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ULTRASONIC CORRELATOR VERSUS SIGNAL AVERAGER AS A SIGNAL TO NOISE ENHANCEMENT INSTRUMENT

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ABSTRACT

Ultrasonic inspection of thick and attenuating materials is hampered by the reduced amplitudes of the propagated waves to a degree that the noise is too high to enable meaningful interpretation of the data. In order to overcome the low Signal to Noise (S/N) ratio, a correlation technique has been developed. In this method, a continuous pseudo-random pattern generated digitally is transmitted and detected by piezoelectric transducers. A correlation is performed in the instrument between the received signal and a variable delayed image of the transmitted one. The result is shown to be proportional to the impulse response of the investigated material, analogous to a signal received from a pulsed system, with an improved S/N ratio. The degree of S/N enhancement depends on the sweep rate. This paper describes the correlator, and compares it to the method of enhancing S/N ratio by averaging the signals. The similarities and differences between the two are highlighted and the potential advantage of the correlator system is explained.

INTRODUCTION

Ultrasonic inspection of materials involves generation of elastic waves using a transducer. These waves are transmitted through the media, detected by a receiver and analyzed. In order to retain meaningful interpretation of the data, a sufficient Signal to Noise (S/N) ratio must be obtained. This poses a problem whenever thick and attenuating material is involved. Using high-gain amplifiers to amplify the highly attenuated waves introduces more noise to the system, and events of interest in the signals are often too small to detect. One method of enhancing the S/N ratio is by averaging several of the received signals, using a digitizer that has this capability. The source impulse signals are repeated several times, and the detected signals are digitized and averaged. The temporal resolution of the events in the received signal depends on the impulse width. The pulse maximum repetition rate is limited by the depth of the investigated area. The pulse source should not be repeated until ultrasonic waves of the previous pulse have significantly dissipated. Another limitation is that the pulse amplitude cannot exceed the breakdown voltage of the transducer. These limit the maximum input energy and determine the limit of the signal to noise enhancement by averaging. The following discussion which describes a correlator, is based on a different principle, and can overcome some of the limitations of the averaged pulse system.

THE CORRELATOR

Principle:

A block diagram of the correlator is shown in Figure 1. A pseudo-random digital pattern is repeatedly generated and used to drive a transmitting transducer after proper amplification. The ultrasonic waves which propagate through the inspected material are detected by a receiver transducer. A correlation is performed between the received signal and a reference signal generated by the second pattern generator which is identical in shape to the drive signal, but delayed by a linearly varying amount, governed by the sweep rate. The use of a digitally delayed reference has the advantage of greater accuracy and stability than complicated analog delay lines [ref. 1 for example].

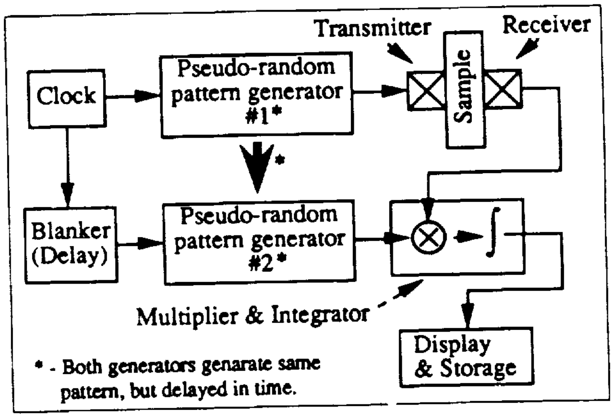

Figure 1. Correlator, schematics.

Theory:

An output $y(t)$ from a linear system can be expressed as the convolution of the system impulse response $h(t)$ with the input $x(t)$ (Figure 2):

$$y(t) = h(t) * x(t) = \int_{-\infty}^{\infty} h(\upsilon)\, x(t-\upsilon)\, d\upsilon \qquad (1)$$

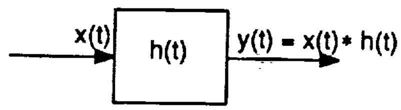

Figure 2. The output as a convolution of the input and the impulse response.

The cross correlation R_{xy} of $x(t)$ and $y(t)$ can be written as:

$$R_{xy}(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_{-T}^{T} x(t)\, y(t+\tau)\, dt \tag{2}$$

and auto-correlation $R_{xx}(\tau-\upsilon)$ of $x(t)$ as:

$$R_{xx}(\tau-\upsilon) = \lim_{T\to\infty} \frac{1}{T}\int_{-T}^{T} x(t)\, x[t+(\tau-\upsilon)]\, dt \tag{3}$$

Substituting (1) and (3) into (2) we get:

$$R_{xy}(\tau) = \int_{-\infty}^{\infty} h(\upsilon)\, R_{xx}(\tau-\upsilon)\, d\upsilon \tag{4}$$

therefore, the cross-correlation of the input and the output is the convolution of the impulse response with the auto-correlation of the input signal:

$$R_{xy} = h * R_{xx} \tag{5}$$

R_{xx} for white noise is the delta-function, (up to a factor k), therefore,

$$R_{xy}(\tau) = k\, h(\tau) \tag{6}$$

so that if white noise is injected to the material, the correlation of the input with the detected output $y(t)$ is the impulse response $h(t)$ of the system (Figure 3).

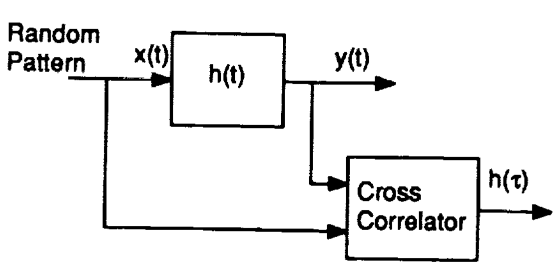

Figure 3. Correlation of random sequenced input with the output yields the impulse response.

In a single-channeled configuration, as applied in the current correlator system, τ is slowly varied according to the sweep rate (*S.R.*), thus, the resultant correlation represents the impulse response transformed to a frequency which is reduced by the inverse of the sweep rate.

The Signal to Noise Ratio Enhancement (*SNRE*) of a system can be defined as:

$$SNRE = \frac{SNR_{output}}{SNR_{input}} \tag{7}$$

where *SNR* is the Signal to Noise Ratio. This can be expressed in terms of bandwidth B of the appropriate signals [2-4], where the $SNRE_{power}$ is given by:

$$SNRE_{power} = \frac{B_{input}}{B_{output}} \tag{8}$$

while the $SNRE_{voltage}$ is given by:

$$SNRE_{voltage} = \sqrt{\frac{B_{input}}{B_{output}}} \tag{8a}$$

Both definitions are equivalent in terms of decibels, since the factor is 20 for voltage as opposed to a factor of 10 for power. As the single-channeled correlation transforms the bandwidth to a frequency reduced by the inverse of the sweep rate *S.R.*, the last equation can be written as:

$$SNRE_{voltage} = \sqrt{\frac{1}{S.R.}} \tag{9}$$

which is fixed for any particular sweep rate. A typical value used for sweep rate is 0.1 µsec/sec. The sweep rate is inversely proportional to the acquisition time T_{aq}.

As a comparison, the averaging process for a pulse-system improves the signal to noise ratio by:

$$SNRE_{voltage} = \sqrt{n} \tag{10}$$

where n is number of averages. Again, the acquisition time is linearly proportional to n, thus,

$$SNRE_{voltage} = \sqrt{T_{aq}} \tag{11}$$

Power efficiency comparison:

In a pulse-system with repetition rate of f pulses per second, the total power P into the material can be approximated as:

$$P_p = V_p^2\, t_p f_p \tag{12}$$

where V is the peak voltage of the pulse, and t is its effective duration. (The index p denotes the pulse-system). Typical values are -300 volts and ~100 nsec duration respectively.

The repetition rate f is limited by the acoustic response in the material. The repetition rate must be low enough to avoid wrap-around of the reflections (Figure 4). The maximum obtained information τ is then not more than the time between the pulses,

$1/f$. The total energy input throughout n averages, w_p, per unit of obtained information, τ_p, can be expressed as:

$$\frac{w_p}{\tau_p} = P_p \frac{T_p}{\tau_p} \geq V_p^2\, t_p f_p\, n \tag{13}$$

where T_p is the total acquisition time (of n averages), and P_p is the input power during this time.

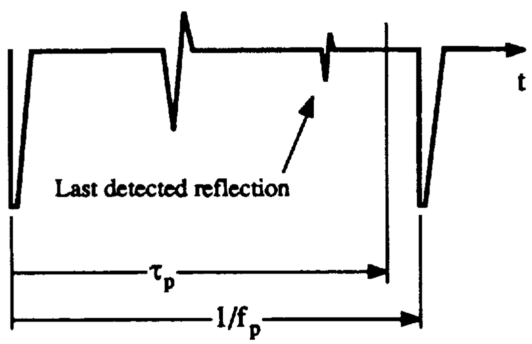

Figure 4. One repetition in a pulse-system that has a repetition rate of f pulses per second, and some possible echoes.

For the correlator system, the input power P is:

$$P_c = \frac{1}{2} V_c^2 \tag{14}$$

where V is the voltage of the amplified digital random signal, which is on half of the time, on average. (The index c denotes the pulse-system). The acquisition time T is directly related to the duration of the obtained information τ through the sweep rate $S.R.$:

$$\frac{T_c}{\tau_c} = \frac{1}{k\,[S.R.]} \tag{15}$$

where k is the number of parallel channels that perform the correlation in the correlator. The total energy input, w, per unit of obtained information, τ, would be:

$$\frac{w_c}{\tau_c} = \frac{1}{2} V_c^2 \frac{1}{k\,[S.R.]} \tag{16}$$

For comparison purposes, if we limit the input power in the correlator system so that both systems input equivalent amounts of power, the ratio of the voltages would have to be:

$$\frac{V_c}{V_p} = \sqrt{2\, t_p f_p} \tag{17}$$

In such a case, the ratio between the quantities 'total input energy -w, per unit of obtained information -τ' of the two systems would be:

$$\frac{w_p/\tau_p}{w_c/\tau_c} \geq \frac{n}{\left(\frac{1}{k\,[S.R.]}\right)} \tag{18}$$

which is similar to the ratio between the *SNRE*'s (in term of power) of the systems for a single channel correlator.

EXPERIMENTS

An 11.5 cm thick wood was used as an example of thick highly attenuating material. Two 2.25 MHz half inch transducer were used in a pulse-echo configuration. A single pulse, with the pulse-system configured for maximum safe voltage into the transmitter, resulted in a signal to noise in the received signal which was less than 1, as can be seen in Figure 5.

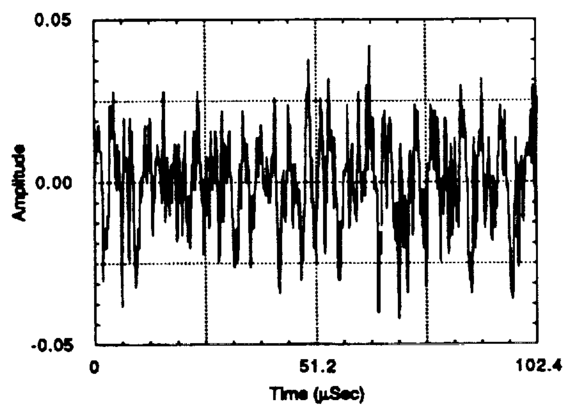

Figure 5. Wood, Single trace obtained with the pulse-system.

Therefore, averaging was required with the pulse-system to be able to detect the signal. A signal obtained after 4096 averages is shown in Figure 6. The excitation is seen on the left side (at relative time 0), and the first arrival through the wood occurs around 57 µsec. Significant noise still exists even in the 4096 averages case, as evident in the time interval 0 to ~57 µsec, before arrival of the first acoustic response of the wood.

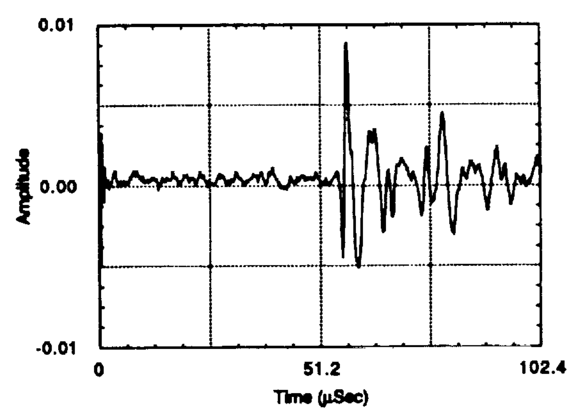

Figure 6. Wood, using the pulse-system, with 4096 averages.

The received signal from a single channel correlator for a sweep rate of 0.1 μsec/sec is shown in Figure 7. The acquisition time was approximately equal to the time required for 4096 averages (hardware dependent of course), although it could be skipped until the expected first acoustic response, thus reduced significantly. The first arrival could be identified again, at ~57 μsec, with a lower noise before first arrival than the noise in the 4096 averages case. (To decrease the noise to the same level, the averaging system required close to 32000 averages). Furthermore, this noise is above the detection frequency of the transducer, thus, further low-pass filtering is possible without deleting actual information.

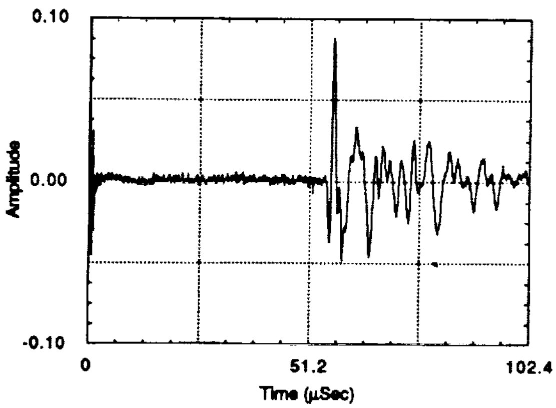

Figure 7. Wood, output from the correlator.

Figure 8 shows the measured signal to noise figures as function of the number of averages in the pulse-system (on a log scale). The noise-level measurements were taken at a region before the expected first arrival, while the signal-level measurements were taken at the region of the first arrival of the acoustic response.

Superimposed on the graph of Figure 8 is the S/N measured from the results of the correlator. The vertical data line on the right represents a single-channel correlator. Increasing values of the input power increased the S/N values as expected. The horizontal coordinate of this data corresponds to an equivalent acquisition time as with the pulse system. A 1024 multiple channel correlator would shorten this time by this factor, thus, shifting this data line to the left, as shown in the left side of the figure.

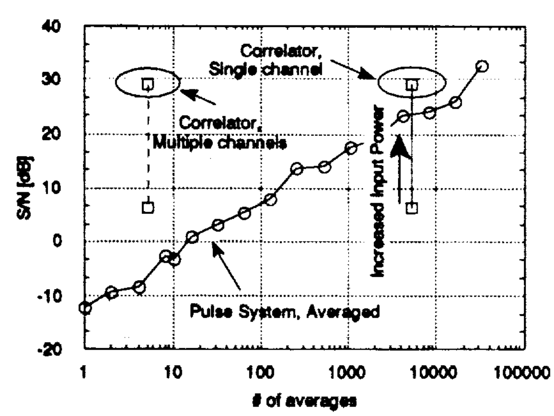

Figure 8. Wood, S/N curve.

A second set of tests were performed measuring ~10 cm thick Teflon. S/N results are shown in Figure 9. Since the attenuation of the material is less than that of the wood sample, the overall S/N figures were better. Yet, the relative behavior of the two systems remain the same. The effect of increasing the number of the channels from a single channel to 1024 channels in a multi-channel correlator is extrapolated in this figure.

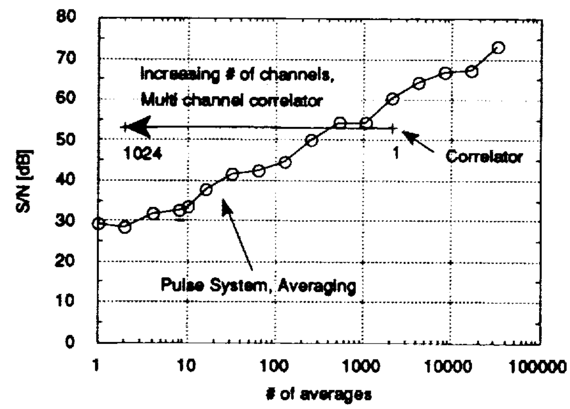

Figure 9. Teflon, S/N curve.

DISCUSSION

Both the correlator system and the averaging pulse-system can enhance the signal to noise ratio, improving it linearly with square root of the acquisition time. The correlator, through its sweep rate *S.R.*, and the averager through the number of averages *n*. The ratio of total input energy per unit of obtained information also have equivalent forms for the two systems.

There are however some important differences between them. While the voltage into the transducer in the pulse-system is limited by the breakdown voltage of the transducer, the correlator system is based on a continuous excitation of the transducer, where the limiting parameter is mainly the maximum power that can be dissipated. The total power can be much higher than in the pulse-system, thus, obtaining stronger signals.

Another major difference is the way the systems collect and enhance the data: A conventional pulse echo averaging system prescribes a fixed minimal time window, according to the thickness of the sample that control the maximum repetition rate. The S/N improves as acquisition time increases (as square root of it). The correlator system, on the other hand, gives prescribed S/N enhancement, according to the chosen sweep rate while the obtained time window increases with the acquisition time. The condition on the correlator corresponding to the maximum repetition rate is the length of the unique pattern in the pseudo-random signal. It should be the inverse of the repetition rate, a condition which is easily obtained.

Furthermore, if the investigated material calls for inspection at a localized suspected region, the correlator system can be configured to skip the early time trace, and start the process of the correlation only at the requested window of time, thus reducing the acquisition time significantly, at any prescribed S/N value. This could not be applied in a conventional pulse echo system, where the minimal time window is fixed.

SUMMARY

The system of choice depends on the relevant problem: The averaging pulse-system is appropriate when the required Signal to Noise Enhancement (*SNRE*) is low and when the full thickness of the material has to be inspected. In this case, fast measurement is possible, where the S/N improves as the averaging continues until adequate signal shows on the screen. The correlator system has the advantage when high *SNRE* is required, particularly when a specific region has to be inspected. The sweep rate will be chosen according to the required *SNRE* and the delay would be set up, and the enhanced trace would almost immediately be obtained. A multi-channel correlator would increase this advantage even more.

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Nondestructive Evaluation of Composite Space Structures

by

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presented to

NDE for Aerospace Requirements
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Monitor: Joe Sciabicca

NDE OF COMPOSITE SPACE STRUCTURES

OBJECTIVES:

Identify promising NDI technologies

- In-space inspection of composites structures
- Technology challenges in design, manufacture, and use

Recommend cost-effective technology developments

SPACE SYSTEMS TO BE CONSIDERED

- Space-Assembled Structures
- Deployed Structures
- Manned Systems

NDE OF COMPOSITE SPACE STRUCTURES

APPROACH:

Review existing spacecraft missions and designs

Result:

- No common problems or requirements identified
- Spacecraft are large, complex
- Cannot be shut down, disassembled

Recommendation:

- 3-level monitoring system
- Technologies selected:
    - Acoustic Emission
    - Spectrophotometry
    - Eddy Current
    - Deflectometry
    - Actinometer

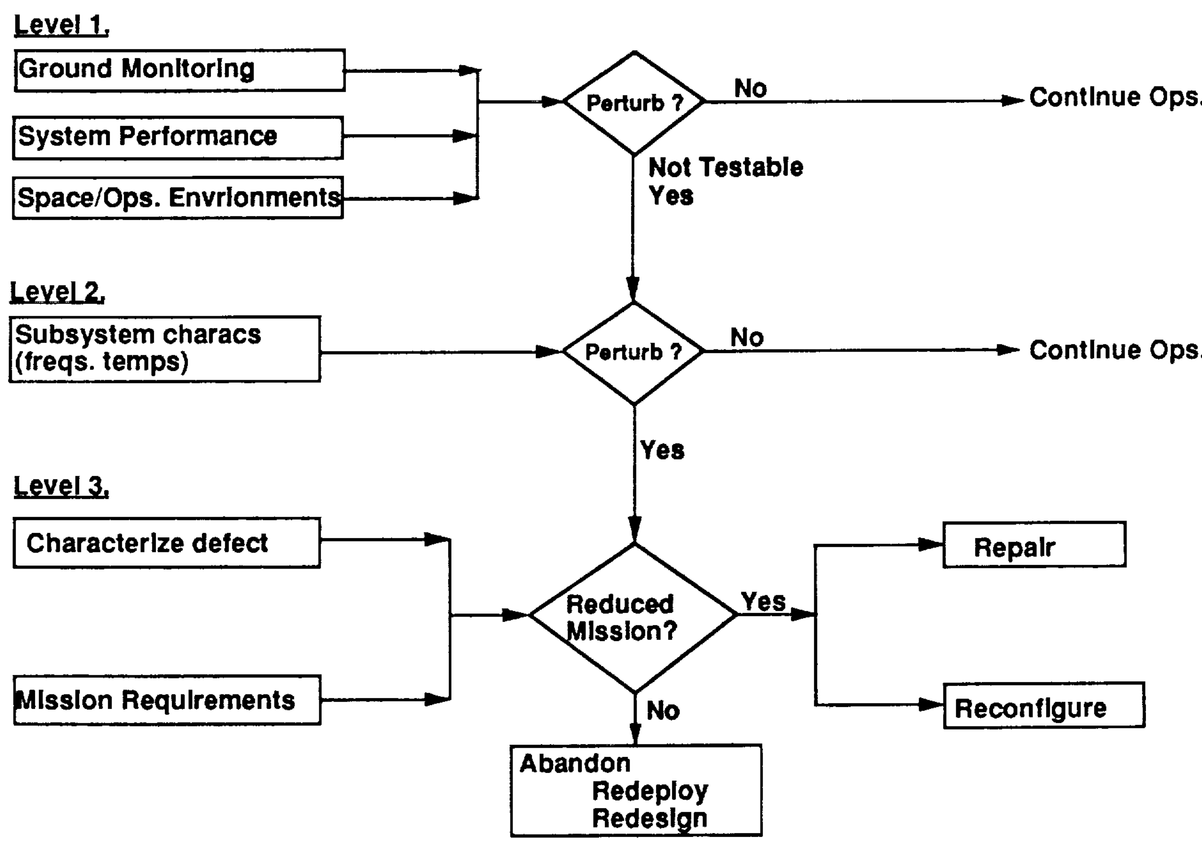


Figure 1. Monitoring Sequence

GEOMETRY MONITORING

Global:
- Interferometers (laser, microwave)
- Extensometers (optical, electrical)
- Goniometers (optical, electrical)

Local:
- Strain gages
- Ultrasonics
- Eddy current
- X-rays/backscatter

DYNAMICS MONITORING

Natural or localized excitation

- o Mode shape, frequency, amplitude
  - Accelerometers
  - Strain gages
  - AE sensors
  - Interferometers

SUBSYTEM LEVEL OF MONITORING

- Subsystem:

  Thermal coatings
  Support structure
  Mirror structure
  Pressure vessels
  Smart structure

- Parameters:

  Dimensional Precision
  Stiffness
  Strength
  Thermal Control
  Leakage (presure vessels)

CRITICAL COMPONENT LEVEL OF MONITORING

- Critical Components:
  - Truss members
  - Joints
  - Beams and structural support
  - Adhesives

- Parameters:
  - Cracks and Delaminations
  - Stiffness
  - Strain
  - Stress
  - Coating degradation
  - Coefficient of Thermal Expansion (CTE)
  - Surface Damage

NDE of Composite Space Structures

DAMAGE MONITORING

Cracks:

- o UT, CT, EC, resistance wires

Deformation

- o Lasers, UT, etc

Impacts

- o Visual, UT, EC, etc

Residual stress

- o Strain gages

Repairs/maintenance, before and after

- o X-rays, ultrasonics, eddycurrents

Externally-induced damage (hostility, impact, AO)

- o Visual
- o Inference from frequency, stiffness, temperature
- o Thickness measurement

Thermal Coatings

- o Thermometry, spectrometry

Internally-induced damage (fatigue, creep)

- o Inference from frequency, stiffness, temperature

SPACE ENVIRONMENT MONITORING

- Debris/meteorites
  - AE sensors
  - Piezofilm sensors
- Atomic oxygen (AO)
  - Silver actinometer
  - Tapered-element oscillating microbalance
- Solar radiation
  - Protons/electrons: Charge devices (Faraday cup, electrometer)
  - Ultraviolet: Spectrophotometer
  - Gammas/x-rays: Dosimeters
  - Flares: Optical, photocells
  - Trapped particles (Van Allen)
- Cosmic Rays (galactic/solar)
  - Emulsions

OPERATIONAL ENVIRONMENTS

Manoeuvers, internal conditioning

- o Accelerometers
- o Strain gages
- o Temperature/pressure/humidity gages
- o Outgassing/effluents
- o System radiation (power source, output beam)

Table I. LOCAL DAMAGE/DEGRADATIONS WITH PRIORITIES

Damage Type (Alphabetical)			Rank	Priority By Rank	
1	Absorp/Emiss	(AB)	2	1	Aging
2	Aging	(AG)	1	2	Absorp/Emiss
3	Bacteria/Fungi	(BF)	9	3	Contamination
4	Cracks, Delams	(CD)	4	4	Cracks, Delams
5	Contamination	(CO)	3	5	Fatigue
6	Crushing	(CR)	7	6	Major Damage
7	Distortion	(D)	8	7	Crushing
8	Electric Currents	(E)	11	8	Distortion
9	Fatigue	(F)	5	9	Bacteria/Fungi
10	Major Damage	(MD)	6	10	Thinning
11	Residl Stress	(RS)	12	11	Electric Currents
12	Thinning	(TH)	10	12	Residual Stress

Note: Low numbers mean high priority or difficulty

Table II. SIGNIFICANT ENVIRONMENTS AND THEIR IMPORTANCE

	Environment (Alphabetical)		Rank	Priority by Rank	
1	Atomic Oxygen	(AO)	7	1	Maintenance and Repair
2	Hostility	(H)	4	2	Maneuvering
3	Internal Environment	(IE)	8	3	Space Assembly
4	Magnetic Fields	(MF)	11	4	Hostility
5	Maint/Repair	(MR)	1	5	Outgassing/Effluents
6	Maneuvering/Reboost	(MV)	2	6	Space Debris/Meteorites
7	Micro/Artif Gravity	(MG)	12	7	Atomic Oxygen
8	Outgassing/Effluents	(OE)	5	8	Internal Environment
9	Space Assembly	(SA)	3	9	System Energy
10	Sp Debris/Meteorites	(SD)	6	10	Solar Radiation
11	System Energy	(SE)	9	11	Magnetic Fields
12	Space Radiation	(SR)	10	12	Micro/Artif Gravity

NDE of Composite Space Structure

Factors in instrumentation

- Costs of development, installation, operation
- Weight, size, power
- Accompanying software
- Inspection coverage
- Impact of space environment
- Need for human intervention
- Reliability

Table VIII. FACTORS IN MONITORING TECHNIQUES

Alphabetical		By Rank	
General Instruments			
1 Accelerometer	1	Accelerometer	1
2 Aco Emission	3	Eddy Current	2
3 Bacteriology	12	Aco Emission	3
4 Break Wires	4	Break Wires	4
5 Compton Bksctr	16	Deflct/Goniom	5
6 Computed Tomo	17	Fiber Optics	6
7 Deflct/Goniom	5	Strain Gage	7
8 Eddy Current	2	Temperature	8
9 Fiber Optics	6	Visual	9
10 Laser/M'wve Intf	10	Laser/M'wve Intf	10
11 M'wave Refl	14	Spect/Refltry	11
12 Spect/Refltry	11	Bacteriology	12
13 Strain Gage	7	Ultrasonics	13
14 Temperature	8	M'wave Refl	14
15 Thermography	15	Thermography	15
16 Ultrasonics	13	Compton Bksctr	16
17 Visual	9	Computed Tomo	17
18 X-Radiography	18	X-Radiography	18
Specialized Instruments			
1 Actinometer	1	Actinometer	1
2 Calorimeter	3	Hygrometer	2
3 Charge Device	6	Calorimeter	3
4 Debris Flux	7	Dosimeter	4
5 Dosimeter	4	TEOM	5
6 Hygrometer	2	Charge Device	6
7 Gravitometer	8	Debris Flux	7
8 Magnetometer	9	Gravitometer	8
9 TEOM	5	Magnetometer	9

Conclusions

Recommended technologies

- Acoustic emission:
  - Cracking, crushing, fatigue, major damage
  - Hostility, maintenance/repair, maneuvering, outgassing/effluents, space assembly, debris/meteorites
- Spectrophotometry:
  - Absorptivity and emissivity
- Eddy current:
  - Aging, cracks, distortion, damage, thinning
  - Maintenance/repair, maneuvering, space assembly
- Deflectometry
- Actinometry
  - Atomic oxygen

Acousitc Emission

Develop sensors:

- Piezo film
- Integral amplifier, processor
- Packaging/mounting

Evaluate signatures:

- Defects
- Events
- Algorithms

Spectrophotometry

Requirements:

- Spectral resolution
- Angular resolution

Develop:

- Multi-band retractable light source
- Wide-angle retractable detector array
- Spectral analysis microprocessor

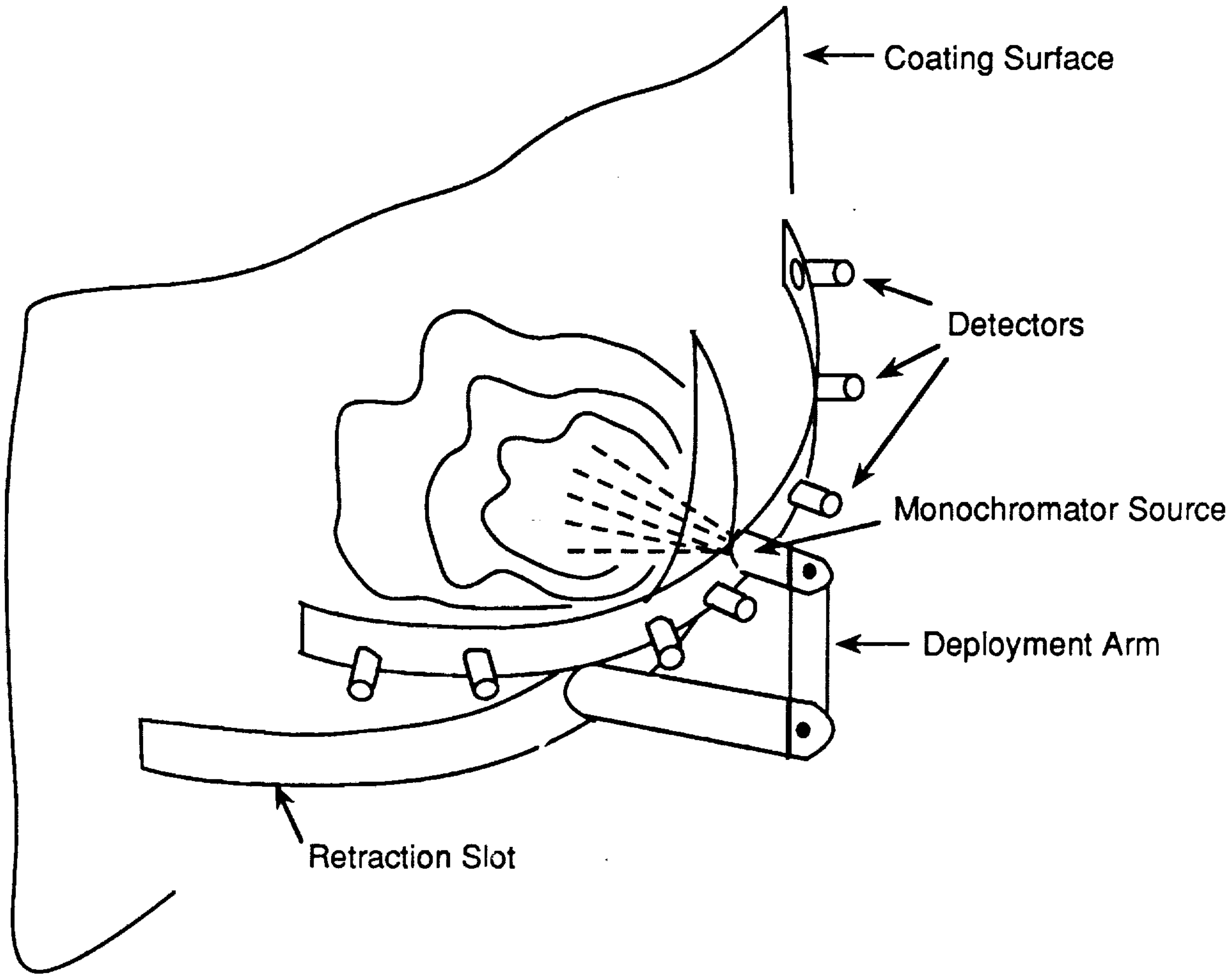


Figure 4. Deployable Spectrophotometer

Eddy Current

Develop:

- Multi-frequency tri-axial probes
- Excitation source, detector
- Correlation algorithms

Calibrate:

- Impedance vs. lift-off
- Impedance vs. conductivity

Deflectometry

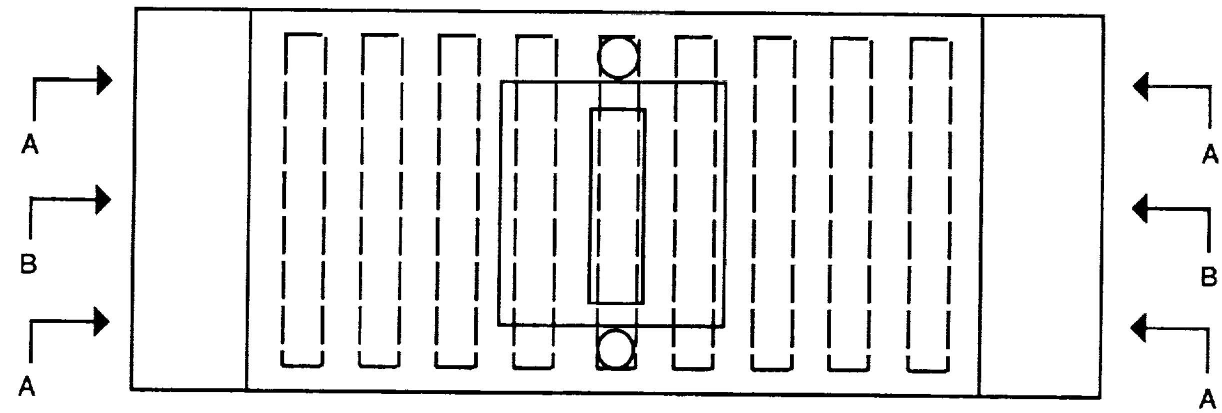
Develop

- Mirror system with CCD detectors
- Encoders
- Differential transformers
- Capacitive sensors
- Fiber optic reflectometer

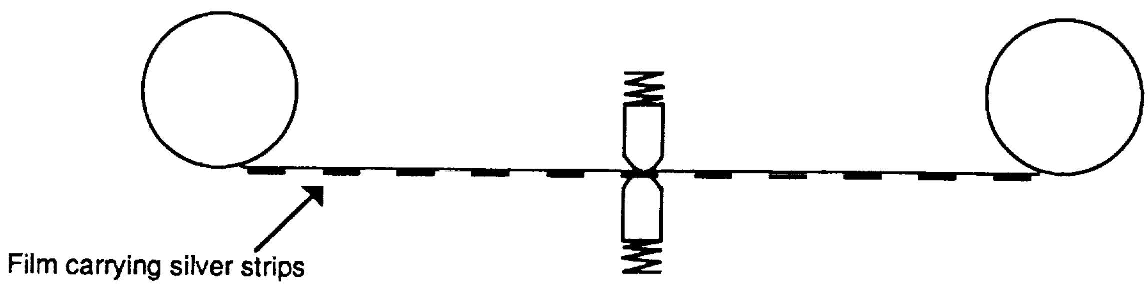
Actinometer

Develop:

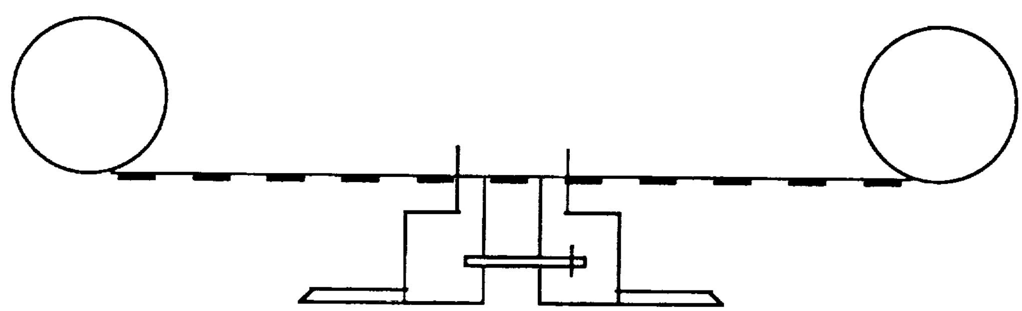
- Film with silver strips, dispenser
- Aperture shutter
- Electrical contacts, resistance measurement



Face View of Aperture

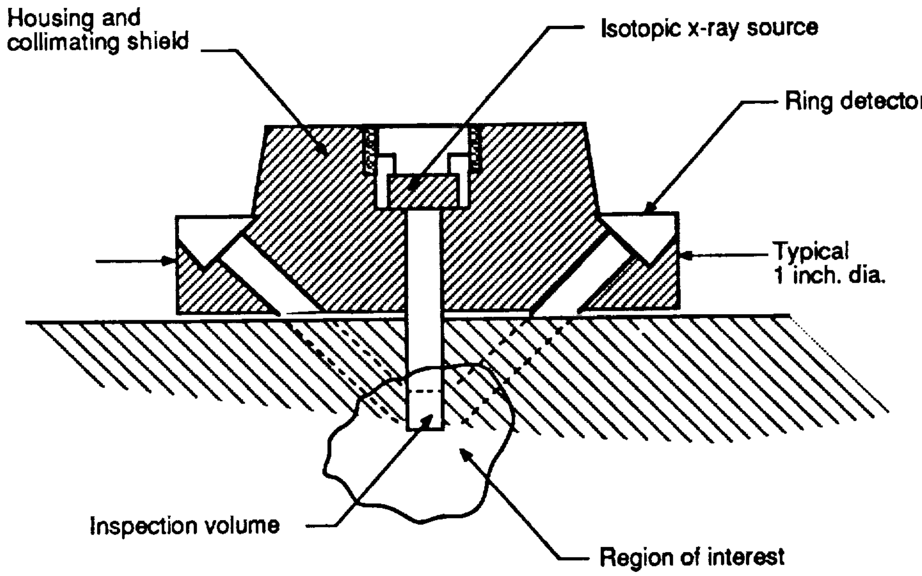


Sections AA: Spring-loaded contacts at both edges of film

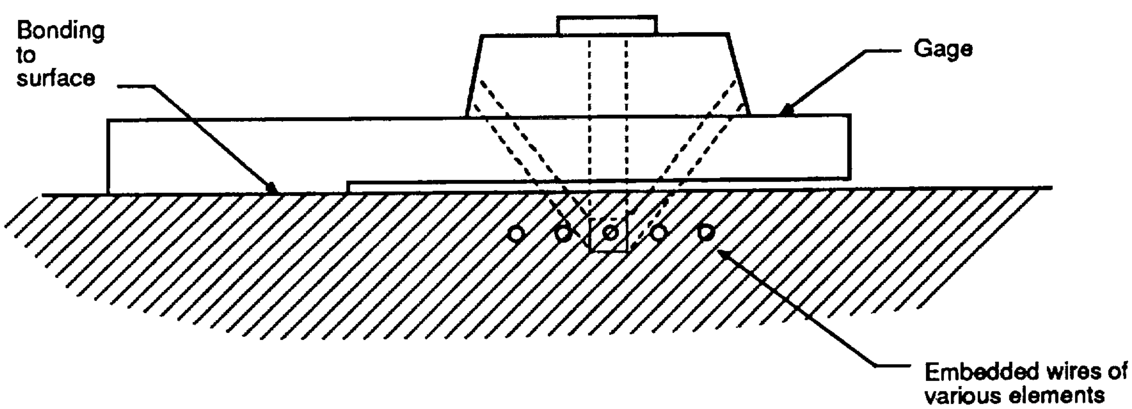


Section BB: Slit Aperture

Figure 3. Multi-use Actinometer



(a) Basic X-Ray Backscatter Gage



(b) Strain Gage Application

Figure 10. X-Ray Backscatter Gage Concept

Data Handling for SPIP Workstation

by

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August 22-24, 1989

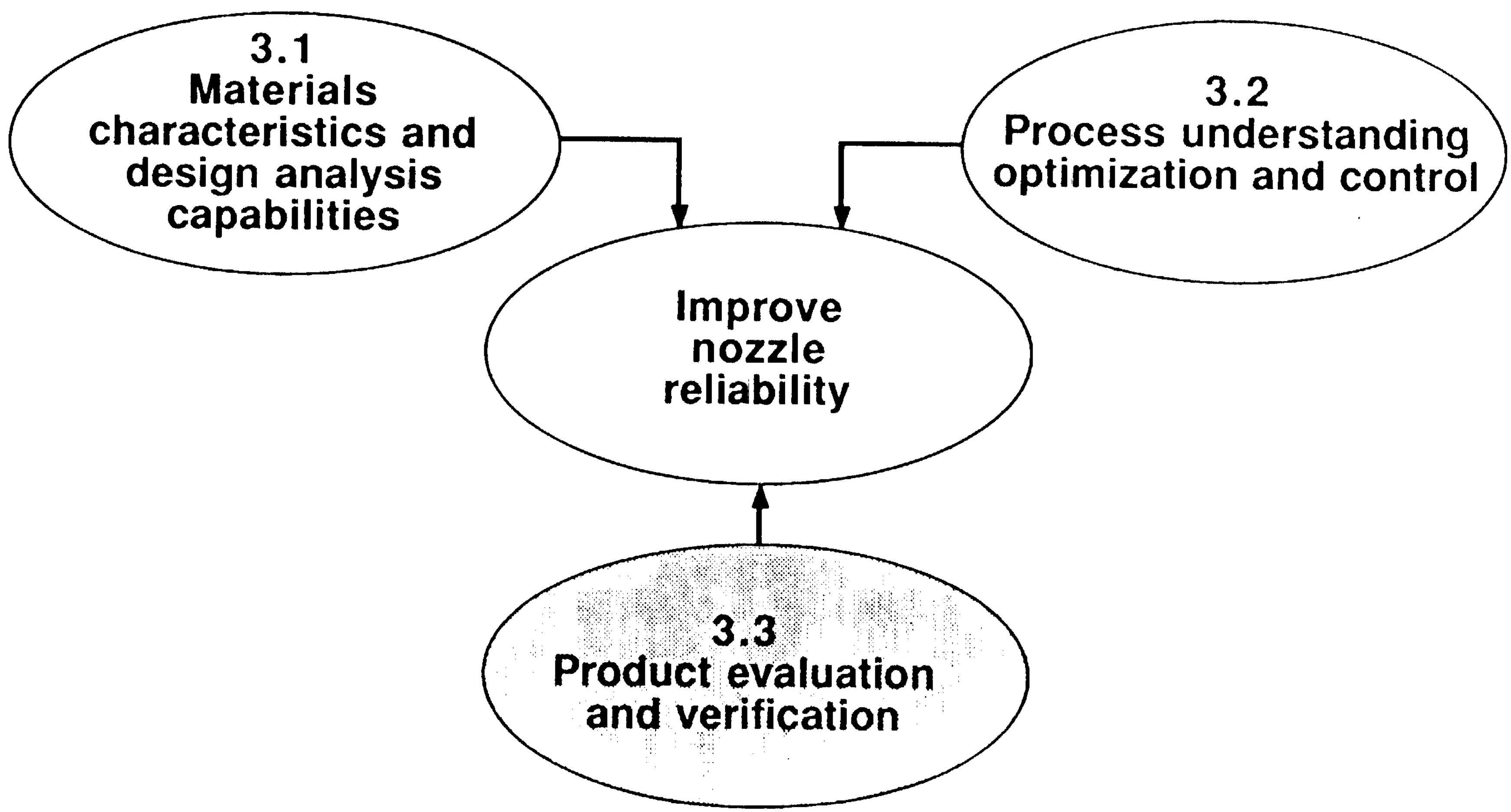
Performed under

Hercules Contract B-I-7-ER-23321
NASA Contract NAS8-37801

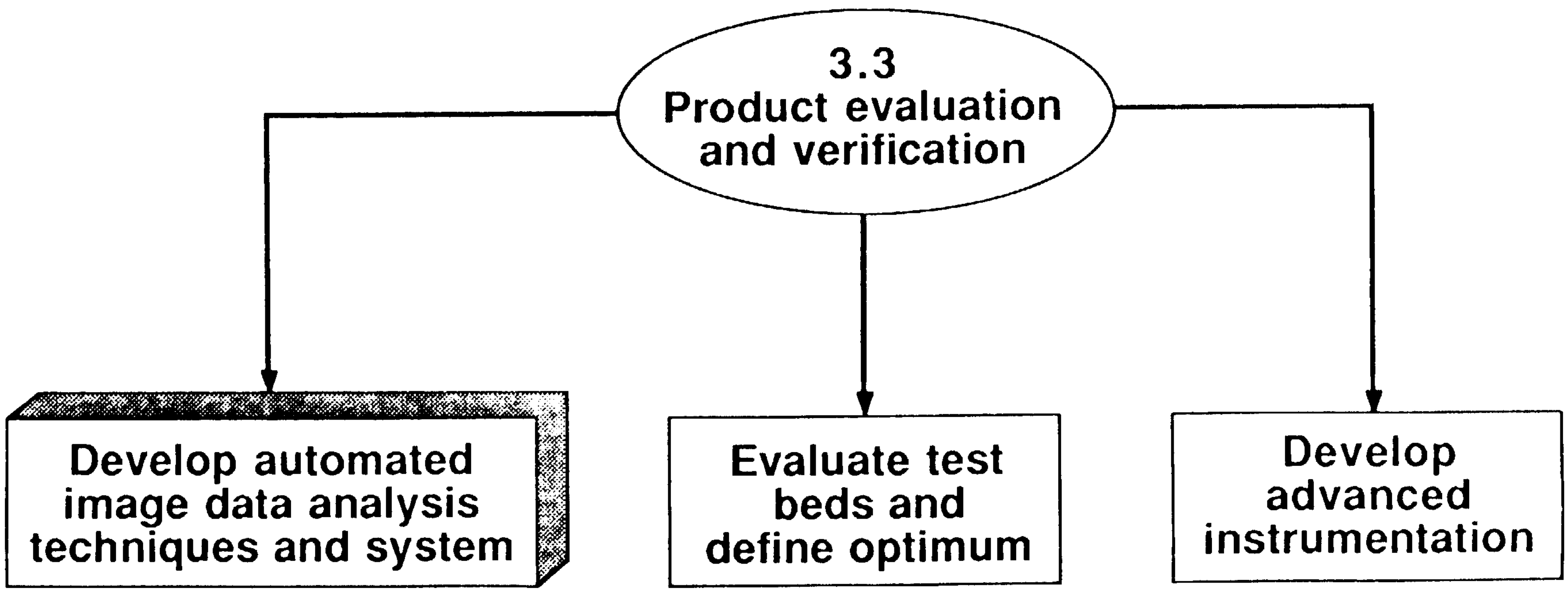
Technical Objective of Solid Propulsion Integrity Program (SPIP) for Nozzles

Improve overall success rate of solid rocket motor nozzles

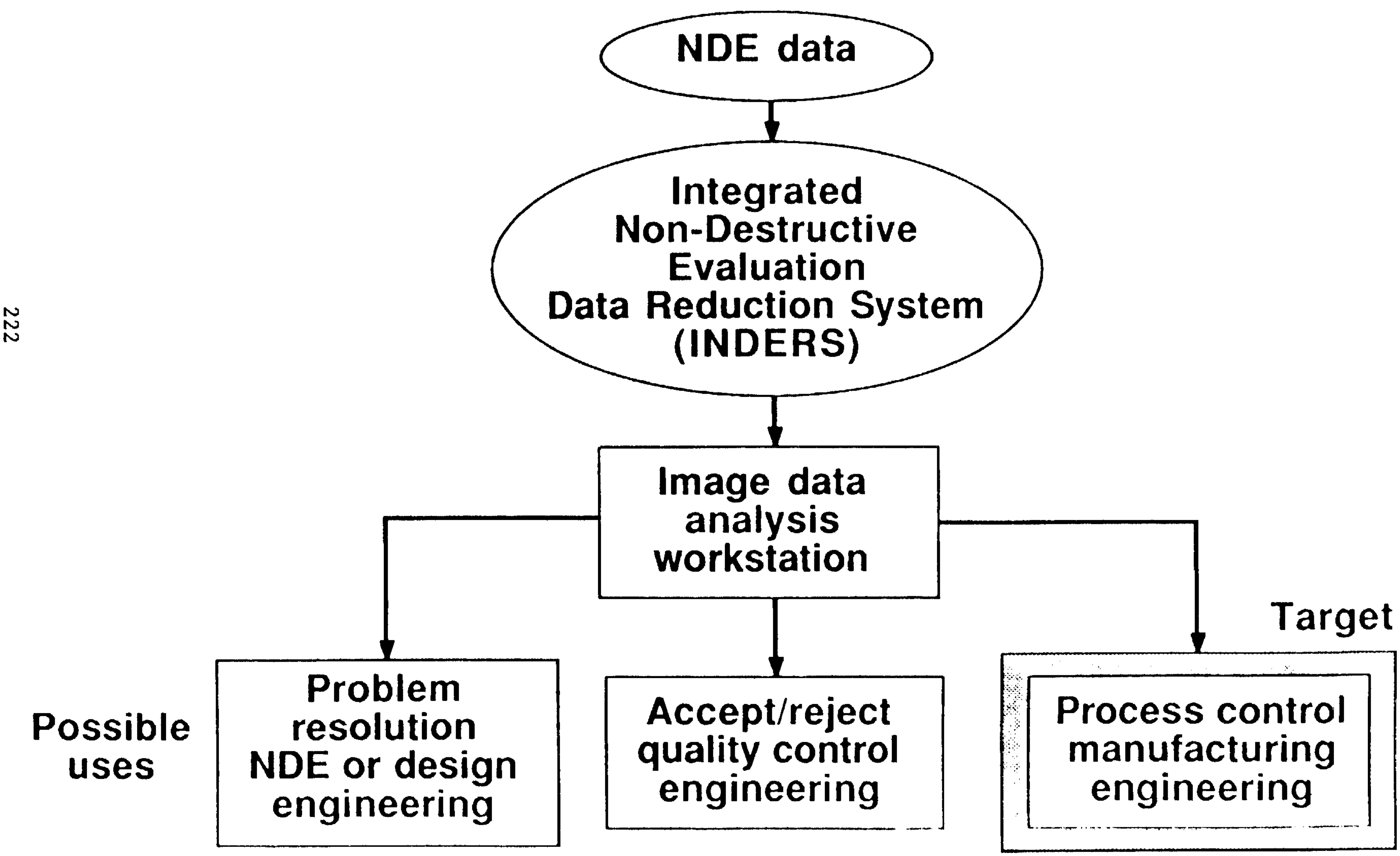
- Through improved understanding and capabilites



Technical Objective (Continued)



Overall System Uses



Program Overview

- Provide tools for nozzle manufacturer
  - To review production of NDE data
  - To review process parameters
  - To relate these to the fabrication process
- Review current production and NDE processes
- Select analysis techniques
  - Data display/management
  - Data prioritization
  - Data classification
- Determine hardware and software requirements
- Implement workstation design

Factory Interveiws

- Nozzle manufacturers and users:
  - Aerojet
  - Hercules
  - Hitco
  - Kaiser Pueblo and San Leandro
  - Thiokol
  - UTC/CSD
- What in-process material properties or features need to be monitored? (mostly from production personnel)
- What NDE derived material properties or features are applicable to the production environment? (mostly from NDE technologists)
- What are the requirements for a user interface with the NDE derived material properties or features? (jointly production personnel and NDE technologists)

Inpsection/QC Process

- NDE usually after cure and machining, before bonding
- Present techniques: Tag end test, weight, compression, radiography, alcohol wipe, tap testing
- Advanced techniques: RTR, CT, UT, ET
- Typical floor paper:
  1. Inspect material
  2. Record flow and volume test for each roll
  3. Verify rolls from different batches are not mixed
  4. Verify tape wrap to specs
  5. Verify bagging to specs
  6. Check vacuum and timing
  7. Verify autoclave or hydroclave procedures
  8. Record weight after cure and inspect for wrinkles
  9. Record thicknesses at 0, 90, 180, and 270 degrees
  10. Check machining
  11. Check radiography inspection
  12. Record thicknesses again

Aerospace Systems Technologies

PRO Types of Data

Boeing Aerospace & Electronics

- Time
- Temperature
- Pressure
- Chemistry
- Dimensions
- Weight
- Volume
- Photo
- Photo-micrographs
- Certifications
- Inspectors Name/Number
- Operators Name/Number
- ETC.

Inspection Considerations

- Based on customer requirements
- Sometimes drive design
- MRB is largest user
- Presently no NDE until after machining

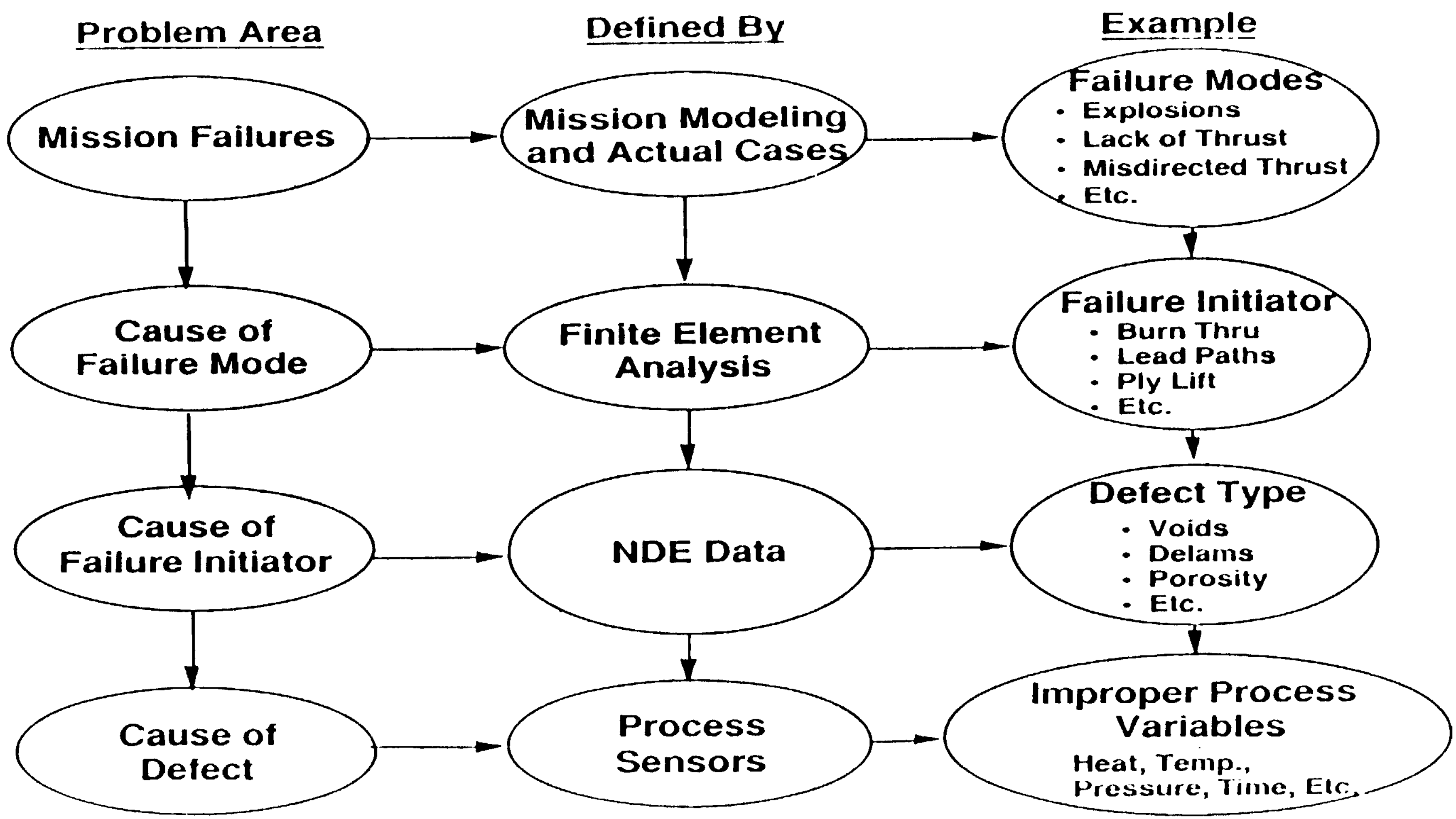
Inspection Recommendations

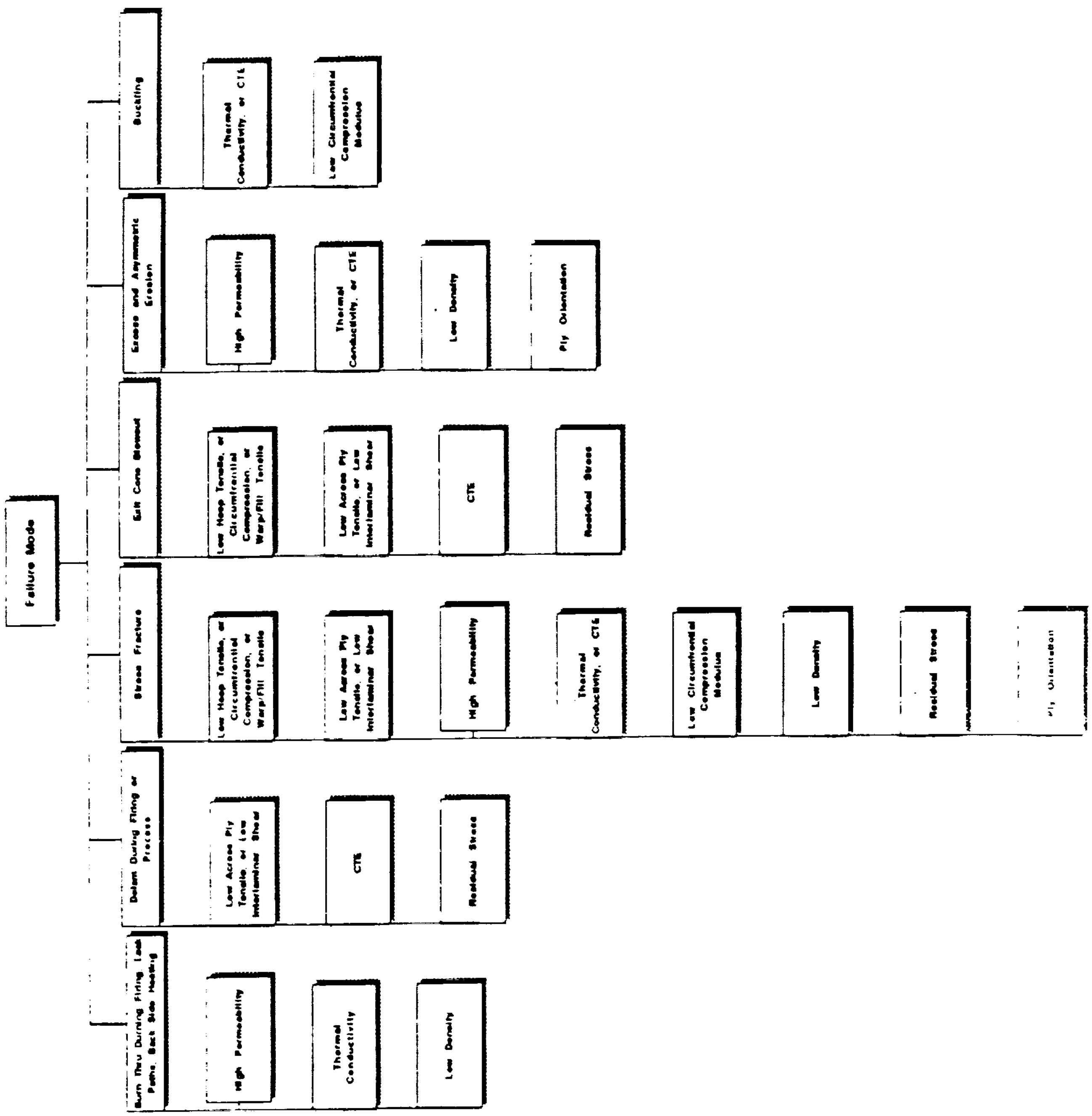
- Catch defect as early as possible
- Report near-tolerance conditions
  (Presently only pass/no pass)
- Provide NDE data before and after cure
- Provide comparison of pre to post fire
- CAD may be helpful in data analysis
- Computerize routing order/inspection data
- CT workstation critiques received
  Reduce CT scan data

Aerospace Systems Technologies

Cause & Effect

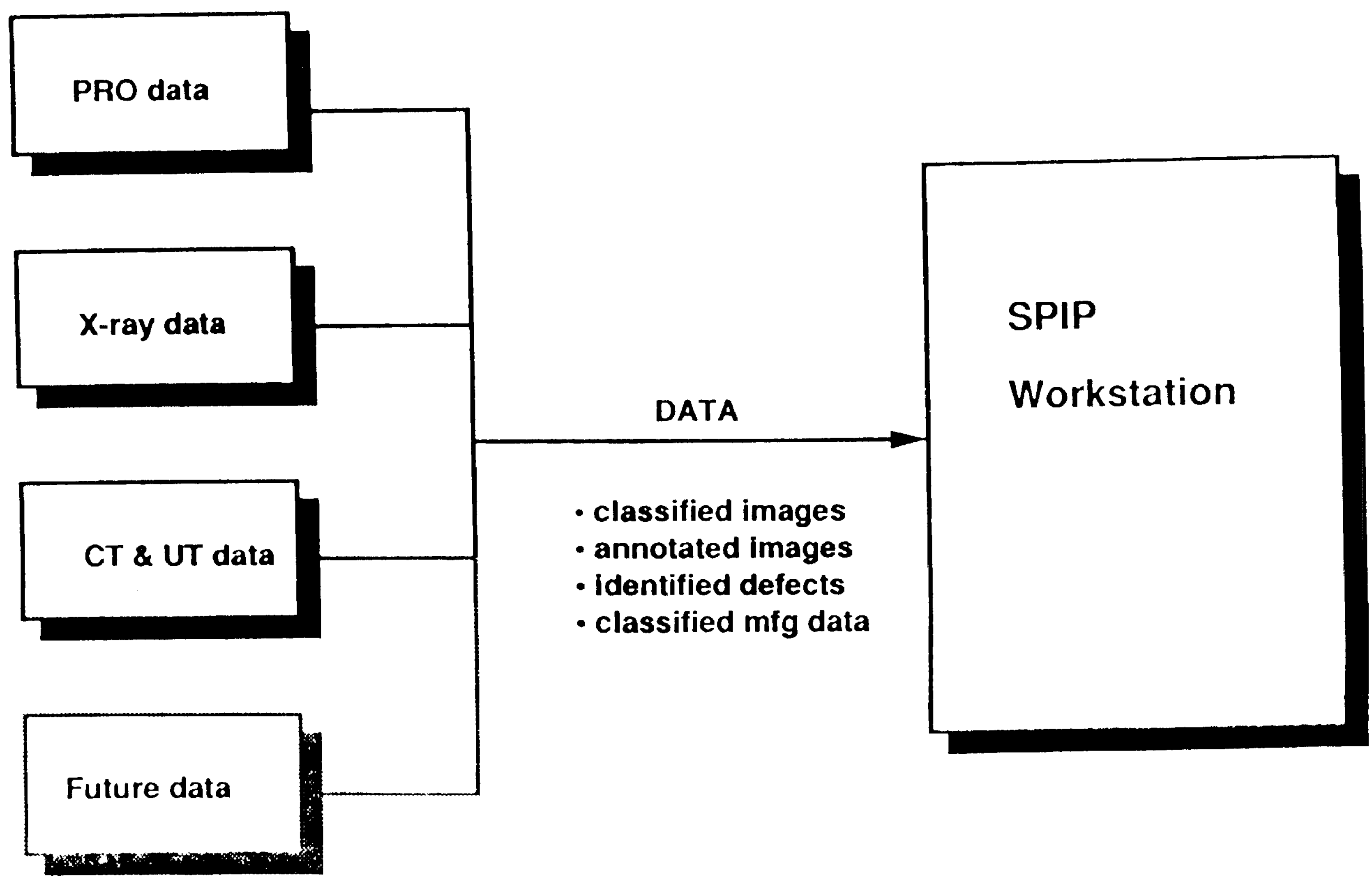
Boeing Aerospace & Electronics




Failure Mode
Buckling
Thermal Conductivity, or CTE
Low Circumferential Compression Modulus
Excess and Asymmetric Erosion
High Permeability
Thermal Conductivity, or CTE
Low Density
Ply Orientation
Exit Cone Blowout
Low Hoop Tensile, or Circumferential Compression, or Warp/Fill Tensile
Low Across Ply Tensile, or Low Interlaminar Shear
CTE
Residual Stress
Stress Fracture
Low Hoop Tensile, or Circumferential Compression, or Warp/Fill Tensile
Low Across Ply Tensile, or Low Interlaminar Shear
High Permeability
Thermal Conductivity, or CTE
Low Circumferential Compression Modulus
Low Density
Residual Stress
Ply Orientation
Delam During Firing or Process
Low Across Ply Tensile, or Low Interlaminar Shear
CTE
Residual Stress
Burn Thru During Firing Leak Paths, Back Side Heating
High Permeability
Thermal Conductivity
Low Density

SPIP Workstation

Interfaces



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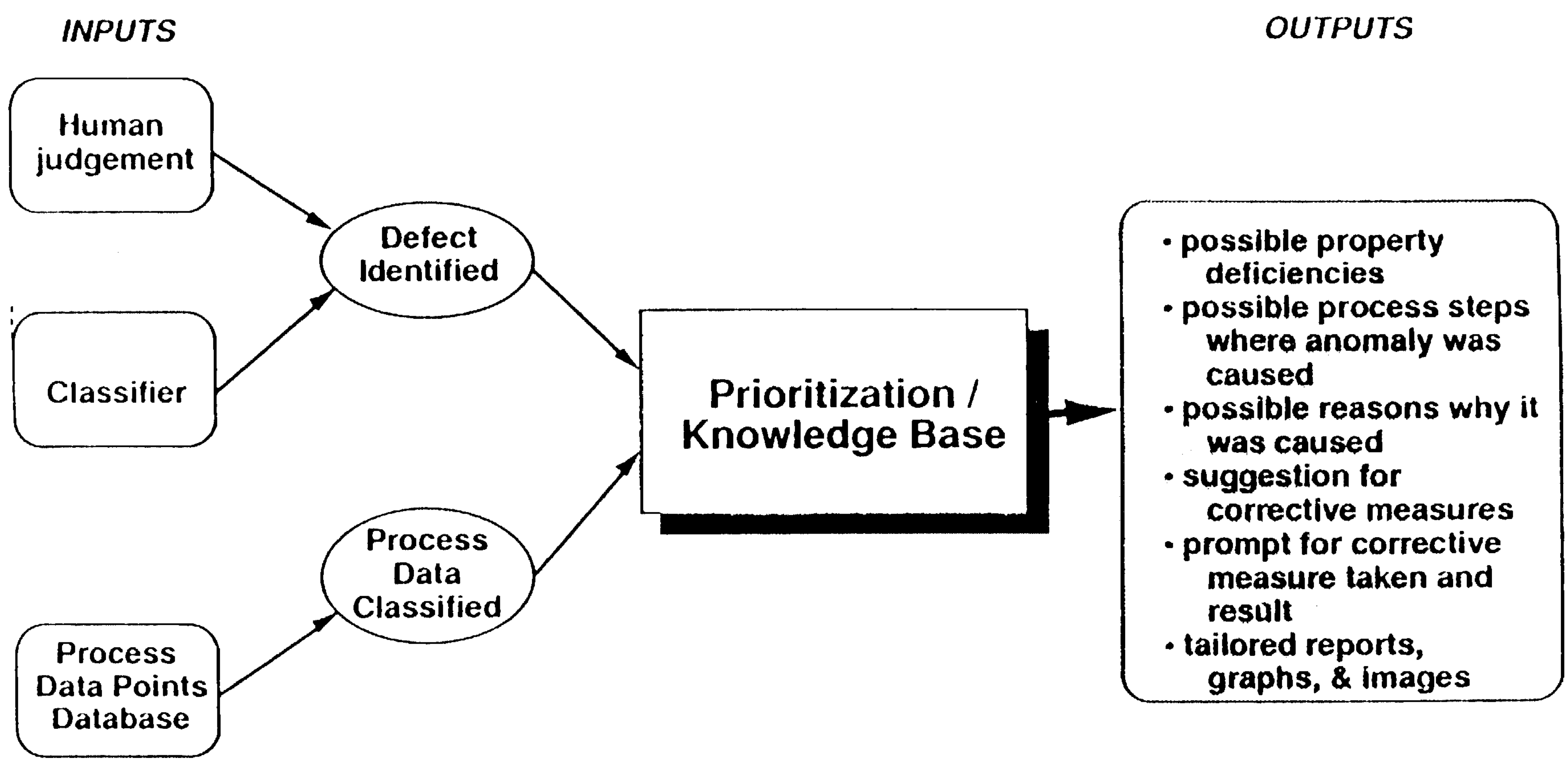
SPIP Workstation Use

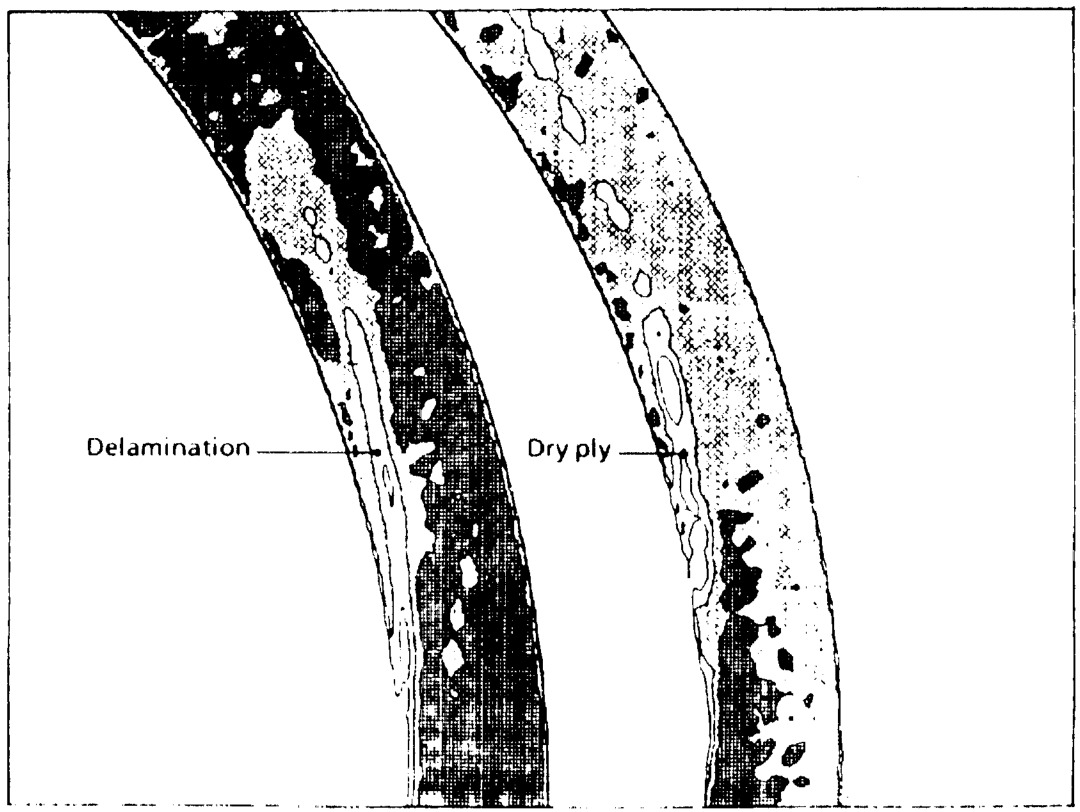


Quality of Data

	Qualitative	Statistical	Quantitative	Physical
Distinguishing features	Human judgement	Relative to nominal or average	Values independent of equipment	Expressed in engineering units
Examples:				
Radiography	Radiograph density	Low density indications (LDIs)	CT image (Hounsfield units)	Density in kg/m3
Ultrasonics	Amplitude	Gated low amplitude indications	Attenuation and wavespeeds (corrected for test factors)	Interlaminar shear strength (PSI)

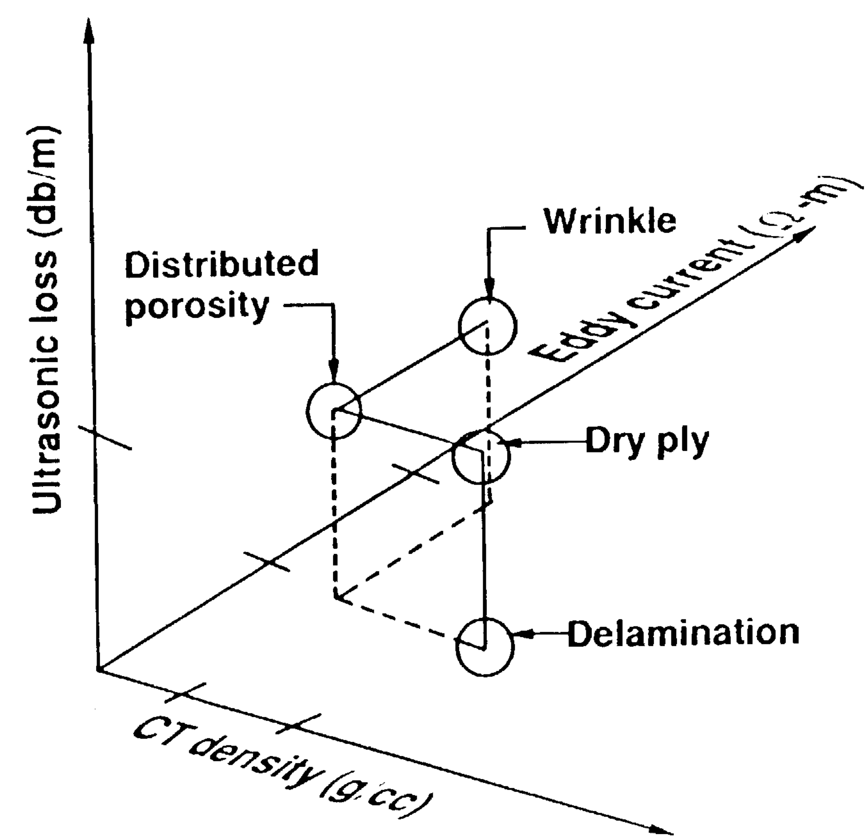
← Worse Better →

The Need for Multimodality

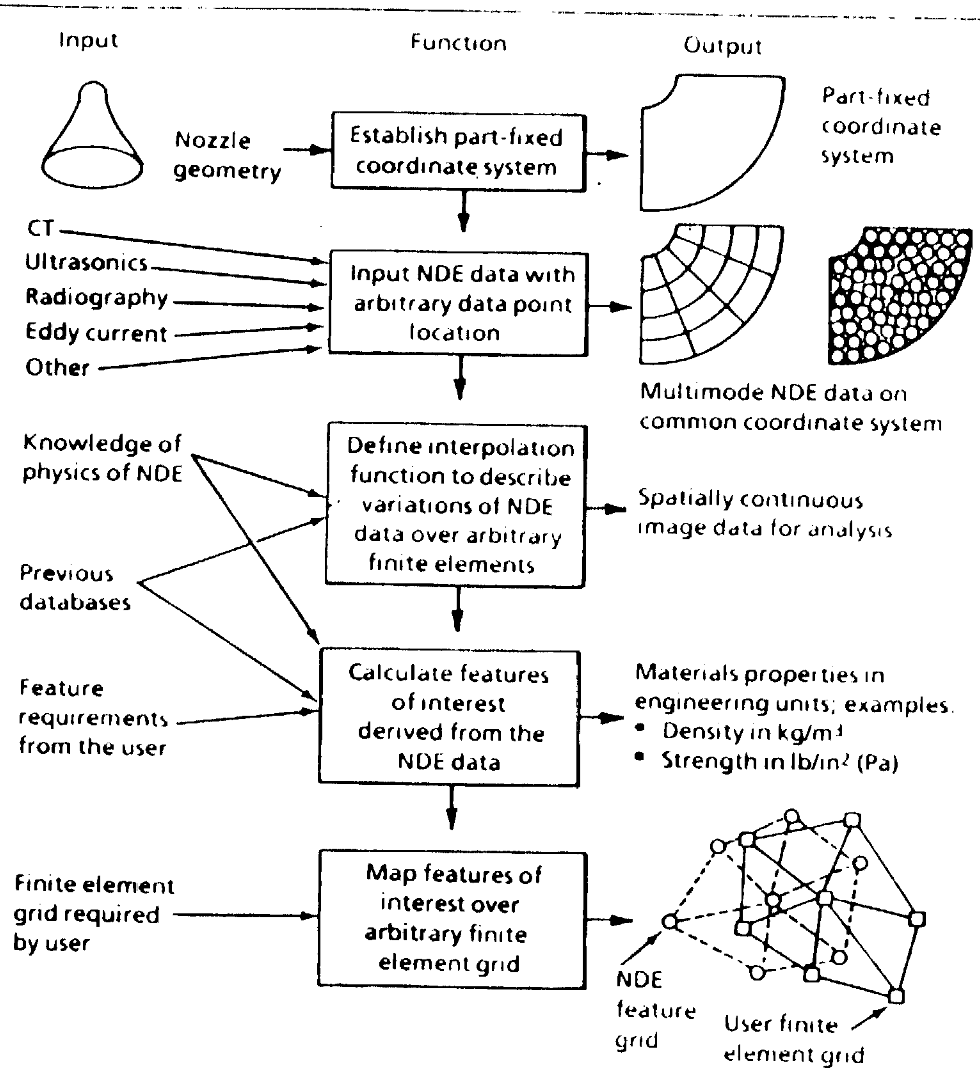


CT images alone may not contain sufficient information to distinguish between an acceptable dry ply and an unacceptable delamination.

Multi-Modal Defect Characterization



Data Transfer



The Boeing INDERS approach to managing NDE data is both systematic and flexible

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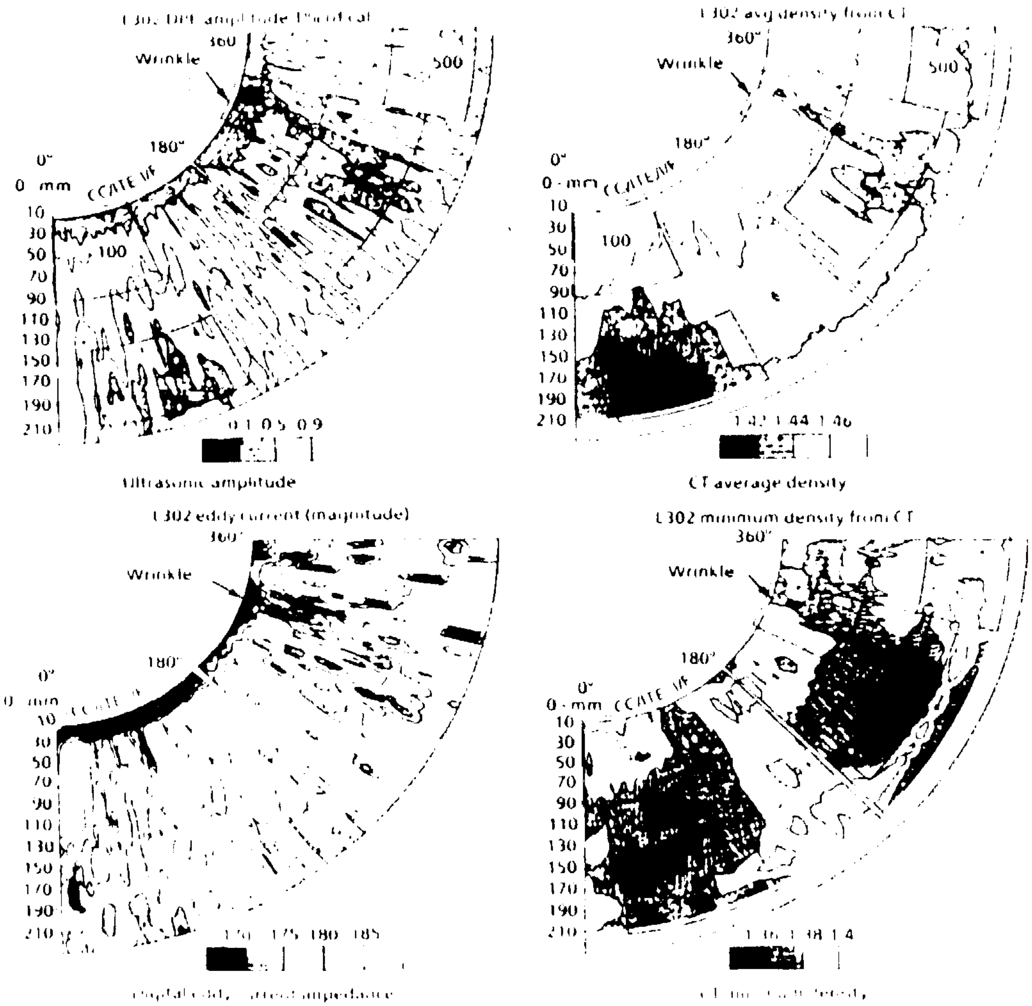
Data Display



The Boeing approach to NDE feature mapping demonstrates the ability to superimpose multiple features on a common surface (IUS nozzle in this case) with outputs in engineering units

Aerospace Systems Technologies

SPIP Workstation

HW/SW Current Options

Boeing Aerospace & Electronics

1	Dupont - Sun Workstation	• INDERS hosted on Dupont • Add Sun WS for SPIP • Image Enhancement & Data Handling • Proven technology
2	Stand-alone Workstation	• End-item inspection data • INDERS may be on WS • Low cost
3	NDE and Mfg Workstations Co-located	• High speed bus between systems for images • Cost out INDERS WS also • X-ray digitizing developed in-house
4	NDE and MFG Workstations Separated	• NDE and Mfg in separate locations • Local area network comm. • X-ray digitizing developed in-house

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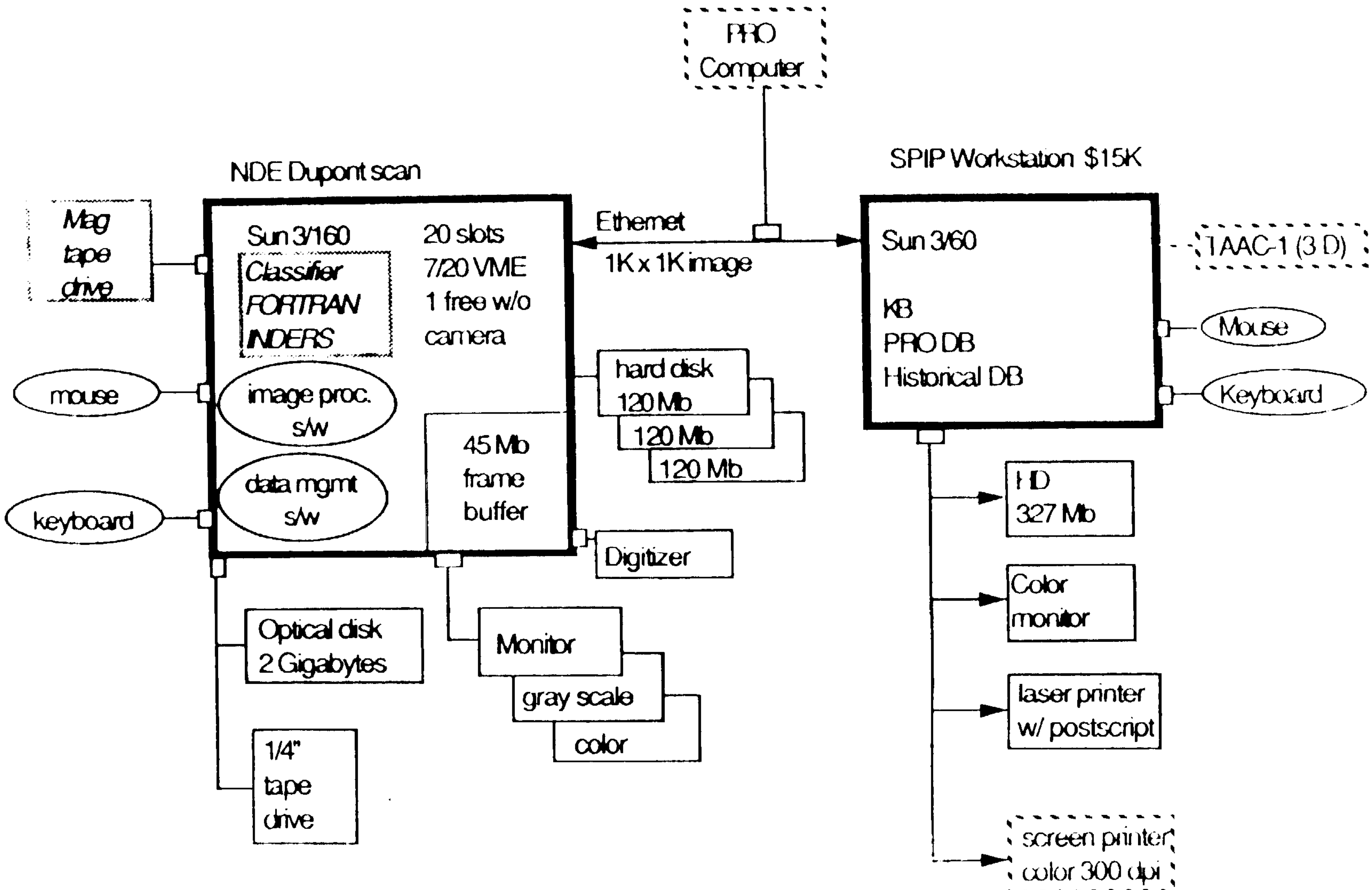
Aerospace
Systems
Technologies

SPIP Workstation Layout #1

Boeing Aerospace & Electronics



ROM $300 - 400K

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Engineering Technology

Required Software Packages for Workstation

Boeing Aerospace

1. Man Machine Interface/Data Display
   - 3-D color graphics
   - Text display
   - Mac style menu interface
   - 3-D manipulation of objects (rotation, translation, magnify, etc)
   - Image enchancement
   - Data base techniques

2. Data Management
   - Spreadsheet type relational database
   - INDERS formatted data files
   - Graphics display files
   - Archival, retrieval, logging
   - Interface to computertized production data

3. Classifying Images
   - Groups anomalies for display and analysis via statistical methods
     - Normal
     - Questionable
     - Anomalous

4. Knowledge Based Analsyis and Prioritization Based on Production Contraints
   - Knowledge base-expert system
   - Dynamic - add, delete
   - Trend analysis
   - Autocorrelation
   - Blob analysis
   - Pattern recognition
   - Edge following
   - Region growth

NDE DATA APPLICATION

PRESENTED AT

SECOND CONFERENCE ON NONDESTRUCTIVE EVALUATION FOR AEROSPACE REQUIREMENTS

PRESENTED BY

JOSEPH H. HILDRETH
ASTRONAUTICS LABORATORY
EDWARDS AFB, CA

CONTENTS

INTRODUCTION

OBJECTIVE OF NDE DRIVEN ANALYSIS

CONCEPTUAL PROCEDURE

REALITIES

SUMMARY

INTRODUCTION

NDE DATA USED SUBJECTIVELY TO DETERMINE ACCEPTABILITY

- RADIOGRAPHY
- ULTRASONICS

NEWER TECHNOLOGY ALLOWS COLLECTION OF QUANTITATIVE DATA

- COMPUTED TOMOGRAPHY

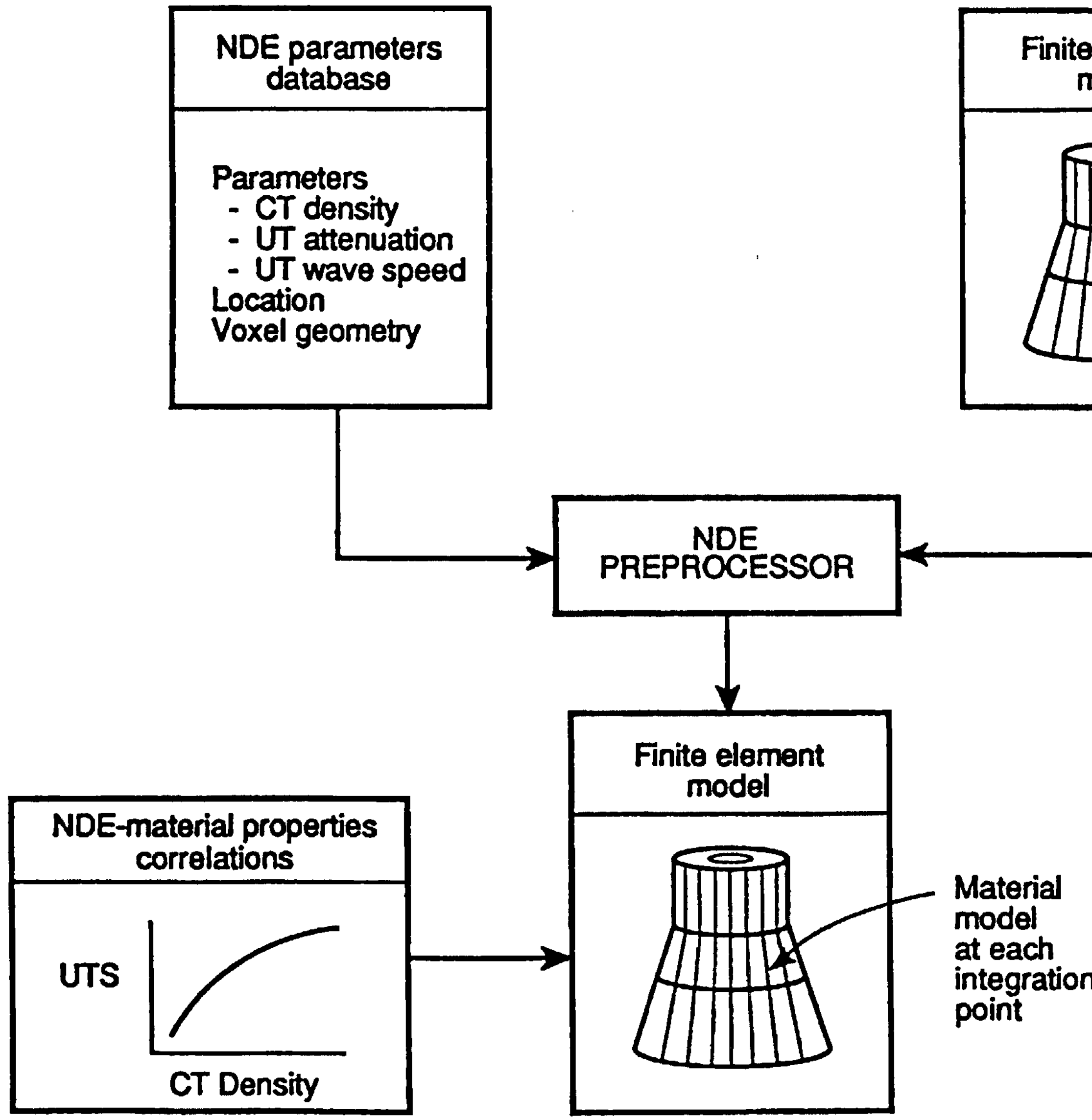
HISTORICALLY, ANALYSIS PERFORMED ON AS-DESIGNED PART WITH MODIFICATIONS

OBJECTIVE OF NDE DRIVEN ANALYSIS

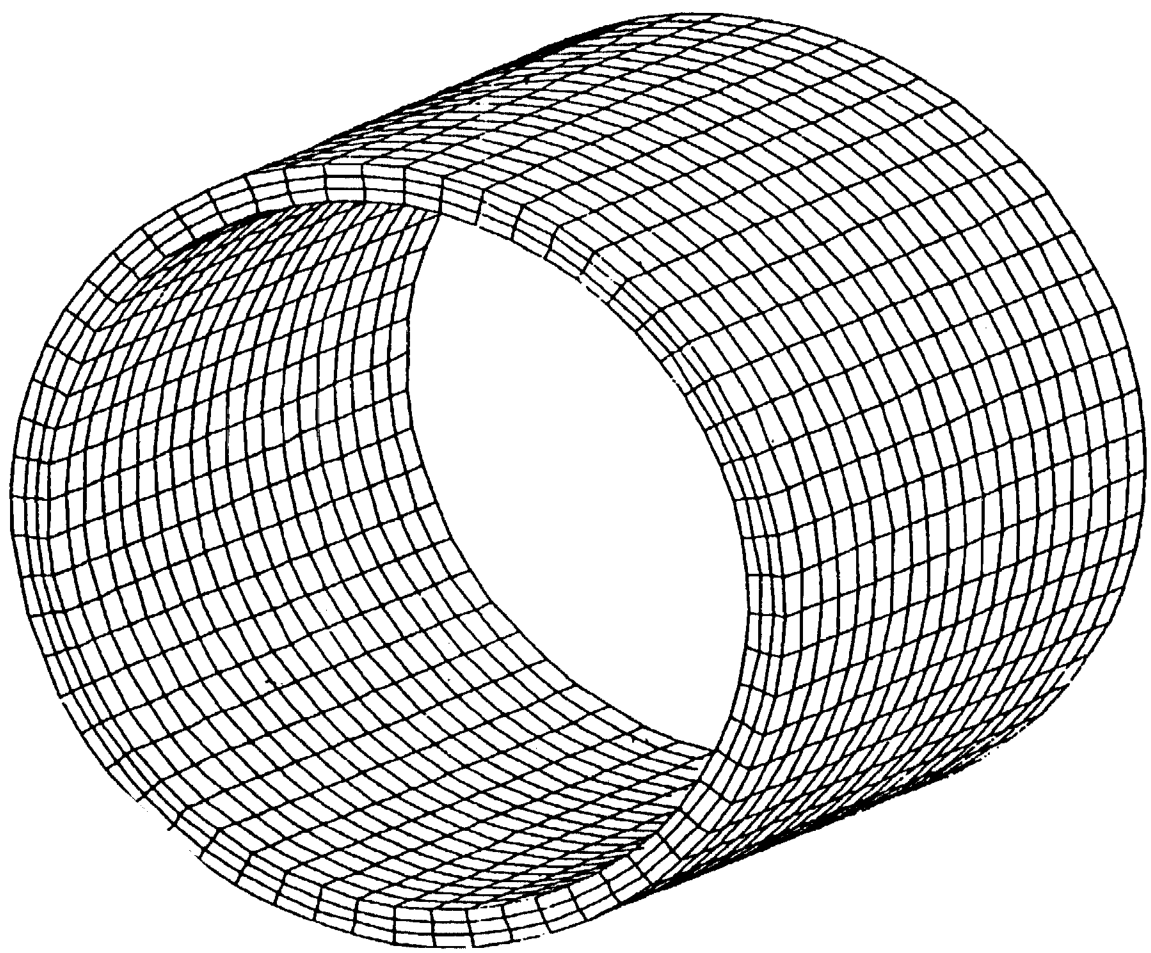
PERFORM COMPUTERIZED ASSESSMENT OF ACCEPTABILITY ON AS-BUILT PART

MOVE THE ACCEPT\REJECT DECISION PROCESS FROM SUBJECTIVE METHODS TO OBJECTIVE METHODS

NDE DRIVEN ANALYSIS METHODOLOGY



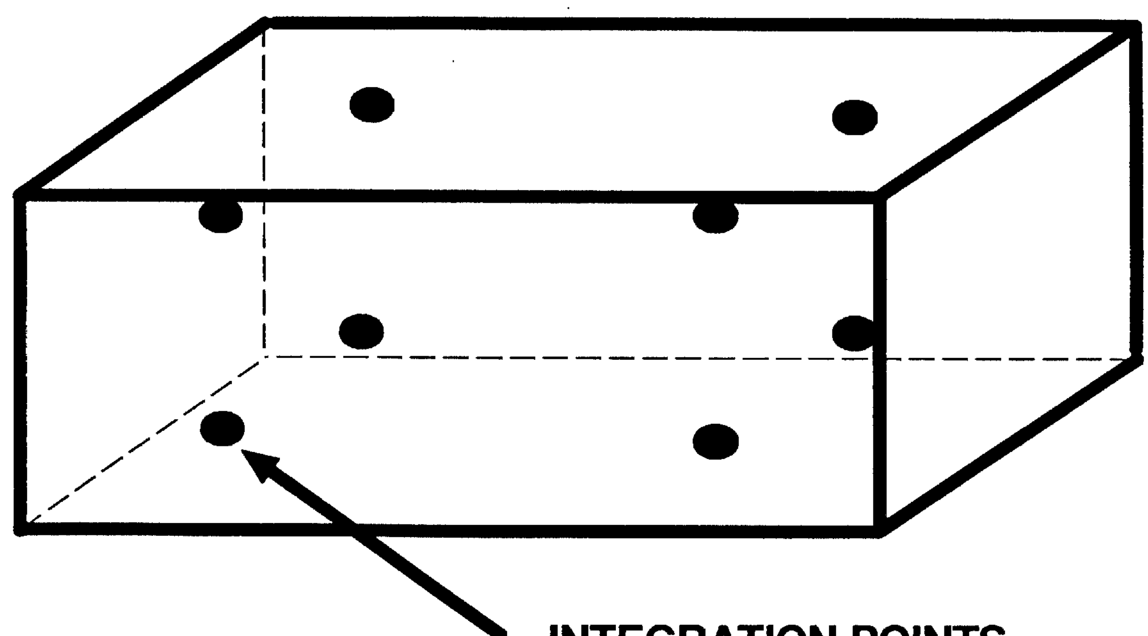
FINITE ELEMENT MESH OF CYLINDER



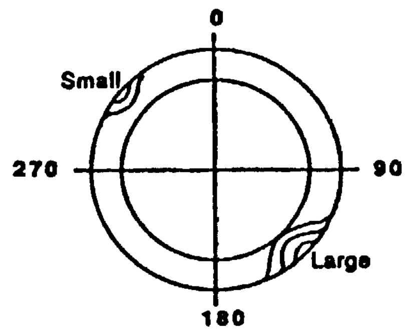
STIFFNESS MATRIX FOR FINITE ELEMENT

$$K = \int_{vol} B^T \, C \, B \, dv$$

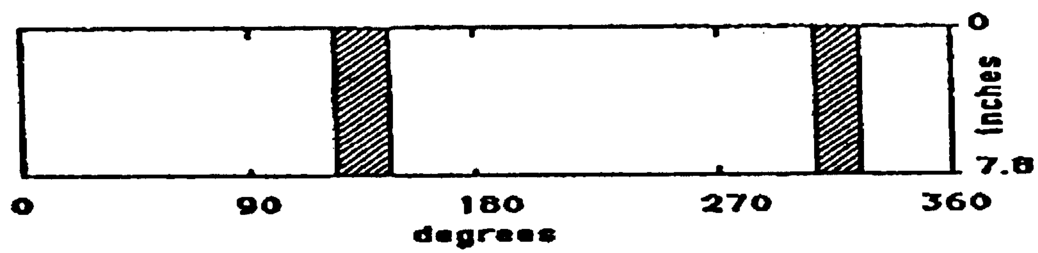
SINGLE FINITE ELEMENT



WRINKLED CYLINDER SPECIMEN GEOMETRY



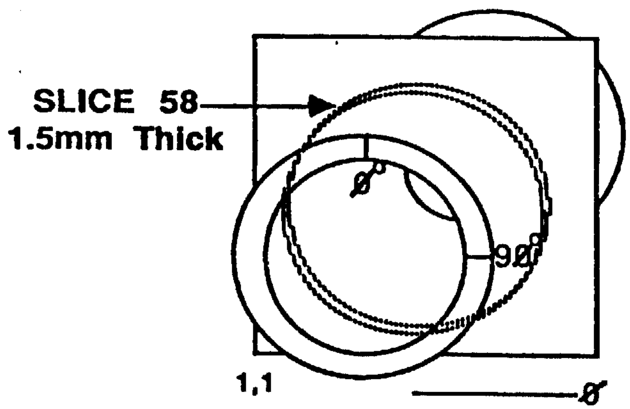
107-1 WRINKLE



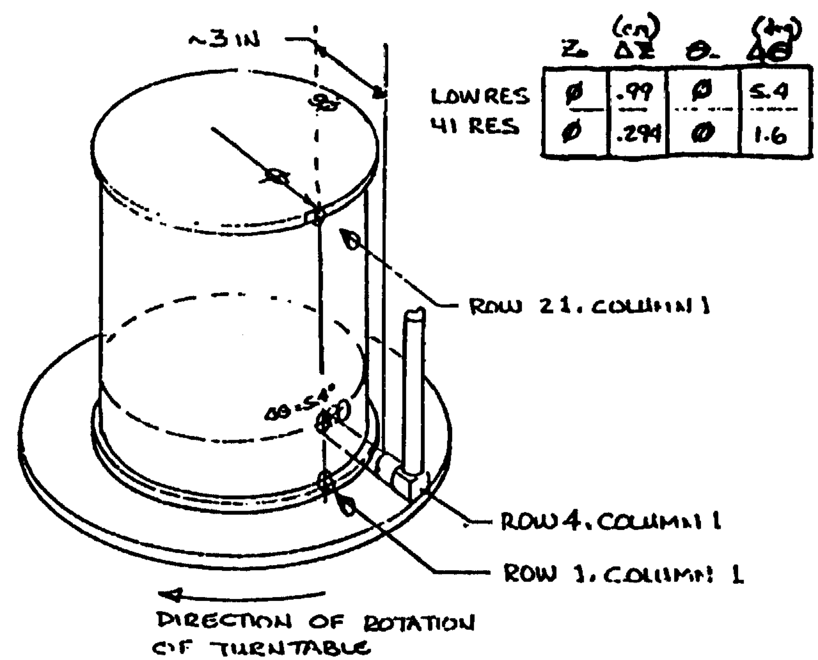
TAPERED AMPLITUDE
<u>WRINKLE CYLINDER</u>

Anomaly:	Wrinkle/wave (2)
Generated by:	Dimpled and machined
Size:	0.1–0.35 Amplitude x 0.8 length 0.0–0.25 Amplitude x 0.8 length
Location (approximate):	135° and 315°

CT Inspection Geometry

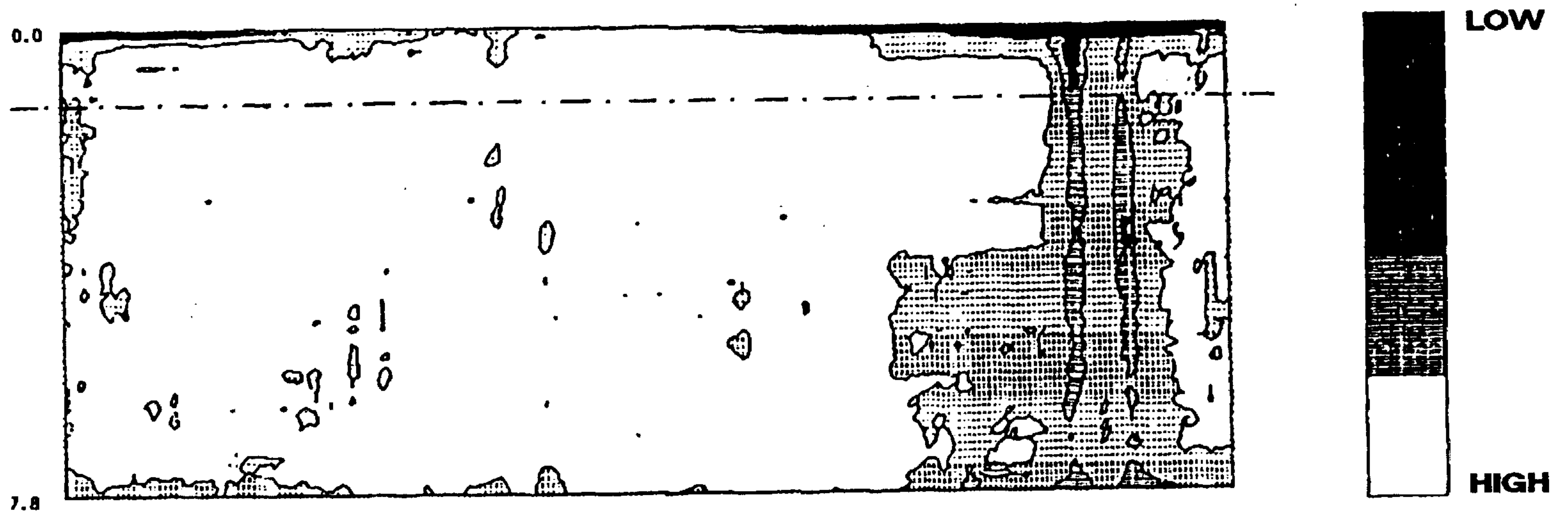


UT Inspection Geometry

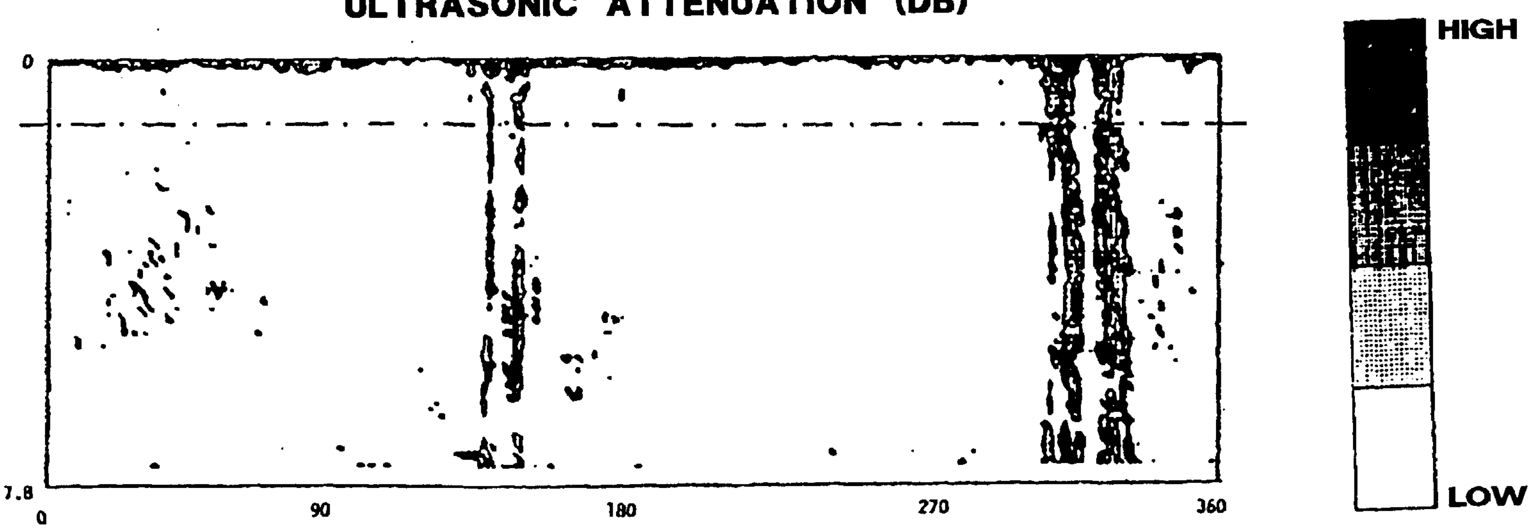


IMAGES OF NDE DATA

CT DENSITY (G/CC)



ULTRASONIC ATTENUATION (DB)



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PROCEDURE

DETERMINE VALUES OF NDE DATA AT INTEGRATION POINTS

DETERMINE VALUES OF MATERIAL PROPERTIES BASED ON NDE INDICATIONS

IF MULTIMODE NDE DATA IS BEING CONSIDERED THEN DETERMINE COMPOSITE AVERAGE OF EACH MATERIAL PROPERTY

TRANSFER MATERIAL PROPERTIES TO ANALYSIS CODE

REALITIES

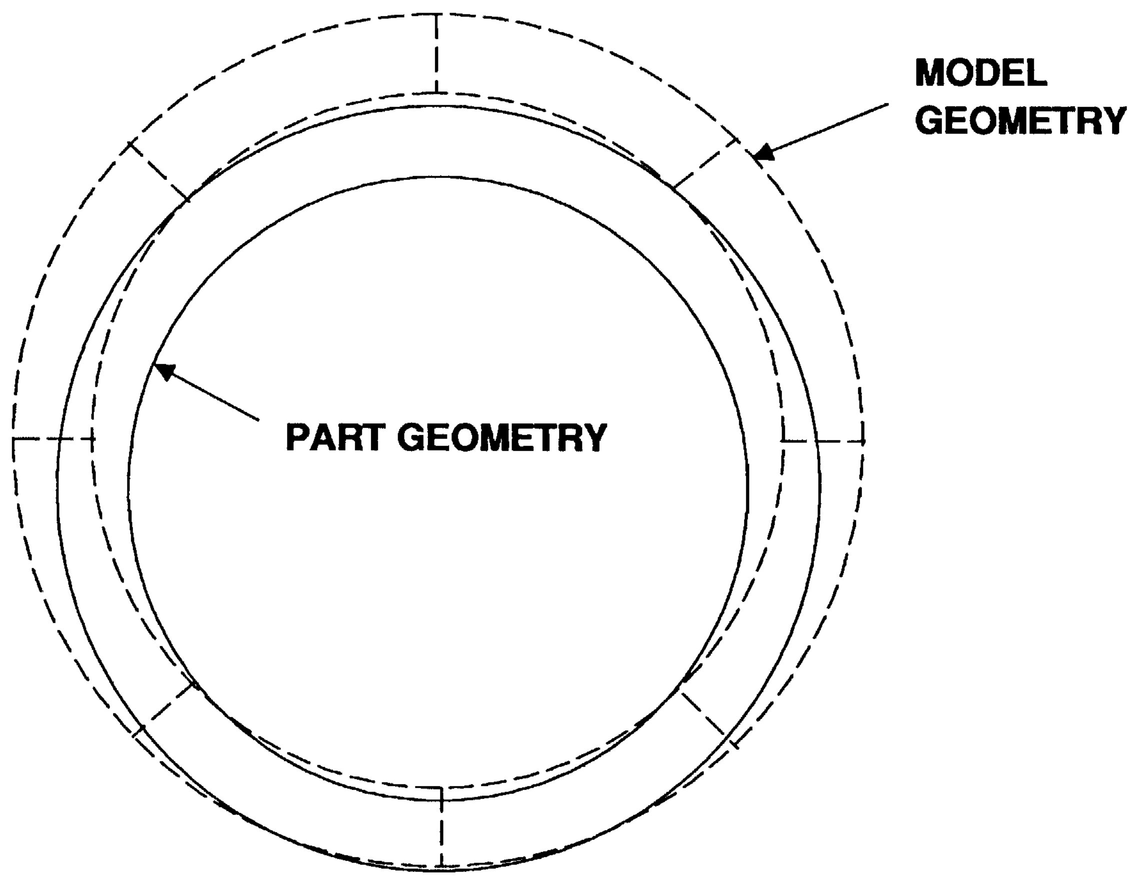
MUST MATCH GEOMETRY OF PART TO GEOMETRY OF ANALYSIS MODEL

CARE MUST BE TAKEN WITH HOW NDE VOXELS ARE USED TO INTERPOLATE VALUES AT INTEGRATION POINTS

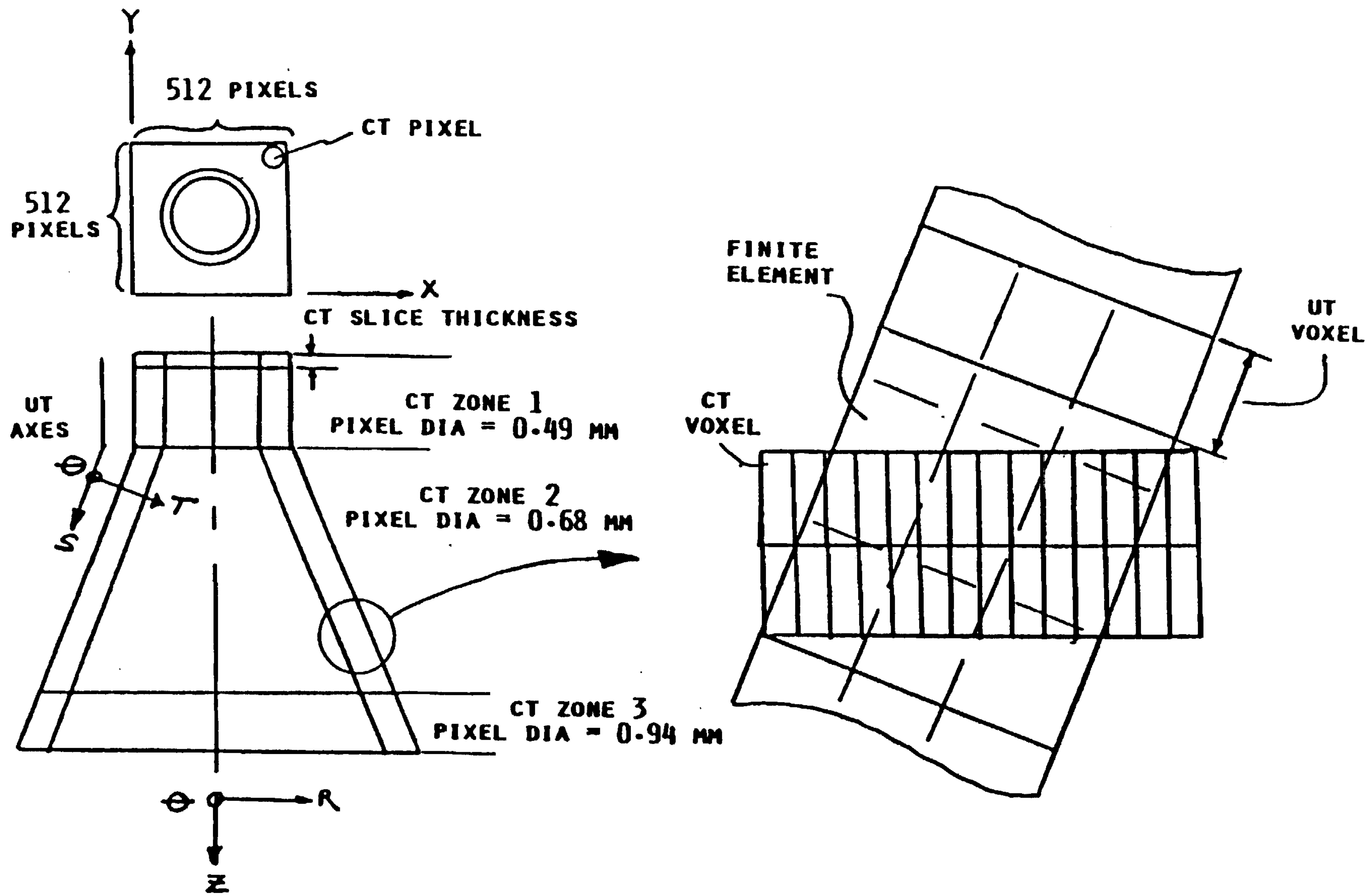
A SUBSTANTIAL EFFORT WILL BE REQUIRED TO DETERMINE CORRELATIONS BETWEEN NDE INDICATIONS AND ANALYSIS INPUT

IF MULTIMODE NDE DATA IS REQUIRED THEN WEIGHTING OF EACH TYPE OF DATA MUST BE DETERMINED

MATCH GEOMETRIES OF PART AND MODEL



NDE VOXELS – FINITE ELEMENT MESH OVERLAY



SUMMARY

DEMONSTRATED A METHODOLOGY FOR INCORPORATING QUANTITATIVE NDE DATA IN FINITE ELEMENT ANALYSIS

CORE OF REMAINING PROBLEM IS THE DEVELOPMENT OF CORRELATIONS BETWEEN NDE INDICATIONS AND MATERIAL PROPERTIES

IF PROBLEM REQUIRES MULTIMODE NDE DATA, THE RELATIVE IMPORTANCE OF EACH DATA TYPE MUST BE ESTABLISHED

ADVANCED TECHNIQUES FOR EXAMINATION OF COATINGS

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ornl

Proceedings for
NDE for Aerospace Requirements Conference
Huntsville, Alabama

COATINGS OF ONE MATERIAL ON ANOTHER TO PROVIDE DESIRED SURFACE PROPERTIES ARE A VITAL PART OF INDUSTRY

- Especially important for critical components
- Allows less expensive materials for structure
- Coatings provide resistance to corrosion, abrasion, erosion, contact stresses, and other environmental attack (e.g., temperature or chemical)
- Protection may not be attainable through other fabrication methods
- Applications include textile, paper, petrochemical, and metal-processing, as well as aerospace industries

ALTHOUGH COATINGS ARE WIDELY USED, USE WOULD INCREASE WITH BETTER ABILITIES TO ASSURE INTEGRITY AND PROPERTIES

- A major problem for many coatings is poor or uncertain adherence of coating to substrate with thermal cycles (or other stress)

- Other properties of concern include thickness, lack of bond, delamination, flaws (porosity, cracks, etc.) microstructure, and homogeneity

- Relative importance of above properties can vary with type of coating and the service environment

- Nondestructive testing (NDT) techniques are beneficially used to evaluate many of these properties of coatings after fabrication and service; advances are needed for improved quantitative data

A WIDE VARIETY OF NDT TECHNIQUES ARE CURRENTLY USED FOR EXAMINATION OF COATINGS; A NON-EXHAUSTIVE LISTING INCLUDES:

- **Thickness:** electromagnetic (eddy-current and magnetic methods), ultrasonic, optical (for transparent coatings), penetrating radiation (e.g., x-ray fluorescence, beta backscatter), thermal
- **Lack-of-bond:** thermal, ultrasonic, acoustic, optical holography
- **Flaws:** electrical continuity, fluid penetrant, ultrasonics, optical holography, thermal

PROBLEMS AFFECTING CURRENT NDT PRACTICE FOR SOME APPLICATIONS INCLUDE:

- Thickness
  - variations in electrical or magnetic properties of coating or substrate affect eddy-current and magnetic techniques
  - inhomogeneities in coating or substrate can affect penetrating-radiation techniques
  - ultrasonic technique requires adequate thickness for resolution and acoustic mismatch between coating and substrate
  - IR thermal techniques can be affected by relative emissivity

- Lack of bond
  - IR thermal techniques can be affected by emissivity
  - bond must be stressed for optical holography
  - ultrasonic techniques require adequate thickness for resolution

- Flaws
  - electrical continuity requires electrical contact with substrate and completely-through flaw
  - ultrasonics and holography may be useful for cracks or other linear flaws; probably not for porosity
  - fluid penetrant affected by natural background of acceptable porosity
  - optical holography requires application of stress

- Adherence
  - with few exceptions, techniques are unavailable for quantitative nondestructive evaluation of coating adherence

RECENT ADVANCES IN NDT TECHNOLOGY OFFER IMPROVED CAPABILITY OR POTENTIAL TO OVERCOME SOME OF THE PROBLEMS FOR COATING EVALUATION

- Multi-frequency and pulsed multiple-parameter eddy-current technology provides the capability to correct for variations in electrical and magnetic properties of coating and substrate
  - two- and three-frequency instruments that simultaneously measure phase and magnitude of all frequencies and process in nonlinear algorithms to correct for variables and solve for 4-6 unknowns (e.g., thickness, conductivity, permeability, etc.)
  - pulsed (and magnetic-saturation) instruments as another approach for ferromagnetic materials for multiparameter analysis

- High-temperature probes offer potential for application to process control

- Ultrasonic guided boundary waves (interface waves) are being investigated by ORNL and others for evaluation of interfaces in bonded structures
  - models developed at ORNL for three-layer interfaces for ceramic joints
  - transmission along interface offers potential for for evaluation and analysis of interface properties (e.g., bond strength)

COATINGS ARE EXPECTED TO BE INCREASINGLY USED TO INCREASE COMPONENT LIFE

- Nondestructive testing will play a vital role for process control, fabrication acceptance, and in-service inspection

- Improved NDT technology will increase the role for both NDT and coatings