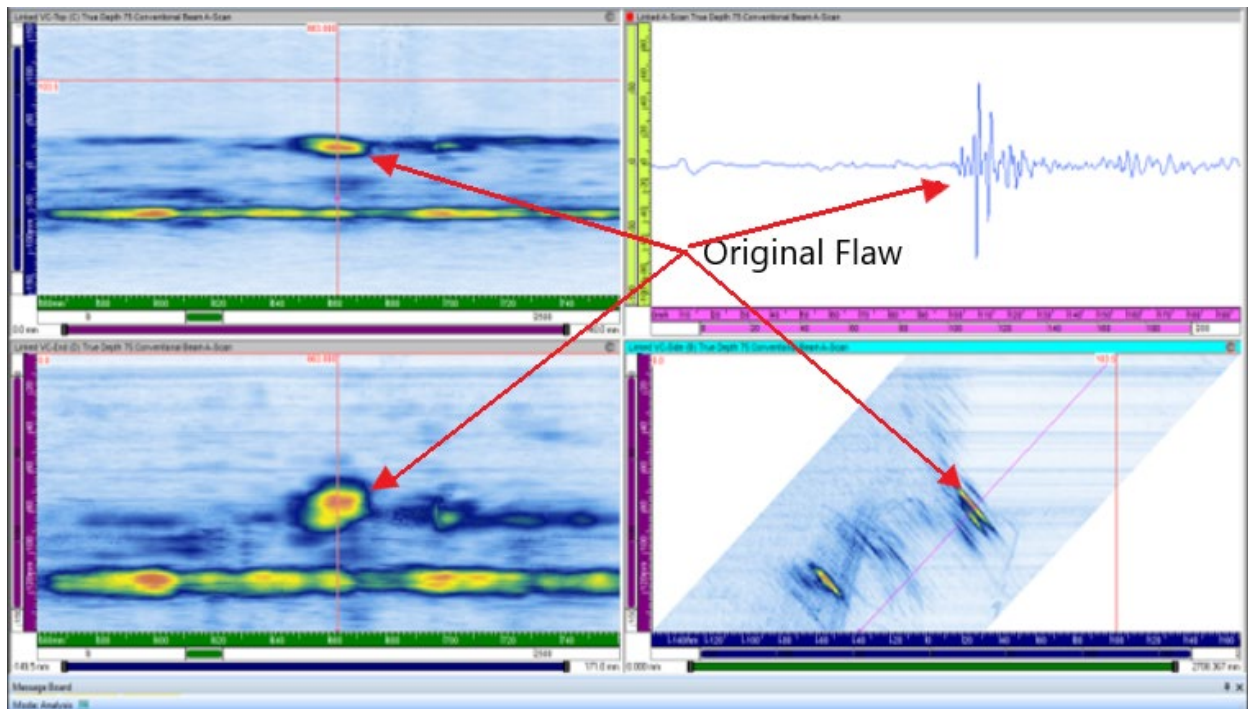


Figure 15. Original flaw selected for modification. The top-right is the A-scan.

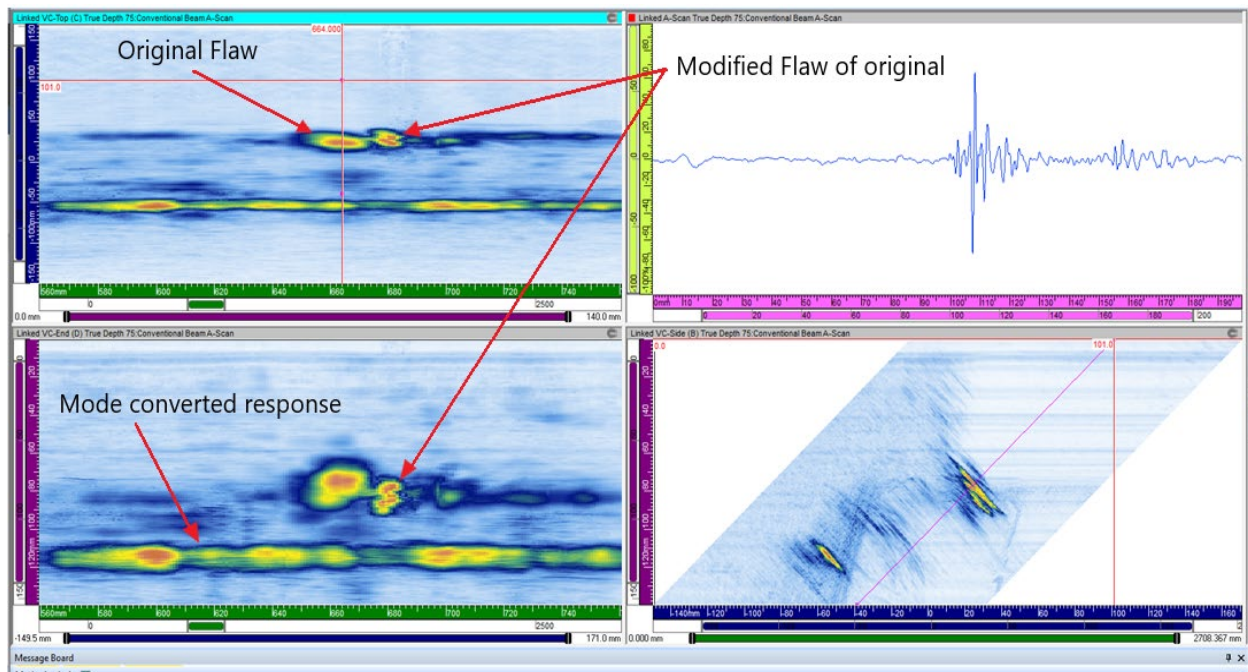


Figure 16. New UT file depicting the original flaw and the virtual modification placed adjacent to it.

As seen in both Figure 15 and Figure 16, a typical mode converted response was present. Since the area of the flaw did not contain any geometric responses, an additional modification was added to move the mode converted response in line with the flaw to simulate a geometric

weld root condition. Figure 17 displays the result of this modification. The images appear normal, and the A-scan response in flaw area exhibits realistic characteristics.

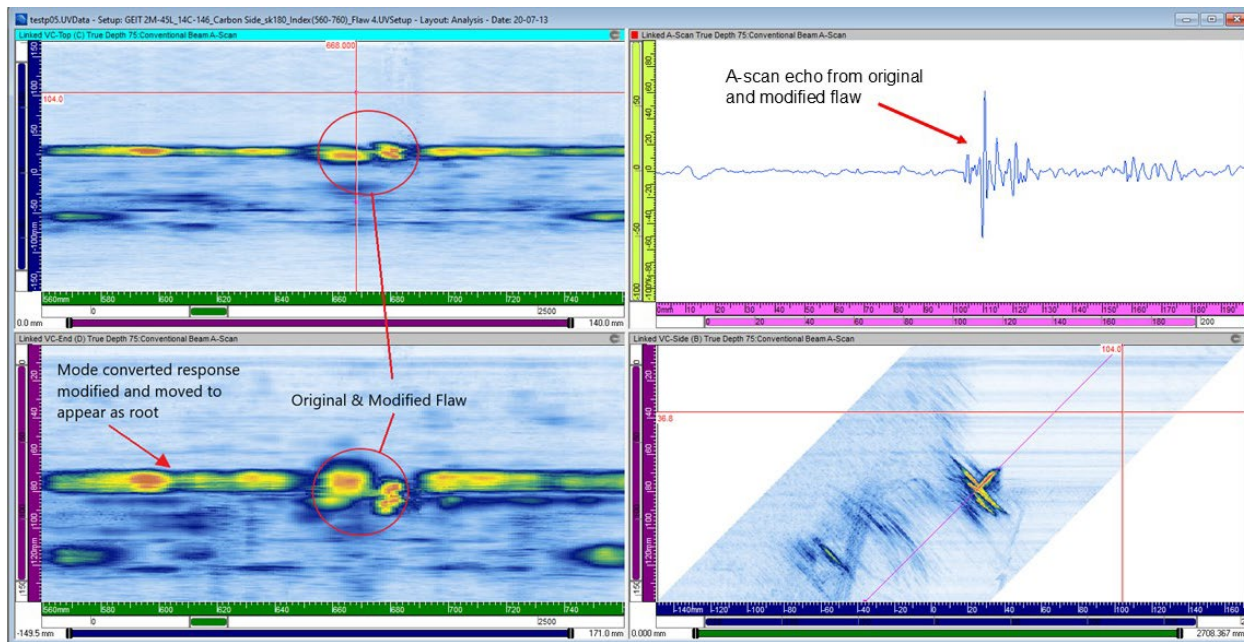


Figure 17. Mode converted response moved in line with flaw area to simulate a root condition.

However, when the A-scan response of the modified root condition was evaluated, it appeared unrealistic, as seen in Figure 18. The reason for the change in the A-scan appearance was not evaluated further, but it is hypothesized to be the result of moving a mode-converted shear response (with a slower sound velocity and therefore shorter wavelength) into an area with responses from longer wavelength longitudinal waves. Regardless of the cause, these results are considered unacceptable, and the modification should be repeated with revised configuration settings until a satisfactory result is obtained. It is important to note that modifications typically require trial-and-error, and there is no guarantee that a satisfactory result can ultimately be achieved.

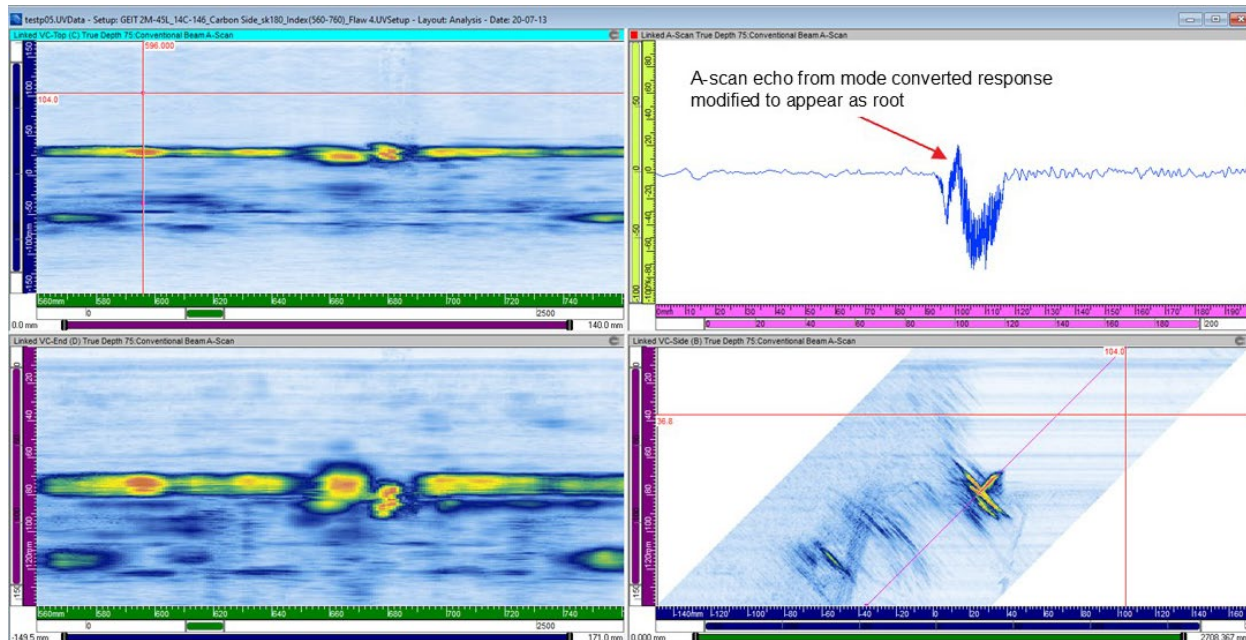


Figure 18. Unrealistic A-scan response from the modified root condition.

3.2.5 Modification Time

The time required to perform a flaw modification varies depending on several factors. The processing time is dependent on the size of the source file, the physical size of the area within the image to be modified, and the number of specific modifications to be performed. The processing time could range from 20 minutes to 1.5 hours, depending on the file size and computer speed. This does not include the time required for the user to determine the modification to be performed, to create the configuration file (which could take a significant amount of time depending on the modification complexity), and to assess the results.

Even after a configuration file is created, executed, and exported, several iterative configuration modifications and processing routines may be required to obtain the desired result. Depending on the experience of the user and the factors described above, it is not unusual for a single modification to take several hours. For more complex data files, such as those comprising multiple beam angles, the configuration development becomes significantly more complicated with the total modification time increasing commensurately.

3.3 Key Considerations for File Modification

There are no specific characteristics or unique UT responses that must exist within a data file selected for modification. However, determining how the file is to be modified requires planning, evaluation, and knowledge of the conditions that exist in plant examinations. Simply creating conceptual theories of what may exist in a welded component will not effectively produce valid virtual flaw results to meet the training and qualification requirements for examination personnel. Furthermore, when the modification is complete, it must be thoroughly evaluated to ensure that the result is realistic. Therefore, the person creating modifications must have experience performing examinations in a plant, working knowledge of the various types of flaws and UT flaw signatures found during inspections, familiarity with the geometric conditions (and their UT

signatures) created from different component configurations, and awareness of flaw degradation mechanisms based on plant operating experience.

The following are required for modifying virtual piping specimens:

1. **Evaluate the Specimen's Configuration:** For a virtual piping specimen, the first step is to evaluate the outer diameter (OD), wall thickness, material (such as stainless steel [SS], carbon steel [CS], dissimilar metal weld [DMW], etc.), and configuration (pipe–pipe, nozzle to safe-end, etc.) of the target file.
2. **Determine the Flaw Types and Quantity:** The number, location, and types of flaws to be placed in the specimen should be determined based on operating experience. The flaws may include planar cracks originating from relevant degradation mechanisms or embedded flaws from the welding process. All of these factors will depend on the result of the system configuration evaluation in step 1 to assure a realistic modification.
3. **Geometric Conditions:** Once flaw selection has been completed, a determination should be made as to whether geometric conditions should be included in the modification or whether the amplitude of any existing geometric responses should be adjusted to create differing conditions. Again, knowledge of in-plant piping configurations is important.

4.0 Empirical Data Source Files Selected for Modification

Ultrasonic data from 17 specimens were used as source files to perform flaw modifications. Every specimen contained at least one flaw. All specimens were representative of DMW piping components, except for specimen 02-24-15, which was an austenitic piping configuration. Six were in-house specimens that were scanned at PNNL, and data files from 11 open Performance Demonstration Initiative (PDI) practice specimens were provided by EPRI.

PNNL concluded that a nominal set of 27 modified data files would provide a thorough analysis of the MVM software. Additionally, this number would provide an adequate pool to assemble a set of test specimens for use in activities such as a round-robin data analysis exercise or for use in evaluating machine learning algorithms for automated or assisted data analysis.

Table 1 is a summary of the modifications that were performed. Section 5.0 describes each modification in detail with before and after images.

Table 1. Summary of flaw modifications.

Virtual Specimen	Digital Modification
02-24-15-1	Cleaned (removed) all flaw signals and enhanced the root response.
02-24-15-2	Placed flaws in root gap areas.
8C-032-1	Moved Flaws 2 and 3 into the same image as Flaw 1.
8C-032-2	Moved Flaw 3 into the image with Flaw 2.
8C-091-1	Cleaned Flaw 3.
8C-091-2	Sourced Flaw 2 from specimen 703-8 and placed it into 8C-091-1.
8C-091-3	Sourced Flaw 3 from 8C-091 and placed it into the file with 8C-032 Flaw 2.
9C-023-1	Sourced the geometric root response from the 30° image and added it over the entire circumference of the 45° image.
9C-023-2	Divided Flaw 3 into two flaws in the 45° and 60° angles, and a geometric root response sourced from the 30° image was added to the 45° angle.
9C-023-3	Removed Flaw 4 from the 45° angle but retained in the 60° data.
9C-023-4	Reduced the amplitude of Flaw 4 in the 45° and 60° angles, and cleaned the flaw from the 70° angle.
9C-034-1	Increased the length of Flaw 2 in the 45° angle.
14C-146-G1	Relocated Flaw 4 within the same file.
14C-146-G2	Reduced the amplitude of Flaw 4.
14C-146-G3	Increased the amplitude of the root response in the Flaw 4 file.
14C-146-G4	Copied Flaw 4 to another location in the same file and left the original flaw unchanged.
14C-146-G5	Sourced a portion of Flaw 2 from specimen 602 and placed it in the file with 14C-146 Flaw 1.
14C-146-G6	Sourced Flaw 2 from specimen 602 and placed it into the cast austenitic stainless steel (CASS) scan of 14C-146.
701-P1-1	Cleaned Flaw 2 and lengthened Flaw 1 over most of the specimen circumference.
703-8-1	Sourced a portion of Flaw 2 and oriented it axially adjacent to original Flaw 2.
705-P1-1	Increased the amplitude Flaw 3.
706-P1-1	Cleaned the weld root response and relocated Flaw 1 to be adjacent to Flaw 2.
706-P2-1	Cleaned Flaw 1 leaving only a very weak Flaw 3 response.
707-P1-1	Extended the length of Flaw 1.
707-P2-1	Cleaned Flaw 2 and its mode converted responses.
709-P1-1	Sourced Flaw 3 from specimen 707-P2.
710-P-1	Rotated Flaw 2 to better represent its off-axis orientation.

5.0 Flaw Modification Results

PNNL created a virtual flaw database containing 27 specimens sourced from empirical flaw data that were collected during previous project work. Descriptions of PNNL's methods for data acquisition can be found in Harrison et al. (2023).

The flaw modification evolution validated the ability to produce realistic virtual flaws, identified anomalies in the process that may fail to produce a virtual flaw that exhibits realistic characteristics, and established a virtual flaw database that may be used for round-robin testing among industry personnel involved in UT examinations or for AI training.

Each of the virtual specimens created and described in this section relied heavily on the 35 years of experience of PNNL's UT Level III in performing examinations in plants to create realistic conditions encountered in actual UT examinations. When performing UT examinations in a plant, and even in performance demonstration qualifications, technicians and data analysts are presented with a variety of UT response conditions that must be closely evaluated to identify possible flaw response signatures. It is not realistically feasible to fabricate specimens containing flaws that could represent every conceivable condition that UT personnel experience in plant piping systems. The ability to create these conditions virtually, based on real-world working knowledge, provides a unique mechanism to sharpen the skills of data analysts.

In each of the modifications below (and listed in Table 1), a description and UT image of the empirical source flaw are provided, the reasoning behind the modification performed is given, and the resulting virtual flaw is shown. When the flaw types cannot be verified, they are listed simply as "crack," although they are assumed to be thermal fatigue cracks (TFCs). Note that all empirical data were acquired using the longitudinal wave mode.

5.1 Specimen 02-24-15

This specimen is an austenitic-to-austenitic SS welded pipe segment with an OD of 24 in. and a nominal wall thickness of 1.2 in. that was cut into three 120° sections. The second section (120° to 240°) was used as the source data and contains four defects: one TFC and three notches, as shown in Table 2 (TW refers to through-wall). Figure 19 displays the original file (2 MHz, 45° refraction angle) with the TFC and two notches visible. All four defects are on the same side of the weld; the TFC is offset from the weld centerline (WCL) by about 0.8 in., and the notches by about 0.3 in.

Table 2. Specimen 02-24-15.

Flaw	Type	TW Depth (%)	Length (in.)	Tilt (deg)
C	TFC	64	1.7	20
d	Notch	15	2.1	0
e	Notch	10	1.7	0
f	Notch	15	2.3	35

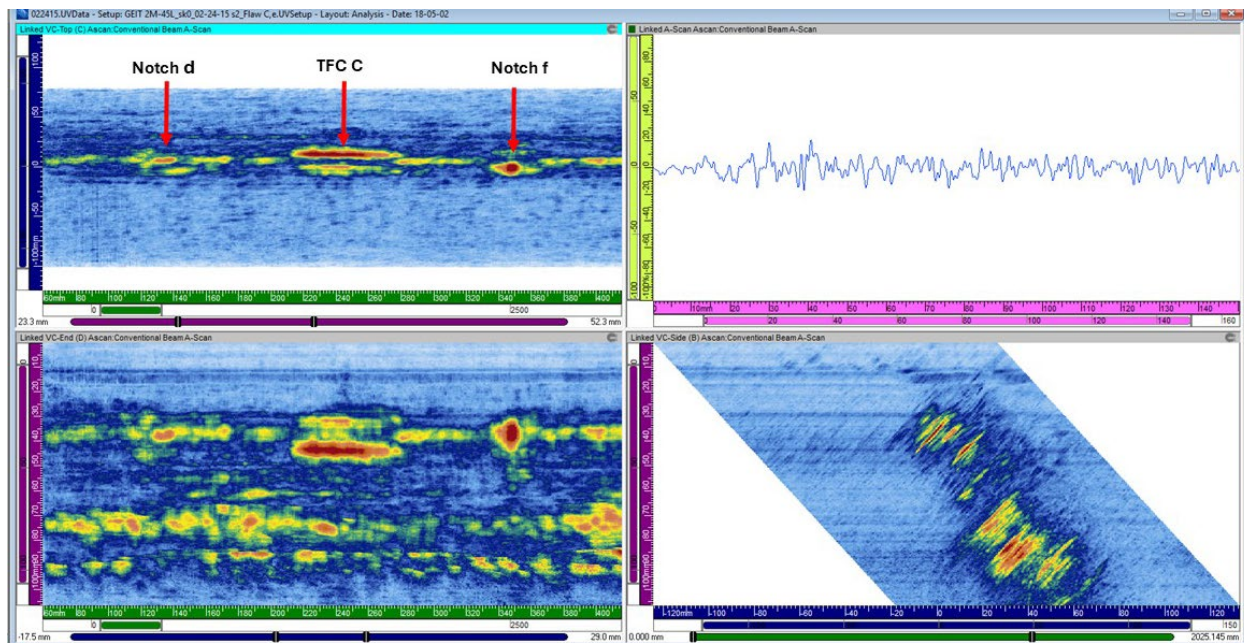


Figure 19. Original TFC flaw in specimen 02-24-15.

Virtual Specimen 02-24-15-1

A review of the empirical data identified a realistic modification would be to remove all existing flaws and increase the amplitude of the geometric root response. Piping welds in a nuclear power plant typically exhibit a response from the geometric weld root condition. At times, this response can appear immediately adjacent to a flaw, requiring a data analyst to discriminate between responses to determine if a flaw exists.

The modification process involved developing and executing two separate configuration files. The first cleaned the existing flaws and increased the amplitude of the root response, as shown in Figure 20. Removing the existing flaws and enhancing the root response did not produce any unintentional artifacts. Thus, these virtual specimens appeared to be realistic and could be used in analysts training.

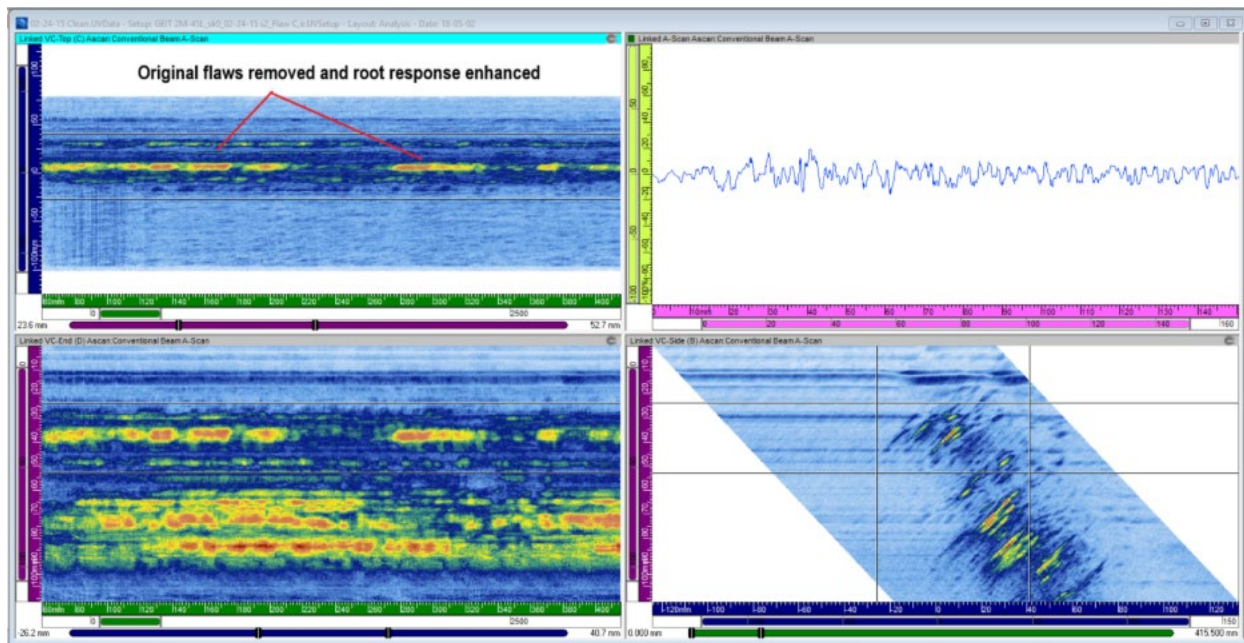


Figure 20. Virtual specimen 02-24-15-1 cleaned of existing flaws and root response amplitude increased.

Virtual Specimen 02-24-15-2

The data file had two areas where the root response was not present over the full circumference of the specimen. This provided an opportunity to place flaws in these two areas that would represent the root response being masked by a flaw, a realistic condition in plant piping systems. When an ultrasound examination is performed on the same side of a weld where a flaw exists, the geometric root response will appear slightly later in time (further in distance) than the flaw response. When a flaw is present close to the weld root, the earlier arrival of the flaw will mask the geometric response from the root. Under this realistic situation, an examiner must pay specific attention to the response arrival time, or location with respect to the root response, to discriminate between the two responses and accurately identify the flaw.

The second configuration sourced the TFC from the original file and placed it into two separate areas where the root response was not present but slightly offset in the axial direction, producing virtual specimen 02-24-15-2 shown in Figure 21. In this case, the added two flaws representing later-arriving root responses produced a virtual specimen with no artifacts that might undermine the realism of the flaw modification.

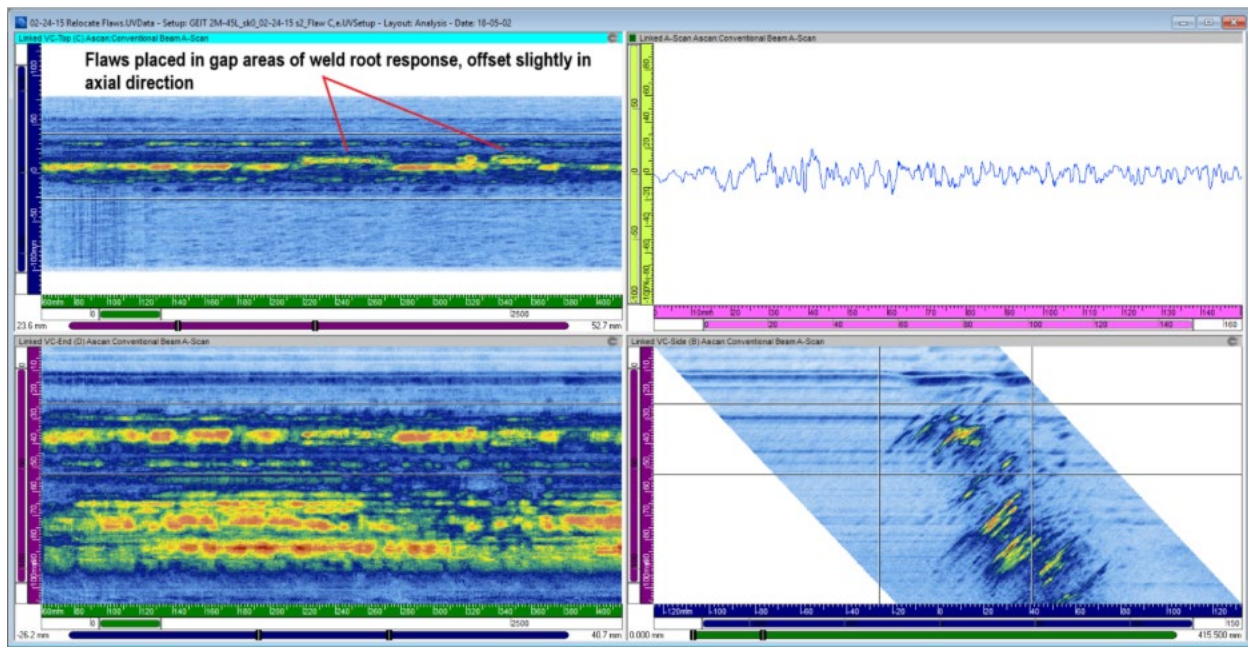


Figure 21. Virtual specimen 02-24-15-2 with flaws placed in areas without a root response but offset axially.

The two virtual specimens created utilizing flaw characteristics in the original specimen 02-24-15 are two realistic cases where geometric root response is high (virtual specimen 02-24-15-1) and that response is masked (virtual specimen 02-24-15-2) by adjacent actual flaw(s) due to its late arrival/indication in the UT scan. While no artifacts were observed in the modified digital UT scans, they produced two virtual specimens covering two realistic scenarios that could help in training analysts.

5.2 Specimen 8C-032

This specimen is a nozzle-to-safe end DMW pipe segment with an OD of 14 in. and a nominal wall thickness of 1.5 in., representative of a pressurizer surge nozzle. Four TFCs exist around the circumference of this specimen spaced 90° apart; the flaw specifications are shown in Table 3. All four flaws were on the same side of the WCL in the buttering. Data were acquired at 2 MHz and 45° from the CS nozzle side of the weld; each flaw was in a separate data file. Two modifications, described below, were performed on this specimen's data files. Flaws 2 and 3 were sourced into the Flaw 1 file to create virtual specimen 8C-032-1, and the Flaw 2 data file was the target file for modification to create virtual specimen 8C-032-2. The original data file with Flaw 1 is shown in Figure 22, Figure 23 displays the original Flaw 2, and Figure 24 displays the original Flaw 3.

Table 3. Specimen 8C-032.

Flaw	Type	TW Depth (%)	Length (in.)	Tilt (deg)
1	TFC	20	0.90	0
2	TFC	40	1.14	19
3	TFC	60	1.81	0
4	TFC	30	0.85	13

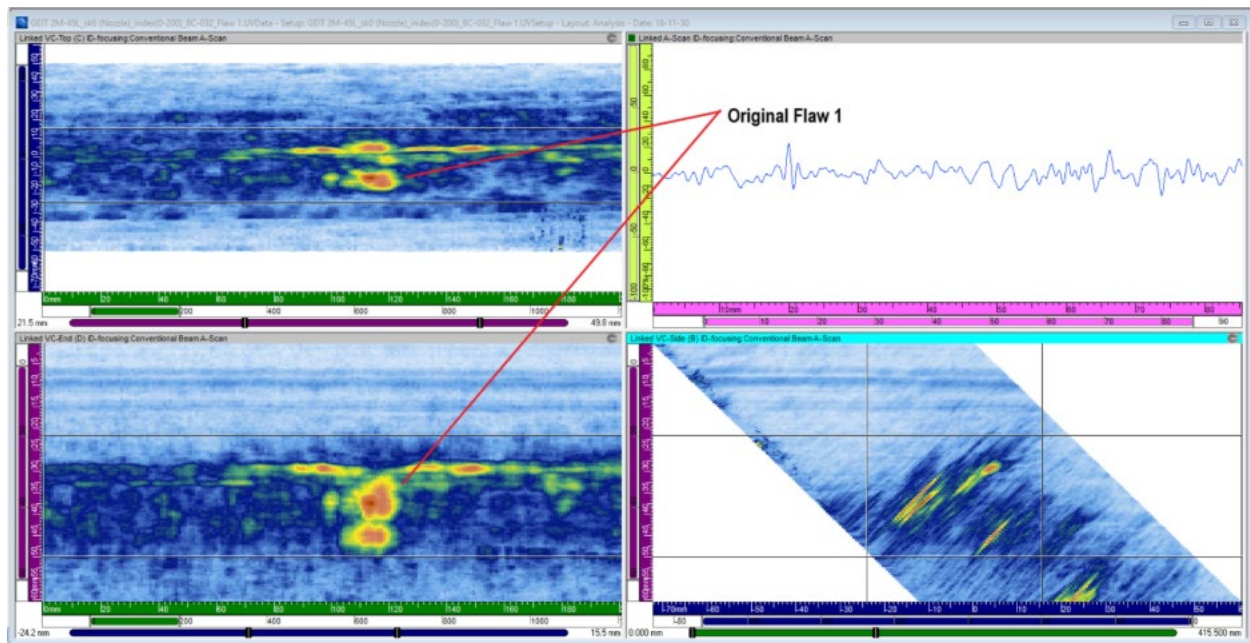


Figure 22. Original Flaw 1 in specimen 8C-032.

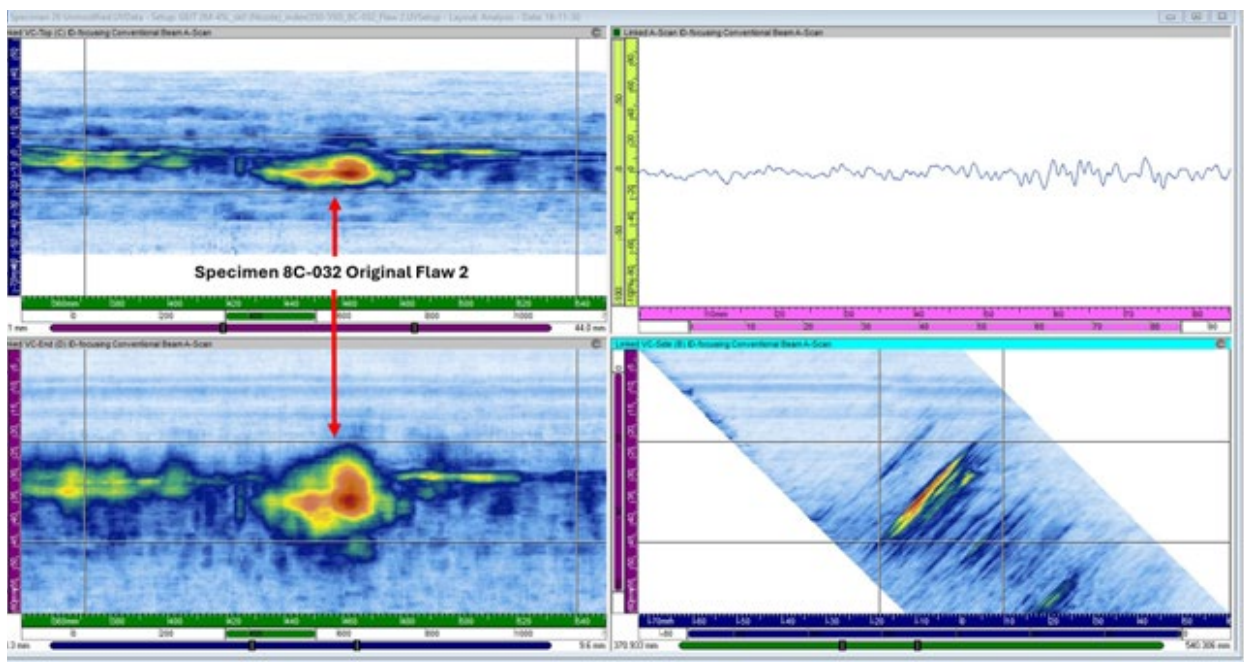


Figure 23. Original Flaw 2 in specimen 8C-032.

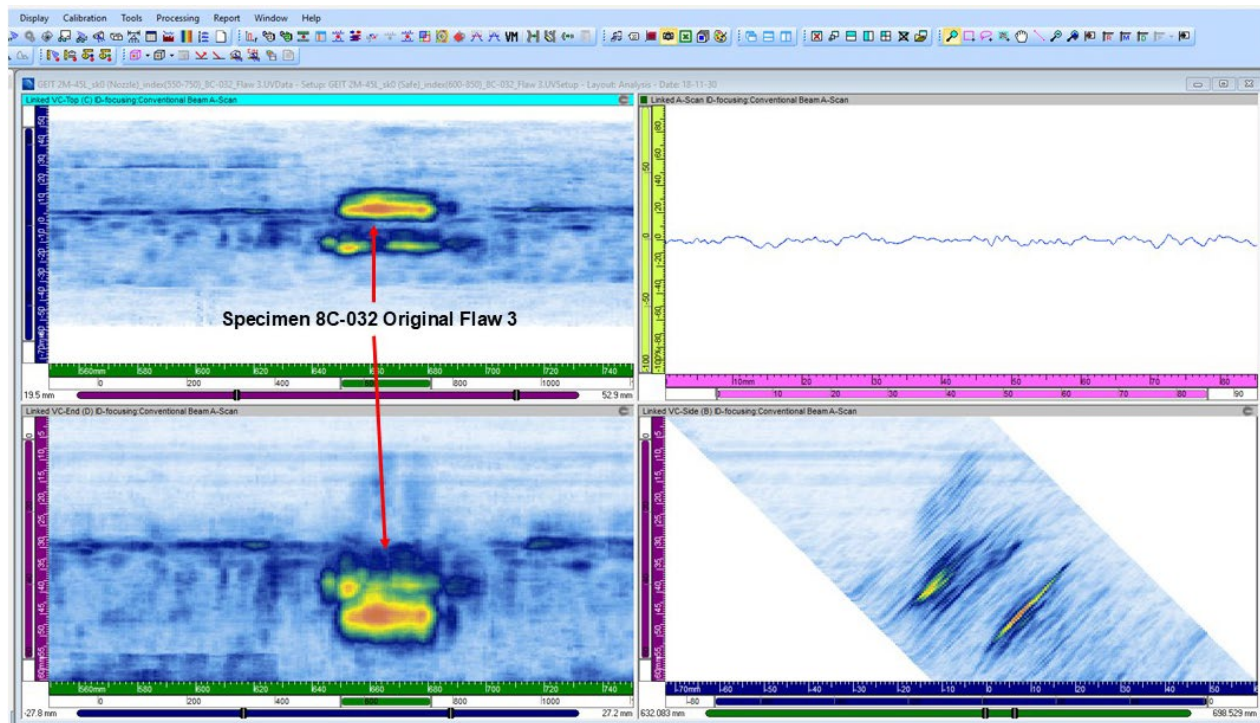


Figure 24. Original Flaw 3 in specimen 8C-032.

Virtual Specimen 8C-032-1

This virtual specimen was created by combining Flaws 2 and 3 into a file with Flaw 1. Flaw 4 was omitted during modification due to it lacking compelling or unique characteristics. Flaw 2 generated a high-amplitude response, and the Flaw 3 response was much weaker. Thus, the resulting file contains three flaws with distinctly different amplitude responses: one much higher than that of Flaw 1 and one much lower.

Figure 25 displays the modified file for virtual specimen 8C-032-1. Flaw 2 is clearly defined and has a high amplitude, while Flaw 3 is much weaker and will require an analyst to pay specific attention to the adjustable software gain setting to identify this flaw and not be drawn solely to the high amplitude response that could distract an analyst's attention away from the much weaker Flaw 3.

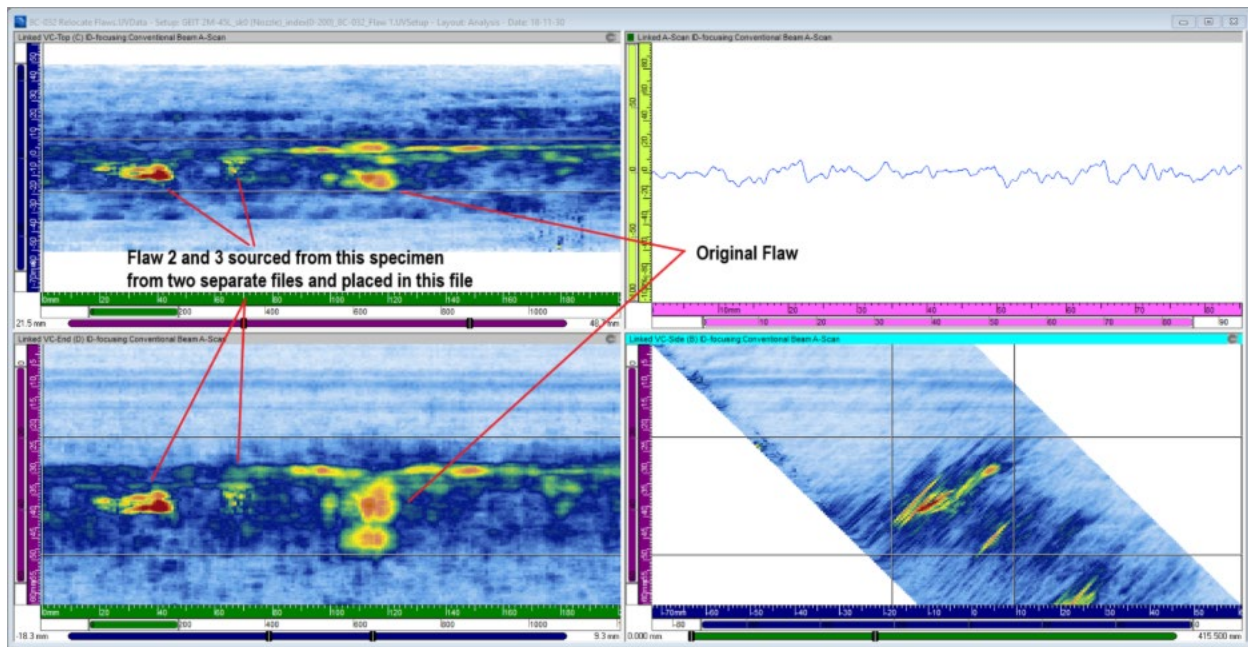


Figure 25. Virtual specimen 8C-032-1. Flaw 2 (left) and 3 (center) were added to the file containing the original Flaw 1 (right).

Realistic flaw response amplitudes are not uniform and vary between flaws and even along the length of a flaw. Producing a specimen with two virtual flaws and the original unmodified flaw each with different response amplitudes represents a realistic field condition where each flaw has its own response amplitude characteristics.

Virtual Specimen 8C-032-2

The data file containing Flaw 2 in specimen 8C-032 was the target file for this virtual specimen. Flaw 3 in specimen 8C-091 (see Table 4) was sourced, compressed in length, then placed into this data file with no modification to the existing Flaw 2. No other modification was performed on Flaw 3, and the empirical UT characteristics were retained. The purpose of this modification was to verify that a flaw could be sourced from a separate data file and placed into a file containing a flaw without affecting the characteristics of the original flaw. Figure 26 shows the resulting data for virtual specimen 8C-023-2 that now contains two flaws representing a condition that could be encountered during an inservice UT inspection.

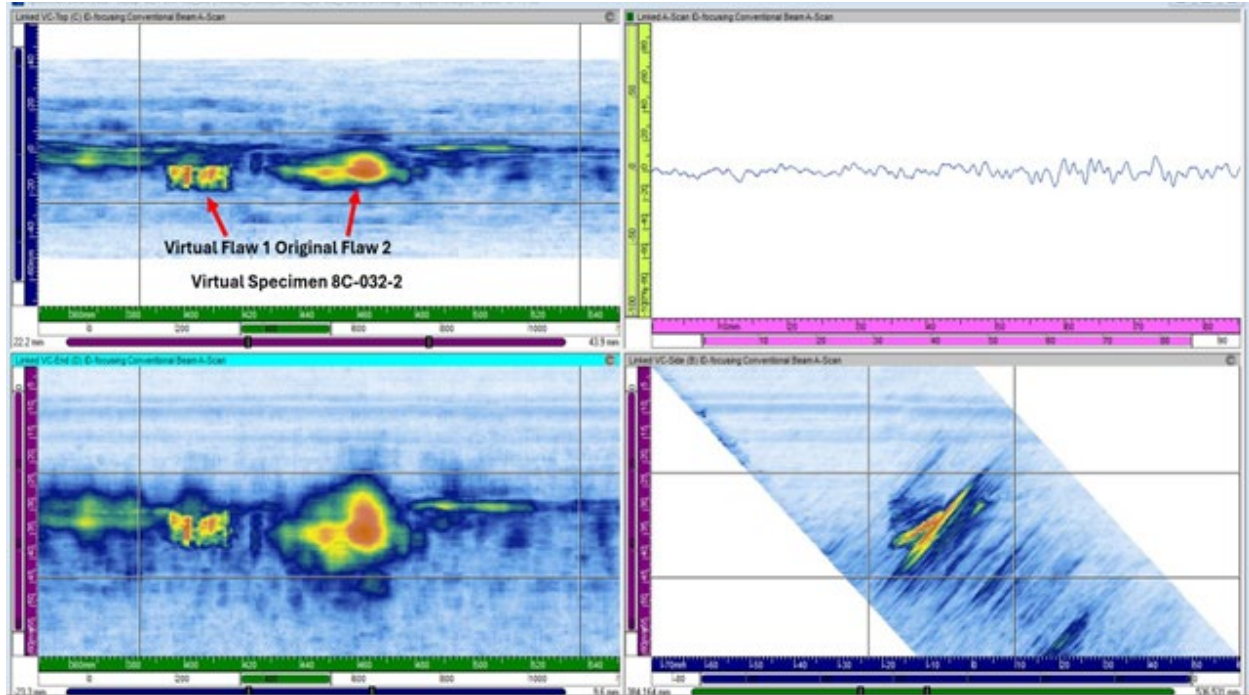


Figure 26. Virtual specimen 8C-032-2.

5.3 Specimen 8C-091

This specimen is a 14 in. OD DMW pipe with a nominal wall thickness of 1.5 in., representative of a pressurizer surge nozzle and used as the source for virtual specimens 8C-091-1 and 8C-091-2. Similar to specimen 8C-032, four flaws exist around the circumference of this specimen spaced 90° apart; the flaw specifications are shown in Table 4. Data were acquired from the CS side of the weld at 45° and 2 MHz. Only the Flaw 3 data file was used for modification; Figure 27 displays the original flaw.

Table 4. Specimen 8C-091.

Flaw	Type	TW Depth (%)	Length (in.)	Tilt (deg)
1	HIPd EDM	30	2.72	0
2	HIPd EDM	18	2.00	0
3	TFC	36	2.78	10
4	TFC	23	2.67	19

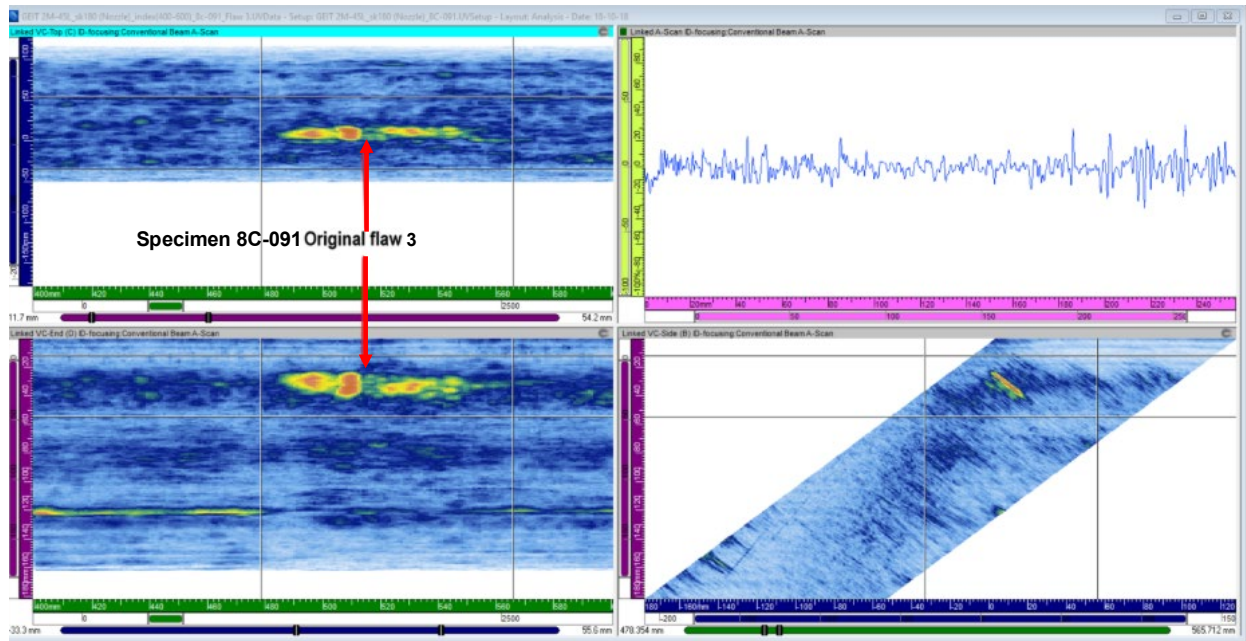


Figure 27. Flaw 3 in specimen 8C-091.

Virtual Specimen 8C-091-1

The empirical data for specimen 8C-091 were analyzed, and a modification established to clean (remove) the existing Flaw 3, source a flaw from a separate DMW data file (specimen 703-8) and place it into this file. This required two configuration files to be created and executed, thereby producing two virtual specimens. The first is shown in Figure 28. Blank or unflawed specimens are important for training because most of the scans performed in the field will not contain any flaws.

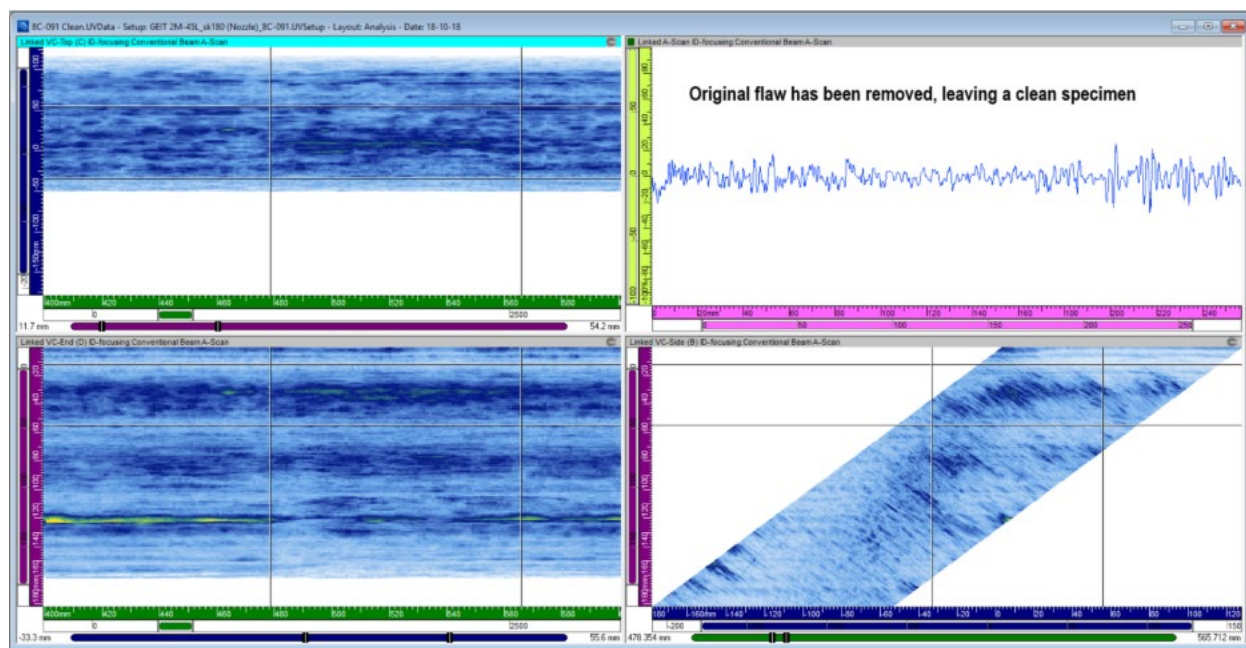


Figure 28. Virtual specimen 8C-091-1.

Virtual Specimen 8C-091-2

Once complete, a second configuration routine sourced circumferential Flaw 2 from specimen 703-8 (see Table 9). The original Flaw 2 is shown in Figure 29.

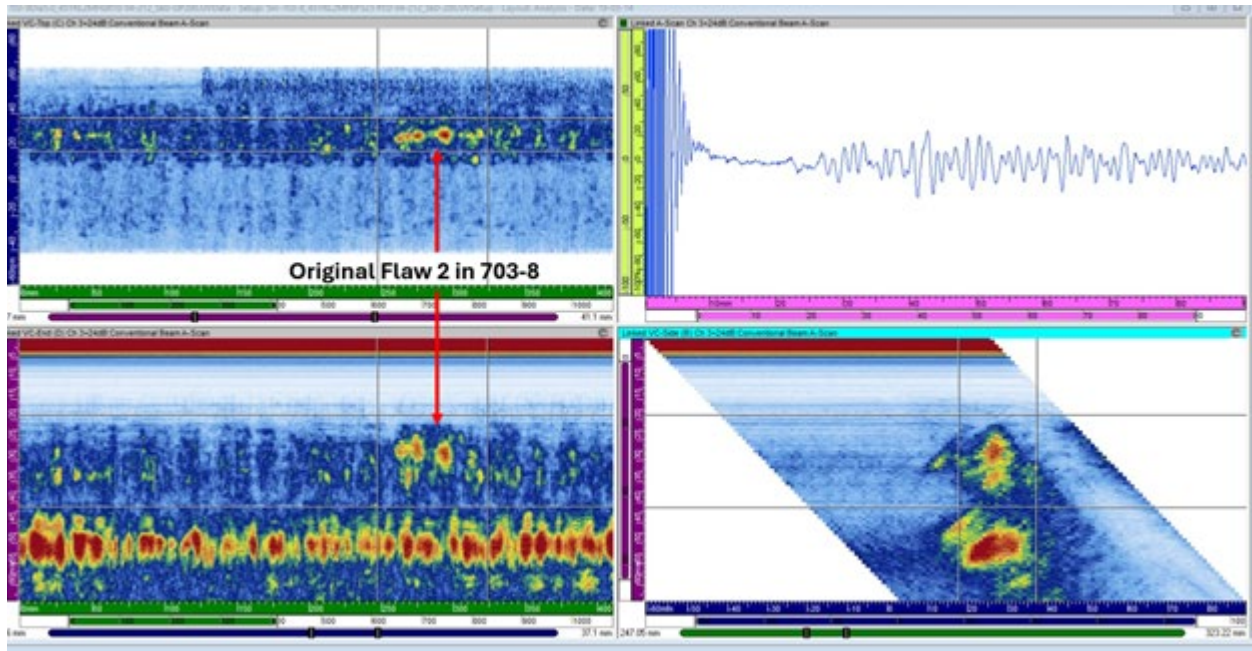


Figure 29. Flaw 2 in specimen 703-8.

The sourced flaw's length was extended, and the modified flaw was placed in the new virtual specimen 8C-091-2 shown in Figure 30. Additionally, the amplitude of the flaw response was reduced during the modification process to a level comparable to that of the geometric responses. This will force an analyst to apply software gain adjustments and distinguish the flaw signal from the geometric signals.

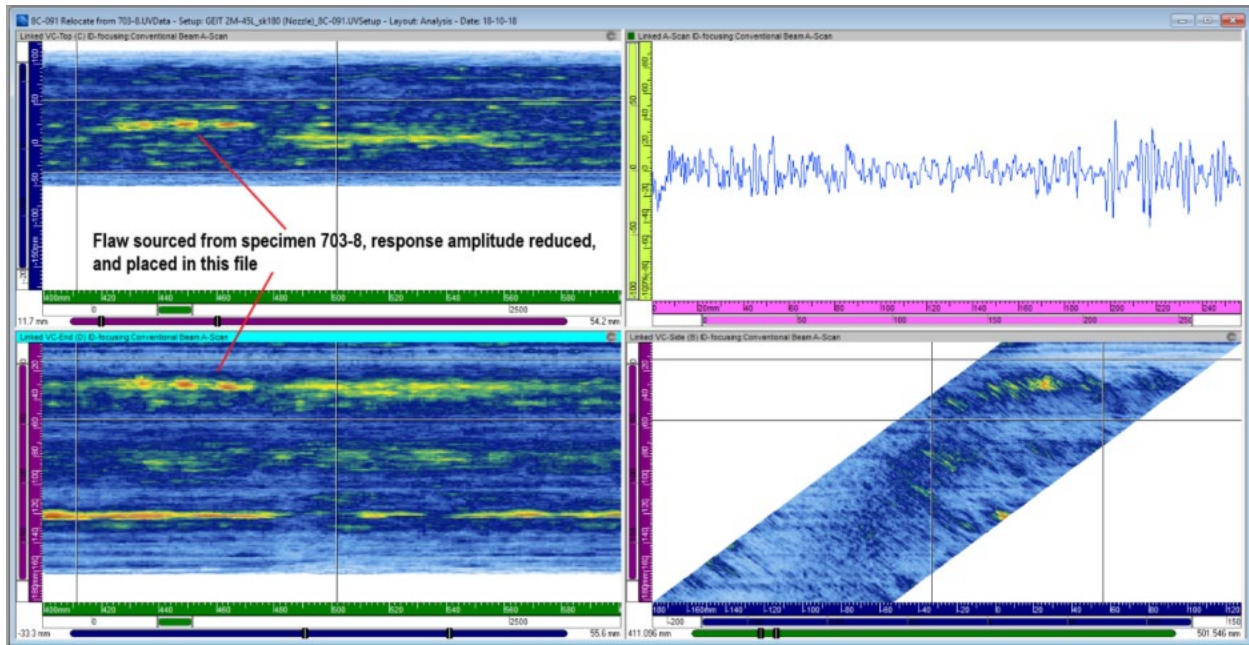


Figure 30. Virtual specimen 8C-091-2.

When specimens containing flaws are fabricated, geometric conditions can be easily inserted in the specimen to produce responses in addition to flaw responses. The fabrication process cannot, however, control the resulting amplitude of the geometric response. Flaw modification software affords the ability to vary the amplitude of all responses to create conditions that are routinely encountered in weld inspections. The realistic condition created for this specimen enhances the root response located to the right of, and offset slightly axially from, the flaw to a level close to the flaw response amplitude.

Virtual Specimen 8C-091-3

This virtual specimen sourced Flaw 3 from the specimen 8C-091 data file, shown in Figure 27, and inserted it into the data file containing Flaw 2 in specimen 8C-032. The original Flaw 2 data from specimen 8C-032 are shown in Figure 23, and the new virtual specimen is shown in Figure 31.

While this virtual specimen was developed to contain two flaws—the original and the new sourced flaw—this would be reported as one flaw as the separation between the two flaws is only 0.25 in. Conditions such as this—flaws that have been identified where the space between the two flaws had not yet cracked or the through-wall dimension is so low a response was not produced—do exist in the field. Regardless, reporting criteria for flaw length would be from the start of the first flaw to the end of the second flaw.

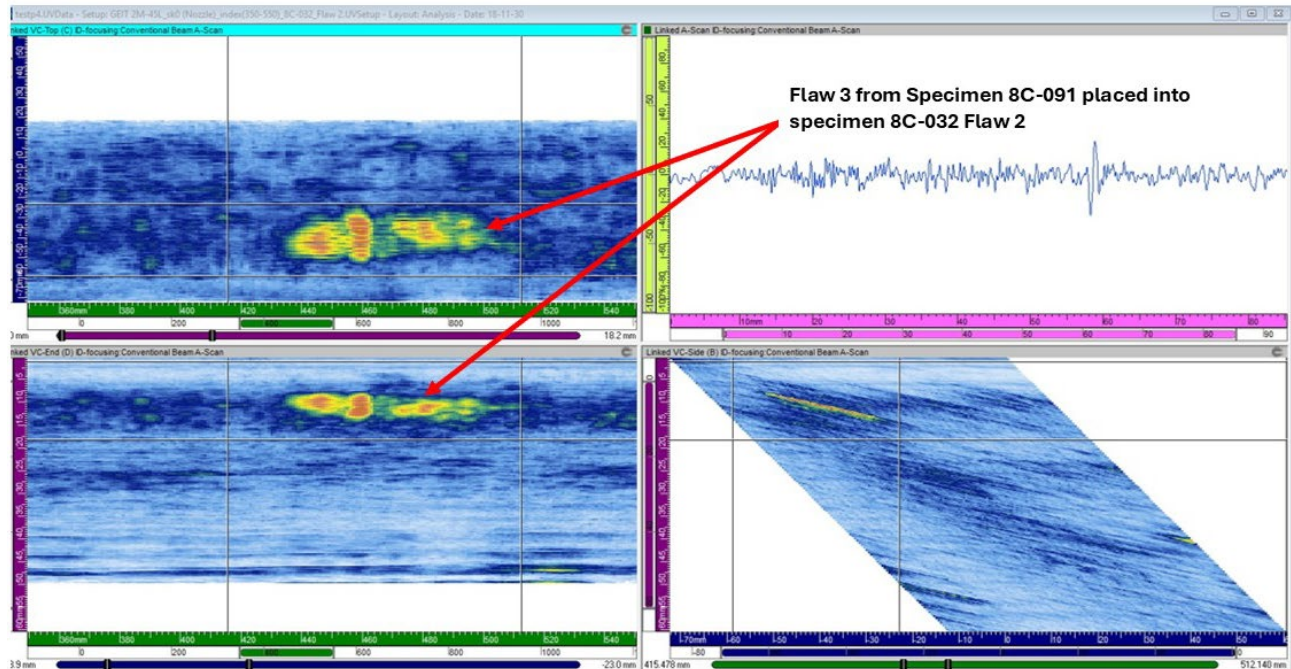


Figure 31. Virtual specimen 8C-091-3.

5.4 Specimen 9C-023

This specimen is a 14.25 in. OD DMW shutdown cooling pipe specimen with a wall thickness of 1.4 in. It contains four TFC flaws spaced 90° around the pipe circumference (see Table 5). All the flaws are on the same side of, and about the same distance from, the WCL (that distance is not specified in the design drawing). Data were acquired from the CS side of the weld using a 1.5 MHz transmit–receive longitudinal (TRL) phased-array probe with 32 elements (8 × 4) in each array. Four separate beam angles, 30°, 45°, 60° and 70°, are in each data file. Flaws 2, 3, and 4 were used as the source for virtual specimens 9C-023-1 through 9C-023-4 that follow. Note that a 30° beam angle is normally not used in the field; however, for cases such as flaw modification, such angles could produce responses beneficial to the creation of virtual flaws.

Table 5. Specimen 9C-023.

Flaw	Type	TW Depth (%)	Length (in.)	Tilt (deg)
1	TFC	34	2.76	2
2	TFC	19	2.01	8
3	TFC	24	2.76	4
4	TFC	11	2.26	12

Virtual Specimen 9C-023-1

This modification sourced the Flaw 2 data file but left the flaw response unchanged. Figure 32 displays the original 45° image of Flaw 2.

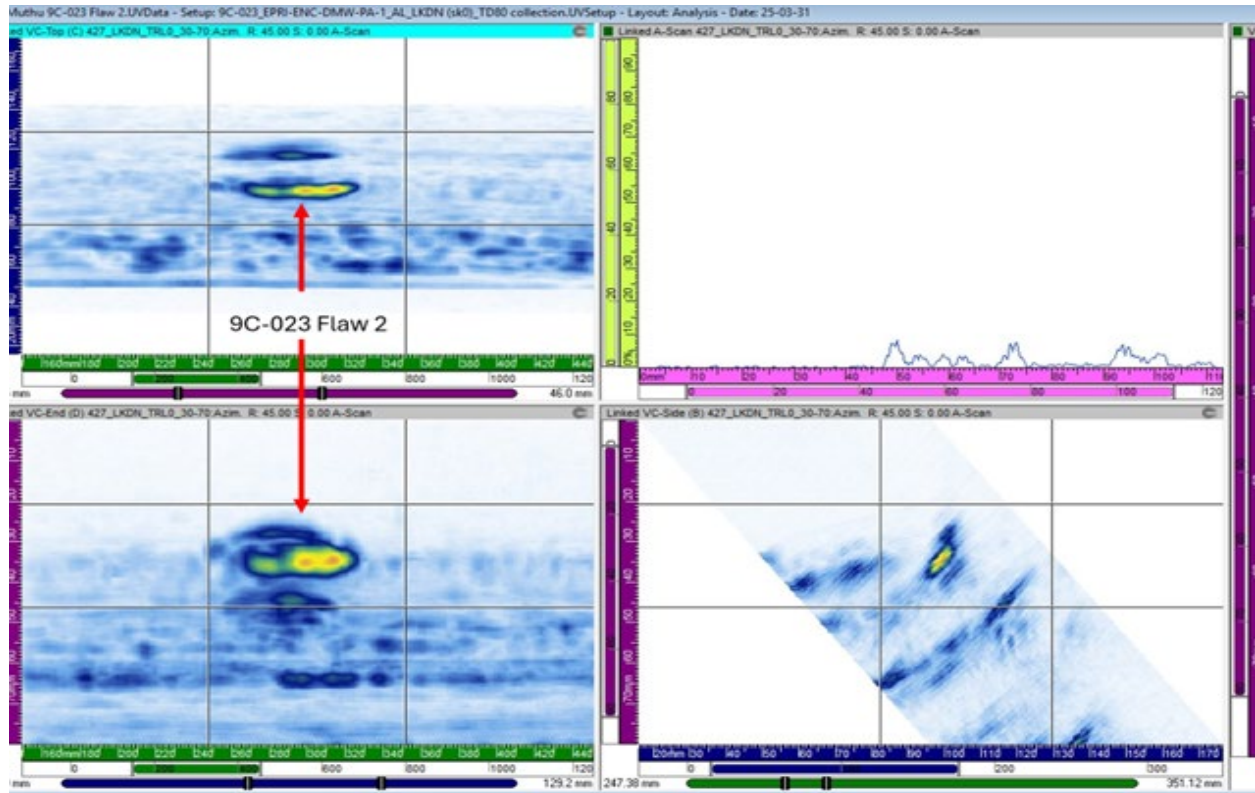


Figure 32. Original 45° image of Flaw 2 in specimen 9C-023.

A geometric root condition extending the entire length of the image in the 30° data was sourced and added to the 45° beam angle to produce the virtual specimen shown in Figure 33.

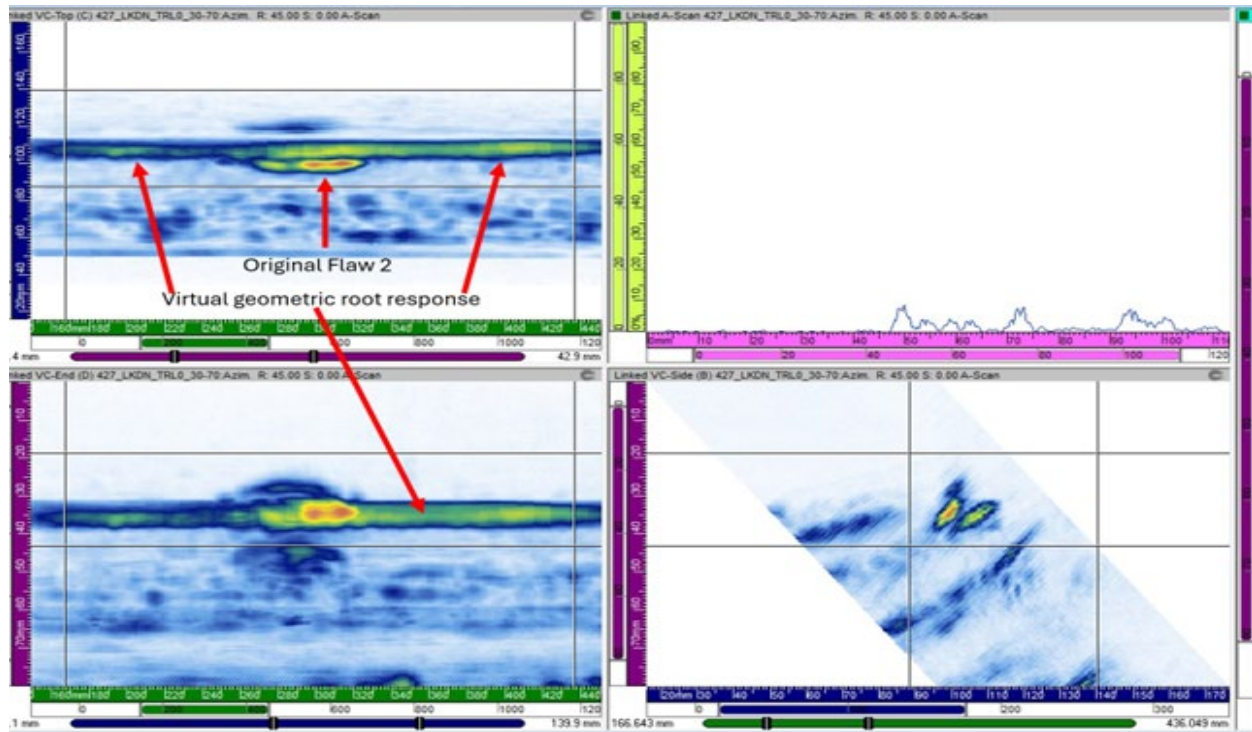


Figure 33. Virtual specimen 9C-023-1 with root geometry added.

A 45° beam angle is the primary angle used for examinations under normal conditions, complemented with higher beam angles when significant geometric response conditions exist. In many situations, geometric responses are received with a 45° beam angle and can be misinterpreted as a flaw, whereas higher angles, such as 60° and 70°, may produce no geometric responses or much lower amplitude responses. The addition of a geometric root condition in the 45° data and not in the 60° and 70° data produced a realistic condition for data evaluation. Thus, for this modification, the 60° and 70° beam angles were left unchanged.

Virtual Specimen 9C-023-2

This virtual specimen used the original Flaw 3 (Figure 34) from the 45° scan as the source.

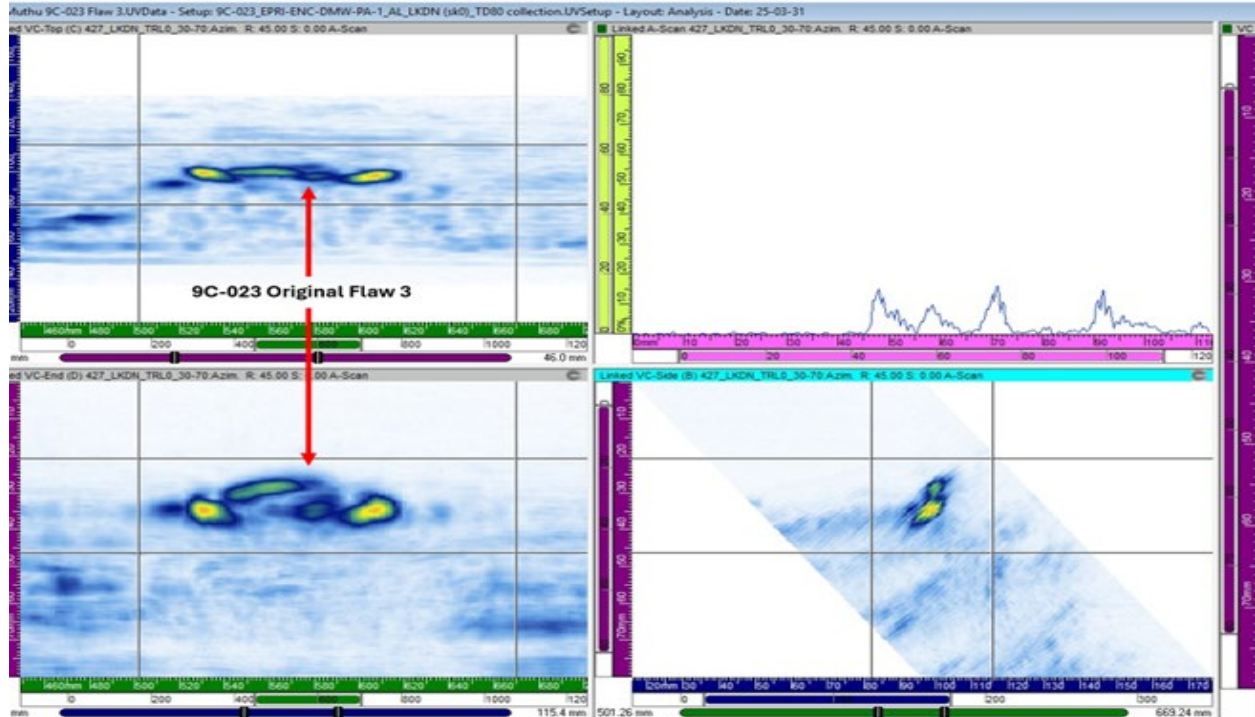


Figure 34. Original Flaw 3 in specimen 9C-023.

The original flaw was 2.76 in. long. The center part of the flaw was removed in the 45° and 60° data, leaving two separate shorter flaws. The root geometry was sourced from the 30° data and added to the 45° data from the beginning of the data scan up to the first flaw and beginning at the end of the second flaw extending to the end of the image. No geometry was added between the two new flaws. This produced a realistic condition where a flaw may mask a root response and require the extensive evaluation of the two responses. While identification of the flaw is the primary focus, the location of a geometric response may provide information to assist an analyst in evaluating the responses. The resulting virtual specimen 9C-023-2 is shown in Figure 35.

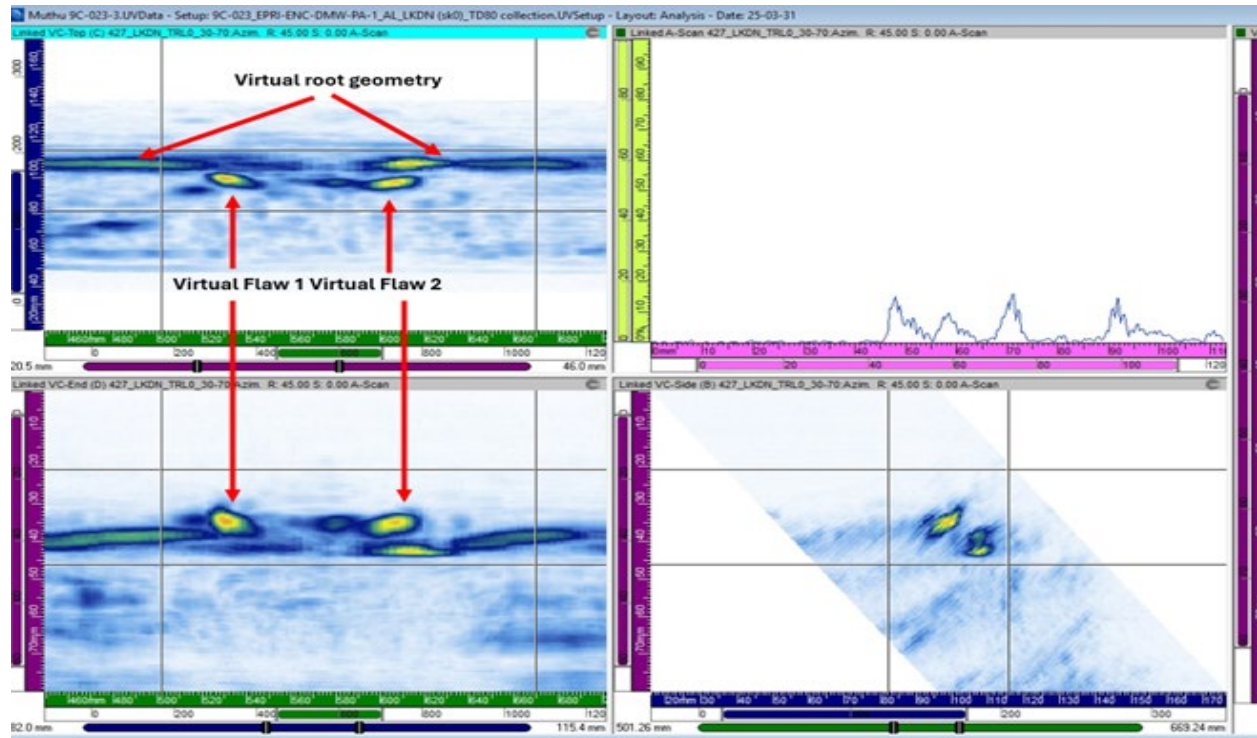


Figure 35. Virtual specimen 9C-023-2 with new Flaws 1 and 2 and root geometry in the 45° data.

Virtual Specimen 9C-023-3

This virtual specimen used Flaw 4 from the 45° scan as the source data file, as shown in Figure 36.

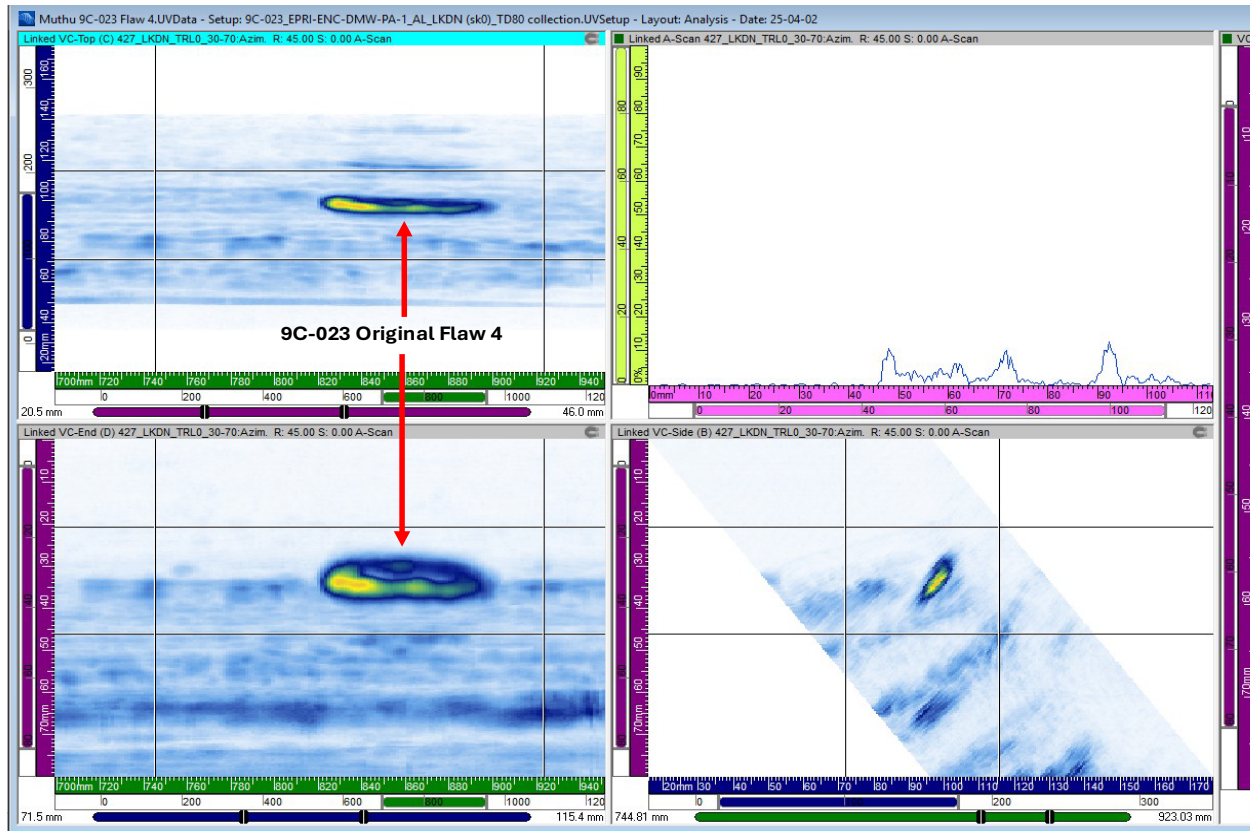


Figure 36. Original Flaw 4 in specimen 9C-023.

The flaw in the 45° data was removed, as shown in Figure 37, but the 60° and 70° scans were not modified, as shown in Figure 38. This represents a realistic condition where the flaw was not identifiable in the 45° scan, either due to the flaw's orientation or a limited scanning access condition, but the 60° and 70° scans produced a flaw response. Examples of this can be seen in Harrison et al. (2023).

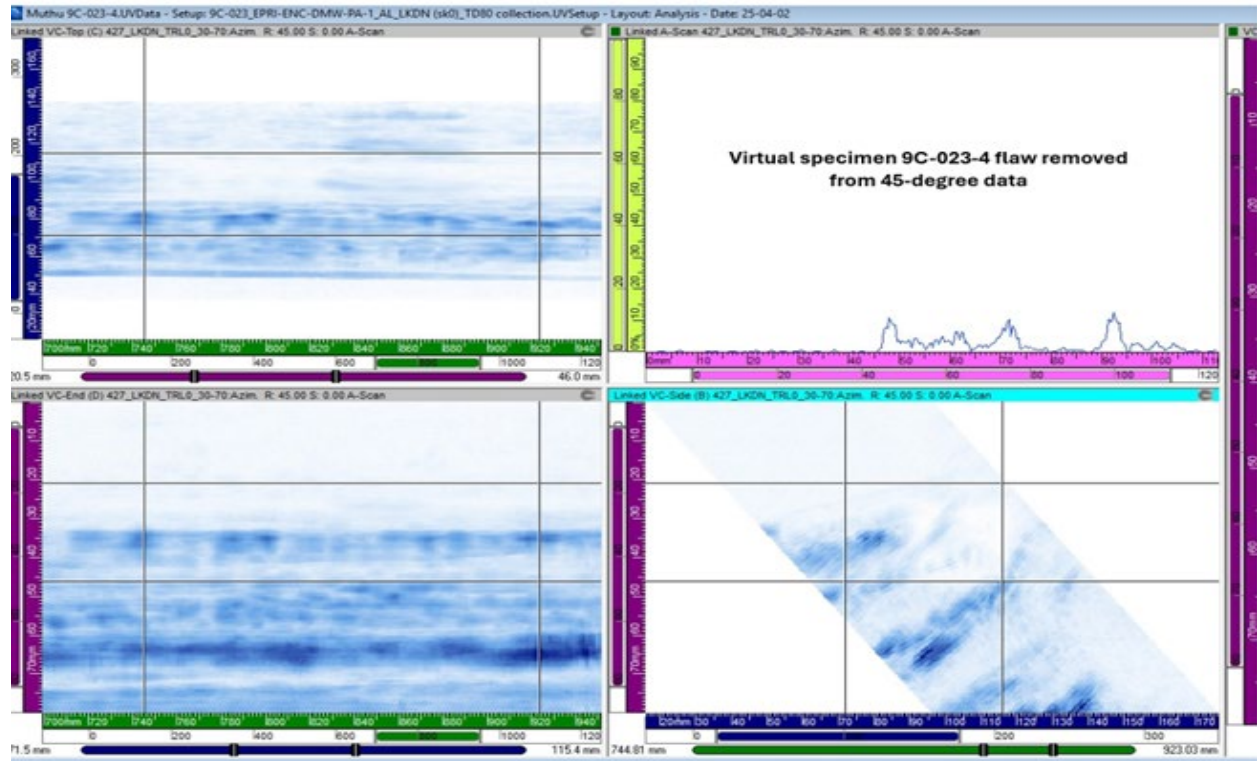


Figure 37. 45° scan of virtual specimen 9C-023-3 with original Flaw 4 removed.

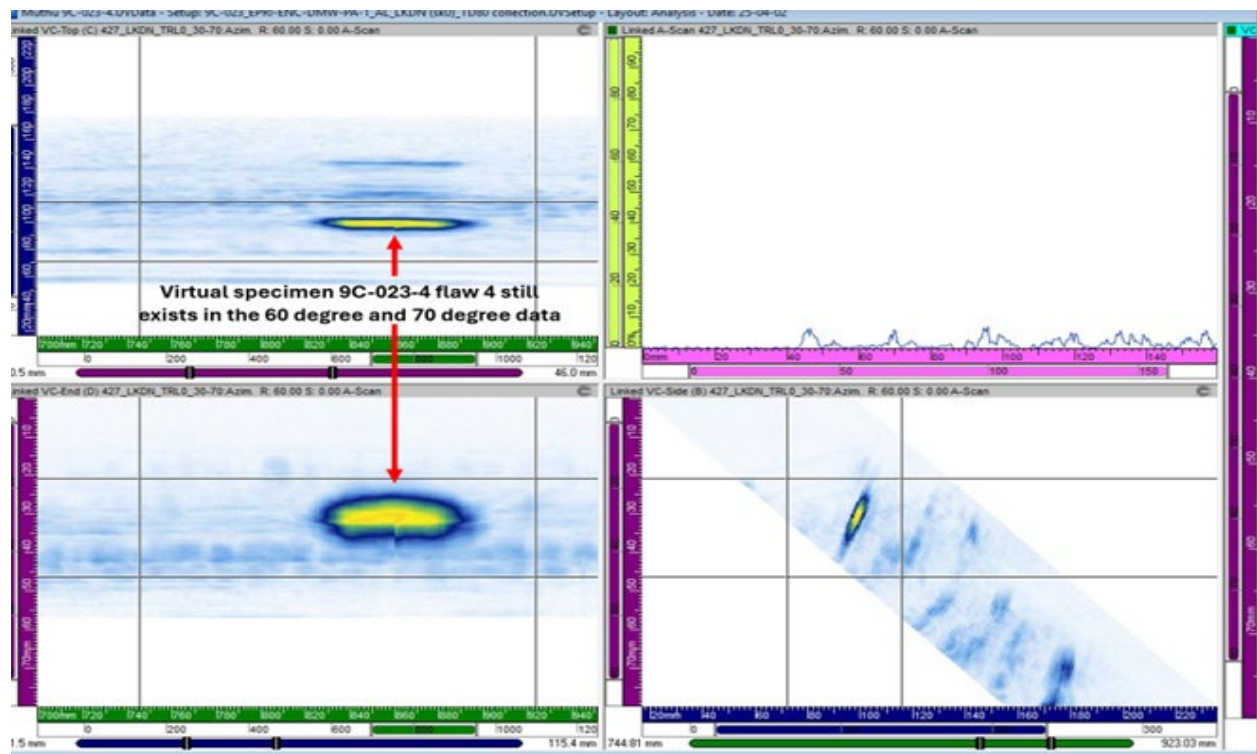


Figure 38. 60° scan of virtual specimen 9C-023-3 with original Flaw 4.

Virtual Specimen 9C-023-4

Flaw 4, shown in Figure 36, was used as the source for this virtual specimen. The amplitude of the flaw response for the 45° and 60° scans was reduced to about the same level as the surrounding geometry, and the flaw response was removed from the 70° scan. Realistic conditions exist in plant piping systems where geometric responses are equal to or exceed the amplitude from a real flaw. If the amplitude and response characteristics are similar, then the primary difference between the responses may be their locations. Thus, correctly identifying the location of a response in relation to the weld is of primary importance to correctly discriminating between geometry and a flaw. The resulting virtual specimen 9C-023-4 is shown in Figure 39.

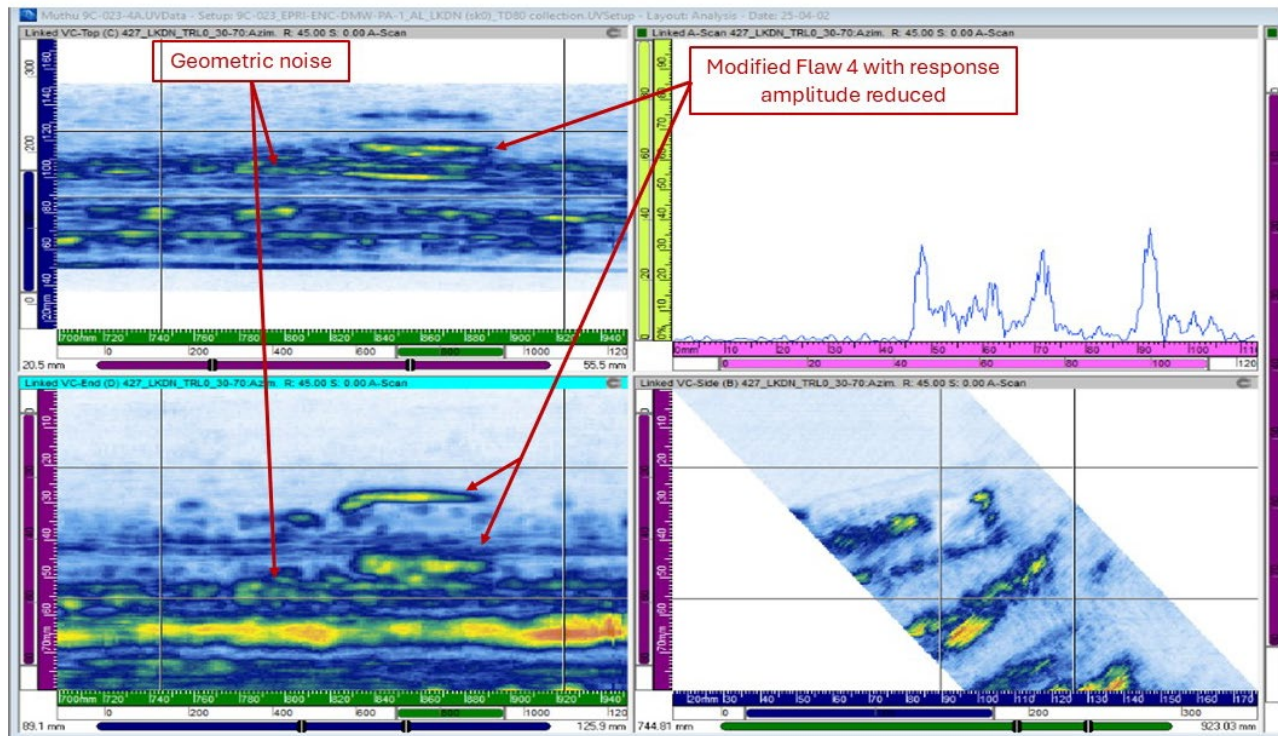


Figure 39. 45° scan of virtual specimen 9C-023-4.

5.5 Specimen 9C-034

This specimen is a 12.8 in. OD cast austenitic stainless steel (CASS) pipe to Inconel 82/182 weld and butter material to CS nozzle with a nominal wall thickness of 1.4 in. This specimen contains four TFCs near the WCL in the buttering (the distance from the WCL was not specified). Each flaw was scanned at 30°, 45°, 60°, and 70°, but only the Flaw 2 data (see Table 6 and Figure 40) from the CS side were sourced to create virtual specimen 9C-034-1. Data were acquired using a 1.5 MHz TRL phased-array probe with 32 elements (8 × 4) in each array.

Table 6. Specimen 9C-034.

Flaw	Type	TW Depth (%)	Length (in.)	Tilt (deg)
2	TFC	31	2.03	0

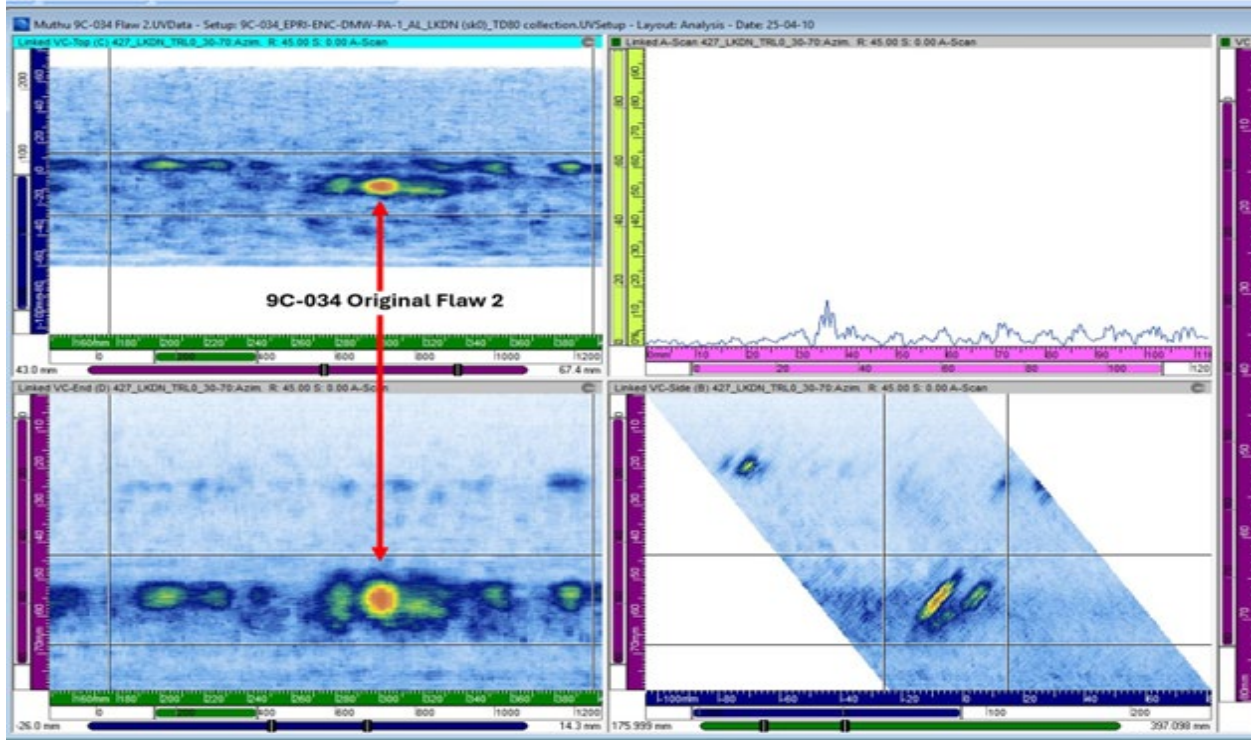


Figure 40. 45° scan of original Flaw 2 in specimen 9C-034.

Virtual Specimen 9C-034-1

This virtual specimen was created by extending the length of the flaw in the 45° scan but leaving the 60° and 70° scans unchanged. This creates a condition where the flaw length must be evaluated to determine if one or more flaws exist, as two separate high amplitude points exist along the flaw. The flaw was seen in the 60° and 70° scans, but the response amplitudes were very weak. Typically, a planar flaw will produce comparable response amplitudes at 45° and 60°, although this is not always possible due to configuration of the inside surface or limitations that prevent sufficient movement of the transducer. Leaving the weak responses created a condition where the higher angles should be used as confirmation that a flaw exists, but an analyst may dismiss them altogether due to the weak responses. Virtual specimen 9C-034-1 is shown in Figure 41.

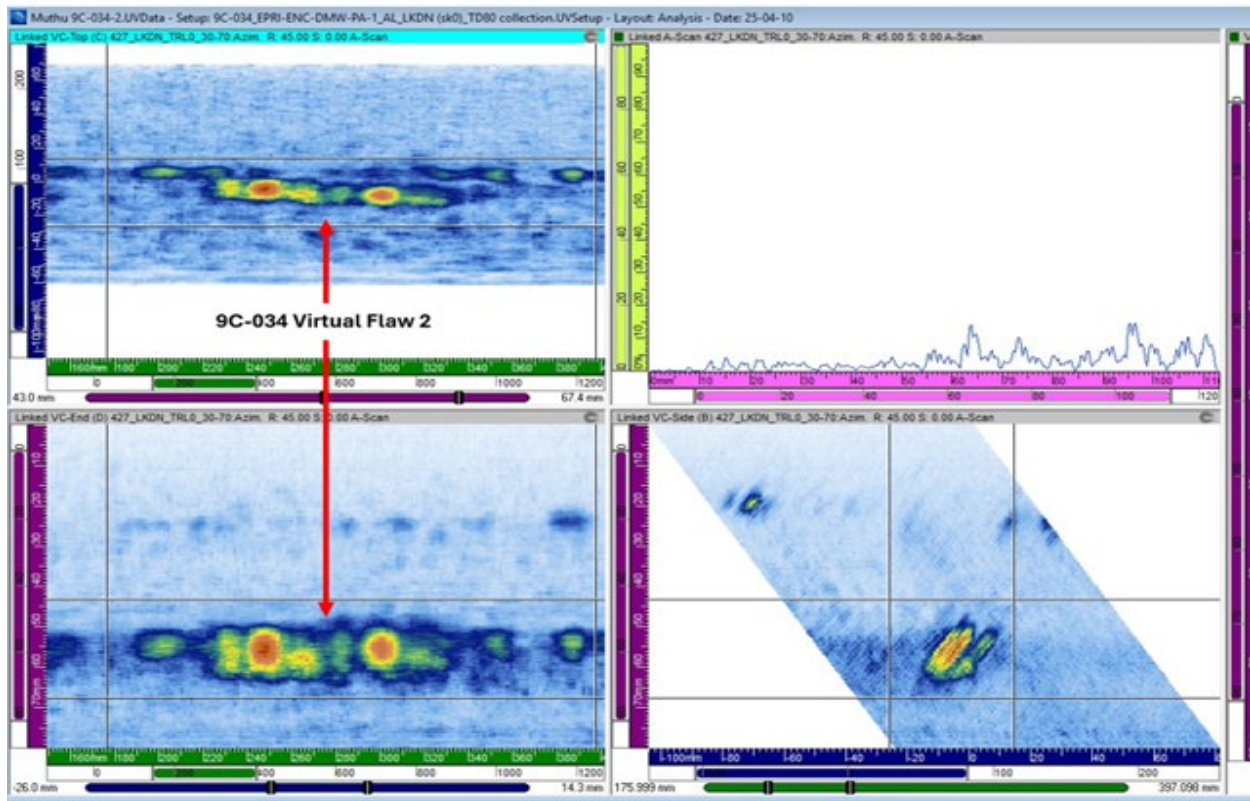


Figure 41. 45° data of Flaw 2 in virtual specimen 9C-034-1.

A flaw with two separate, distinct amplitude peaks along its axis is common among real flaws and represents the flaws meandering through-wall dimension that presents a larger reflective face in areas along the flaw.

5.6 Specimen 14C-146

This specimen is a large-bore 36 in. OD DMW specimen with a wall thickness of 3.30 in. representative of an RPV nozzle to CASS cold leg pipe. The specimen contains two axial and three circumferential TFCs. Data were acquired using a 2 MHz probe at 45° from the CS side of the weld. Only the circumferential flaws were used for modifications, and their parameters are shown in Table 7. Flaws 1 and 3 were approximately on the WCL, and Flaw 4 was about 0.5 in. on the CS side of the WCL. Flaw 4, shown in Figure 42, was sourced to create virtual specimens 14C-146-1, -2, and -3.

Table 7. Specimen 14C-146.

Flaw	Type	TW Depth (%)	Length (in.)	Tilt (deg)
1	TFC	10	3.01	0
3	TFC	20	4.01	0
4	TFC	16	2.97	0

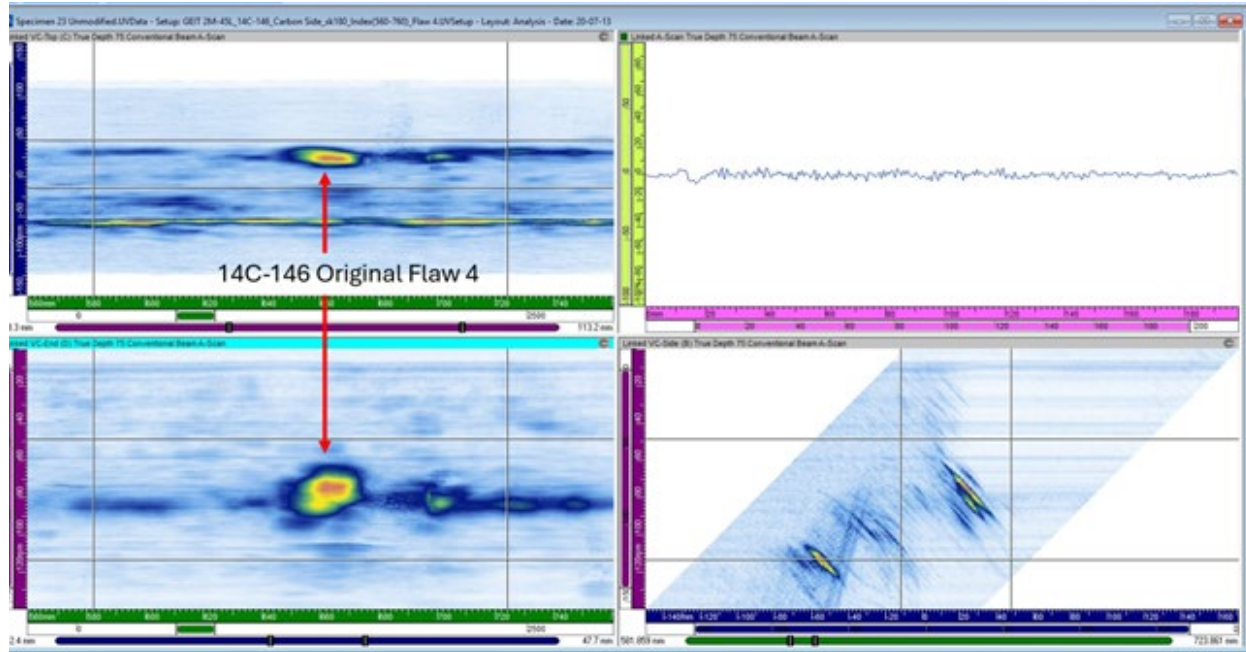


Figure 42. Original Flaw 4 in specimen 14C-146 from the CS side of the weld.

Virtual Specimen 14C-146-1

This specimen was created by a simple modification of moving Flaw 4 from one location in the data file to a different location in the same file and cleaning its original location in the modified file. Identifying the original response as a flaw is straightforward based on its location and amplitude. This modification was selected to provide a basis to determine if a clear virtual flaw response, in its simplest form, could be identified by an analyst as having been modified. Figure 43 displays the virtual flaw in the new location.

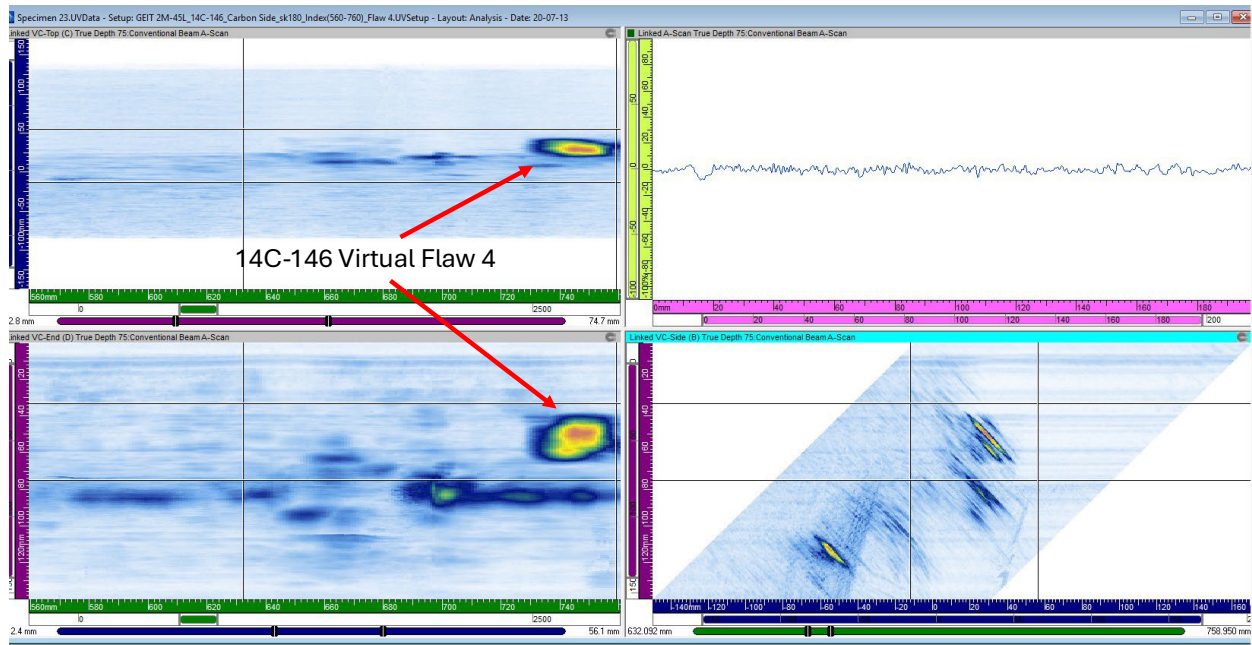


Figure 43. Virtual specimen 14C-146-1 with the flaw placed in a new location.

Virtual Specimen 14C-146-2

Flaw 4 in Specimen 14C-146 was sourced to produce a virtual specimen with the flaw response amplitude greatly reduced. The result was a weak flaw response appearing to have the same signal intensity as geometric responses in the same data file. This is a real condition, and data analysts must pay attention to evaluating the location of all responses regardless of amplitude. Virtual specimen 14C-146-2 is shown in Figure 44.

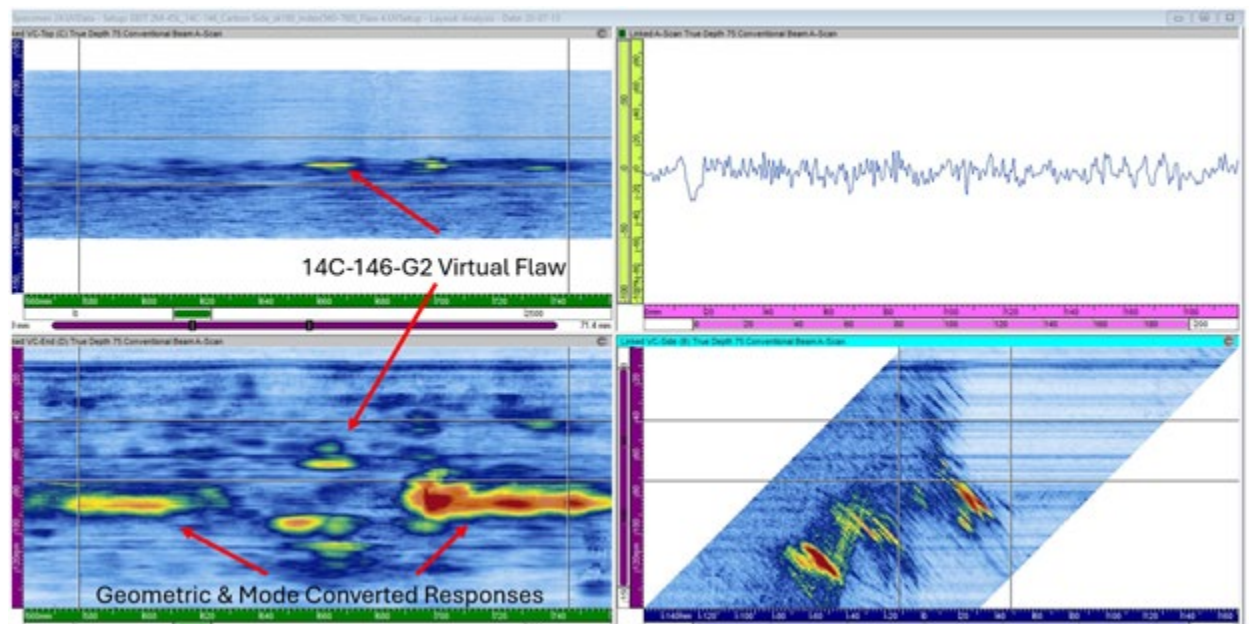


Figure 44. Flaw 4 with reduced amplitude in virtual specimen 14C-146-2.

Virtual Specimen 14C-146-3

This virtual specimen once again focuses on Flaw 4 in specimen 14C-146 as the source flaw. The flaw was left in its original condition, but the amplitude of the existing geometric root response was increased over the entire length of the data file and adjacent to the flaw. The objective applied in virtual specimen 14C-146-2 was used here to produce flaws comparable to real in-plant conditions that may not produce a high amplitude response above geometric responses, but data analysts rely on the image location and the characteristics of the echo to properly identify a flaw. The resulting virtual specimen 14C-146-3 is shown in Figure 45.

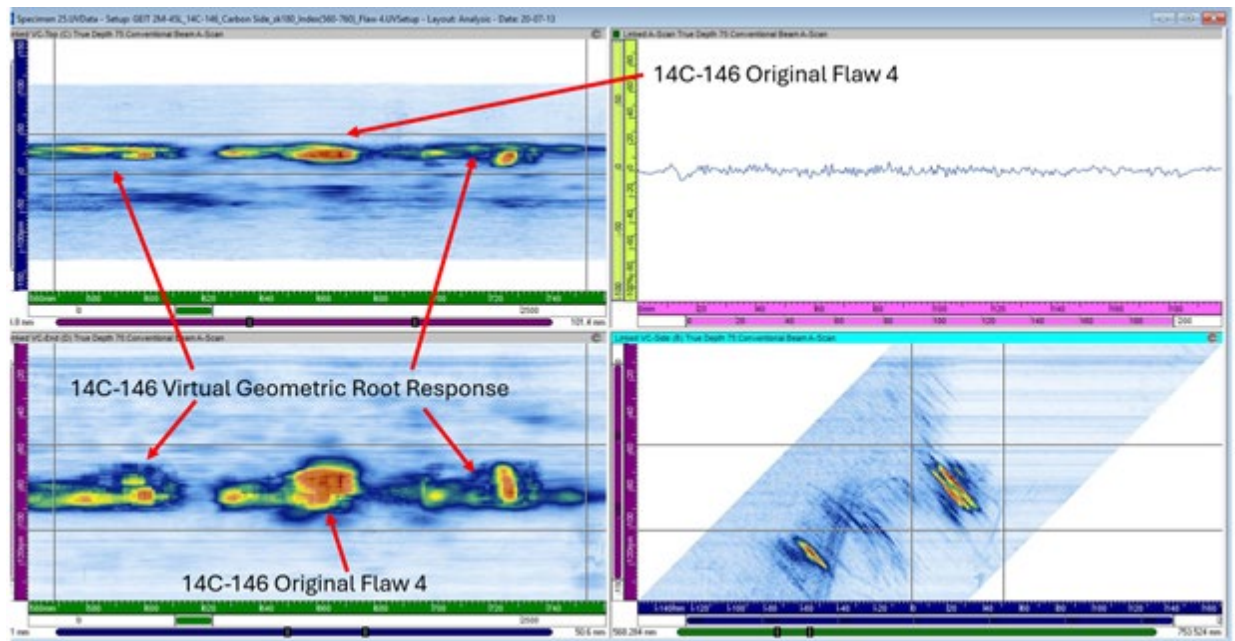


Figure 45. Virtual specimen 14C-146-3 with enhanced geometric root response.

Virtual Specimen 14C-146-4

This virtual specimen sourced Flaw 4 from specimen 14C-146 data that were acquired utilizing a 1.5 MHz 32 element (8 × 4) phased-array probe. The original Flaw 4 data from the 45° focal law is shown in Figure 46.

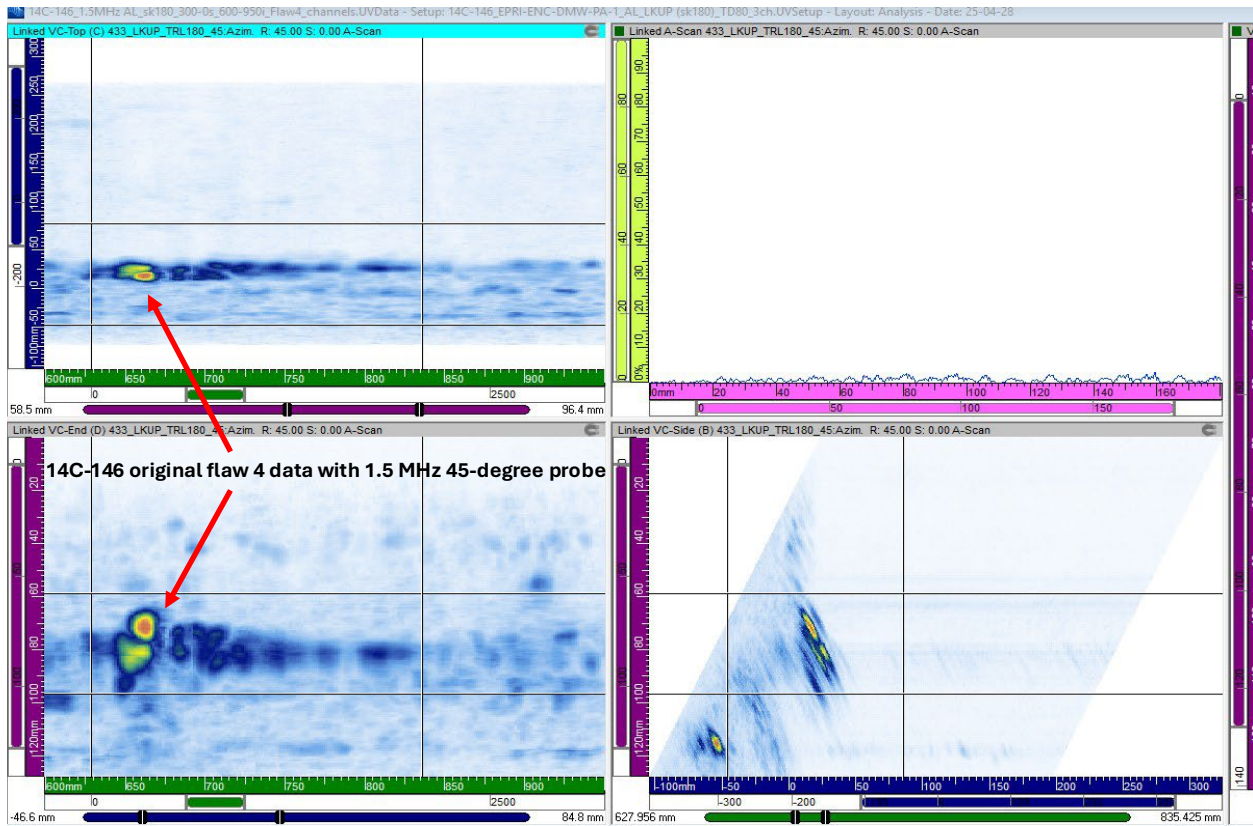


Figure 46. Original Flaw 4 from 1.5 MHz 45° data for specimen 14C-146.

The original flaw response was copied to another location within the same file without any modification to the size or response amplitude, leaving the original flaw unchanged, as shown in Figure 47. This specimen was created to determine if the virtual flaw could be identified as having been modified and to compare the characteristics of the original flaw and the copied flaw in the virtual specimen.

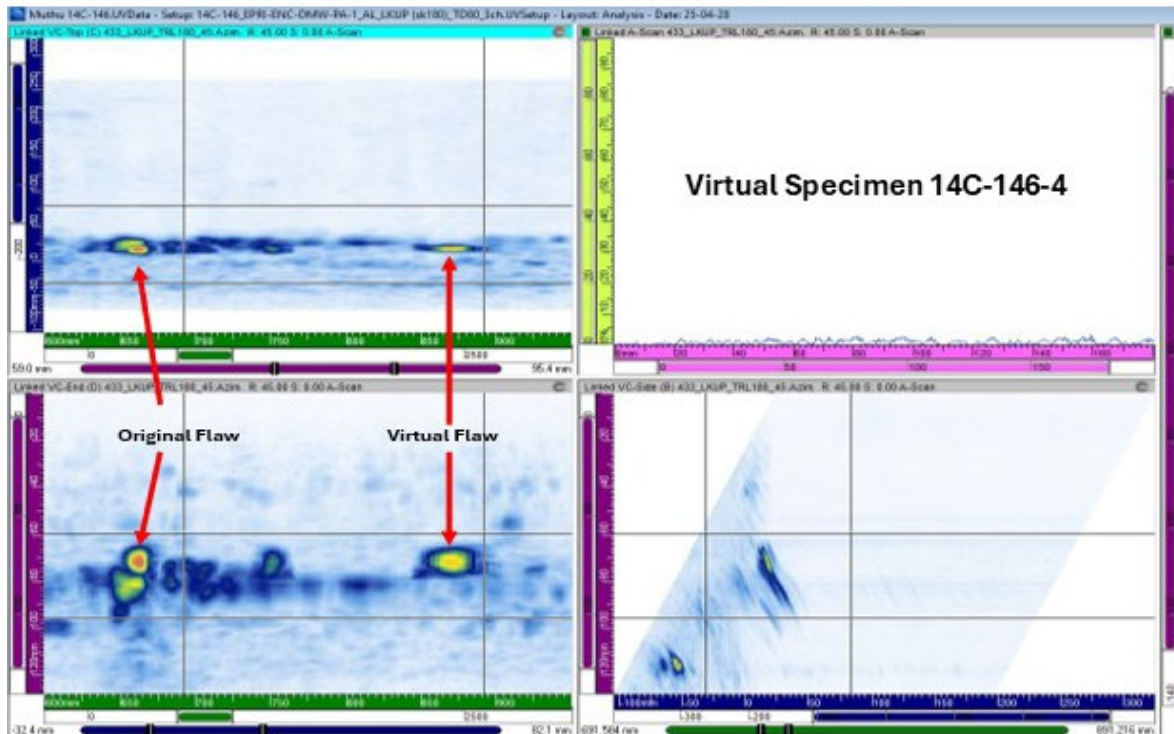


Figure 47. Virtual specimen 14C-146-4.

The original and virtual flaws both lie along the same plane as the geometric weld root, thus analysis of the response data based on physical separation is not possible. The difference is the response from both flaws exhibits a higher amplitude than the weld root. In some as-welded conditions the weld root may produce a response such that its amplitude is comparable to the flaw's response, so an analysis based on amplitude is not reliable. The echo-dynamic characteristics of each response must be evaluated to determine the source. Flaw signatures will exhibit a sharp, well defined echo characteristic that may also exhibit facets from branches extending from a crack's main surface. A weld root has more width compared to a planar flaw and will exhibit a broad echo characteristic that will not travel in response time to the extent a flaw will as the probe is moved toward and away from the flaw.

Virtual Specimen 14C-146-5

This virtual specimen was created by sourcing Flaw 2 from specimen 602, which is a large bore, 34 in. OD, RPV nozzle to safe-end DMW with a wall thickness of 2.95 in. Flaw 2 is a circumferential crack 4.8 in. long with a 38% through-wall depth. It was scanned from the CS side of the weld with a 2 MHz probe at 60°. Only a portion of the flaw was sourced to create the virtual specimen. Figure 48 displays the original flaw with a boxed area indicating the extracted segment.

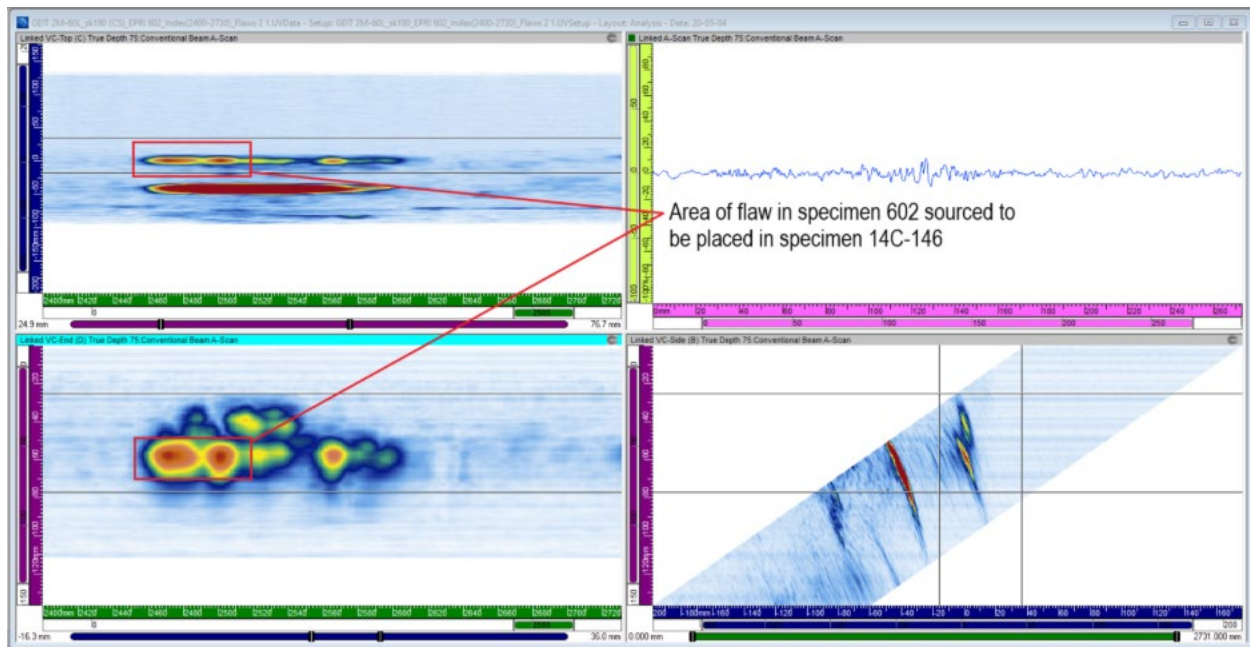


Figure 48. Original Flaw 2 in specimen 602. The box shows the portion of the flaw response that was sourced for virtual specimen 14C-146-5.

The data file for Flaw 1 in specimen 14C-146 was selected as the target location for the new virtual flaw from specimen 602. Figure 49 displays this data file in its original form before modification. The virtual specimen contains two flaws, the original Flaw 1 from specimen 14C-146 and the virtual Flaw 2 from specimen 602. The axial locations of the two flaws were slightly offset so that the two do not appear in the same axial plane. Figure 50 shows the modification result.

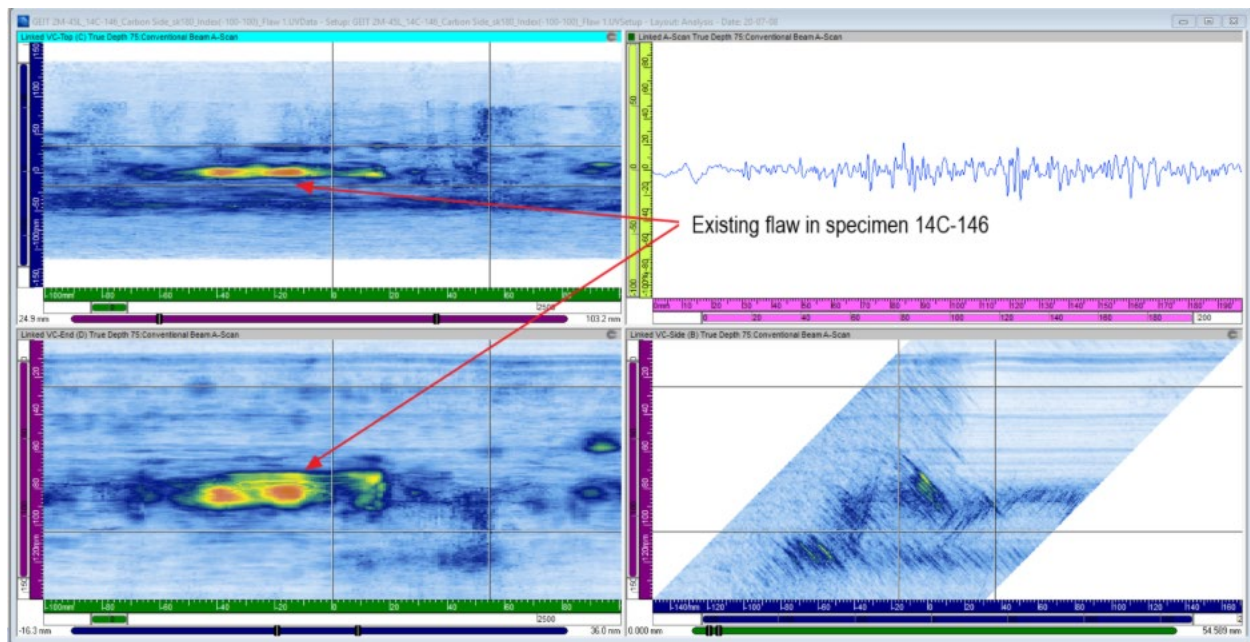


Figure 49. Original Flaw 1 in specimen 14C-146.

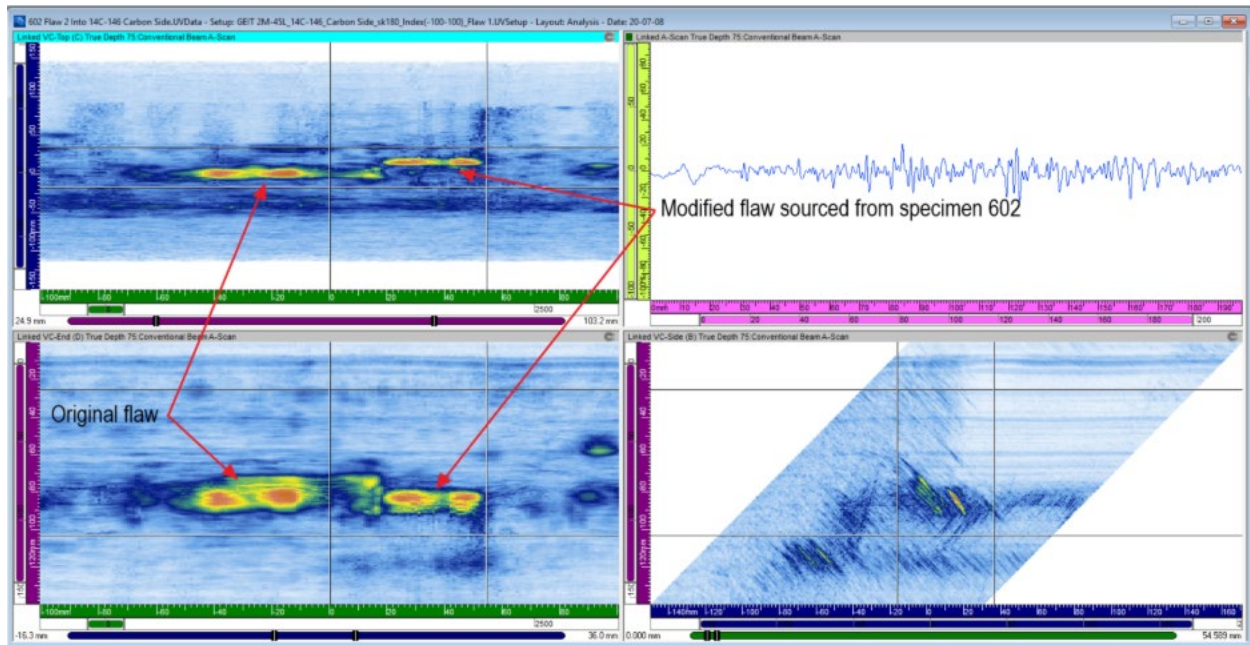


Figure 50. Virtual specimen 14C-146-5.

Planar flaws do not always initiate and propagate along or within the same plane and can challenge the ability to correctly define the response. The original flaw is very near the weld centerline/root. Pacing the modified flaw offset axially from the original flaw replicates this condition, thus requiring an analysis of the response characteristics to correctly identify both as flaws.

Virtual Specimen 14C-146-6

This virtual specimen sourced Flaw 2 from specimen 602, shown in Figure 48. The target data file was a 2 MHz, 45° scan from the CASS side of specimen 14C-146 where no flaw responses were present. Flaws 1 and 3 of this specimen are present in the weld root area near the WCL but were not detectable in the data from the CASS side. The original image from the CASS side of specimen 14C-146 is shown in Figure 51.

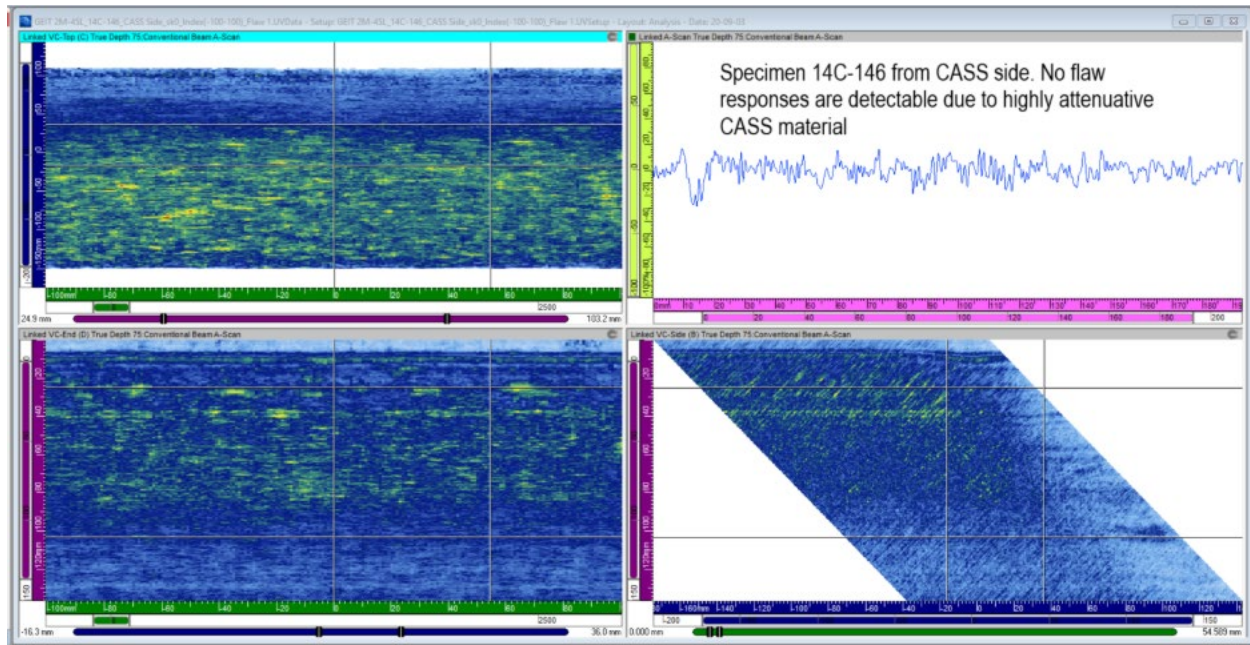


Figure 51. Specimen 14C-146 from the CASS side of the weld. No flaws were detected in this scan.

Flaw 2 from specimen 602 was placed into this data file and produced an interesting result. The flaw response had a high amplitude in the original scan and previous sourced flaws, when placed in a representative target specimen, retained the flaw response amplitude; however, when it was placed into the CASS material, the response amplitude was reduced. No adjustments were made to the response amplitude during the modification; it was simply placed into the data file as originally sourced from specimen 602. The modification algorithm appears to have automatically and realistically blended the flaw signal into the noisy CASS background. The virtual image is shown in Figure 52.

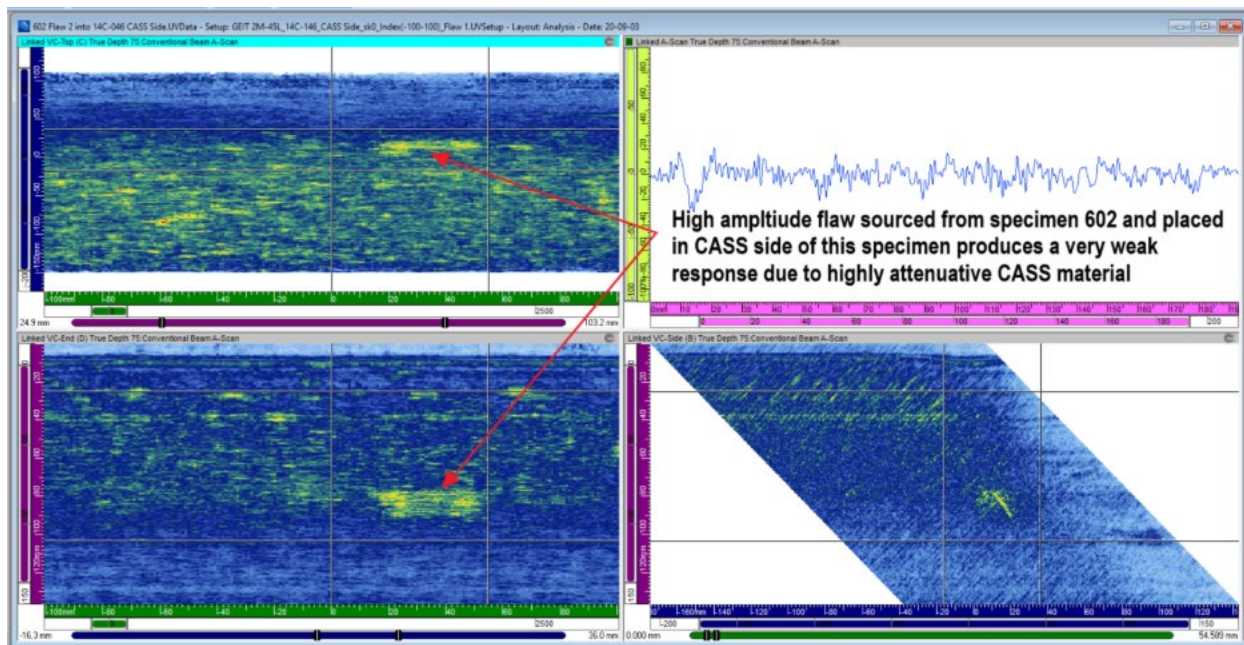


Figure 52. Virtual specimen 14C-146-6. The signal of a high amplitude flaw placed into the CASS scan of specimen 14C-146 was attenuated and blended into the CASS background.

The coarse grain structure and attenuative properties of CASS material that has been widely documented in reports (e.g., Jacob et al. 2019) significantly complicates the detection of flaws with ultrasound. While virtual flaws in CASS components are not a focus of this research, the results of this specimen may provide insight into the possible use of virtual flaws in CASS components.

5.7 Specimen 701-P1

Specimen 701-P1 is a small-bore, 2.0 in. OD, austenitic pipe specimen with a wall thickness of 0.28 in. containing two circumferential flaws. The flaw parameters are shown in Table 8. Note that Flaw 2 is a lack of fusion (LOF) defect and is not surface breaking. Flaw 2 is also on the opposite side of the weld as Flaw 1, and it is tilted in the opposite direction, as indicated by the “-” sign in the table. The original scan data are shown in Figure 53. Data were acquired with a 3.5 MHz probe at 70°. Note that this was a full circumferential scan with the scan origin in the middle of Flaw 1, so that flaw appears to be split at the two extremes of the scan.

Table 8. Specimen 701-P1.

Flaw	Type	TW Depth (%)	Length (in.)	Tilt (deg)
1	TFC	92	1.72	15
2	LOF	38	0.42	-15

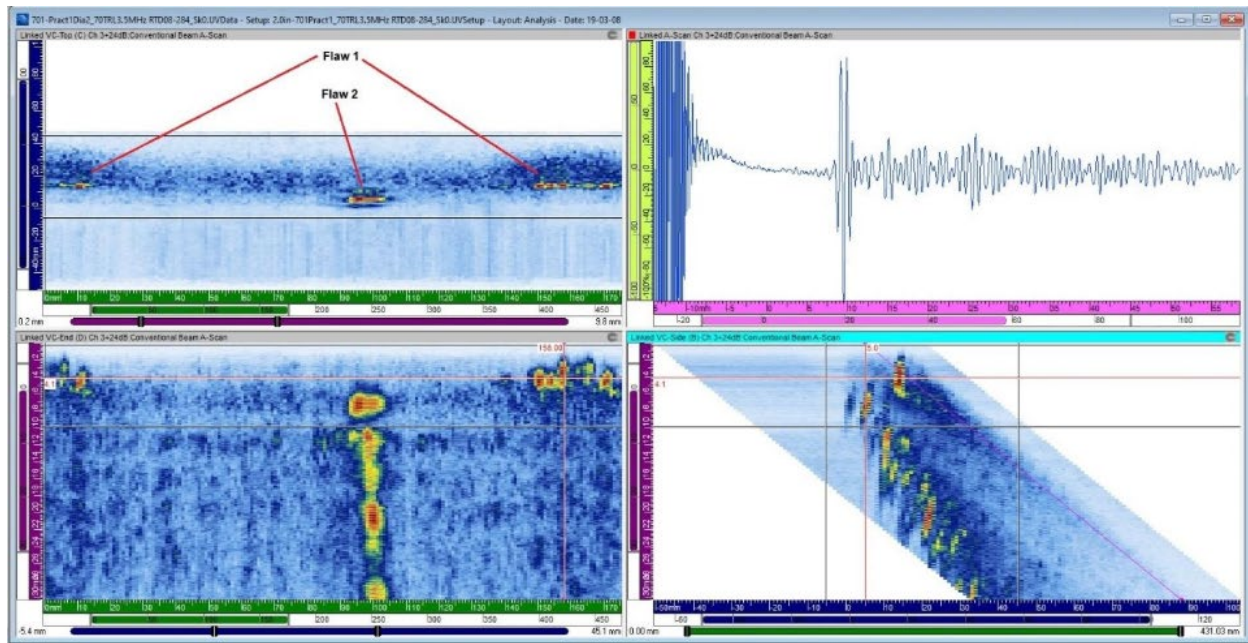


Figure 53. Specimen 701-P1. The split of Flaw 1 at the two extremes of the scan is due to the origination of the scan on that flaw.

Virtual Specimen 701-P1-1

One of the most difficult analysis situations to interpret is a flaw that extends over the entire length of the specimen, especially if no geometric conditions exist for comparison. Flaws that extend over the entire length of a component do exist in the field, although they are not common, while a geometric root response more commonly appears over the entire length of the circumference. To simulate this flaw condition, a virtual specimen was created by removing Flaw 2 and extending the length of Flaw 1 over most of the circumference. The new virtual flaw, based on its length and location, possesses response characteristics that could be interpreted as originating from either a flaw or a geometric root response, thus posing a challenge to analysts. Figure 54 displays the new virtual specimen.

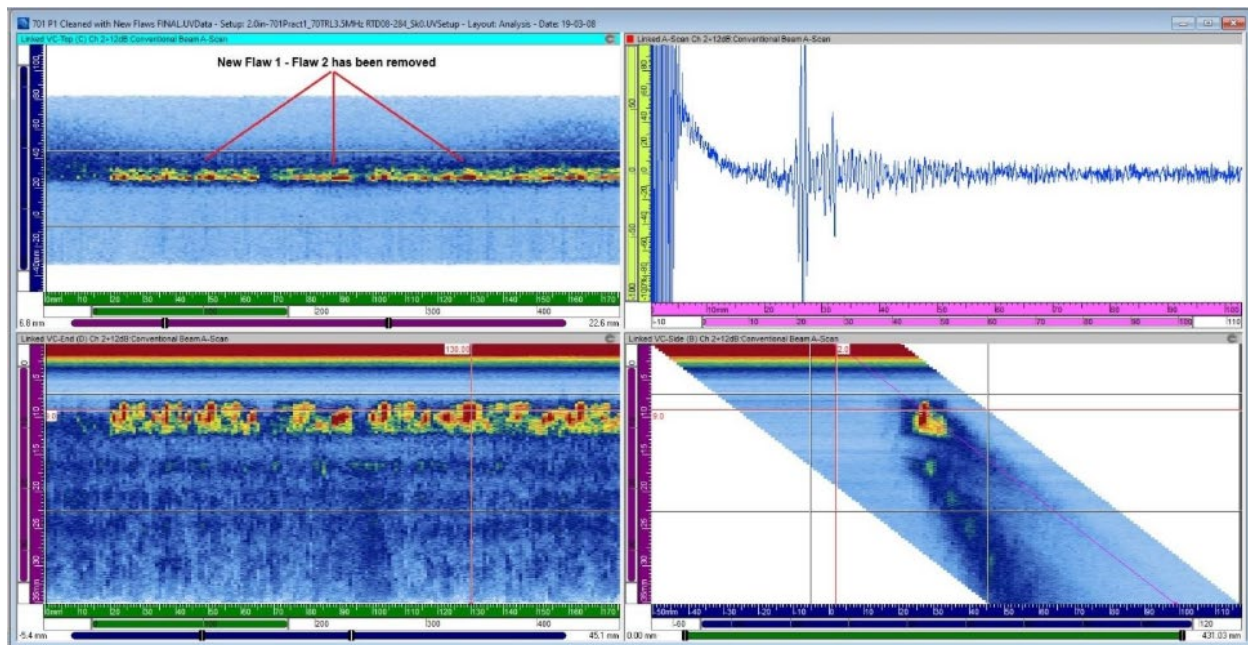


Figure 54. Virtual specimen 701-P1-1.

The flaw now extends over most of the entire pipe circumference. A unique characteristic of the new virtual flaw is that it does not exhibit a smooth, continuous pattern of relatively equal amplitude but is broken in places at varying amplitudes. This is indicative of a response from the jagged, faceted face of a planar flaw with meandering through-wall dimensions.

5.8 Specimen 703-8

Specimen 703-8 is a 4.8 in. OD DMW piping specimen with a wall thickness of 0.60 in. containing two flaws. Flaw 1 is axially oriented, and Flaw 2 is circumferential and located about 0.5 in. from the WCL in the buttering; see Table 9. Data were acquired at 2 MHz and 45° from the SS side of the weld. The original, unmodified data file is shown in Figure 55.

Table 9. Specimen 703-8.

Flaw	Type	TW Depth (%)	Length (in.)	Tilt (deg)	Skew (deg)
1	Axial EDM	39	0.50	3	5
2	Crack	28	2.48	0	0

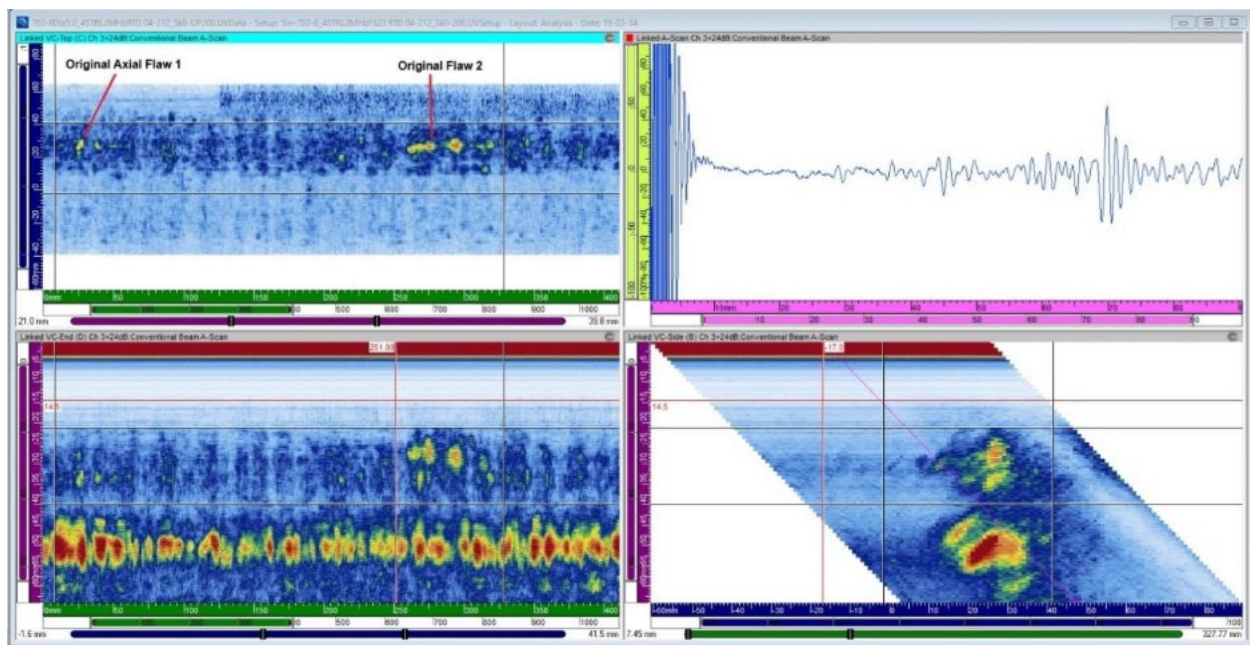


Figure 55. Specimen 703-8 with one axial and one circumferential flaw.

Virtual Specimen 703-8-1

This virtual specimen was created by retaining both flaws and sourcing part of Flaw 2, reorienting its axis, and placing it adjacent to the original Flaw 2. This presents an axial component to the original Flaw 2 that could appear as a geometric condition extending from the root rather than a flaw and distract an analyst from identifying the weaker amplitude Flaw 1. The virtual specimen is shown in Figure 56.

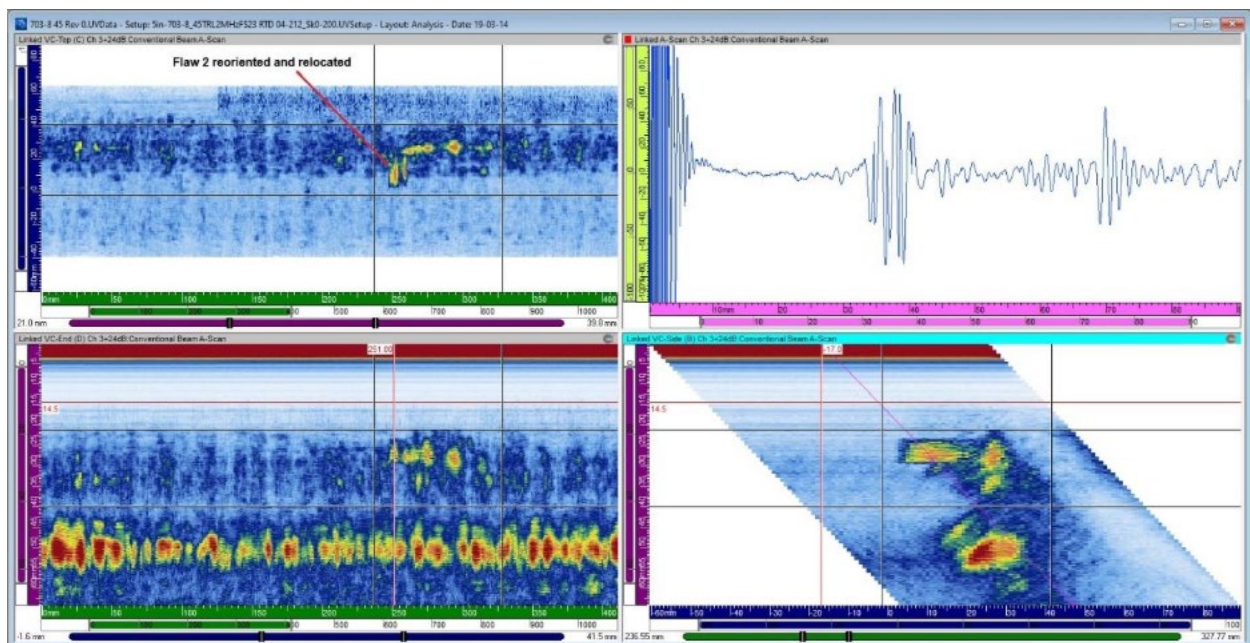


Figure 56. Virtual specimen 703-8-1 with an axial component added to Flaw 2.

A planar flaw will not always propagate in a straight line or parallel with a weld. Varying stress patterns within the material or the as-welded condition in the area of the flaw may create facets or branches of the flaw that propagate in various orientations. This virtual specimen creates a scenario where both a circumferential and axial component exist in virtual flaw 2.

5.9 Specimen 705-P1

Specimen 705-P1 is a 14 in. OD DMW piping specimen with a wall thickness of 1.15 in. This specimen contains three flaws. Flaws 1 and 2 are axially oriented and Flaw 3 is circumferential; see Table 10. Flaw 3 was located on the WCL. Figure 57 displays the original specimen data image; only Flaw 3 is visible in the scan. Data were acquired at 1.5 MHz and 45° from the CS side of the weld.

Table 10. Specimen 705-P1.

Flaw	Type	TW Depth (%)	Length (in.)	Tilt (deg)	Skew (deg)
1	Axial EDM	36	0.69	3	10
2	Axial crack	17	0.35	0	0
3	Crack	19	0.89	0	0

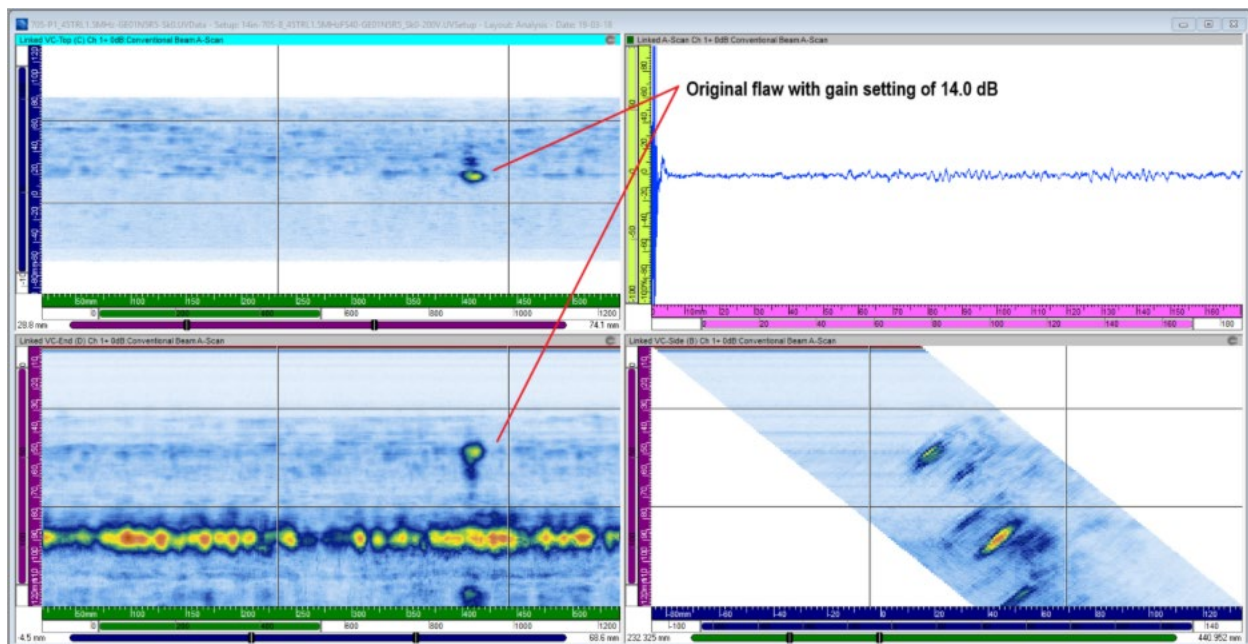


Figure 57. Scan of specimen 705-P1 showing Flaw 3.

Virtual Specimen 705-P1-1

Flaw 3 produced a weak response amplitude; therefore, a modification was developed to leave the flaw in its original location but increasing the amplitude of the flaw response. This modification was performed to assess the effects of adjusting the source, target, and amp factor settings in an MVM configuration file. Figure 58 displays the new virtual flaw.

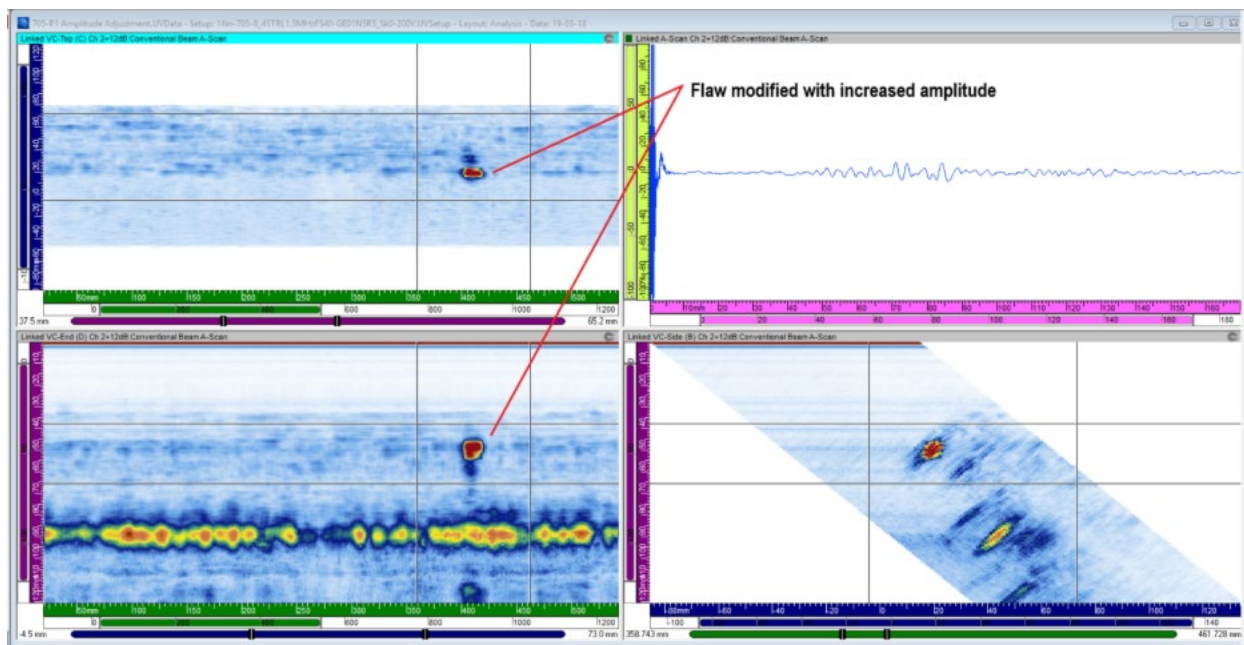


Figure 58. Virtual Flaw 3 in specimen 705-P1-1 with the amplitude response increased.

5.10 Specimen 706-P1

Specimen 706-P1 is a 12 in. OD DMW piping specimen with a wall thickness of 1.15 in. The specimen contains two circumferential flaws, Flaws 1 and 2 shown in Figure 59, and one axial flaw, Flaw 3, which is not shown in the circumferential scan data nor was it used for modification. Flaws 1 and 2 are both located on the same side of the weld about 1 in. from the WCL in the buttering. Data were acquired at 1.5 MHz and 45° from the CS side of the weld. The flaw details are described in Table 11.

Table 11. Specimen 706-P1.

Flaw	Type	TW Depth (%)	Length (in.)	Tilt (deg)	Skew (deg)
1	Crack	28	3.92	0	0
2	Crack	67	3.68	20 (upper part only)	0
3	Axial EDM	23	0.50	0	0

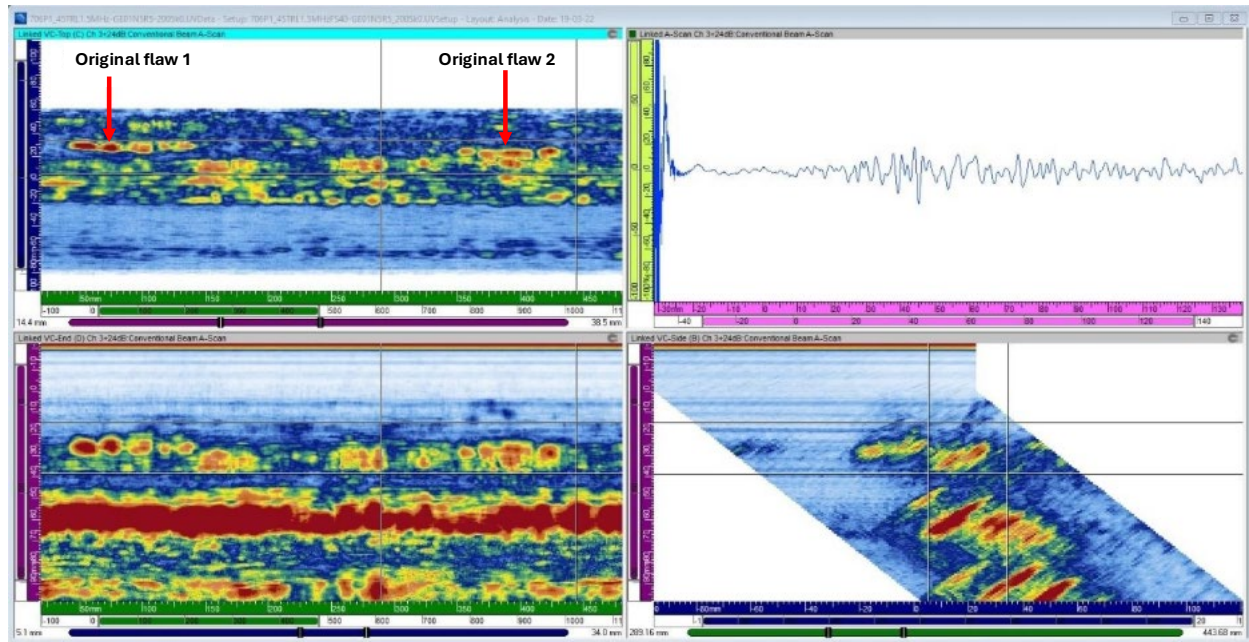


Figure 59. Original Flaws 1 and 2 in specimen 706-P1.

Virtual Specimen 706-P1-1

A modification was performed to relocate Flaw 1 adjacent to Flaw 2, placing Flaw 1 at an axial distance between the weld root and Flaw 2. By having two flaws close together circumferentially, but separated axially, a condition is produced where the flaw closer to the weld root could be misidentified as a geometric root response, or the flaw further from the root misidentified as a counterbore or other geometric condition. During the initial modification, a realistic blending of the noise surrounding the relocated flaw was not possible. The general background “base metal” noise was much higher in the area around the flaw and could not be adjusted to appear realistic. A revised modification was prepared to clean the root response and the original Flaw 1 location, then move Flaw 1 as originally planned. The resulting virtual specimen 706-P1-1 image is shown in Figure 60.

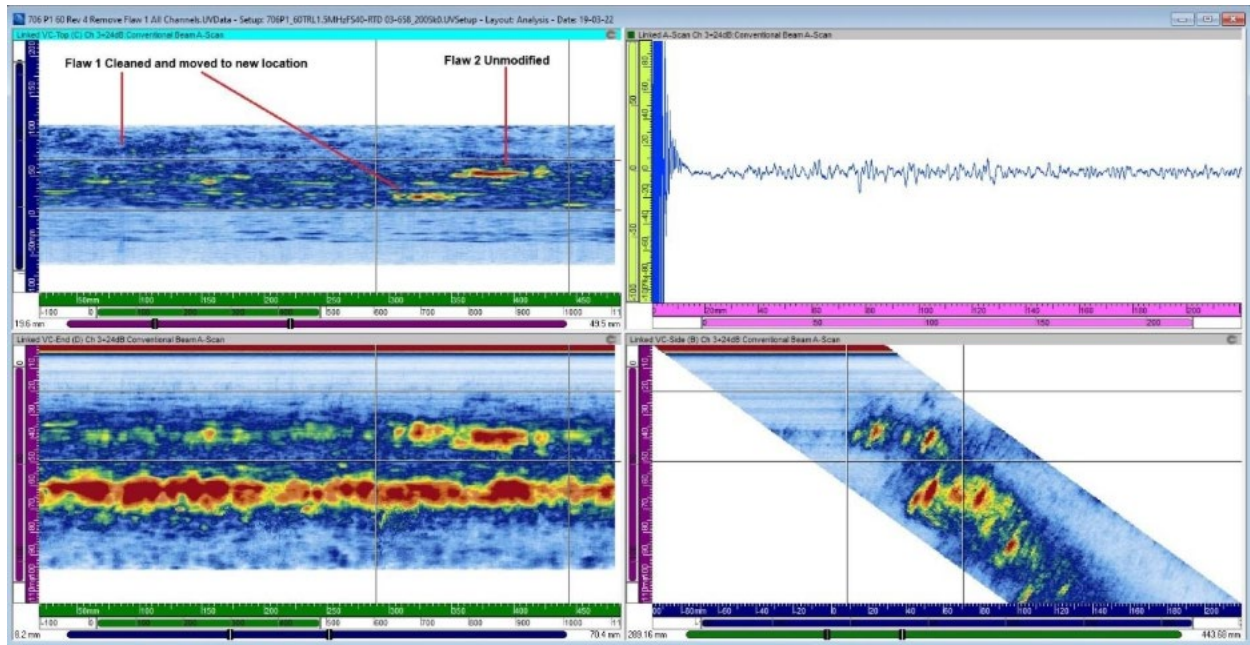


Figure 60. Virtual specimen 706-P1-1.

5.11 Specimen 706-P2

Specimen 706-P2 is a 12 in. OD DMW piping specimen with a wall thickness of 1.15 in. The specimen contains two circumferential flaws, Flaw 1 and 3 shown in Figure 61, and one axial Flaw 2. Flaws 1 and 3 were located on the same side of the weld, Flaw 1 about 0.2 in. from the WCL and Flaw 3 about 0.8 in. from the WCL. Flaw 1 was multifaceted, with portions having different skews and tilts. Data were acquired at 1.5 MHz and 60° from the CS side of the weld. The flaw details are described in Table 12.

Table 12. Specimen 706-P2.

Flaw	Type	TW Depth (%)	Length (in.)	Tilt (deg)	Skew (deg)
1	Crack	77	3.43	5–15	0–5
2	Axial EDM	24	0.45	5	5
3	Crack	21	0.94	10	0

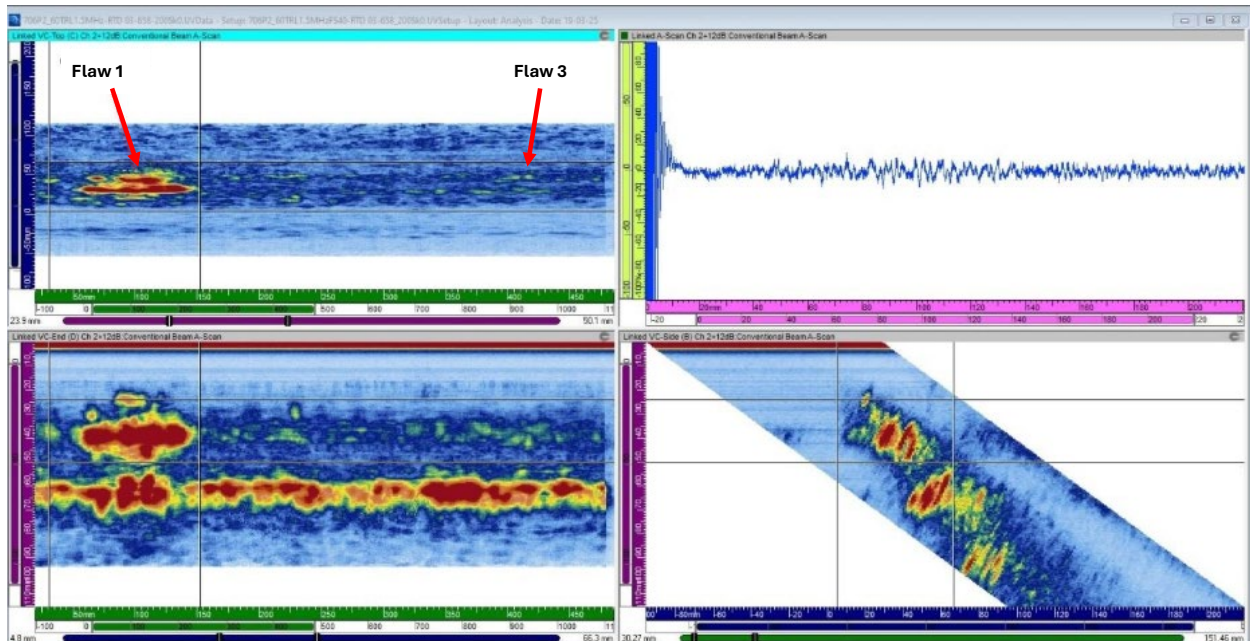


Figure 61. Original Flaws 1 and 3 in specimen 706-P2.

Virtual Specimen 706-P2-1

This modification removed Flaw 1, which had a strong response amplitude, but retained Flaw 3, which exhibited a weak response amplitude. The resulting virtual specimen 706-P2-1 is shown in Figure 62. Very weak flaw responses can be easily overlooked even if no geometric conditions exist that may mask the flaw response. The different materials contained in DMW components are not only attenuative but also produce noise from the grain structure that can reach a level comparable to a weak flaw response. In such cases, particular attention must be given to all weak responses, and background noise must be distinguished from flaws. The high amplitude of Flaw 1 will easily catch a data analyst's eye, and Flaw 3 could be overlooked. By removing the high amplitude Flaw 1, the very weak response from Flaw 3 could still be easily overlooked without thoroughly adjusting the gain setting to investigate the weld for weak flaw responses.

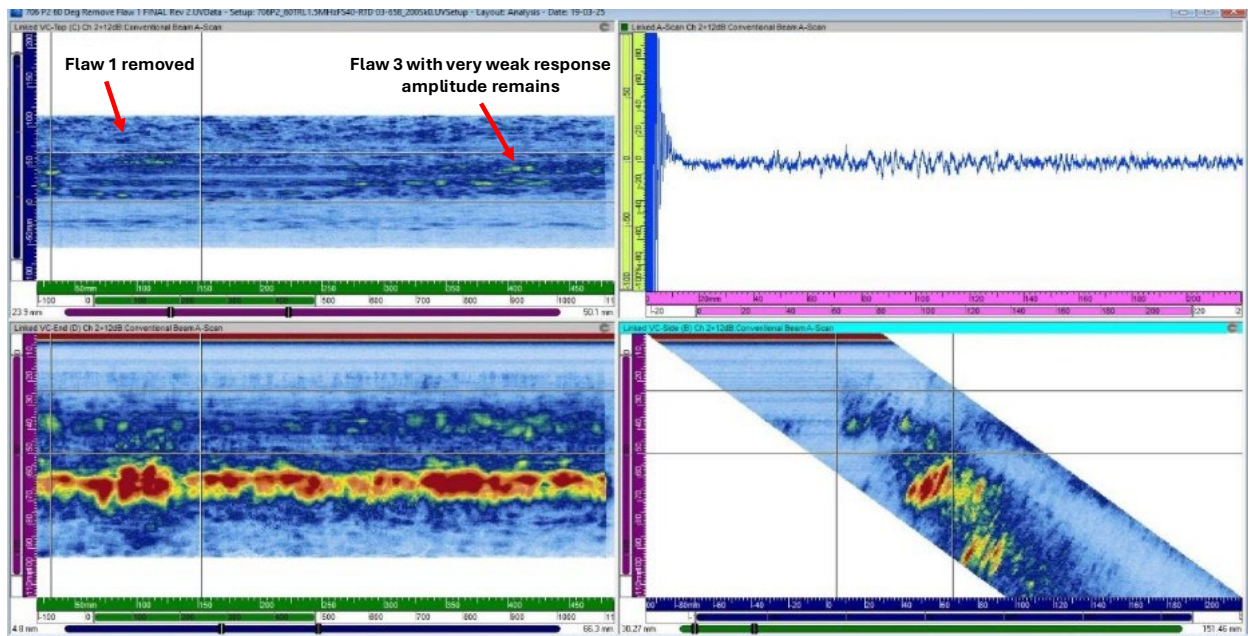


Figure 62. Virtual specimen 706-P2-1.

Flaw 3 has sufficient length and depth to theoretically produce a response amplitude significantly higher than was obtained; however, several factors such as flaw orientation, restrictions to probe movement to adequately ensound the flaw, and material characteristics all impact the amplitude result. These conditions are routinely encountered during in-plant examinations and must be considered during data analysis.

5.12 Specimen 707-P1

Specimen 707-P1 is a 12.7 in. OD DMW piping specimen with a wall thickness of 1.15 in. The specimen contains two circumferential flaws on the same side of the WCL, Flaws 1 and 2, shown in Figure 63, and an axial flaw. Flaw 1 was multifaceted, with portions having different skews and tilts. Both Flaws 1 and 2 were located on the same side of the weld in the buttering, Flaw 1 about 0.3 in. from the WCL and Flaw 2 about 1.0 in. from the WCL. The flaws are described in Table 13. Data were acquired at 1.5 MHz and 45° from the CS side of the weld.

Table 13. Specimen 707-P1.

Flaw	Type	TW Depth (%)	Length (in.)	Tilt (deg)	Skew (deg)
1	Crack	63	2.67	0–25	0–15
2	Crack	40	1.84	0	0
3	Axial EDM	28	0.49	0	10

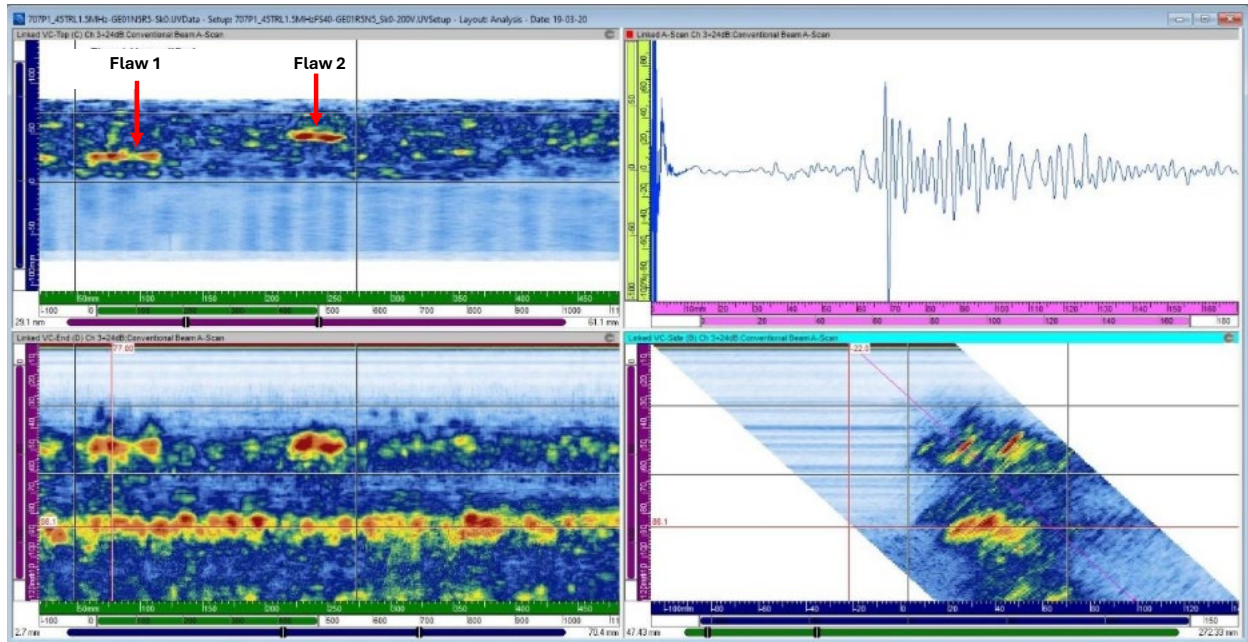


Figure 63. Original specimen 707-P1 showing Flaws 1 and 2.

Virtual Specimen 707-P1-1

This virtual specimen was created by extending the length of Flaw 1 beginning at 3.0 in. toward Flaw 2 to 8.0 in. circumferentially and retaining its 0.33 in. axial distance from the weld root. Virtual specimen 707-P1-1 is shown in Figure 64. The extended length of virtual Flaw 1, offset axially from original Flaw 2, could cause it to be mistaken for a response from a geometric condition. The analyst must give specific attention to the various characteristics of the response, such as a sharp echo with facets versus the broad-based response typical of a geometric root response, to correctly identify the flaw.

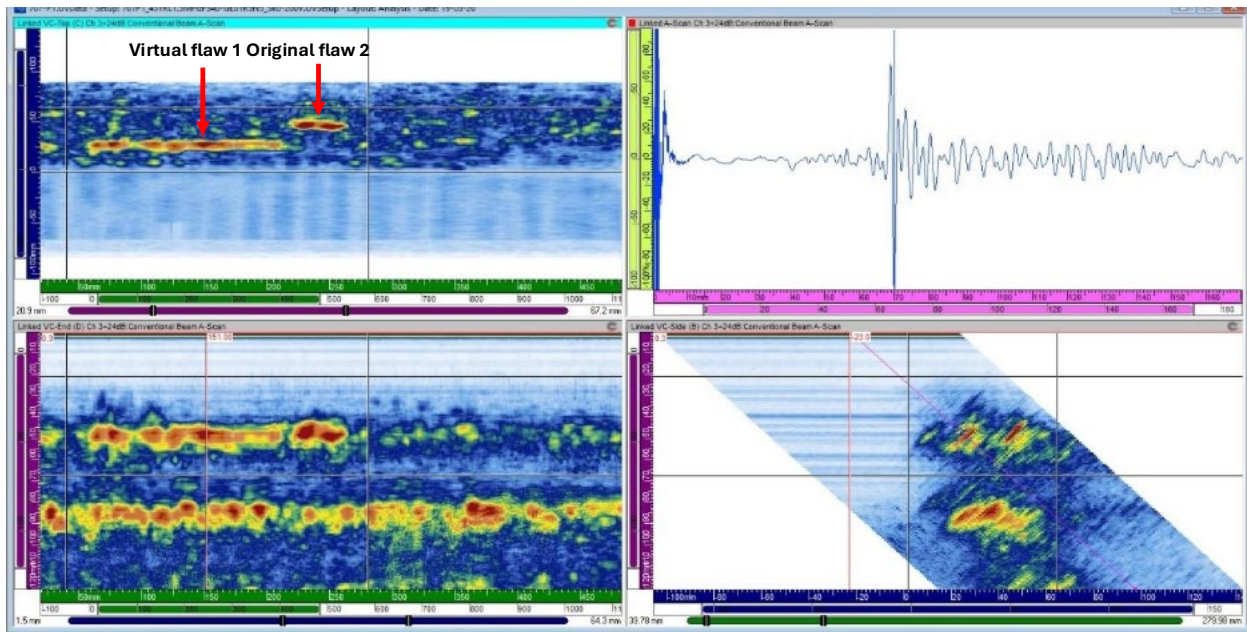


Figure 64. Virtual specimen 707-P1-1.

This virtual specimen once again uses the concept of two flaws offset axially from each other. When piping sections are welded together in a shop environment, the joint fit-up can be more efficient than inside a plant when the piping sections are joined together. To effect a correct fit-up in the plant, conditioning of the inside surface may be required. In such cases ultrasonic reflectors from geometric sources can be created. These can appear anywhere from near the weld root or further away near the outer edge of the heat affected zone. Flaws can also originate in this area, so it is important for training and qualification purposes to have flaws located at varying axial distances with respect to the weld.

5.13 Specimen 707-P2

Specimen 707-P2 is a 12.7 in. OD DMW piping specimen with a wall thickness of 1.15 in. The specimen contains one axial (Flaw 1) and two circumferential flaws, Flaws 2 and 3 shown in Figure 65 and Table 14. Data were acquired at 60° with a 1.5 MHz probe from the CS side of the weld. Flaw 2 was about 0.4 in. from the WCL on the SS side of the WCL, and Flaw 3 was on the WCL. Flaw 2 was multifaceted, with portions having different skews and tilts.

Table 14. Specimen 707-P2.

Flaw	Type	TW Depth (%)	Length (in.)	Tilt (deg)	Skew (deg)
1	Axial EDM	15	0.50	0	0
2	Crack	63	2.26	0–25	0–10
3	Crack	32	1.07	0	0

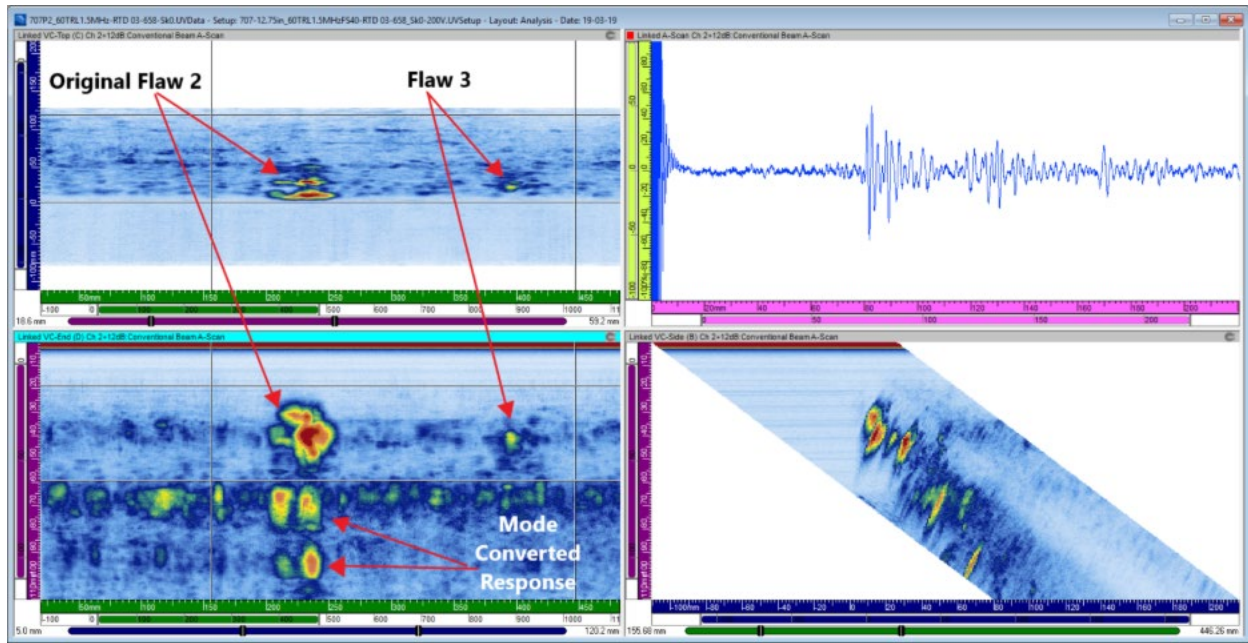


Figure 65. Original specimen 707-P2 showing Flaws 2 and 3.

Virtual Specimen 707-P2-1

This virtual specimen was created by removing the prominent Flaw 2 response and retaining the weak response from Flaw 3. The response from Flaw 2 also included a significant mode converted response that required removal so that no traces of Flaw 2 remained. If only the primary flaw response was removed or relocated during flaw modification, a keen data analyst will note the presence of the mode converted response and suspect that the file has been modified or some unrealistic anomaly exists. This modification was performed to test whether the software could adequately remove the mode converted signals. Figure 66 displays the virtual specimen 707-P2-1 image with all response components from Flaw 2 removed, leaving only geometric responses from the inside surface and Flaw 3 at its original location and amplitude.

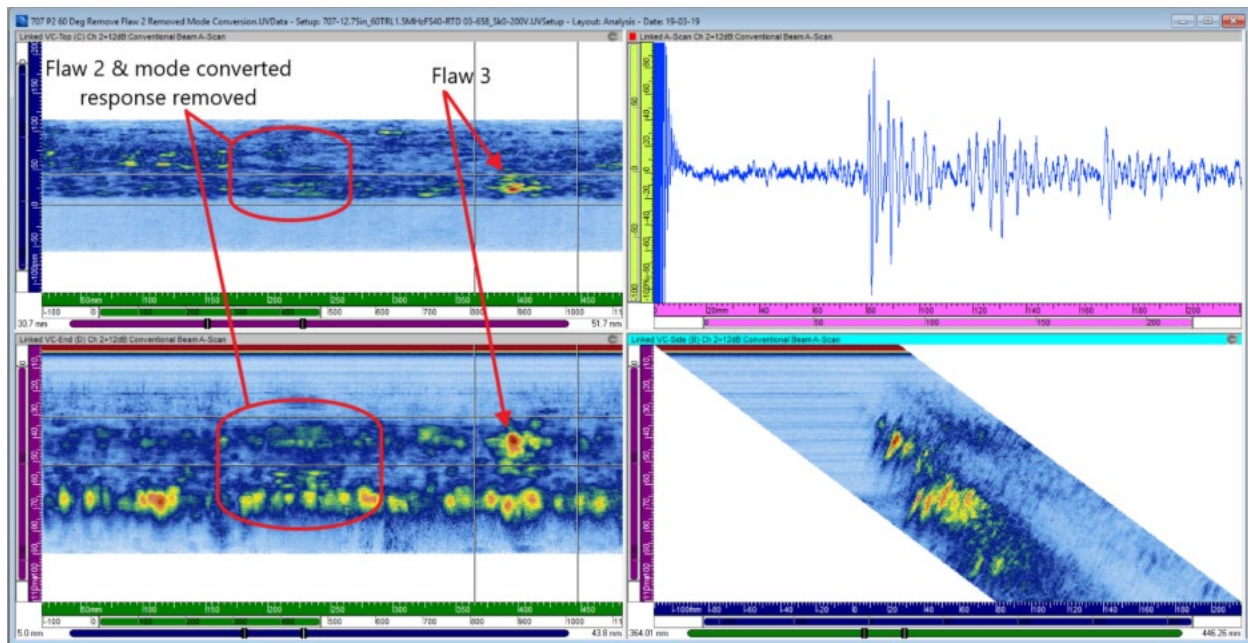


Figure 66. Virtual specimen 707-P2-1.

5.14 Specimen 709-P1

Specimen 709-P1 is a 27.8 in. OD DMW piping specimen with a wall thickness of 1.72 in. that contains only one axial flaw. The flaw is described in Table 15. Figure 67 shows the original scan; the flaw was not detected because it was axially oriented. Data were acquired at 2 MHz and 45° from the CS side of the weld.

Table 15. Specimen 709-P1.

Flaw	Type	TW Depth (%)	Length (in.)	Tilt (deg)	Skew (deg)
1	Axial EDM	10	0.30	0	10

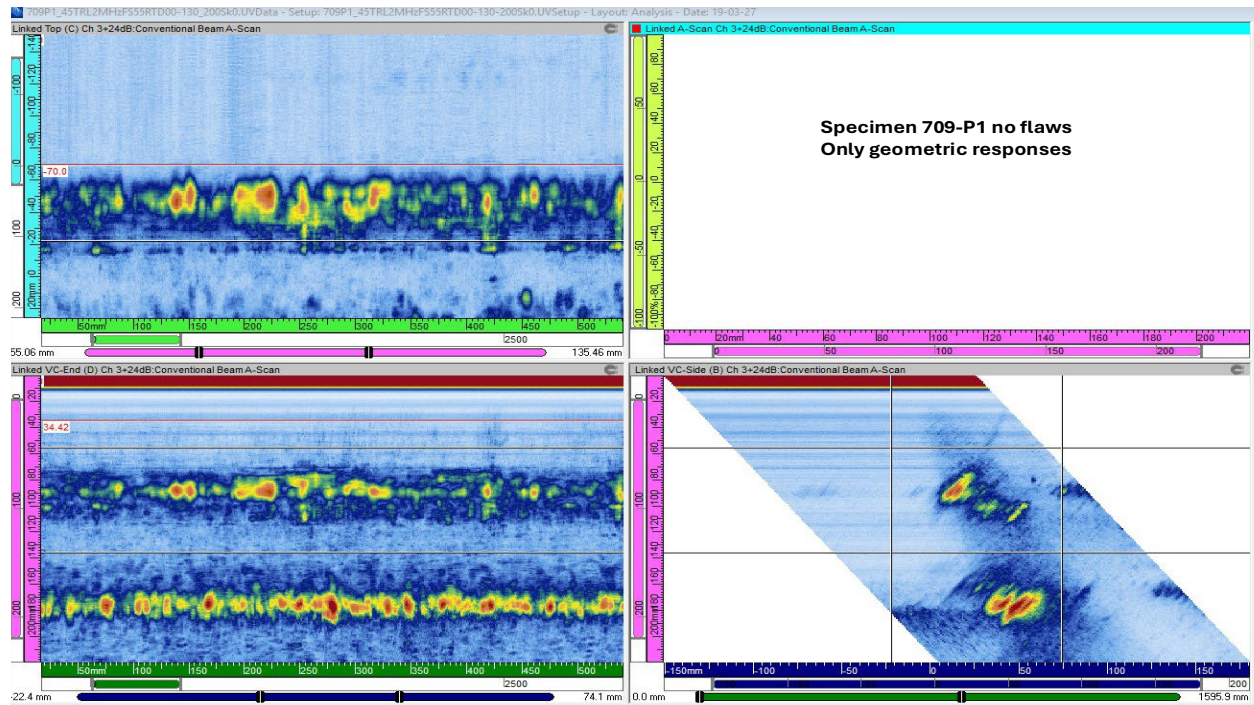


Figure 67. Original specimen 709-P1 with no visible flaws.

Virtual Specimen 709-P1-1

The original specimen (709-P1) contained only one axial flaw and no circumferential flaws. Our work involved the modification of circumferential flaws, so a virtual specimen was created by sourcing circumferential Flaw 2 from specimen 707-P2 (Figure 65) and placing it into the 709-P1 data file. Figure 68 displays the image of virtual specimen 709-P1-1 with the virtual circumferential flaw.

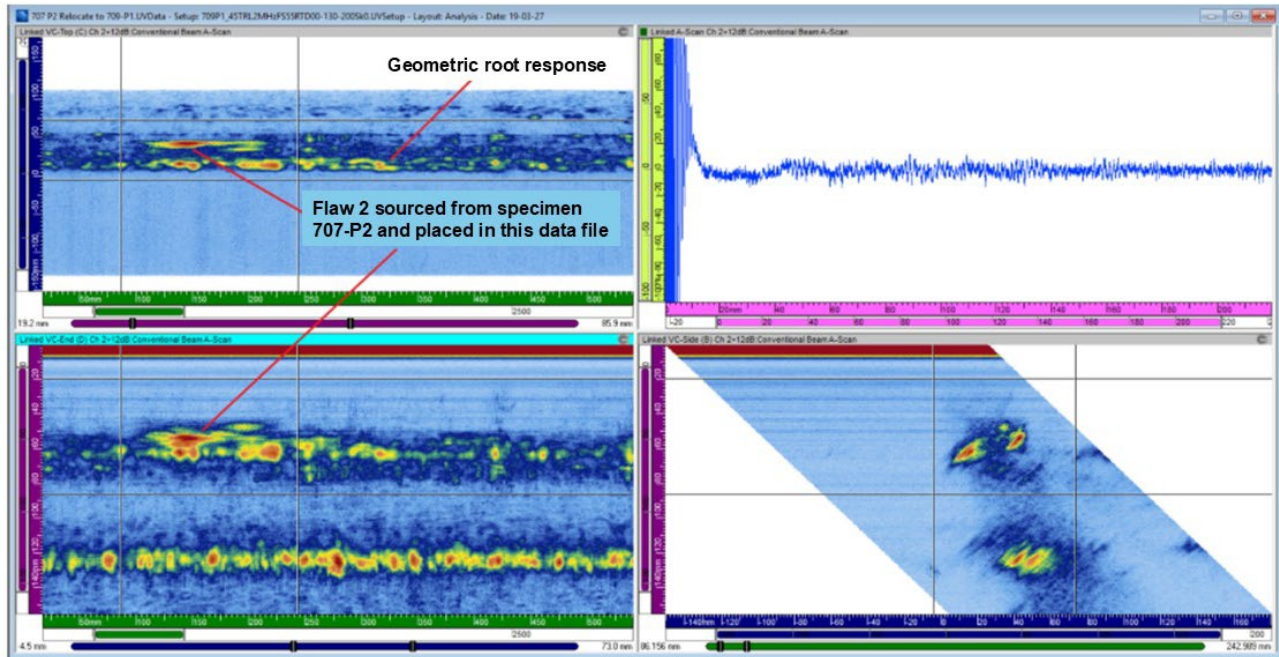


Figure 68. Virtual specimen 709-P1-1.

5.15 Specimen 710-P

Specimen 710-P is a 27.9 in. OD DMW piping specimen with a wall thickness of 2.15 in. that contains one axial flaw and one off-axis circumferential flaw. An off-axis flaw is a circumferential flaw that is less than 45° skewed from parallel to the WCL. The lower portion of Flaw 2 is approximately 20° offset from parallel with no tilt. Both flaws are offset from the WCL in the buttering by about 0.5 in. Data were acquired at 1.5 MHz and 45° from the CS side of the weld. The flaws are described in Table 16 and, due to the flaw orientations, only a partial response from the original Flaw 2 is shown in Figure 69.

Table 16. Specimen 710-P.

Flaw	Type	TW Depth (%)	Length (in.)	Tilt (deg)	Skew (deg)
1	Axial EDM	25	0.50	0	10
2	Crack	44	1.83	0–16	0–19

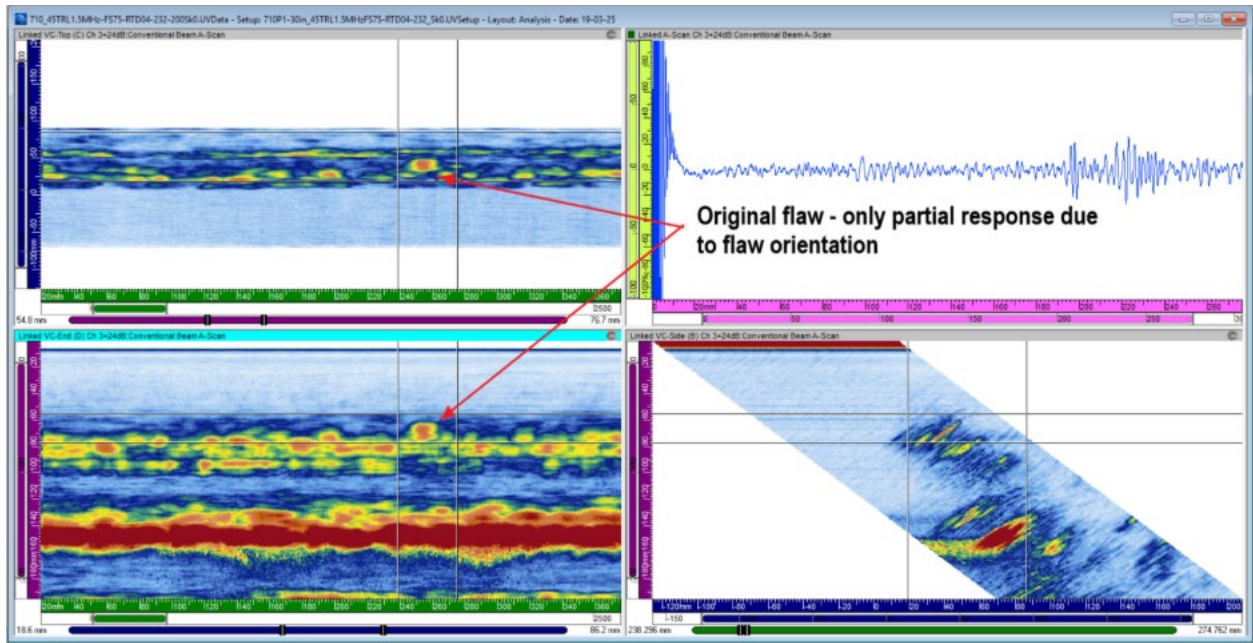


Figure 69. Specimen 710-P with a partial response from Flaw 2.

Virtual Specimen 710-P-1

Due to the off-axis orientation of Flaw 2, a response was only detected from a small portion of the flaw. A modification was performed to test if extending the length and orientation would make the result more representative of its true length. The new virtual specimen and flaw are shown in Figure 70.

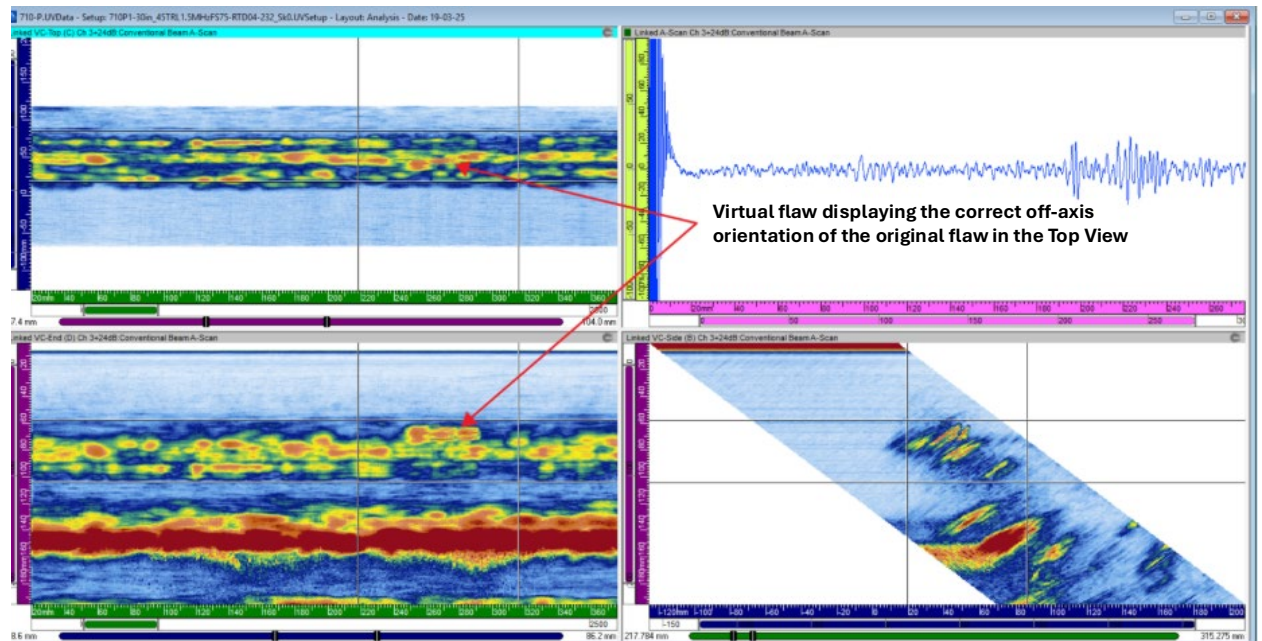


Figure 70. Virtual specimen 710-P-1.

6.0 Recommendations for the Use of Flaw Modification Software

The following details the training and experience required to create UT virtual flaws based on PNNL's experience in evaluating the MVM flaw modification software. Currently, this is the only software that focuses on creating virtual specimens for potential personnel training and qualification.

No requirements currently exist in a recommended practice, code, or standard to address a level of personal competence to create virtual flaws or perform flaw modifications. To date, virtual flaw technology is used in research and has not been implemented by industry for creating specimens for the training and certification of candidates for UT examinations. This confirmatory research conducted by PNNL for the U.S. NRC is intended to inform regulatory guidelines and ensure staff readiness for the potential future adoption of this technology by industry. PNNL has identified several challenges that remain before the virtual flaw technology could be utilized. These are:

1. The essential parameters for the MVM software (or any competing software package that might emerge) to produce valid results are unknown and need to be defined for consistent implementation.
2. Industry standards and ASME Code actions are needed to formalize the use of virtual flaws for training and qualification.
3. Successful implementation requires defined personnel training and competency requirements for generating virtual flaws.
4. Procedural guidance needs to be developed for flaw realism assessment.
5. Regulatory guidelines need to be prepared for application acceptance.

A basic user's manual has not been published for the MVM software. However, EPRI has published three technical reports describing the historical development and evolution of the software (EPRI 2018, 2022, 2023), and a general "Basic Operation Guide" is available to collaborators. Over time, this guide has been expanded to describe the various functions of MVM. If the MVM software is to be used more broadly by industry or vendors, then a more comprehensive user's manual should be made available.

PNNL's ability to create virtual flaws was gained solely from training and instruction from the EPRI software engineer, hands on experience, and working through several flaw modification scenarios to achieve a desired result. The following training, experience, and certification recommendations are based on PNNL's experience to date.

Recommended Personnel Qualifications

As a prerequisite, personnel creating virtual flaws should possess working knowledge of UT and hold a certification to support a minimum competency level.

UT Training & Certification

A minimum Level II certification in accordance with ASME Section XI, Appendix VII.

- For the creation of virtual flaws intended to comply with the requirements of ASME Section XI, Appendix VIII, an Appendix VIII qualification to the supplement for which virtual flaws are to be created should be required.

Recommended MVM Software Training

A minimum of 24 hours training on the MVM software.

- Eight hours of classroom training, describing the workflow process and different functions of MVM.
- Sixteen hours of hands-on training covering the following:
 - Sourcing data files.
 - Identifying the modifications to be performed.
 - Creating a configuration file.
 - Exporting and evaluating results.

Recommended Equipment

Hardware

- A Windows PC running Windows 10 or later, with a minimum of 32 GB of RAM is required. No other special hardware is required.

Software

- Eddyfi Technology's UltraVision (UV) software is required to identify flaws to be sourced and verify the accuracy of a modification process.
- MVM software is required to create virtual flaws and perform flaw modifications.

7.0 Conclusions

PNNL collaborated with EPRI under an MOU with NRC to evaluate EPRI's MVM software. The MVM software can produce modified flaws that exhibit real flaw characteristics when applied appropriately. The modification process can be time consuming, depending on the complexity of the modification, but it is more cost effective than the fabrication of specimens containing flaws. The ability of a data analyst to modify empirical data and create virtual ultrasonic responses with real world conditions would expand training and test datasets. Moreover, given the extensive training, expert judgment, and procedural competency required to successfully utilize the current MVM software for virtual flaw creation, it may be necessary for future versions of MVM or similar tools to incorporate greater automation and workflow guidance if widespread industry use is anticipated.

It is practically not possible to fabricate specimens that would contain all the possible scenarios of flaw and geometric response characteristics that exist in an operating nuclear power plant. In this study, PNNL produced 27 virtual mockups representing a range of realistic inspection scenarios. Modifications included adjustments to geometric root responses, removal and relocation of flaws, changes in flaw dimensions and amplitudes, and insertion of flaws originating from other specimens. All modifications targeted different objectives in the personnel training and qualification.

At this time, the realism of the virtual flaws has not been independently validated by certified Level III personnel. A round-robin evaluation has been identified as the preferred method to obtain such verification. Additionally, the suitability of virtual flaws for use in AI training and evaluation remains under investigation.

Personnel performing flaw modifications must possess sufficient knowledge and experience in ultrasonic examination techniques and operation of the UV software. This is required to assess the quality and realism of a virtual flaw, as a modification may not be representative of a real flaw. Additionally, the essential parameters required to produce valid results are unknown and must be defined.

Prior to regulatory acceptance allowing the use of virtual flaws for training, certification, or qualification purposes, some actions are required by industry. These include but are not necessarily limited to the following:

- Establishing minimum training and experience requirements for personnel conducting flaw modifications.
- Developing procedural guidance on how to determine if a flaw is acceptable for use.
- Initiating ASME Code actions necessary to allow the use of virtual flaws within Section XI, Appendix VII and Appendix VIII training, certification, and qualification.

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Pacific Northwest National Laboratory

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99354

1-888-375-PNNL (7665)

www.pnnl.gov