Application of Digital Radiography to Weld Inspection for the Space Shuttle External Fuel Tank

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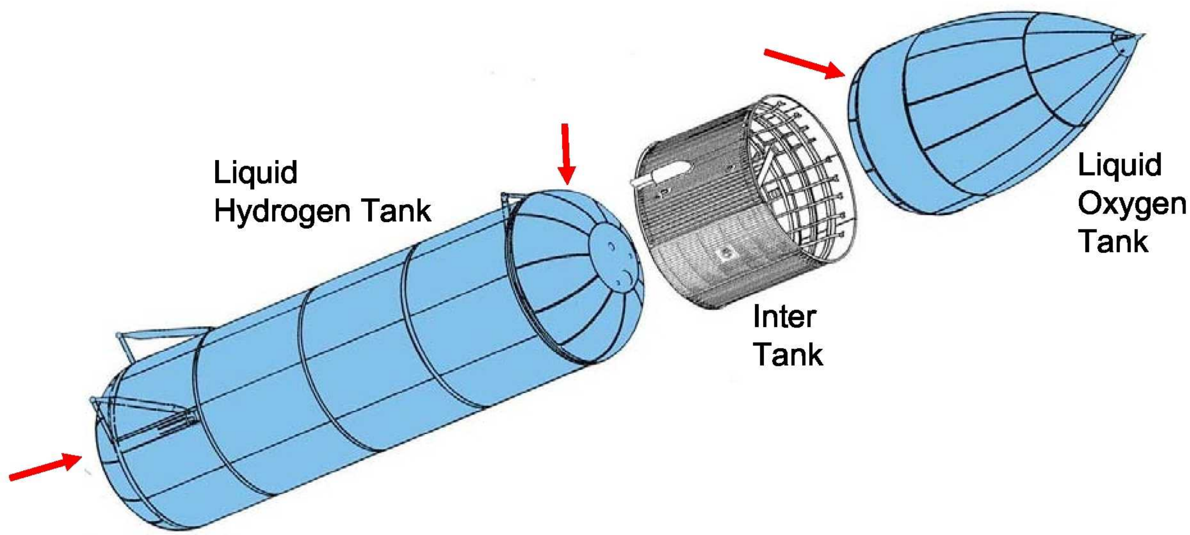
Background: External Fuel Tank

- **External Fuel Tank Background**
  - ET holds cryogenic liquid hydrogen and oxygen fuel for shuttle main engines
  - The fuel tanks are 2219 and 2195 Al alloy welded structures
  - Material thicknesses range from 0.140" to 1.0"
  - Total length of weld undergoing radiography is approx. 3000 feet
  - NASA established a goal to replace a significant portion of film with digital radiography

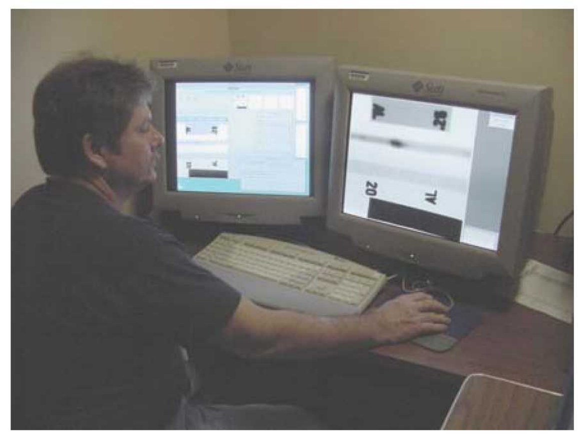


Three ET Domes chosen for digital radiography implementation

BSX/THZ POD Study

- **Topics**
  - Objectives for film to digital conversion
  - Digital system characteristics
  - POD (Probability of Detection) study
  - Qualification
  - Implementation
  - Lessons Learned

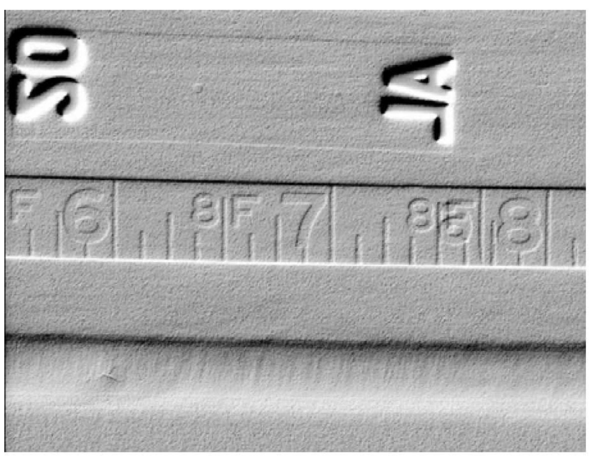
Film Reader

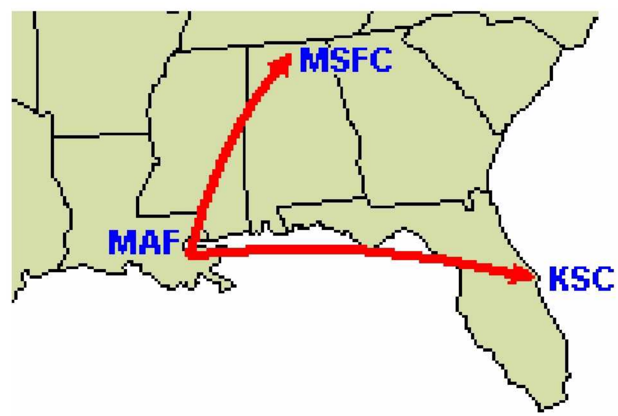


Digital Workstation

Objectives for Digital Radiography Conversion

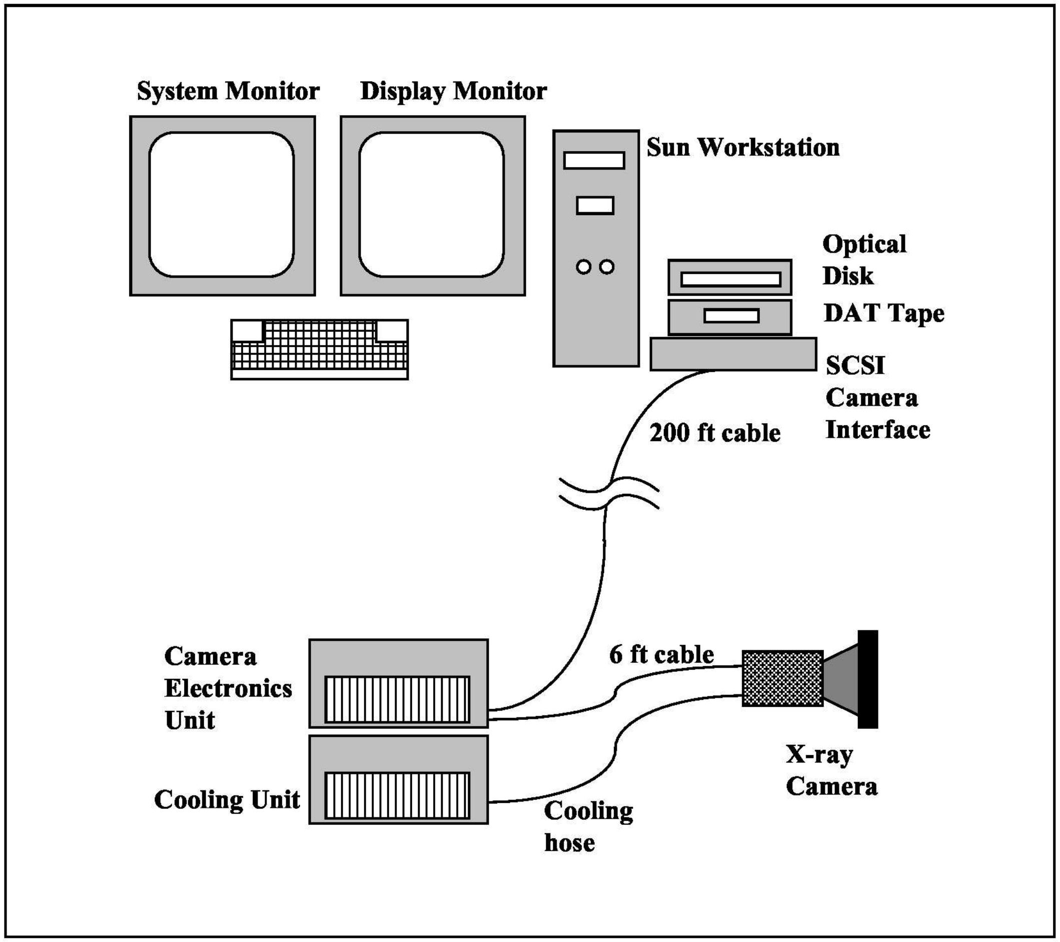
- Eliminate film, chemicals, and associated environmental concerns
- Improve efficiency of radiography process
- Provide enhanced archival capability
- Enhance inspections with digital imaging tools
- Provide electronic distribution of radiography data to multiple NASA sites

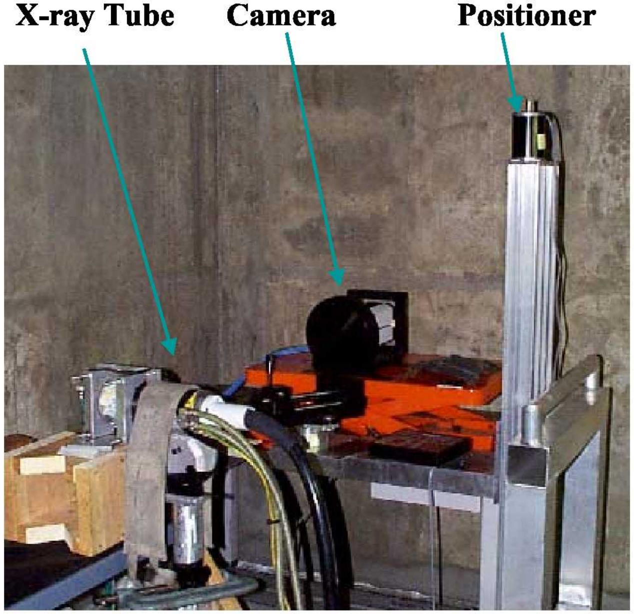




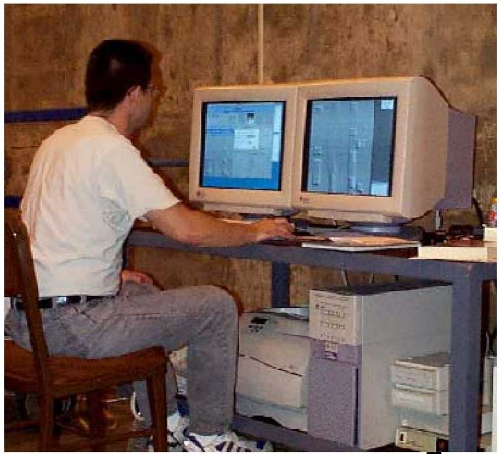
Digital Radiography System Characteristics

- **Two main concerns for digital radiography system:**
  - **Sufficient sensitivity to detect small cracks**
  - **Ability to be integrated into existing External Tank tooling**





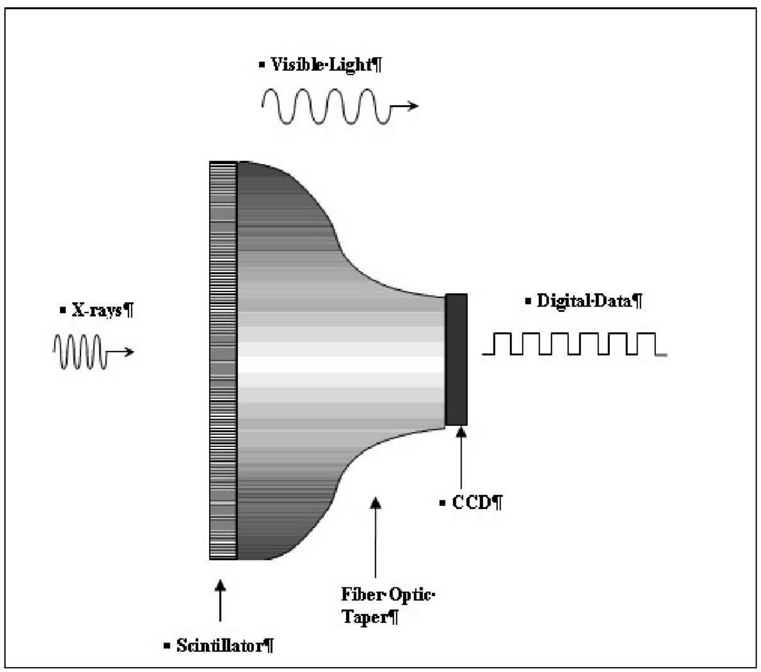
Inspection configuration



Sun Workstation

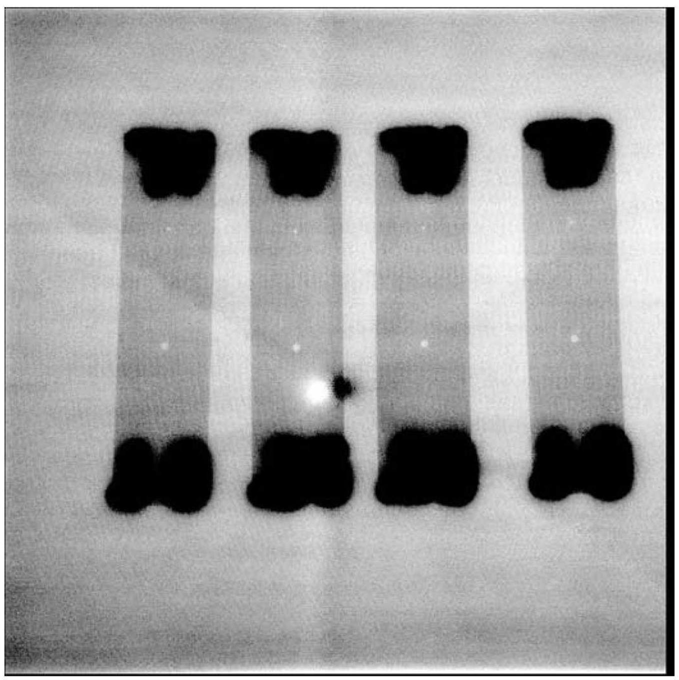
Digital Radiography System Characteristics

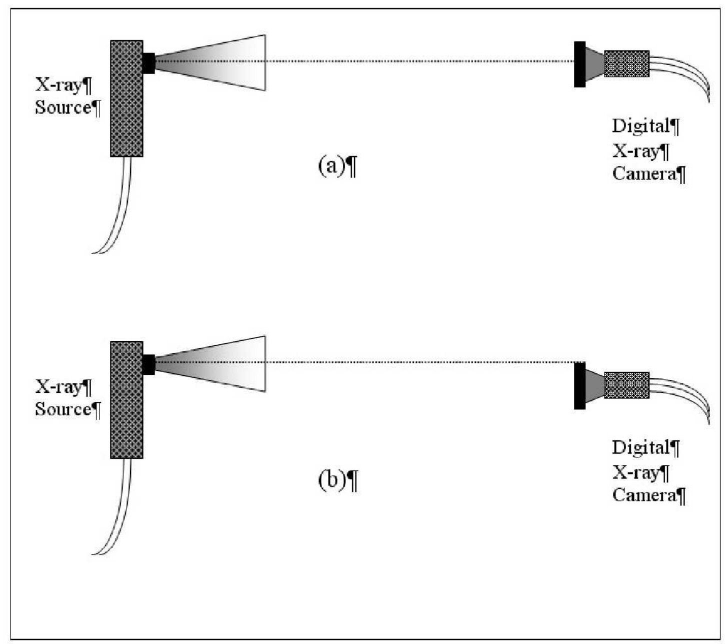
- **Characteristics of the digital x-ray camera**
  - High sensitivity (resolution and contrast)
  - Scintillating fiber faceplate enhances resolution
  - 2K by 2K scientific CCD enhances both resolution and contrast
  - Fiber optic taper transfers the 4” image from the scintillator to the CCD and also protects the CCD by absorbing incident X-rays
  - This design is suitable for low energy inspections (<100 kV)
  - Energies used on ET are in the 40kV to 70kV range



Digital Radiography System Characteristics

- **Digital x-ray camera technique**
  - Basically the same technique as film for ET welds
  - Yxlon MG165 system
  - Digital technique for 0.320” Al: SFD 40”, 70kV, small focal spot, 30 second exposure
  - DR performance is generally improved with lower kV and higher mA than film





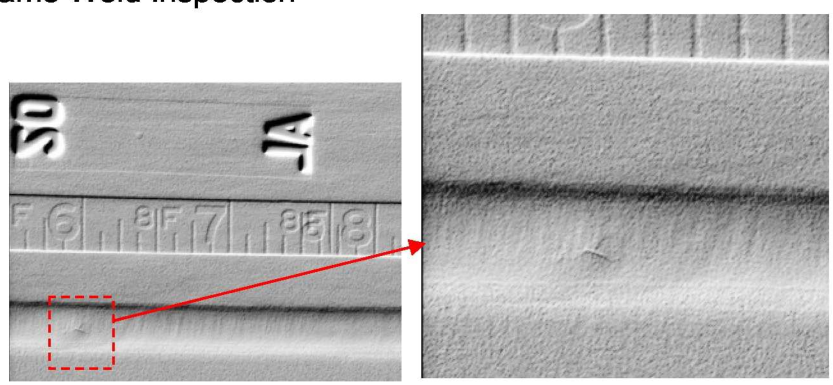
→ Figure·2.11.·(a)·Center·to·center·alignment.·(b)·Offset·alignment.¶

Digital Radiography System Characteristics

- **Production inspection considerations**
  - **Camera is mounted to tooling allowing access to welds**
  - **Remaining components are cart mounted and mobile**
  - **Equipment proved to be sufficiently robust for production use**
  - **Several months of production floor testing combined with system sensitivity resulted in moving forward into next phase of implementation**

Frame Weld Inspection

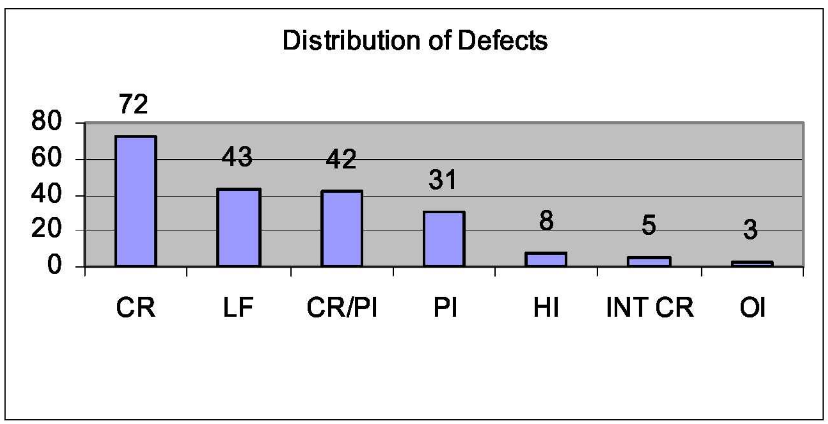
Gore Weld Inspection



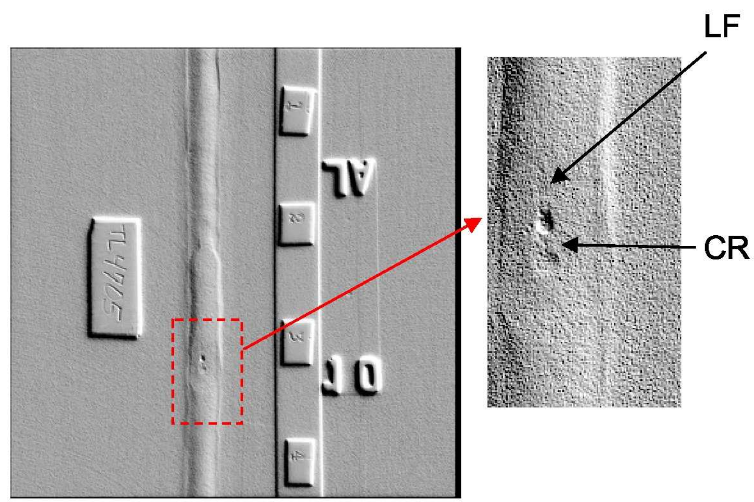
Detection of small cracks

POD Approach

- Material, weld process, and x-ray detection of weld defects were already well understood
- Goal was to ensure that digital x-ray sensitivity was comparable to film
- Parallel film and digital inspection of all samples
- Defects included the types found in ET welds
  - Cracks
  - Lack of Fusion
  - Oxide inclusions
  - Heavy Inclusions
  - Porosity with associated cracks
- 90/95 POD for film radiography of cracks in ET welds is 0.28T (28% material thickness)
- Success criteria was that digital demonstrate a comparable POD result to film



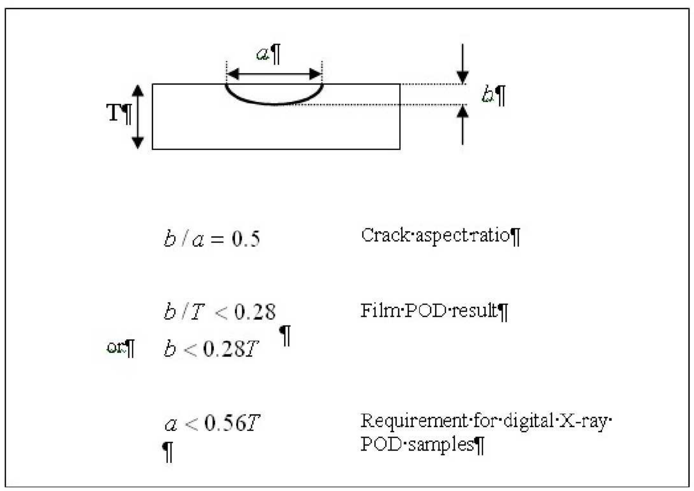
Distribution of defects used in POD



Weld repair containing porosity with associated cracks and Lack of Fusion

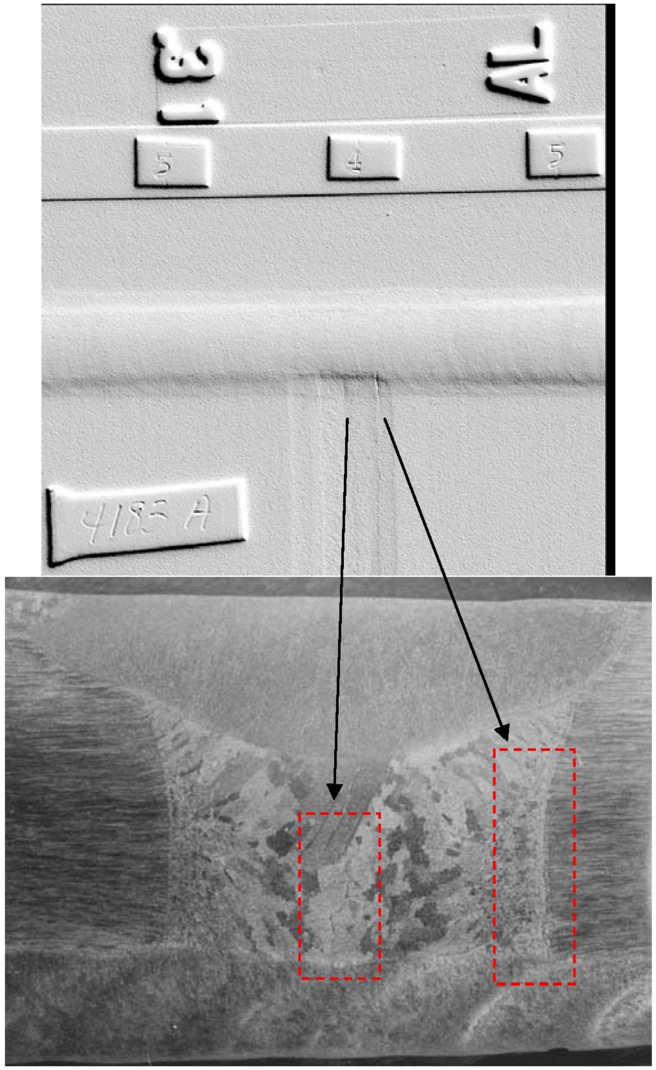
POD Approach

- 2219 and 2195 Aluminum alloys included
- POD samples selected by Lockheed Martin and NASA NDE engineers
- Six x-ray interpreters with floor experience performed interpretation
- Worst case weld defects occur in repairs
- Repairs also allow defects to be easily created in a controlled manner
- Typical cracks in ET welds exhibit a 2:1 aspect ratio
- Linear defects (cracks and LF) were selected with a length of 0.56T or smaller



POD Results

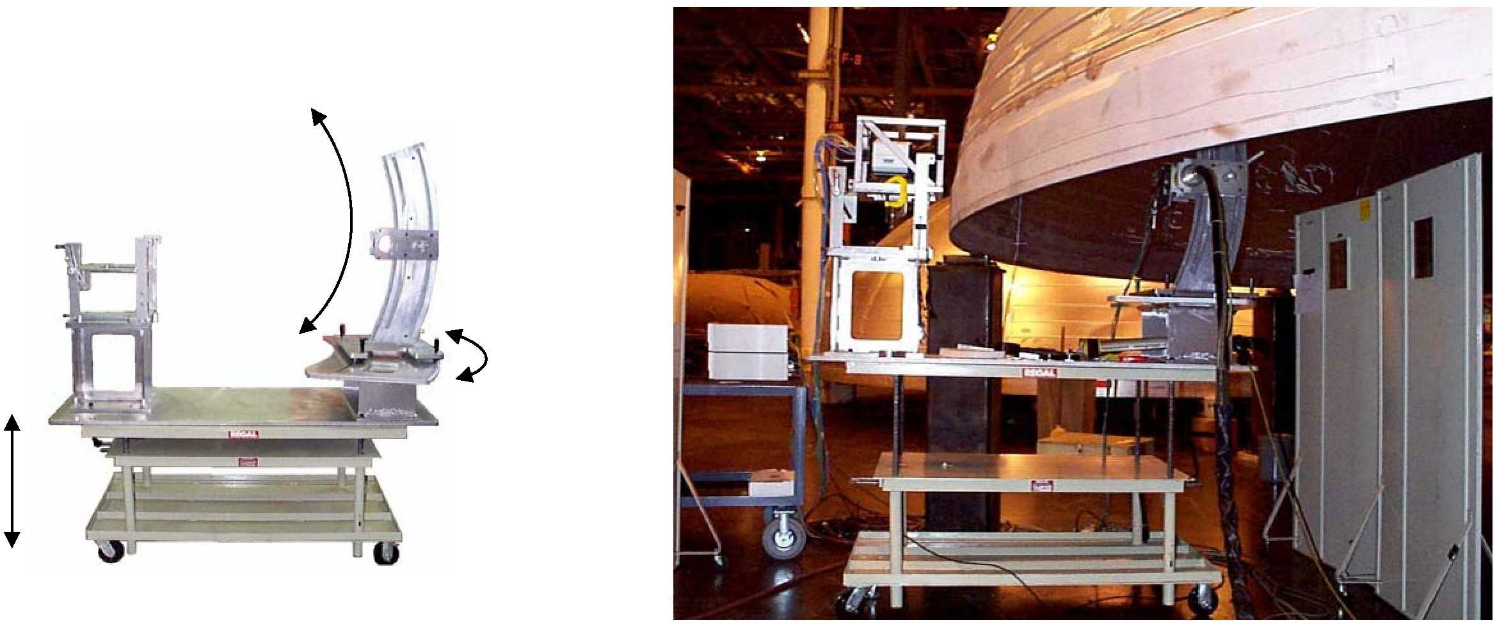
- 255 sample inspections were performed
- Six defects were missed out of the 255 inspections
- Subset of POD samples were dissected to verify flaw sizes
- POD result for digital from binomial analysis was 95/95 for defects 0.28T or smaller
- Comparison of digital and film results on selected POD samples concluded that the images were comparable



DR image (top) and photomicrograph (bottom) of cracks formed at a weld intersection

Digital Radiography Qualification

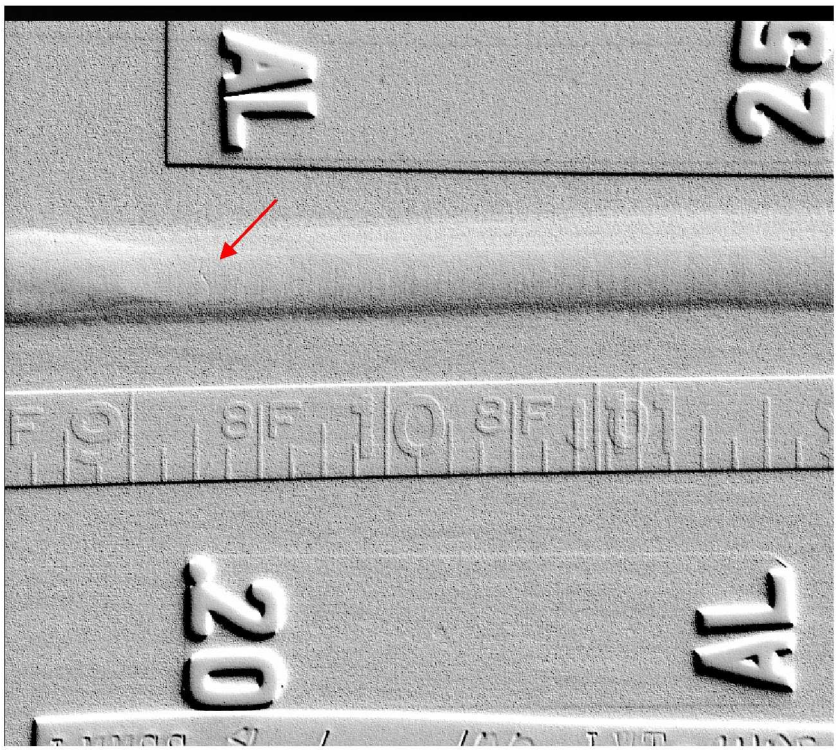
- **Qualification is performed to demonstrate capability to detect critical defects in production hardware**
- **Equipment, personnel, tooling, and parts to be inspected resemble production environment as closely as possible**
- **Tooling designed to position digital radiography system on dome**
- **Allows adjustment of elevation and angle**
- **Designed for use on ET T-ring application**



Tool and test configuration for qualification testing

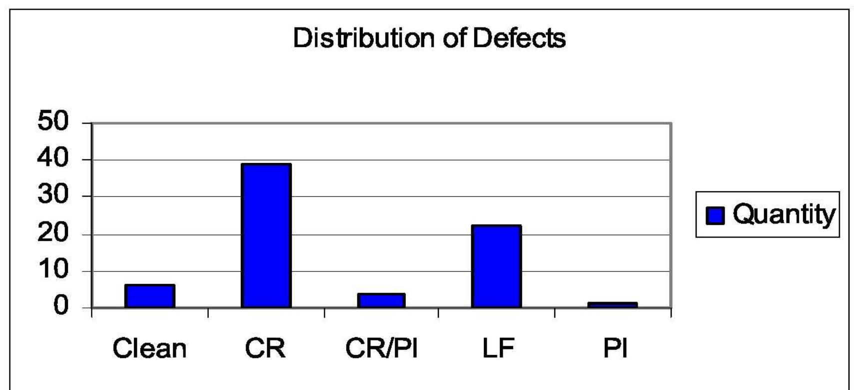
Digital Radiography Qualification

- Two scrap production domes were acquired for the qualification test
- 2219 Al and 2195 Al domes
- Material thicknesses from 0.200” to 1.0” including 0.200” to 0.500” tapered welds
- 63 defects were induced with multiple weld repairs
- Six interpreters with varying experience were selected to read data



Qualification sample consisting of a transverse crack

Qualification Test Article



Distribution of Qualification Defects

DR Qualification: Blind Results

- Each interpreter given either film or digital data
- DR results: 189 defect shots with 3 missed
- Film results: 189 defect shots with 3 missed
- Neither method had false positives

Interpreter	DR Miss	FR Miss	DR False Positive	FR False Positive
PO#1		0		0
PO#2		3		0
PO#3		0		0
PA#1	1		0	
PA#2	0		0	
PA#3	2		0	
Total	**3**	**3**	**0**	**0**

Table 3. Summary of results for the blind comparison.

DR Qualification: Cumulative Results

- Each interpreter given both film and digital data
- DR results: 378 defect samples with 6 missed
- Film results: 378 defect samples with 6 missed
- DR had 2 false positives, film had none

Interpreter	DR Only Miss	FR Only Miss	DR False Positive	FR False Positive
PA#1	1	2	0	0
PO#1	0	0	0	0
PO#2	2	3	2	0
PA#2	0	0	0	0
PA#3	2	1	0	0
PO#3	1	0	0	0
Total	**6**	**6**	**2**	**0**

Table 4. Summary of results for the cumulative comparison.

DR Qualification: Results by Interpreter

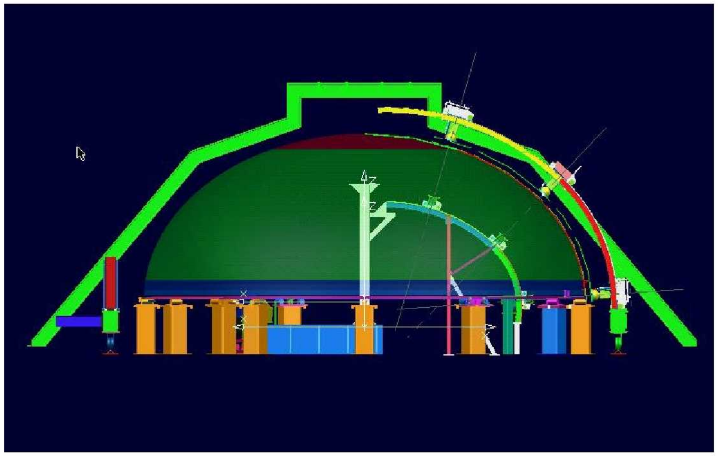
- **Performance of interpreters appeared to be a function of experience**
- **PO#2 accounted for two DR and three film misses as well as two DR false positives**
  - **This interpreter was the least experienced of the six**
  - **Became a level II just prior to participating in this study**

Interpreter	Method	Dome	Weld	Position	Defect Type	Defect Size
PA#1						
	DR	ET 105	HFF3	13' 5 1/8"	CR	0.100
	FR	ET 65	HAF1	14' 7 3/8"	CR	0.084
	FR	ET 65	HAF2	10' 7 1/2"	CR	0.185
PO#2						
	DR	ET 105	HFF3	13' 5 1/8"	CR	0.100
	DR	ET 105	HFF1	20' 5 3/8"	LF	0.210
	FR	ET 65	HAF4	16' 8 1/2"	CR	0.133
	FR	ET 65	HAF2	16' 10 1/4"	CR	0.107
	FR	ET 65	HAG4	0' 8 1/4"	LF	0.141
PA#3						
	DR	ET 65	HAF2	16' 10 1/4"	CR	0.107
	DR	ET 65	HAF1	4' 6 3/8"	CR	0.123
	FR	ET 65	HAF2	10' 7 1/2"	CR	0.185
PO#3						
	DR	ET 65	HAF1	14' 7 3/8"	CR	0.084

Table 5. Details of missed samples.

Digital Radiography Implementation

5017 T-ring Tooling



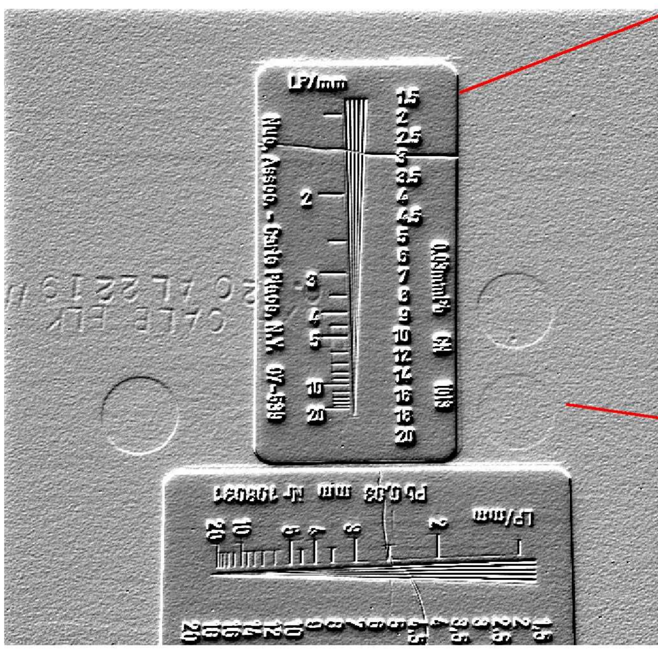
5354 Dome Tooling

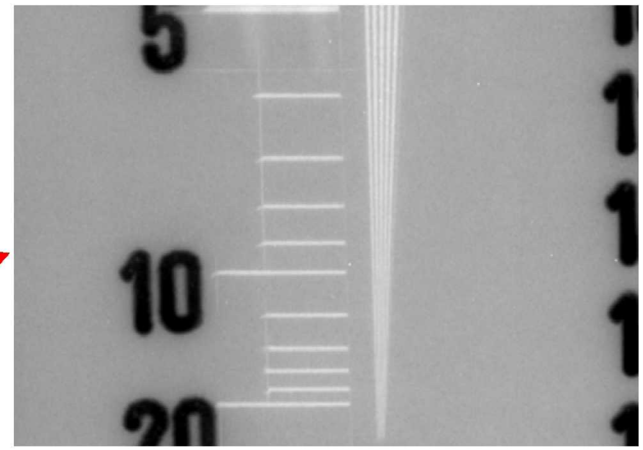
Engineering Requirements

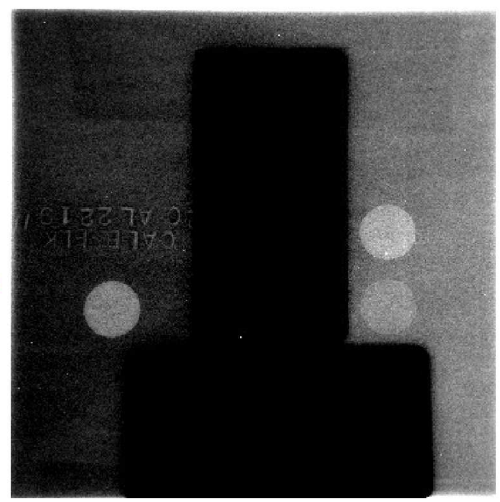
- Density: 1000 to 3000 counts in region of interest
  - Film is logarithmic process versus linear process for digital
  - Digital output is 12 bits so possible values of 0 to 4095
  - 1000 to 3000 range eliminates extremes at either end of range
- Display system calibration to standard test pattern
  - NIST traceable light meter
  - Intensity and contrast are measured
- Secure database and data backup
- Cal standards run before and after inspection
- Temperature requirement for CCD operation: -12°C max

Engineering Requirements

- **Digital radiography calibration block**
  - **Vertical and horizontal line pair gauges**
  - **1% contrast resolution (97, 98, 99 % of thickness)**
  - **Inspected before and after each weld**

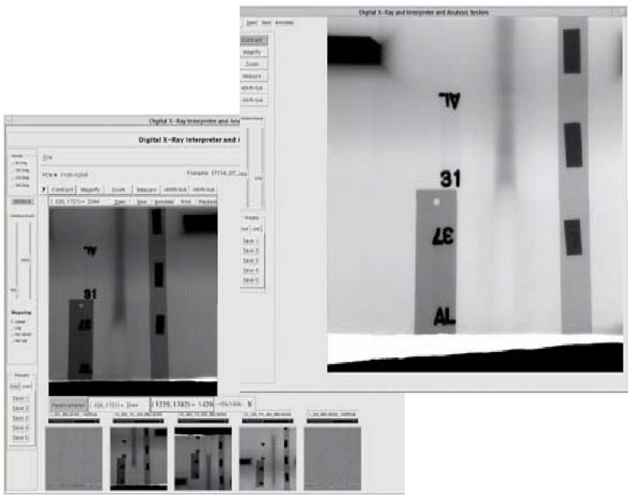




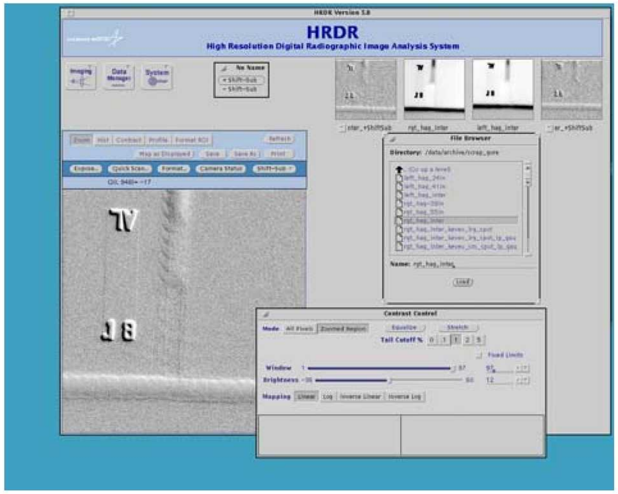


Lessons Learned

- Computer literate personnel with film interpretation experience are a plus
- Automated tooling speeds acquisition and produces repeatable data
- Integration of IQIs into tooling design
- Customized interpretation software improves efficiency
  - All imaging tools available
  - Required tools applied automatically
  - Automatic +15% / -30% penetrameter calculation
  - Playback controls simulate film spool operations



Customized software operates on a series of images



Original software has all tools but only operates on one image at a time

Conclusion

- **Feasibility Study**
  - HRDR 2K camera was field tested with ET test panels and hardware
  - 2-2T sensitivity, frequently 2-1T sensitivity
  - System proven practical for production inspection

- **POD Study**
  - Limited statistical study conducted on test panels
  - Certified interpreters participated in the study establishing their credentials for future flight hardware inspections
  - Result: 0.28T DR POD comparable to film POD

- **Qualification Study**
  - Flight hardware with worst case defects
  - Certified interpreters
  - Engineering requirements began to be incorporated into inspections
  - Results: DR and film inspections were comparable

- **Implementation**
  - Tooling design and fabrication
  - Finalized engineering requirements
  - Enhanced software