# DETERMINING BONDING, THICKNESS, AND DENSITY VIA THERMAL WAVE IMPEDANCE NDE

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Bonding, density, and thickness of coatings have a vital effect on their performance in many applications. Pioneering development work by the author on thermal wave nondestructive evaluation (NDE) methods during the past 25 years has resulted in an array of useful techniques for performing bonding, density, and thickness measurements in a practical shop environment. The most useful thermal wave methods for this purpose are based on thermal wave surface impedance measurement or scanning. A pulse of heat from either a thermal transducer or a hot gas pulse is projected onto the surface, and the resulting temperature response is analyzed to unfold the bonding, density, and thickness of the coating. An advanced emissivity independent infrared method has been applied to detect the temperature response. These methods have recently been completely computerized and can automatically provide information on coating quality in near real-time using the proper equipment. Complex shapes such as turbine blades can be scanned. Microscopic inhomogeneities such as microstructural differences and small, normal, isolated voids do not cause problems but are seen as slight differences in the bulk thermal properties. Test objects with rough surfaces can be effectively nondestructively evaluated using proper thermal surface impedance methods. No contact with the test object is required, and no couplants or other contaminants are used. Thermal wave NDE might be called a "Wave of the Future", as well as a "Wave at the Past". Recent work done on thermal wave NDE by independent groups in the U.S., as well as abroad, has confirmed the potential of some of these methods for practical coating NDE applications. Some of the basic principles involved, as well as metallographic results illustrating the ability of the thermal wave surface impedance method to detect natural nonbonds under a two-layer thermally sprayed coating, will be presented in this paper.

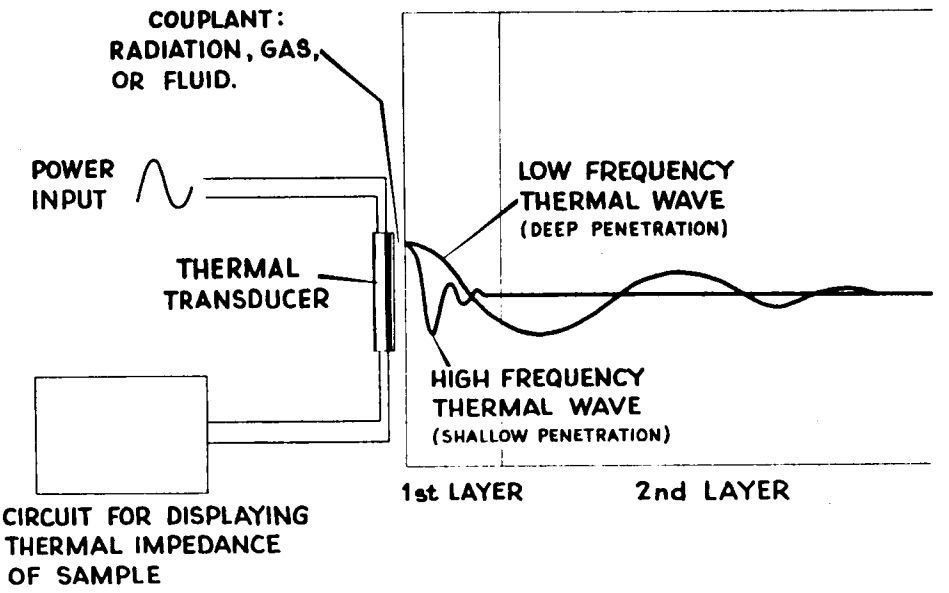
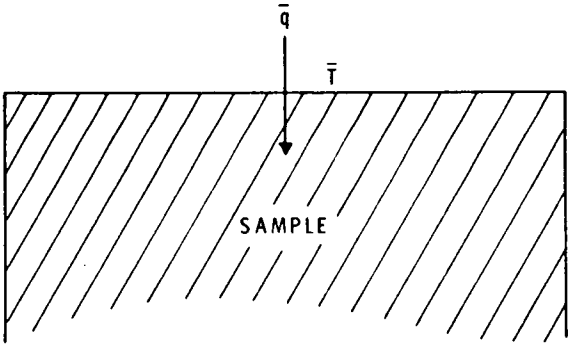



Figure 1.




FOR SINUSOIDAL $\bar{q}$ AND $\bar{T}$, THE THERMAL SURFACE IMPEDANCE IS DEFINED AS

$$Z = \left[\frac{\bar{T}}{\bar{q}}\right]_{x=0}$$

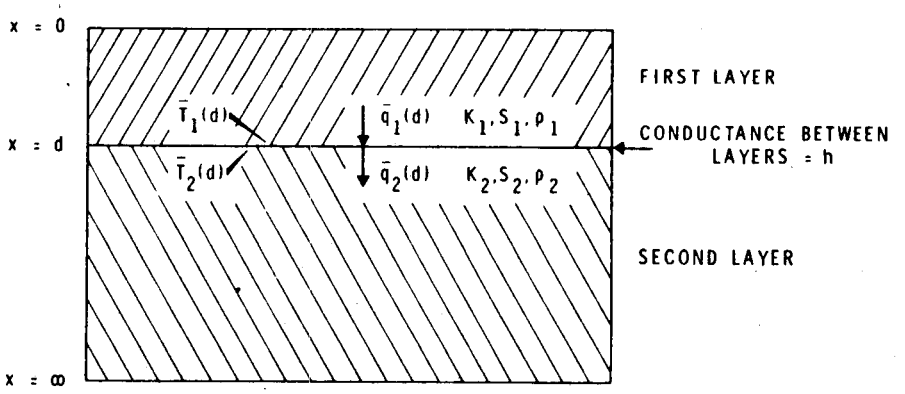
Figure 2.

$$\text{Heat Flow, } g = C\, e^{-(1-j)x/\delta} \qquad (1)$$

$$\text{Penetration Depth, } \delta = \sqrt{\frac{K}{\pi f S \rho}} \qquad (2)$$

$$\text{Surface Thermal Impedance, } Z = \left[T/q\right]_{x=0} \qquad (3)$$

Figure 3.




BOUNDARY CONDITIONS

$$\lim_{x \to \infty} \bar{q} = 0$$

$$\bar{q}_1(d) = \bar{q}_2(d)$$

$$\bar{T}_1(d) = \bar{T}_2(d) + \frac{\bar{q}_2(d)}{h}$$

Figure 4.

# THERMAL SURFACE IMPEDANCE FOR A LAYER IN GOOD CONTACT WITH A SEMI-INFINITE SECOND LAYER

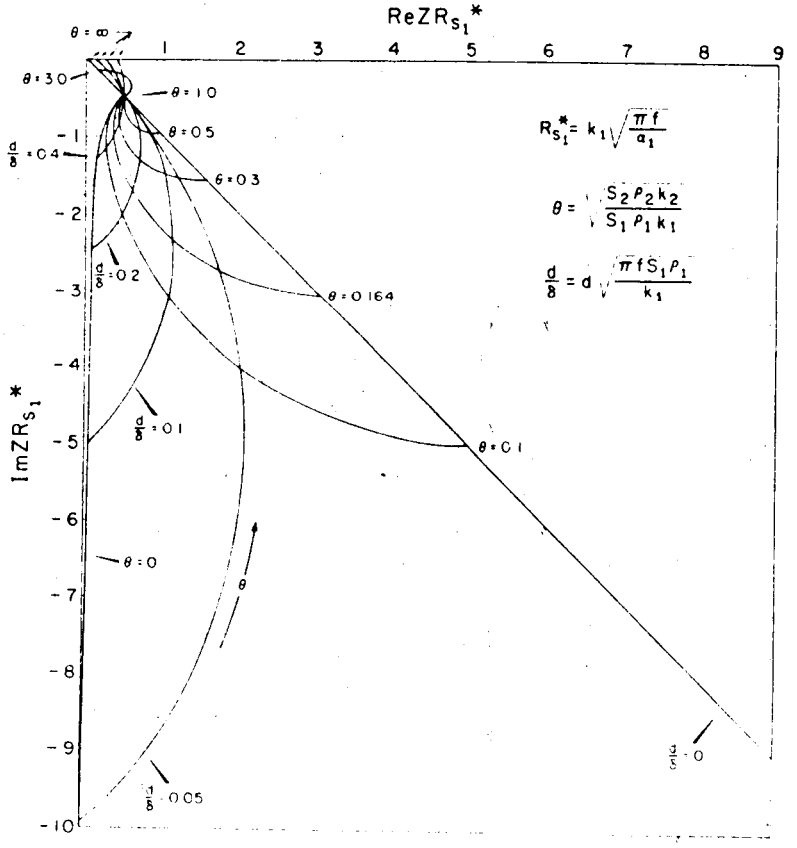
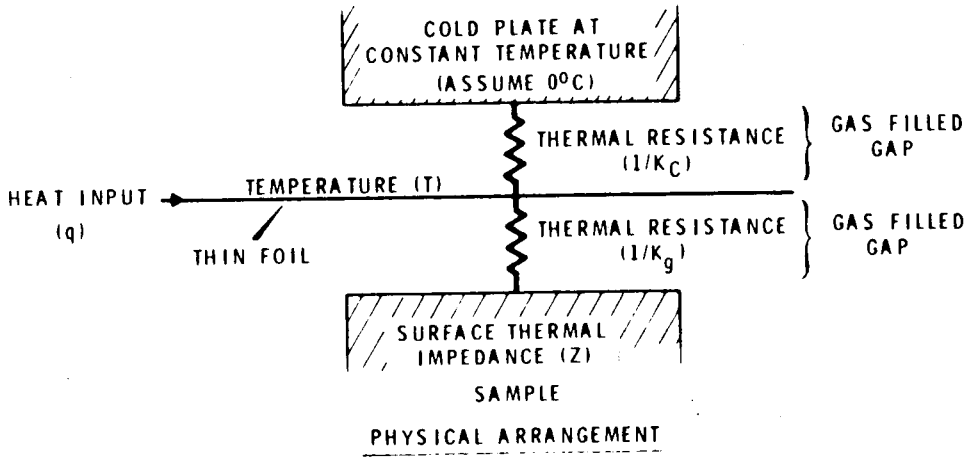
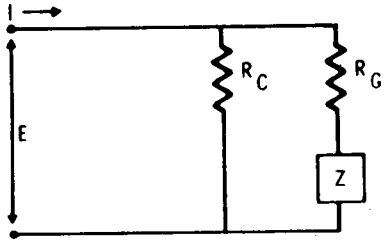



Figure 5.

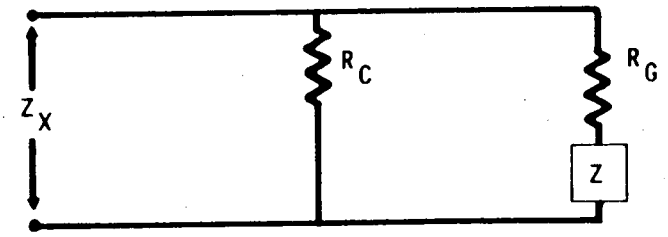



| ELECTRICAL QUANTITY | THERMAL EQUIVALENT |
|---|---|
| E | T |
| I | q |
| R | 1/K |
| Z = E/I | Z = T/q |

Figure 6.

RELATIONSHIP BETWEEN THERMAL INPUT IMPEDANCE OF TRANSDUCER, AND THERMAL SURFACE IMPEDANCE OF SAMPLE




$$\frac{1}{Z_X} = \frac{1}{R_C} + \frac{1}{R_G + Z}$$

HENCE

$$Z = \frac{R_C Z_X}{R_C - Z_X} - R_G$$

AND

$$Z_X = \frac{R_C(R_G + Z)}{R_C + R_G + Z}$$

Figure 7.

BLOCK DIAGRAM OF THE SINUSOIDAL THERMAL WAVE TESTER



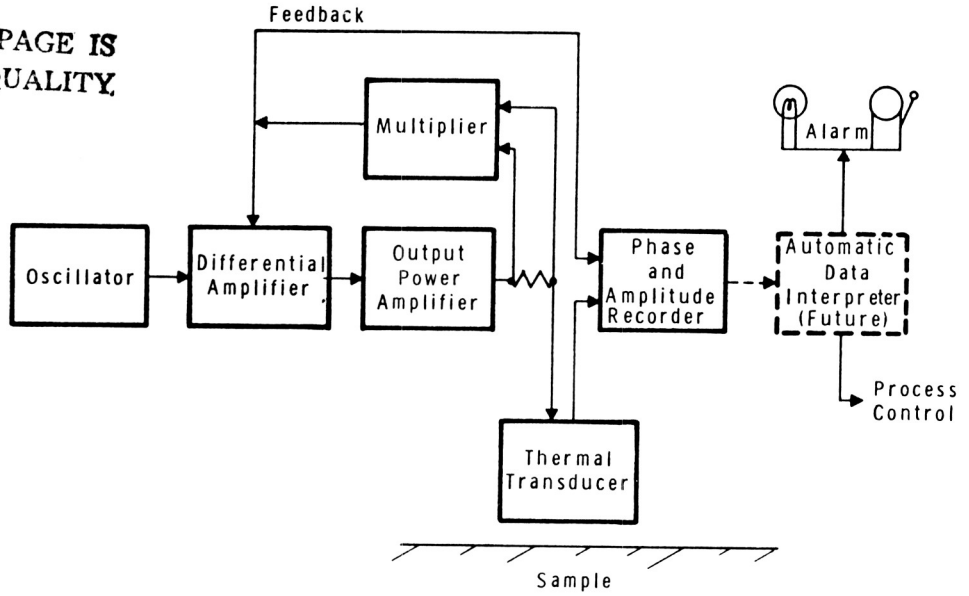



Figure 8.

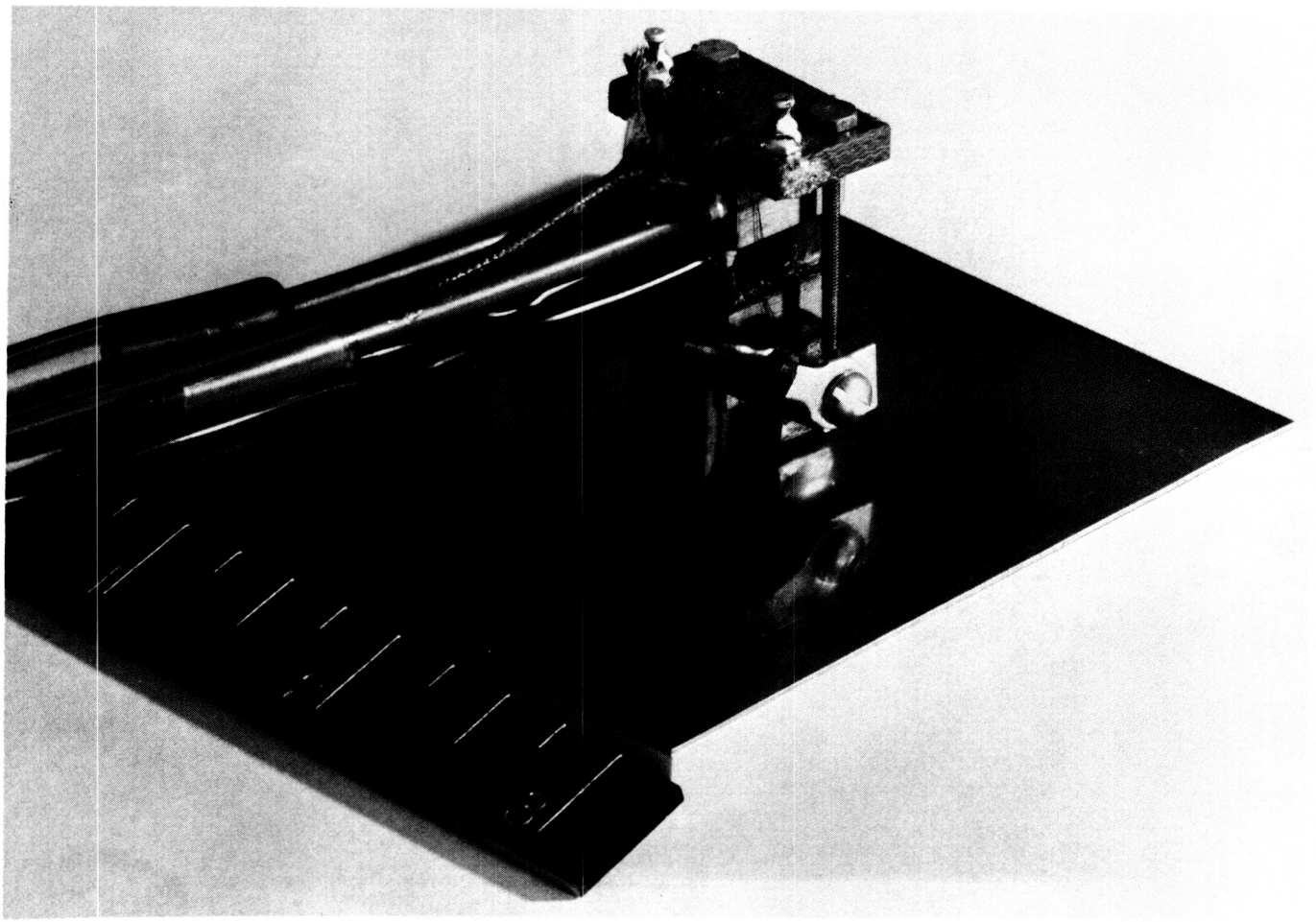


Figure 9.

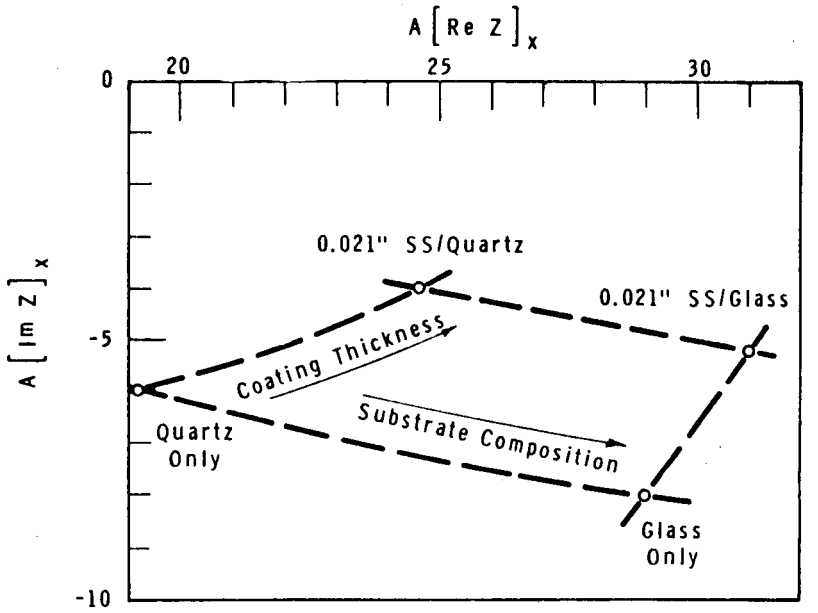



Figure 10.

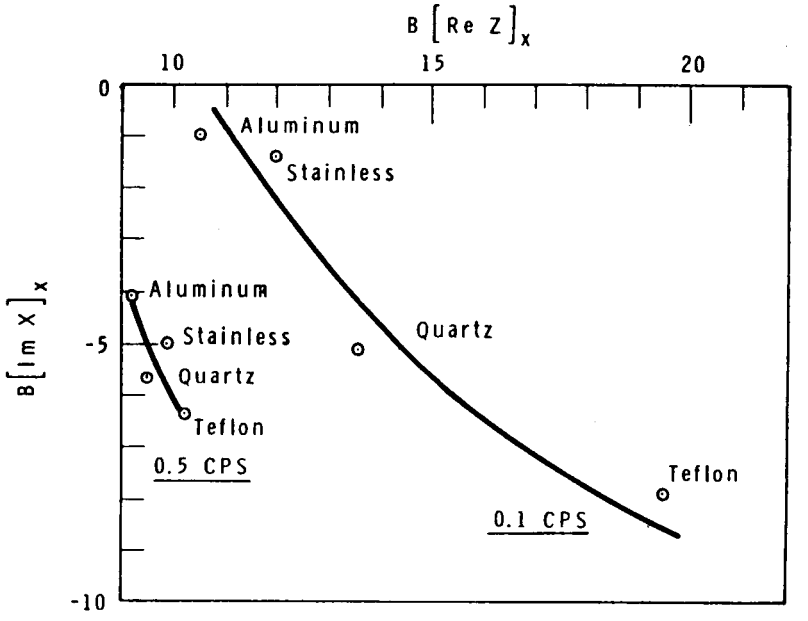



Figure 11.

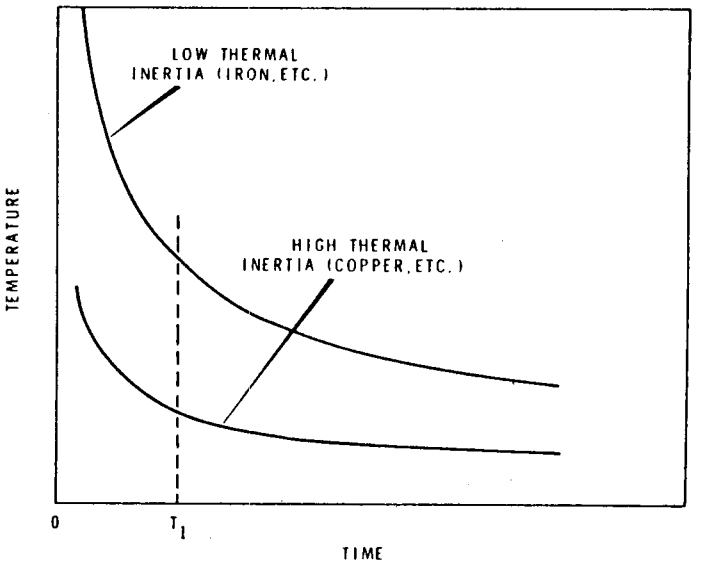



Figure 12.

$$\frac{\mathcal{L}\{f(t)\}}{\mathcal{L}\{y(t)\}} = Z(\bar{p})$$

THEN, FROM THE DEFINITION OF THE LAPLACE TRANSFORM,

$$\mathcal{L}\{f(t)\} = \int_0^\infty e^{-\bar{p}t} f(t)\,dt$$

$$\mathcal{L}\{y(t)\} = \int_0^\infty e^{-\bar{p}t} y(t)\,dt$$

WHEN f(t) AND y(t) CONVERGE SO THAT THESE TWO INGEGRALS ARE BOUNDED AFTER REPLACING $\bar{p}$ BY $j\bar{\omega}$, WE CAN WRITE:

$$\mathcal{L}\{f(t)\} = \int_0^\infty e^{-\bar{j}\omega t} f(t)\,dt$$

$$= \int_0^\infty f(t) \cos \omega t\, dt - \bar{j} \int_0^\infty f(t) \sin \omega t\, dt$$

AND

$$\mathcal{L}\{y(t)\} = \int_0^\infty e^{-\bar{j}\omega t} y(t)\,dt$$

$$= \int_0^\infty y(t) \cos \omega t\, dt - \bar{j} \int_0^\infty y(t) \sin \omega t\, dt$$

AND HENCE,

$$Z(\bar{j}\omega) = \frac{\int_0^\infty f(t) \cos \omega t\, dt - \bar{j} \int_0^\infty y(t) \sin \omega t\, dt}{\int_0^\infty y(t) \cos \omega t\, dt - \bar{j} \int_0^\infty y(t) \sin \omega t\, dt}$$

Figure 13.

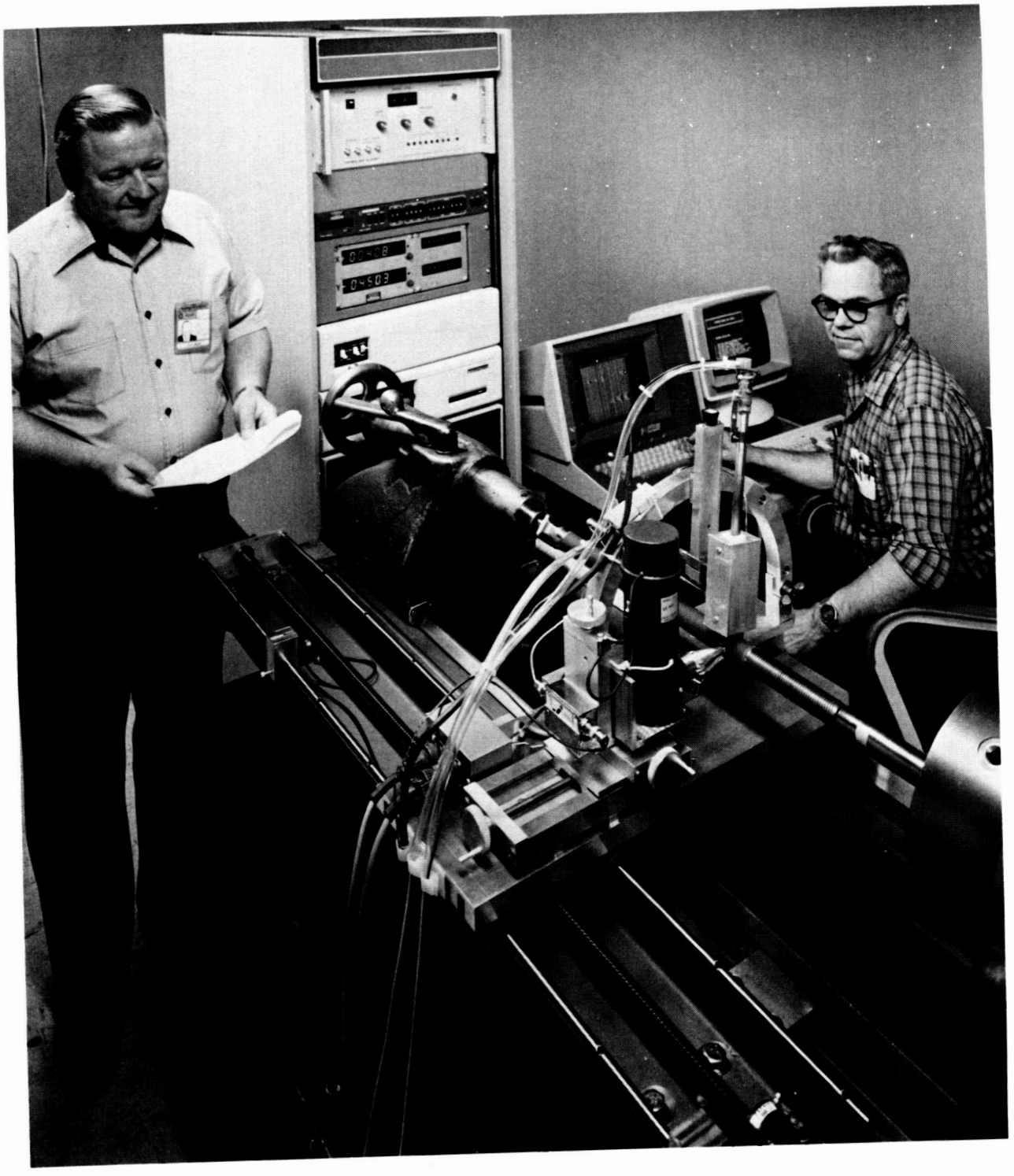
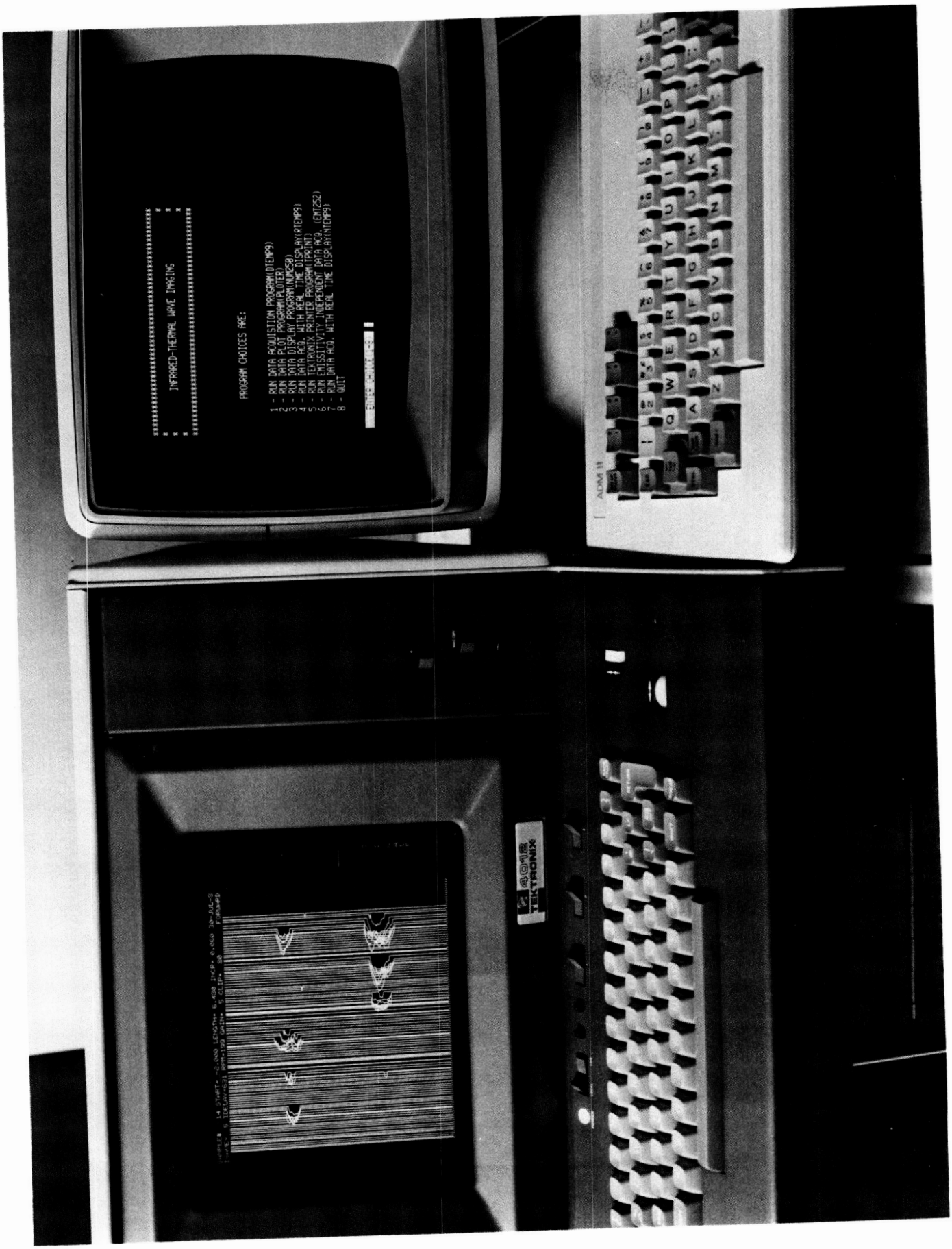


Figure 14.



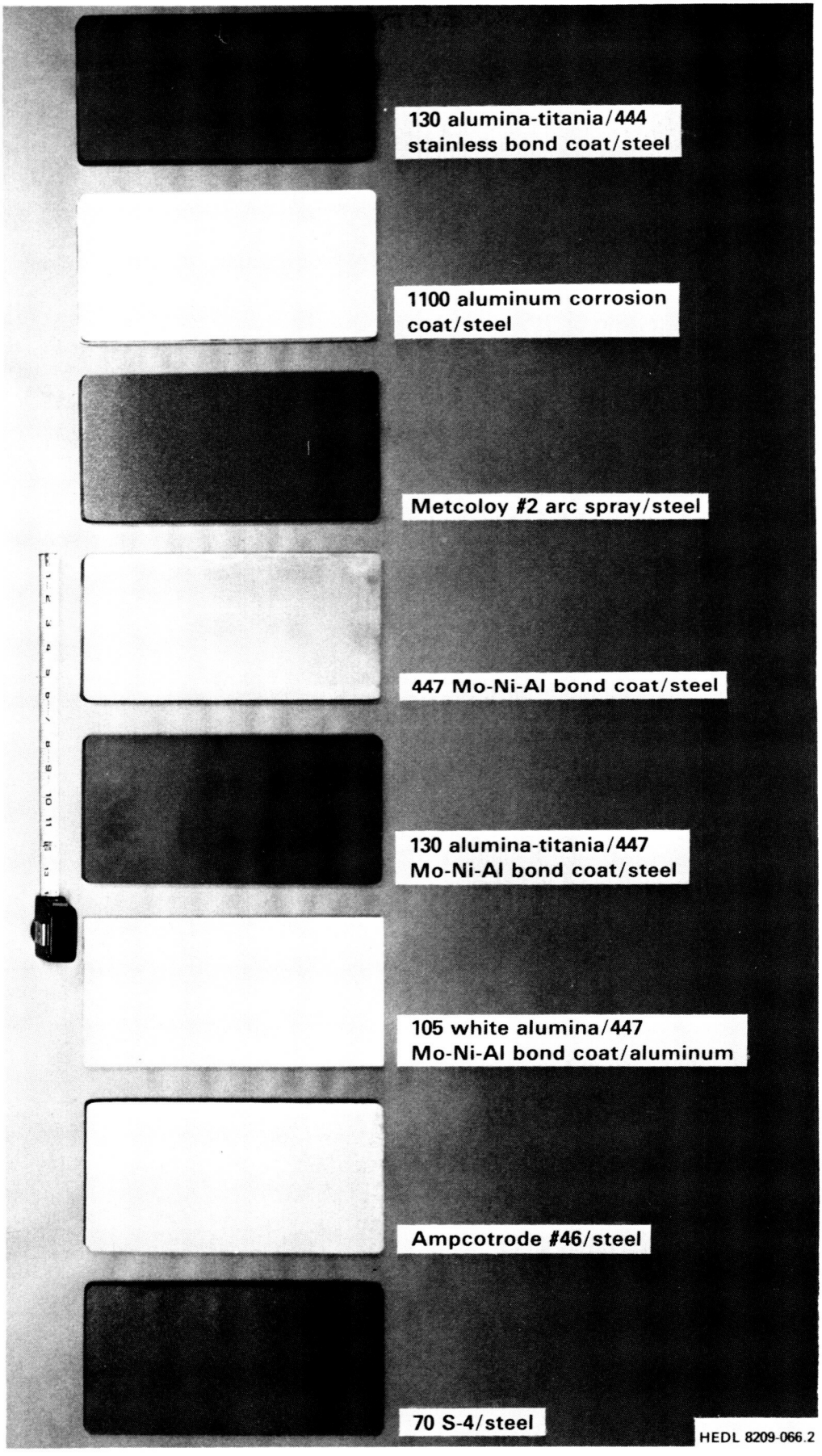
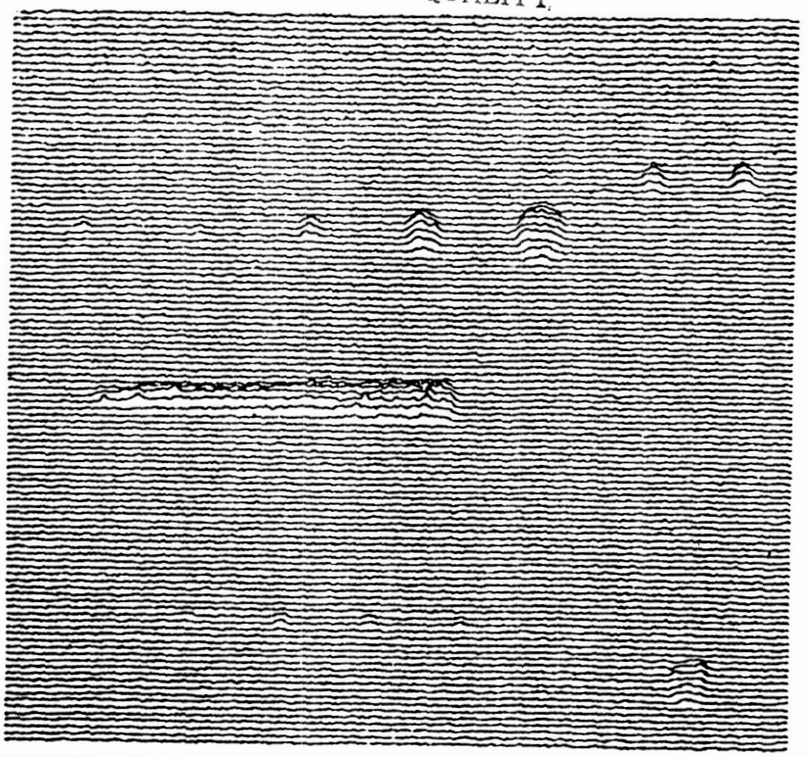
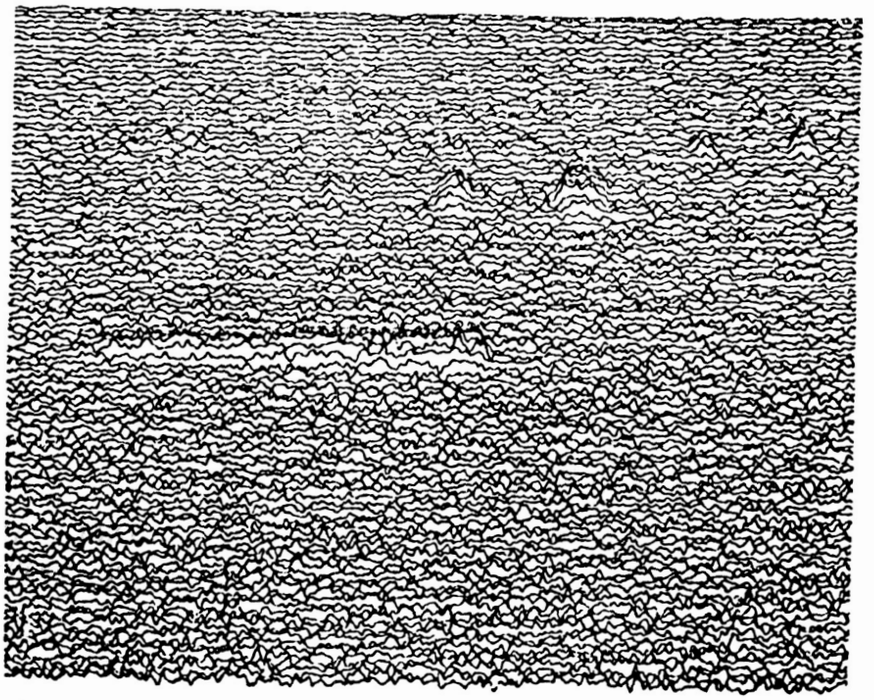



Figure 16.



EMISSIVITY INDEPENDENT INFRARED-THERMAL SCAN RESULT SHOWING ALL NONBONDS IN SIDE #1 OF PSNS CYLINDRICAL THERMAL SPRAYED TEST SPECIMEN #11.

Figure 17.



ORDINARY EMISSIVITY DEPENDENT INFRARED-THERMAL SCAN RESULTS ON SIDE #1 OF PSNS CYLINDRICAL THERMAL SPRAYED TEST SPECIMEN #11. NOTE THAT MOST 1/8 INCH DIAMETER NON-BOND INDICATIONS ARE HIDDEN IN THE BACKGROUND EMMISSIVITY VARIATIONS.

Figure 18.

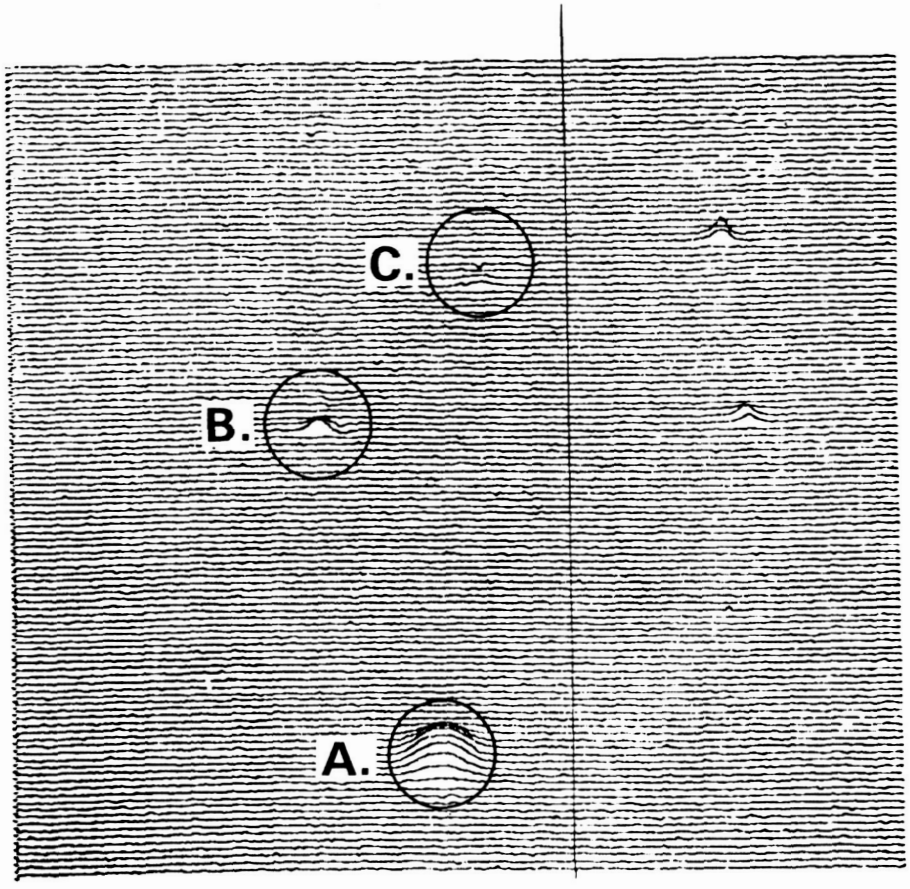



Figure 19.

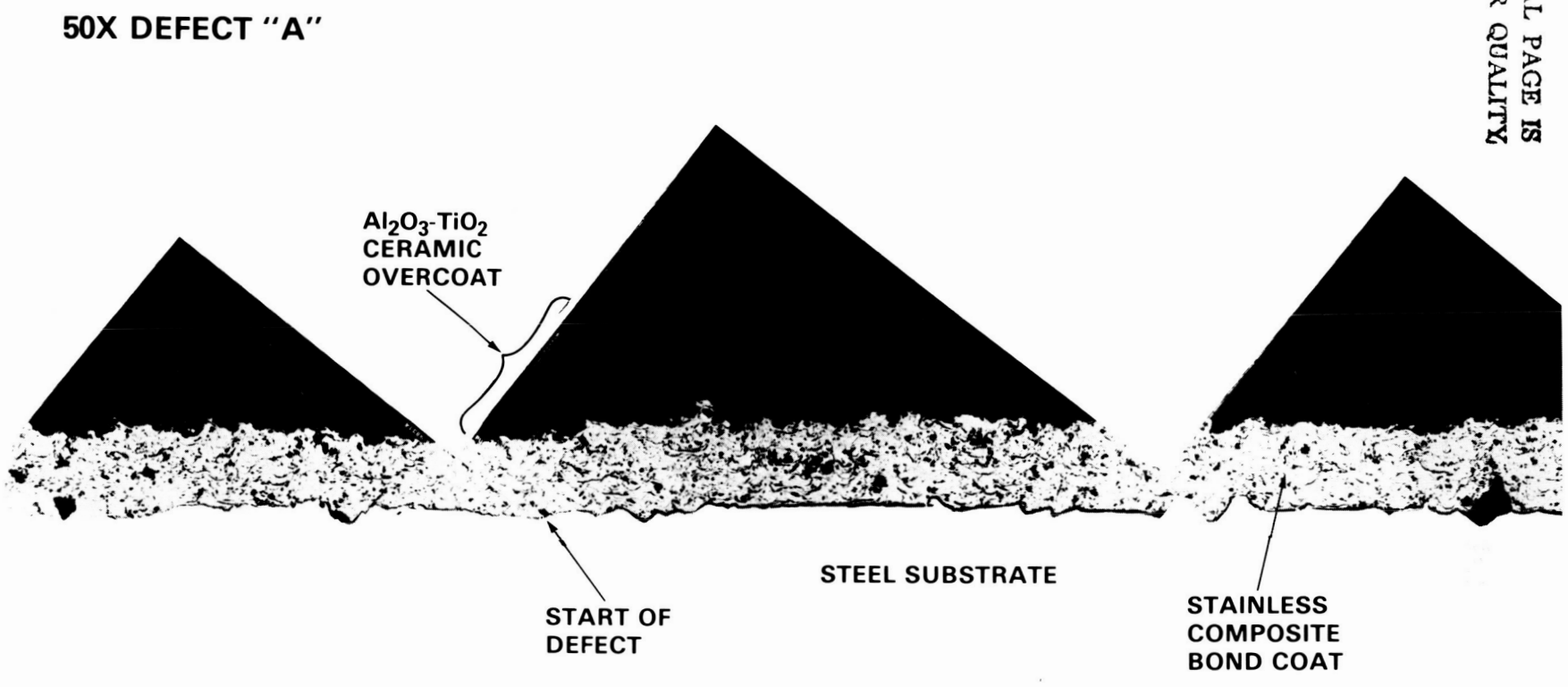



Figure 20.

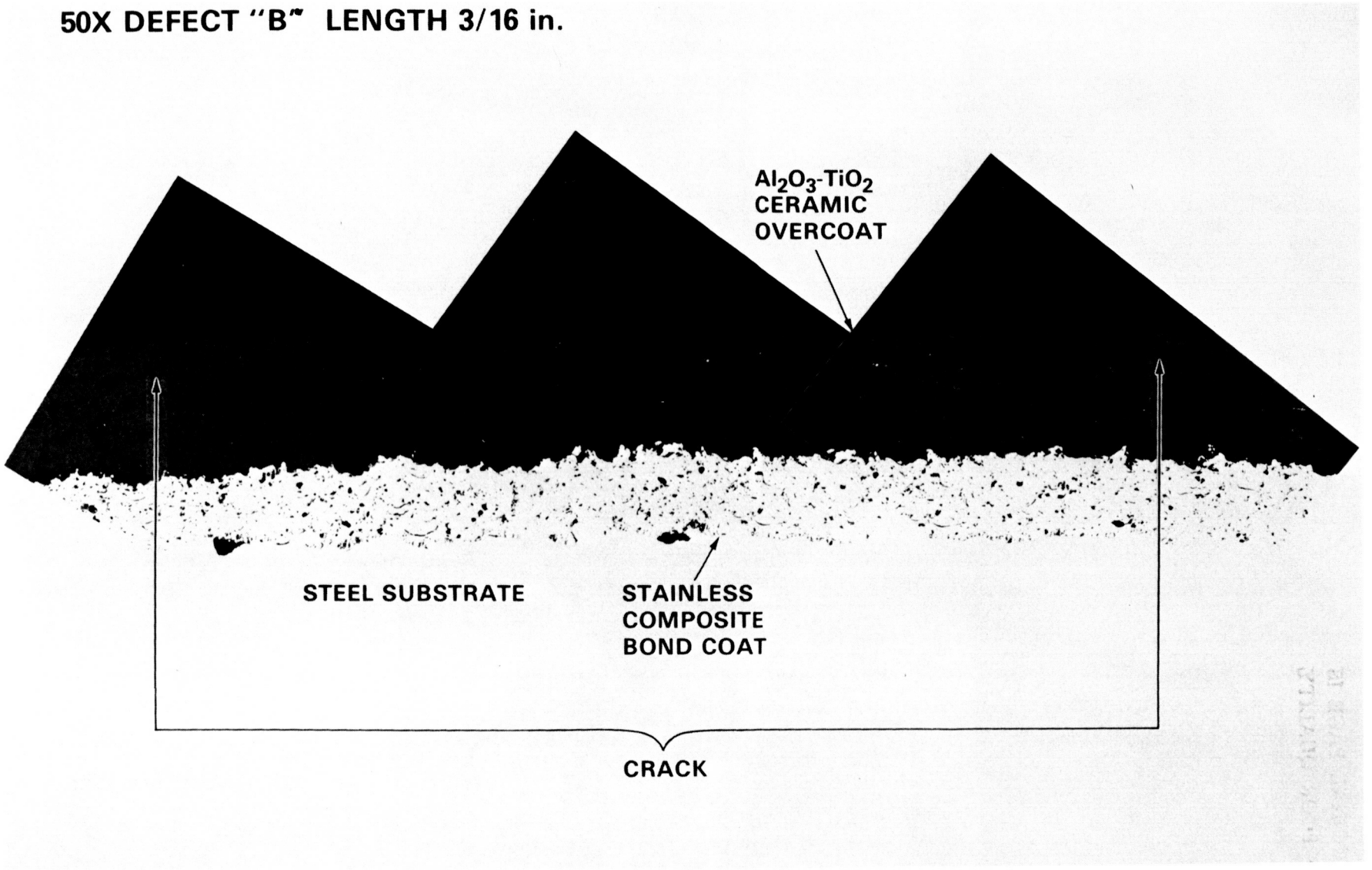



Figure 21.

# DEFECT "C"
# LENGTH 0.085 in.

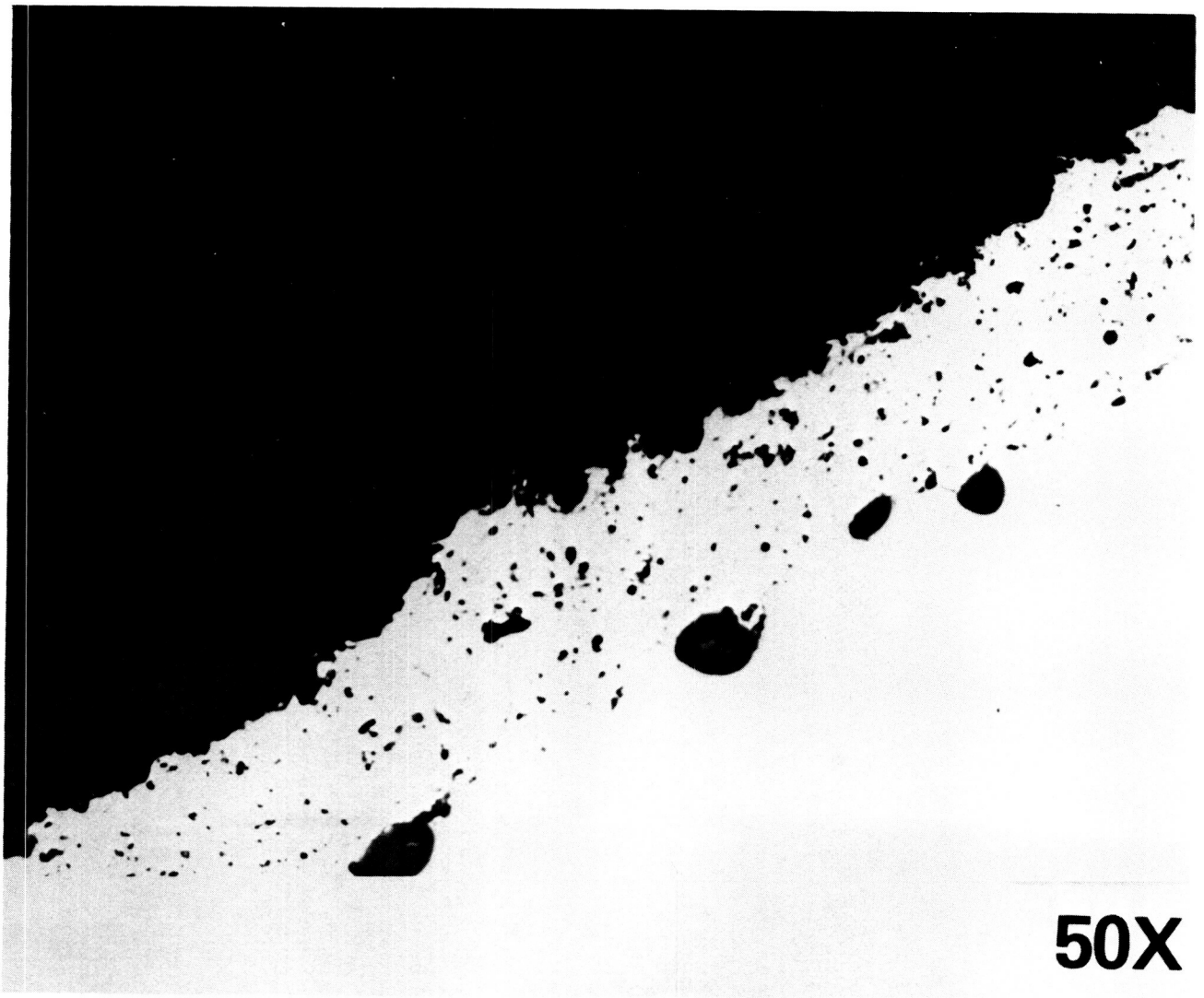



Figure 22.