ADVANCES IN NONDESTRUCTIVE EVALUATION TECHNOLOGY

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INTRODUCTION

Quantitative nondestructive evaluation (NDE) is becoming one of the fastest growing fields paralleling the importance of technology in most specializations. Materials are being pushed to their limits of strength, life, and temperature with extreme pressure on economy, requiring quantitative measurement to characterize materials' properties. Development of new sensors, technologies, and applications is at an exciting threshold. However, of most importance, a fundamental understanding of the physical limitations of a given technology is helping to focus research on those topics that have the highest potential of a major breakthrough.

Research at NASA Langley's Materials Characterization Instrumentation Section has followed the philosophy of improving the science base of NDE and advancing the state of the art of quantitative interpretability of physical measurements of materials. (See fig. 1.) Most of the effort has been applied to advanced ultrasonics. New methods are evolving that separate materials' parameters, in contrast with some conventional methodologies in which several different properties simultaneously affect the choosen measurement. Thus separated, "images" of materials similar to X-ray photos may be studied independently. One such image may be material elastic properties, another may represent material stress, while a third may localize material attenuation. These additional quantitative results can have considerable impact on the correct interpretation of NDE data for a critical part.

In this paper we shall examine details of several R&D programs choosen to highlight our last several years. A brief look at acoustic nonlinear theory will introduce the basis upon which some exciting instrumentation has been developed. Applications of these technologies will be presented in the area of stress measure ment, characterization of metal heat treatment, and evaluation of material internal structure. A second focus of the program is on quantitative transducers/measurements that have resulted in better data in irregular inhomogeneous materials such as composites. Examples are presented of new capabilities resulting from these advances that include fatigue and impact damage evaluation.

The future of the research program is most exciting with new imaging and measurement theories being combined with new physical understanding of materials. At present, our future programs thrust will focus on linear and nonlinear acoustics, thermal mapping for flaws, new sensors, and, of most importance, a science base upon which all these concepts must be built. To build without improving the science base is to risk a stale technology.

NONDESTRUCTIVE RESEARCH AT NASA LANGLEY

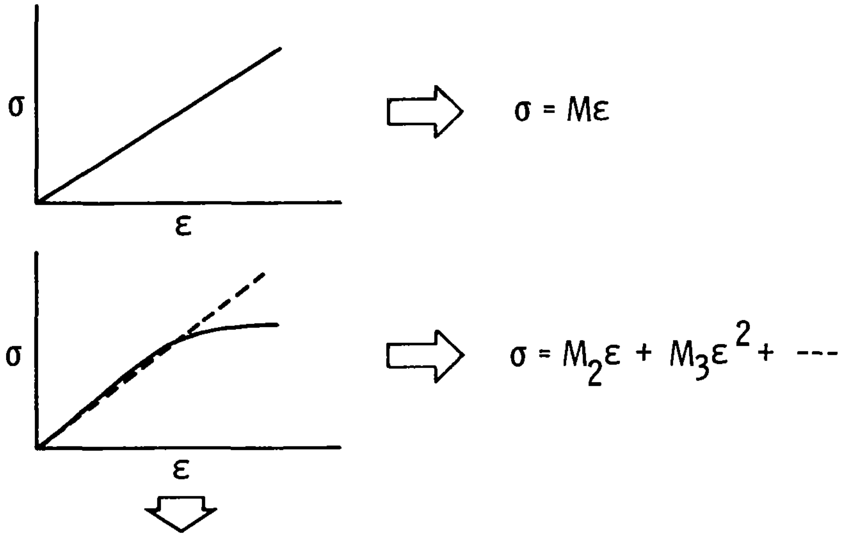
- IMPROVE SCIENCE BASE OF NDE
- DEVELOP MATERIAL MEASUREMENTS WHICH DEPEND ON ISOLATED MATERIAL PROPERTIES
- IMPROVE INTERPRETABILITY OF NDE IMAGES
- ADVANCE THEORY/APPLICATIONS OF NONLINEAR ACOUSTICS
- IMPROVE MEASUREMENTS OF MATERIAL STRESS
- IMPROVE TECHNOLOGIES FOR STRUCTURAL NDE

Figure 1

THEORY OF NONLINEAR ACOUSTICS

Figure 2 presents in a simplified fashion a stress-strain curve of two materials. The upper curve shows a "linear" material response and the Hookeian equation that describes the material behavior. In reality, higher order elastic properties are already "operating" on the material behavior, even in the straight-line figure. The lower curve shows gross nonlinearity that requires many terms in the non-Hookeian equation to correctly describe its behavior. For both of these cases nonlinear acoustics has played an important role in measuring material properties.

Our nonlinear acoustics research program is developing the correct physical models that describe how important material properties can be measured. For example, current research on stress in materials has resulted in a model of material elasticity that includes for the first time the important contributions of residual stress. Other theoretical efforts have identified thermodynamic properties of materials that may result in a measurement technique capable of determining internal material stress/strain. A long-term goal of the program is to develop elements of an equation of state for solids to understand how to quantitatively measure important material properties.



NONLINEAR MATERIAL PROPERTIES

- ENGINEERING MODULUS DEPENDS ON STRAIN AND STRAIN RATE
- MATERIAL THERMODYNAMIC PROPERTIES (e.g. COEFFICIENT OF THERMAL EXPANSION, THERMAL CONDUCTIVITY)
- IMPACT STRENGTH - SHOCK WAVE EFFECTS
- OPTICAL REFRACTIVE INDEX VARIATIONS WITH RESPECT TO σ, TEMPERATURE

Figure 2

APPLIED LOAD CHANGES ACOUSTIC SPECTRA

Figure 3 shows the experimental acoustic spectra of a simple threaded fastener for four levels of applied load. The spectra predicted from acoustic theory represent the resonances of the tested bolt in the range of the 200th harmonic. With increasing stress load, each harmonic shifts down in frequency as shown in the figure. The linear shift with respect to stress is predicted from acoustic nonlinear theory and can be used to determine preload in critical fasteners. These tests have led to the development of precision measurement instruments which are capable of determining stress in critical fasteners.

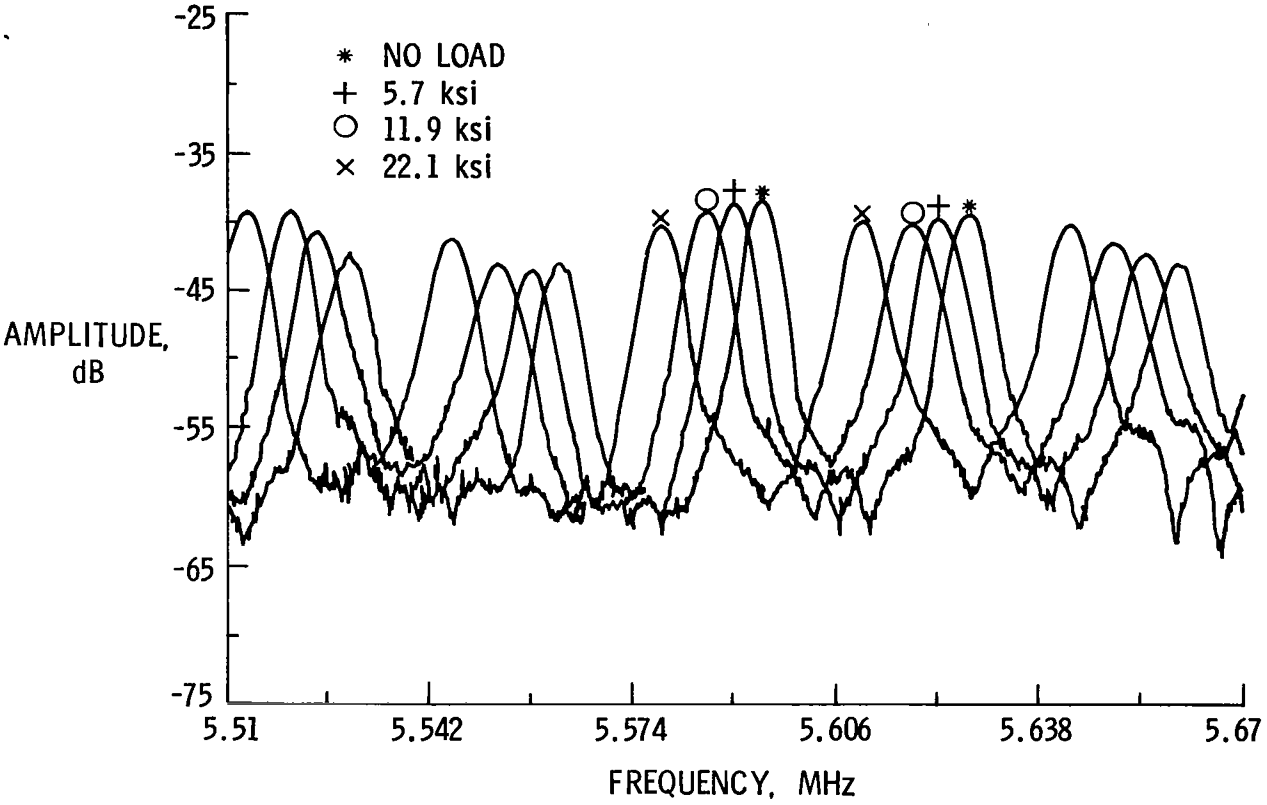


Figure 3

NEW ULTRASONIC STRAIN MEASUREMENT TECHNIQUE

When a solid is placed under tension, it not only elongates, it also undergoes a change in sound speed as predicted by nonlinear theory. The change in acoustic properties is similar to the combined effects of elongating a pipe organ tube (strain) and replacing the tube's air with a gas of lower sound speed. The resulting tone will decrease. As shown in figure 4, a stress of 54 ksi applied to an aluminum rod produced a normalized frequency decrease of $\Delta v/v = 16 \times 10^{-3}$. Strain for that same load was 6×10^{-3} and normalized acoustic velocity decrease was $\Delta v/v = 16 \times 10^{-3}$.

This data shows that the state of the art for ultrasonic technology/analysis has reached that of strain gages. An additional important feature is that the ultrasonic system measures strain directly in the member being strained, not in an externally applied gage to which the strain must be coupled. This improvement in measurement technology goes far beyond strain sensing. It represents a new tool for materials testing allowing higher order elastic properties to be easily determined.

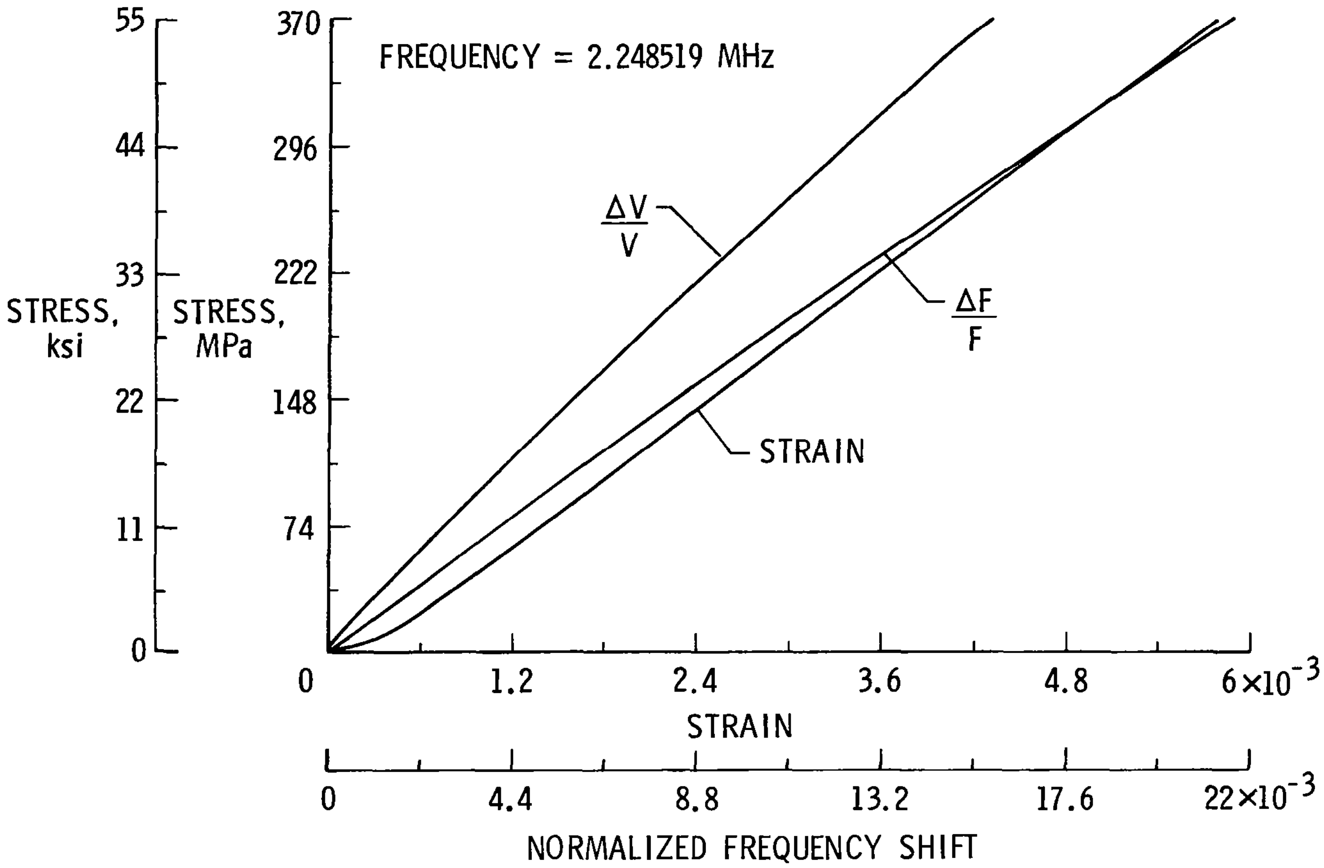


Figure 4

The data in figure 5 was obtained from the same threaded rod (not a standard tensile geometry) of the previous figure after it was annealed to simulate thermal loss of strength. Instead of failure occurring at a load of 54 ksi, the aluminum plastically flowed at 28 ksi and failed at 39 ksi. Measurements of sound velocity at zero load (related to the second-order modulus) showed little variation between quenched and annealed material and thus are not useful for identifying "soft" aluminum.

The nonlinear acoustic properties, however, measured from the "linear range" of this figure have been able to clearly identify the "soft" aluminum. The most sensitive of these parameters is the normalized shear wave change in frequency per unit stress. A 30-percent change occurred from annealed to quenched in that parameter for these tested samples. In similar tests we have applied advanced nonlinar acoustic measurements to stressed materials to examine new methods of determining residual stress.

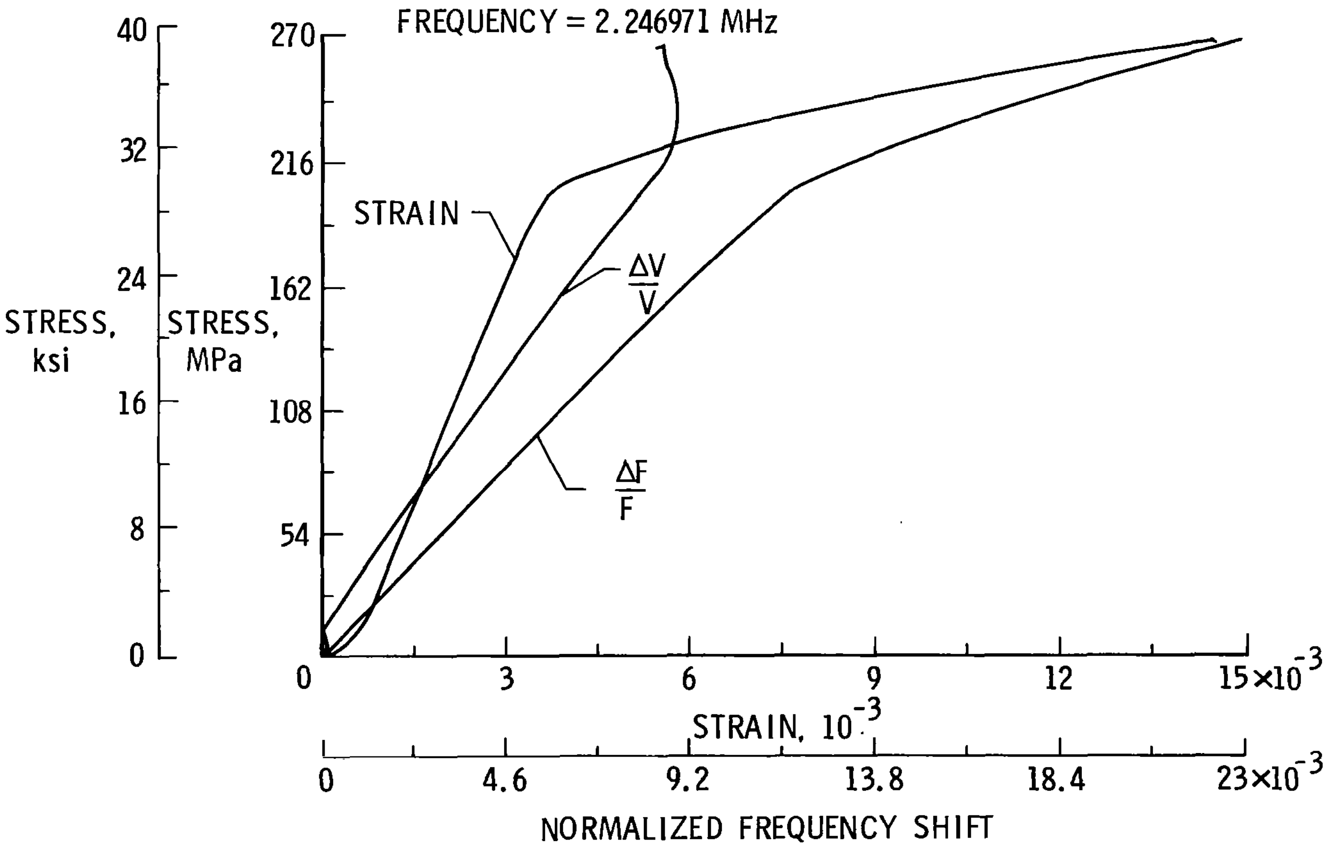


Figure 5

ULTRASONIC C-SCAN TECHNOLOGY

Ultrasonic C-scans represent an outstanding method of investigating internal properties of materials nondestructively. In effect, the resulting data appears as an ultrasonic "X-ray" - that is, an image of the tested part projected on a two-dimensional plane. In general, a transducer source emits ultrasonic waves that are usually focused by a lens and propagate through a material to a receiving transducer. Usually, a liquid couplant or bath used to increase the coupling efficiency requires a water tank or "squirters" for the test. The transducers (used singly in reflection or in pairs) are moved in a scanning configuration, building up an acoustic image of the material (fig. 6). We have developed extensive technological improvements in analysis and instrumentation for C-scan measurements. Examples include tone burst spectroscopy for quantitative measurements, spectral line fitting for data analysis, and integrated backscattering for improved imaging.

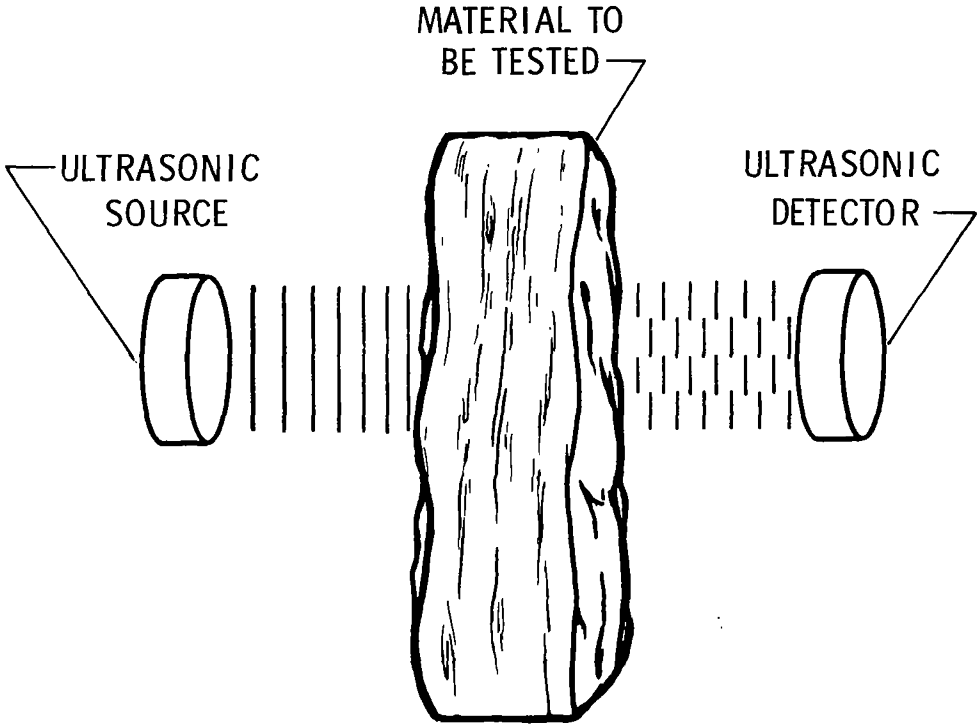
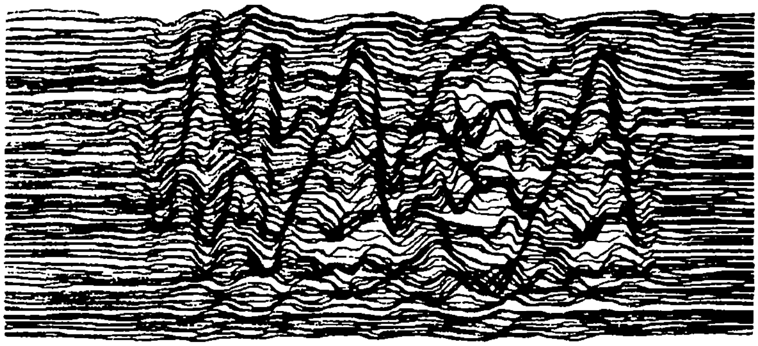


Figure 6

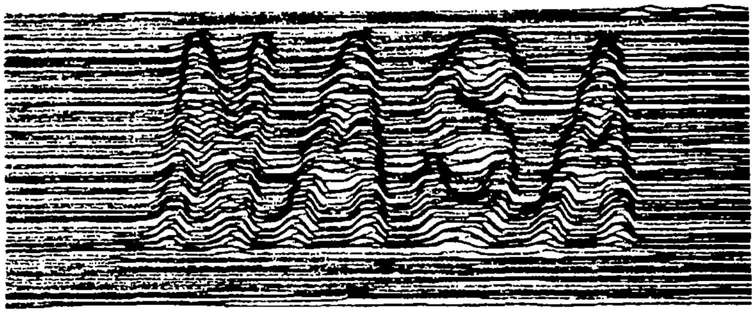
NEW TRANSDUCER TECHNOLOGY FOR NDE

One of the most severe limitations of the current quality of NDE images is the transducer itself. Conventional transducers are phase sensitive and as such are affected by the shape of the acoustic phase front incident on them. For accurate measurement of acoustic attenuation in materials, a phase-insensitive device is necessary. We have developed the first practical acoustic power detector that is insensitive to wave front phase distortion.

Figure 7 shows two ultrasonic C-scan images of the letters "NASA" machined in a metal plate. The upper image, obtained with conventional phase-sensitive transducers (PZT), is highly distorted by phase artifacts, especially at letter interfaces. The lower figure, obtained with our phase-insensitive acousto-electric transducer (AET), shows clear letters, representing a more quantitative measurement technique.



PZT



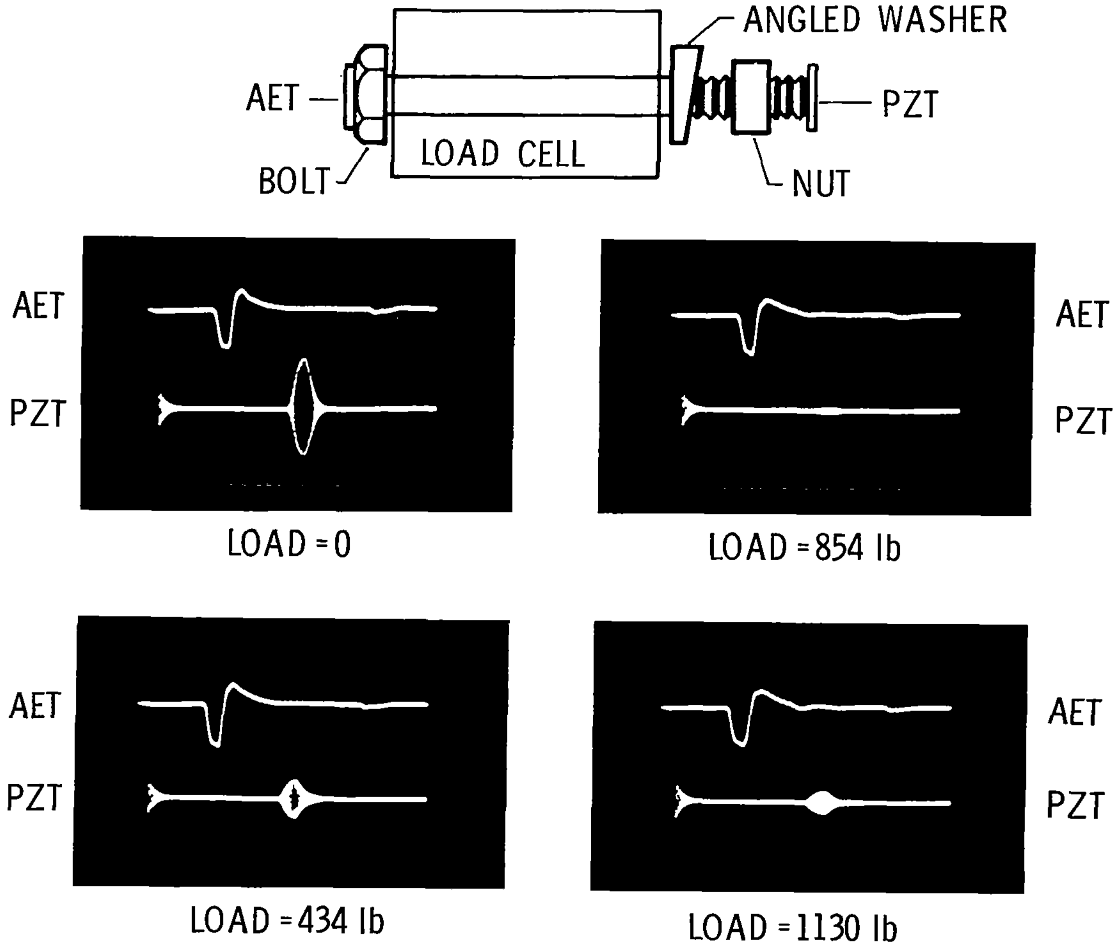
AET

Figure 7

APPLICATION OF THE AET FOR QUANTITATIVE NDE

The phase-insensitive AET discussed in the previous figure represents a significant improvement in the state of the art for absorption measurements. An example of the improved accuracy of ultrasonic absorption measurements is shown in figure 8. A threaded fastener is shown loaded asymmetrically by an angled washer. A conventional PZT transducer mounted on the right side of the bolt was used to generate and measure an ultrasonic wave. The phase-insensitive AET mounted on the left of the bolt also measured the ultrasonic wave.

The four oscilloscope photos show the effect of increasing load on the bolt. Note that the PZT signal decreases, nulls, and then increases with load while the AET signal remains constant. There is no actual loss of acoustic amplitude for this case, only a "wrong" signal from the PZT caused by phase cancellation. Artifacts such as this may lead to incorrect analyses of critical parts and costly unnecessary repairs.



LOAD = 0

LOAD = 854 lb

LOAD = 434 lb

LOAD = 1130 lb

Figure 8

TONE BURST ACOUSTIC SPECTROSCOPY (TBS)

The block diagram (fig. 9) below shows a new acoustic spectroscopy system that eliminates gating influences on spectra. Conventional acoustic spectroscopy utilizes short pulses or step-like signals. The Fourier transform of such signals depends on the detailed pulse rise, pulse width, and pulse fall, which influence the spectra measured for pulse propagation through samples. Also, since all the energy is generated in a short period of time (typically nanoseconds), the pulse is quite large in amplitude, leading to nonlinearities in the transducer.

In contrast, the TBS technique uses wide signal gates (several microseconds), which require lower amplitude signals but over longer times. By tracking the frequency emitted by the gates with a spectrum analyzer, a pure acoustic spectra is obtained without gating artifacts.

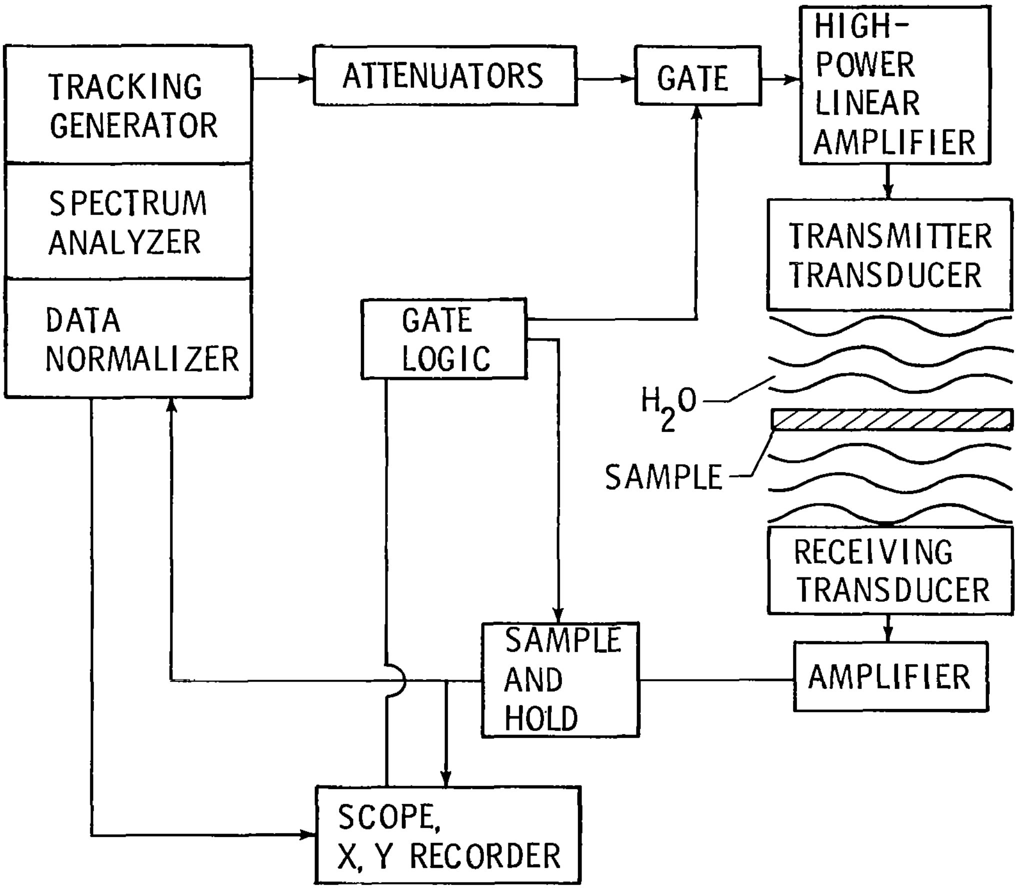


Figure 9

AET POWER SPECTRA OF COMPOSITES

The data in figure 10 was obtained by combining the TBS system of the previous figure with the AET power transducer to achieve a first for irregular inhomogeneous material - clear spectral characterization for NDE analysis. The acoustic spectra represent longitudinal standing harmonic modes of the sample, which was a laminated graphite/epoxy composite.

The composite sample was clamped in a test machine and fatigued until cracks developed on the sample sides. The cracks were measured with a replicating technique and the fatigued samples were ultrasonically examined. The fatigue-induced damage increased the acoustic absorption, decreasing the amplitude of the resonance spectra, as shown in the figure. Such research may result in a measurement technology capable of assessing the degree of fatigue damage in composites.

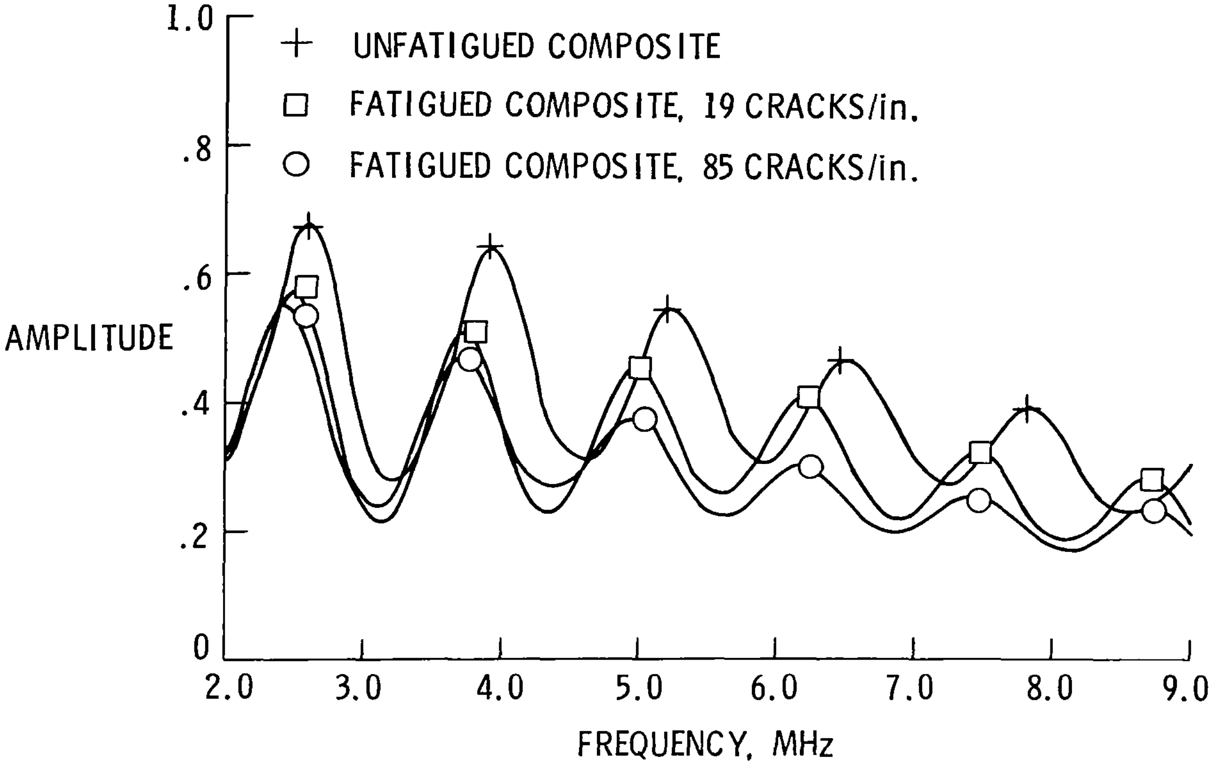


Figure 10

TRANSDUCER MEASURES 10^{-8} INCHES

A new broadband electrostatic transducer measures displacement of less than 10^{-8} inches in water. The high-resolution capability of this newly patented device is a result of a novel fabrication technique insuring exacting parallelism of elements and internal pressurization to maintain precision internal spacing. The transducer is simply a capacitor with one stationary plate and one "plate" composed of an 11-mm-thick metal film (fig. 11). This device has been used to examine absolute ultrasonic wave amplitudes with frequencies up to 30 MHz. It has been quite successful as a standard to which other transducers may be compared.

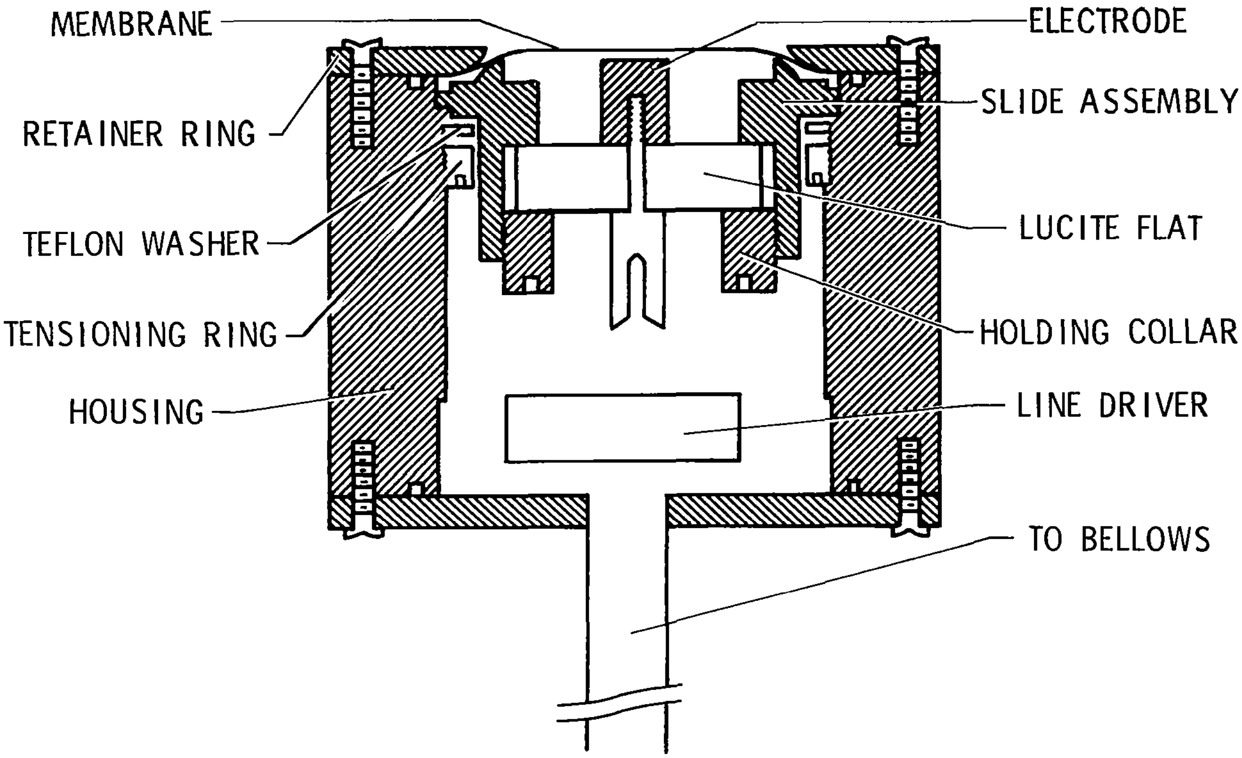
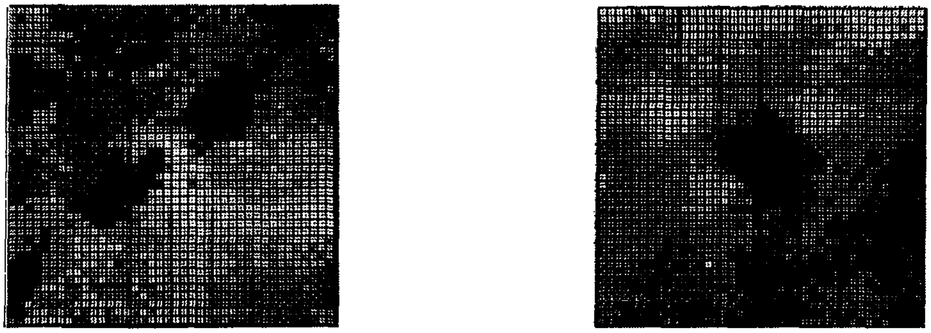


Figure 11

QUANTITATIVE NDE IMAGING

This advanced C-scan (fig. 12) brings together many subelements of our NDE research program. The details shown are of impact damage to a graphite/epoxy composite based on tone burst spectroscopy combined with a power transducer (AET). The image on the right shows surface damage only at the site of impact since the physics of the imaging represents impedance reflections. Using the same C-scan data we obtained an image based on the slope of the attenuation versus frequency curve, which is independent of impedance. Thus, a totally different image was generated from the same data, representing different material physics. The slope data shows damage off center from the impact on a 45° ply. This internal damage, not seen with conventional methods, represents attenuation mechanisms such as scattering from cracks.



SLOPE, dB/MHz-cm

INTERCEPT, dB

ACOUSTOELECTRIC RECEIVER

4 TO 8 MHz

Figure 12

IN SITU FIBER SENSOR FOR COMPOSITE STRAIN AND ACOUSTIC EMISSION

Figure 13 shows a block diagram of an optical fiber interferometer developed to improve the reliability of composites through monitoring. The technique involves optically coupling reference fibers to fibers embedded in the composite matrix. The result is a set of optical fringes which, when spatially filtered, results in an optical signal proportional to strain. Results of an acoustic emission event (left) and cantilever beam strain (right) are shown.

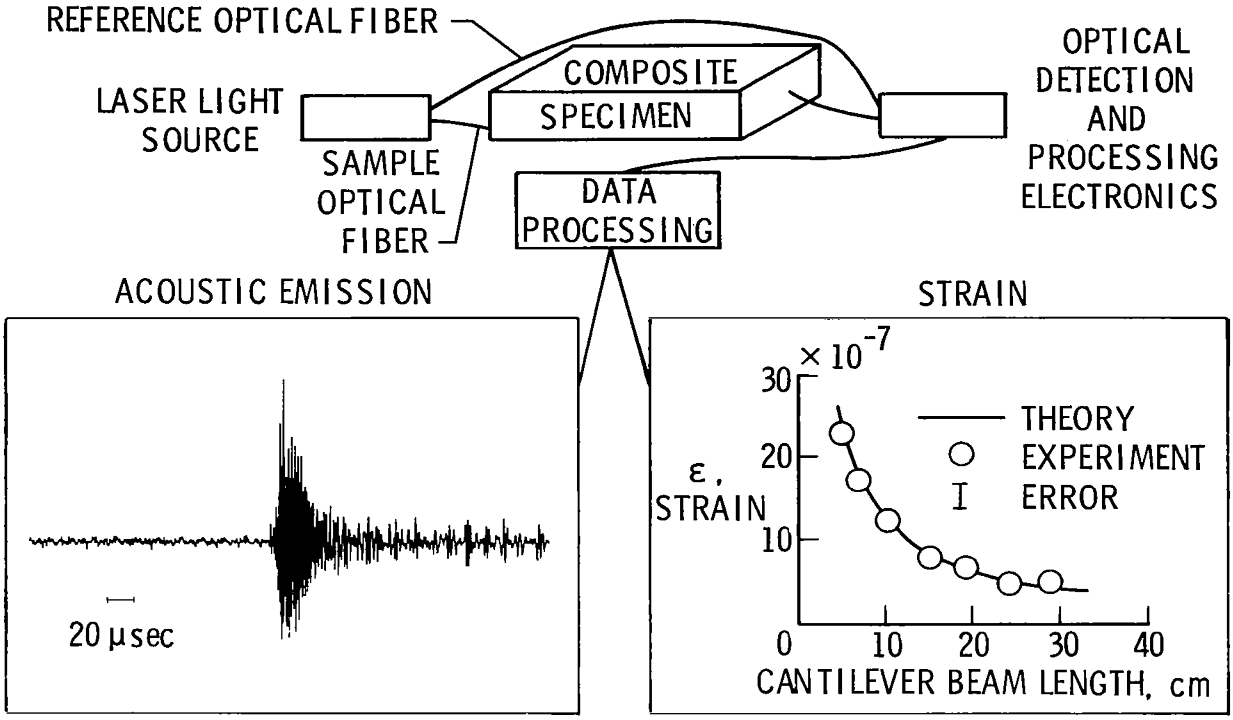
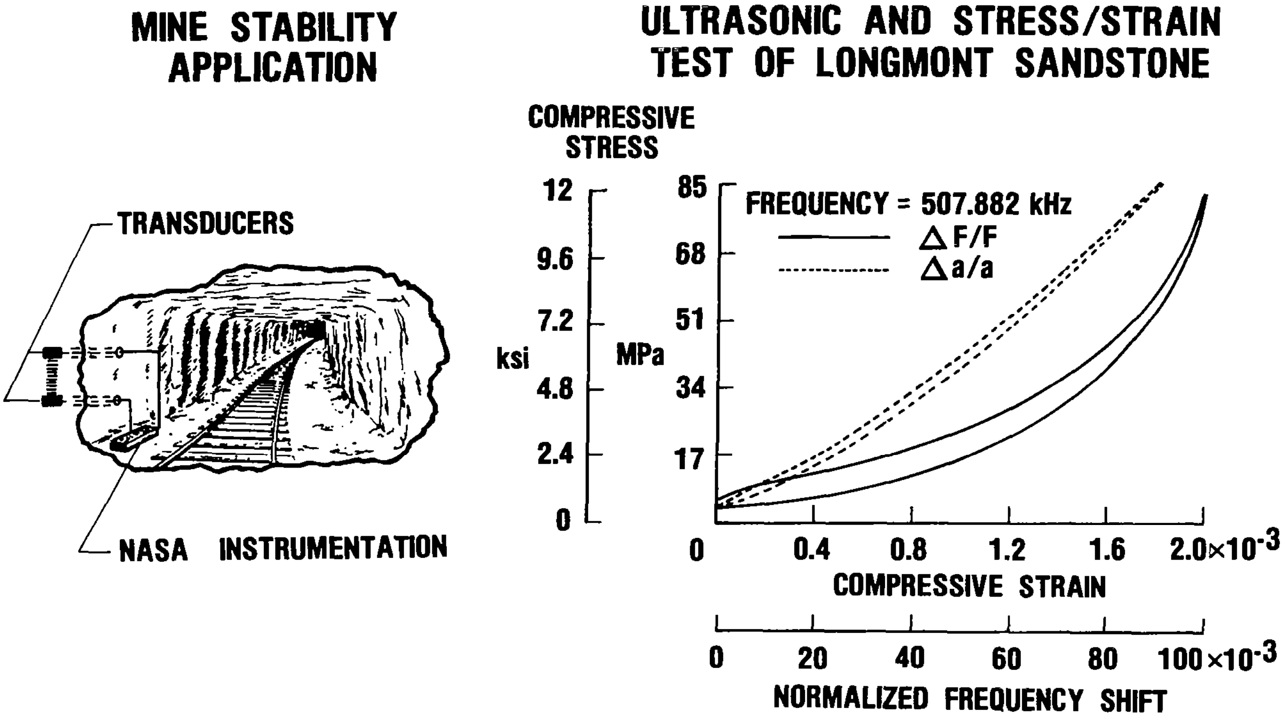


Figure 13

ULTRASONIC TECHNOLOGY UTILIZATION-MINING

Two applications of our in-house research on ultrasonic propagation in stressed solids have helped improve mining technology. The first is a mine roof bolt tension monitor that measures bolt tension ultrasonically. The second (fig. 14) is an in situ rock strain sensor. The figure on the left shows an artist's impression of how the system would function in a mine shaft. The figure on the right shows a compressive test on Longmont sandstone, comparing the sensitivity of strain gage data ($\Delta a/a$) with that of ultrasonic data ($\Delta F/F$). The relative change in natural velocity in the $\Delta F/F$ curve shows that the ultrasonic sensor is 100 times more sensitive to the applied load than the conventional strain gage, and, more importantly, it measures strain directly in the rock itself.



MINE STABILITY APPLICATION

ULTRASONIC AND STRESS/STRAIN TEST OF LONGMONT SANDSTONE

Figure 14

ULTRASONIC TECHNOLOGY UTILIZATION - SKIN BURNS

A technique developed in part by one of our researchers is being optimized to detect the level of burn damage to human skin. The treatment of skin burn would improve significantly if the burn physician could distinguish third-degree burns (killed tissue) from second-degree burns (viable tissue). In this technique a short high-frequency wave is launched into the tissue in question. The depth of burn, which is related to the degree of burn, is measured from the ultrasonic signal. As shown in figure 15, the technique detects the outer layer of skin (epidermis), the burn interface (depth of burn), and the fat interface (total depth of skin tissue). With this technique optimized for skin burn analysis, the prognosis for burn patients may improve significantly.

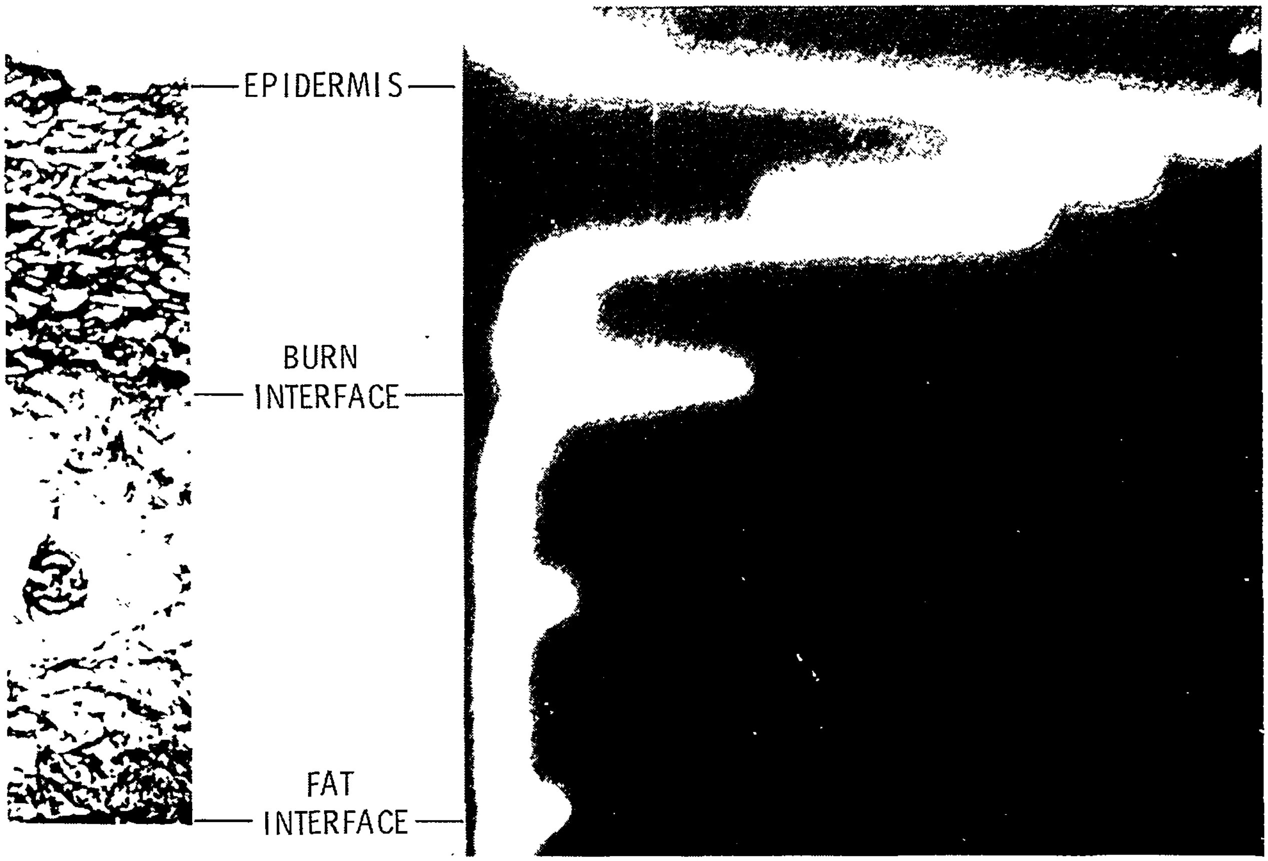


Figure 15

CONCLUSION

This paper has examined nondestructive research at NASA Langley Research Center. In order to fully meet the challenge of the future we must address problems of nondestructive measurements in materials (fig. 16).

- WE MUST IMPROVE NDE SCIENCE BASE
- IMPROVE NDE TECHNOLOGY
- DESIGN FOR INSPECTION
- DEVELOP QUANTITATIVE MATERIALS CHARACTERIZATION INSTRUMENTATION

Figure 16

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