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STEAM GENERATOR TUBE BURST
AND
COLLAPSE PREDICTIONS

by

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Based on work carried out on NRC/RSR program "PWR Steam Generator Tube Integrity Program", NRC Contract Number B2097 for the Metallurgy and Materials Research Branch, Dr. Joseph Muscara, Program Manager.

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This presentation summarizes the results of the burst and collapse tests performed as part of Phase I of the Steam Generator Tube Integrity (SGTI) program at Battelle Pacific Northwest Laboratory, sponsored by the Metallurgy and Materials Research Branch, Reactor Safety Research Division of NRC. The burst and collapse tests were performed to establish margin-to-failure predictions for mechanically defected PWR steam generator tubing under operating and accident conditions. The main objective of the SGTI program is to establish a large data base to assist NRC in their licensing duties as regards PWR steam generators. The two main areas of investigation in this program are the behavior of defected steam generator tubing under various pressure test conditions and the assessment of the single frequency eddy current inspection method which is the presently accepted in-service inspection (ISI) method for examining and qualifying in-situ PWR steam generator tubing. The pressure tests conducted on the defected tubing include burst, collapse, leak rate and cyclic fatigue tests. All defected specimens used for the pressure tests were inspected using the single frequency eddy current method. This procedure developed significant data allowing comparison of the eddy current indications with the actual defect geometries and the burst pressures for these specimens.

DESCRIPTION OF EXPERIMENTS

Defect Geometries

All tubing used in this program were fabricated from Inconel 600 representative of that currently in use in PWR steam generators and were supplied by a vendor who normally supplies such tubing to the industry. Four sizes of tubing were examined: 0.875 in. x 0.050 in; 0.750 in. x 0.050 in; 0.750 in. x 0.043 in; and 0.625 in. x 0.034 in, where the first number in each set represents the outer diameter and the second number the nominal wall thickness. All tubing, upon receipt, were carefully examined for defects and ovality using eddy current and ultrasonic inspection techniques. The tubes were then cut into 12 inch specimen lengths and then the defects were machined into them. After machining, each specimen defect was replicated using a silicone casting compound. Thus, precise knowledge of each defect geometry was obtained. The types of geometries were selected to emulate known or expected defects in PWR steam generators. These defects, shown in Figures 1 through 5, are Electro Discharge Machining (EDM) slots, elliptical wastage, elliptical wastage plus through-wall EDM slots, uniform thinning, denting plus elliptical wastage and denting plus uniform thinning. The range of defect lengths, depths and geometry combinations was quite extensive, as shown in Figure 6. All told, close to 600 tube specimens were prepared and tested.

Burst Tests

Burst testing was conducted in an autoclave assembly. Pressurization of both the tube (or primary side) and the autoclave (or secondary side) was with water chemically simulating PWR steam generator feed water. During burst testing the autoclave and its load of tubes were simultaneously pressurized to 2250 psi, then heated to 600°F. The autoclave (secondary side) was then slowly depressurized to 1000 psi. When thermal and pressure equilibrium was achieved, the tubes (primary side) were pressurized at a rate of 1000 to 2000 psi/min. Exact burst pressures were determined by sudden loss of pressure in the tubes.

Collapse Tests

For the collapse tests each tube specimen was placed inside a smaller pressure vessel and this assembly was then placed in the autoclave. These tests were carried out by first pressurizing the tube and the surrounding small pressure vessel simultaneously to 2250 psig, using the same water chemistry as for the burst tests. The autoclave was then pressurized to 2250 psi and heated to 600°F. After thermal and pressure equalization occurred, the tubes were vented to 1600 psig, thus establishing an external pressure differential of 650 psig. The small pressure vessel (secondary side) was then pressurized at the rate of 1000 to 2000 psi/min. until collapse of tube specimen occurred. Collapse was determined by a marked decrease in pressure in the secondary vessel, usually accompanied by a noticeable clicking sound eminating from the test assembly.

Bulge Tests

Bulge tests were conducted to give insight into the problem of through-wall cracks widening due to internal pressure. These tests consisted of internally pressurizing tubes with through-wall EDM slots. Neopreme bladders inside the tubes allowed pressurization of the tube with the limited flow capacity available. Slot lengths were 1/4, 1/2 and 1-1/2 inches in two tube sizes, 0.875 x 0.050 in. and 0.750 x 0.043 in. A grid for detecting local deformation was placed on the specimens using a photo-emulsion. Specimens were pressurized with cold, ~70°F, water under ambient air conditions, until the slot deformed sufficiently to allow extrusion of the neopreme and resultant leakage and loss of pressure.

Leak Rate Tests

In the leak rate experimental set-up, a matrix of tube specimens containing through-wall slots, and through-wall slots with elliptical wastage were pressurized with hot water (600°F) from a pressurized source and vented through the slot to the atmosphere. The hot water reservoir was maintained at 600°F and 3000 psig. The fluid was vented through the specimen by use of a pressure reducing and controlling regulator. For any size defect an initial choked flow pressure and flow upstream of the defect was established. Then the pressure was gradually increased until the defect widened and a new choked flow pressure was attained. Leak rates, pressure and temperature for each specimen were recorded once each second until the maximum pressure flow capacity of the system was reached.

Eddy Current Tests

The single frequency eddy current (EC) examination of the defected tubing was performed according to the Summer 1976 addenda to the ASME Boiler and Pressure Vessel Code, Section XI, Appendix IV, inspection requirements. A commercially available EC test instrument was used in performing the tube examinations. The instrument, Automation Industries EM 3300, contains the electronic circuitry to drive the inspection coil, the X and R separation circuitry, and a CRT display for viewing the signal patterns generated by the X and R impedance components of a defect signal. The differential bobbin-style probes were also commercial units purchased with the EC instrument. In addition, strip chart and magnetic tape recorders, tube support tray and other test apparatus were assembled from existing laboratory equipment.

RESULTS

Burst Tests

The two primary factors governing the burst pressures for the defected tubes studied in this program are the defect depth and the defect length. This is true for all types of defects with the possible exception of the elliptical wastage type defect, where, because of the unique geometry, depth alone appears to be the predominant parameter. Figure 7 shows the burst pressure of various defect depths and length combinations of EDM slots in 0.875 x 0.050 in. tubes as a function of Maximum Degradation (i.e., defect depth/wall thickness). As can be seen, the data is fairly consistent, showing definite trends. Figure 8 shows the same data as a function of defect length. Again definite trends are discernible. It is quite clear that for any given EDM slot depth, the burst pressure approaches an asymptotic value as the defect length exceeds approximately 1.0 inch in length. The data developed for the burst pressures of EDM slots in the other tube sizes were quite similar to that shown in Figures 7 and 8. Figures 9 and 10 show similar plots for the uniform thinning specimens and Figure 11 shows the burst pressure as a function of depth for the elliptical wastage specimens. In this latter case the length of the defect was not considered.

All the data from burst tests were put into nondimensional form by dividing the burst pressure of each defect specimen by the burst pressure of the same tube with no defects. The depth of defect was divided by the wall thickness and the length of defect was divided by the square root of the product of the inner radius of the tube and the wall thickness. These data were used to develop a curve fit using a least square methodology.

The curve fit equations developed were:

For EDM slots

$$\frac{\Delta P}{\Delta P_o} = 1 - \frac{h}{t} + \frac{h}{t} e^{-0.373 L/\sqrt{Rt}} \qquad (1)$$

For Uniform Thinning

$$\frac{\Delta P}{\Delta P_o} = \left(1 - \frac{h}{t}\right)^{\left(1 - e^{-.13\ L/\sqrt{R(t-h)}}\right)} \qquad (2)$$

For Elliptical Wastage

$$\frac{\Delta P}{\Delta P_o} = \left(1 - \frac{h}{t}\right)^{0.604} \qquad (3)$$

where

$\frac{\Delta P}{\Delta P_o}$ = Ratio of defected to undefected burst pressures

h = Defect depth

t = Wall thickness

R = Inner radius of tube

L = Defect length

It should be noted that these equations hold for all sizes of Inconel 600 tubes tested. Figures 12 and 13 show predicted burst pressure ratios for all EDM slots as a function of defect depth and length, respectively. Figures 14 and 15 are similar plots for the uniform thinning specimens, and Figure 16 is the plot of the burst predictions for the uniform wastage. Figures 13 and 15 clearly show the asymptotic nature of the effect of length for EDM slots and uniform thinning defects. Figures 17, 18 and 19 show the comparison of predicted burst parameters to actual burst parameters for all tubes tested.

Collapse Tests

Figures 20, 21 and 22 present the collapse data for the EDM, uniform thinning and elliptical wastage defects, respectively, in the 0.875 x 0.050 in. tube specimens. These data are typical of that achieved for the other size tubes. As can be seen, the severity of the EDM defect had little effect upon the collapse pressures. This is as one would expect since the external pressure would tend to close the defect rather than to open it as in the case of internal pressure in the tube. The other types of defects do show a strong relation between defect depth and length and collapse pressure. However, it should be noted that even with defect depths of 75 to 90 percent of wall for the uniform thinning and elliptical wastage specimens, the collapse pressures were considerably above the external pressure differential that one might expect to occur in the event of a LOCA, approximately 1000 psi.

Bulge Tests

The results of the bulge tests are shown in Figure 23, superimposed upon Hartzman's[1] prediction of critical pressures for degraded tubes with axial through-wall cracks under internal pressure. The curve used for comparison

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(1) Hartzman, M., "Factors of Safety of Degraded Cylindrical Tubes with Axial Through-Wall Cracks Under Internal Pressure". NRC Mechanical Engineering Branch memo to J. P. Knight, January 4, 1977

is that for the 0% wall degradation. The comparison data was generated by applying Hartzman's equations to the defect geometry used in these tests. This correlation appears to indicate that, for at least the specimens tested, Hartzman's work does give a good indication of the critical crack length, crack opening pressure relationship.

Leak Rate Test

The leak rate tests have been completed. However, the data is still being analyzed and the results will be reported at a later date.

Eddy Current Tests

The results of the signal interpretation showed significant error in the eddy current estimation of defect depth. The complex shape of several signals made determination of the phase angle difficult. Signals from nearly identical geometries produced very different signal patterns and depth indications. Figures 24, 25 and 26 show the comparison between the ECT indicated depth of flaw and the actual depth of flaw for all tube sizes tested for the EDM slots, uniform thinning and the elliptical wastage defect specimens, respectively. In these figures, if the eddy current inspection procedures resulted in exact indications of defect depth, all data points would fall along the 45° line. Any points below this line are conservative since the actual degradation is less than the indicated degradation and the defect depth is overestimated. Any points above this line are unconservative since the defect depth is underestimated. As can be seen, considerable error was found, particularly in the EDM slot and uniform thinning specimens. The former tended toward unconservative results while the results for the latter tended to be uniformly conservative.

As far as present practice is concerned, it is necessary to assess the results of the eddy current tests against the actual burst pressures of the tubes inspected. Figure 27 presents the depth indications of the eddy current tests and the resultant burst pressure of each tube tested regardless of the geometry of the specimens. The cross hatch section on this figure represents that region where present plugging practice is employed. That is, accepting a plugging criteria of an indicated defect depth of 55% of wall thickness, there are no tube failures below a pressure differential of 4000 psi across the tube. However, if one extends the 55% indicated line across the plot and examining those points that are above the line and to the right of the 4000 psi pressure vertical line, it can be seen that a great many tubes are presently being plugged that have burst pressures well in excess of 4000 psi. They do not have to be plugged. Part of the reason for this is that present plugging practice does not consider defect length. We have shown previously that defect length is an important parameter affecting the burst pressure of the tubes.

CONCLUSIONS

Assuming that the mechanical defects studied in this program do emulate the actual defects found in in-service PWR steam generators, then:

1. Present plugging practice using single frequency, differential wound bobbin, eddy current inspection devices leads to overly conservative results in many cases.

2. In general, the eddy current inspection procedure presently commonly used for ISI's does not define the flaw dimensions accurately.

3. If a procedure can be developed that accurately defines the flaw geometry, then we now have analytic tools for defining margins-to-failure for each defected tube.

NRC reports issued prior to this presentation giving background information are:

- NUREG-0359 - "Steam Generator Tube Integrity Program", Quarterly Report, January 1 - March 31, 1977.

- NUREG/CR-0277 - "Steam Generator Tube Integrity Program", Annual Progress Report, January 1 - December 31, 1977.

- NUREG/CR-0086 (PNL-2653-1) - "Reactor Safety Research Programs", Quarterly Report, January 1 - March 31, 1978.

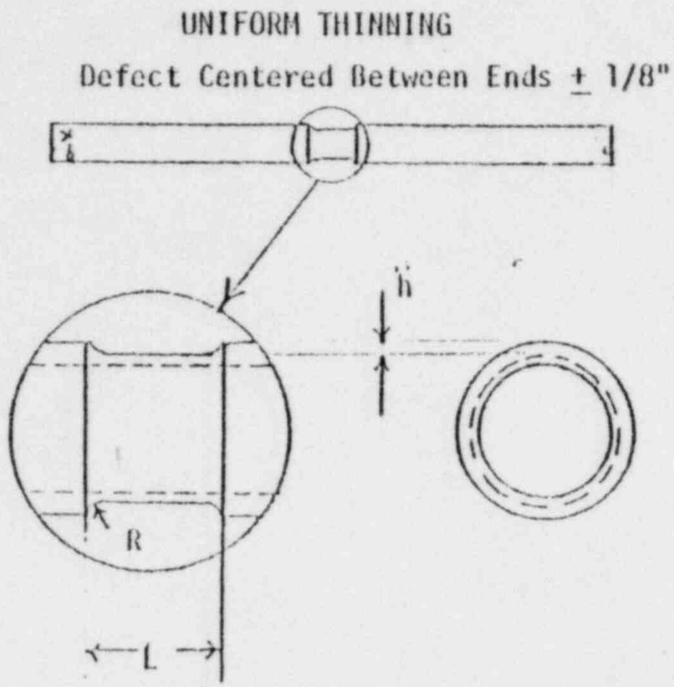


FIGURE 1. Uniform Thinning
Specimen Geometry

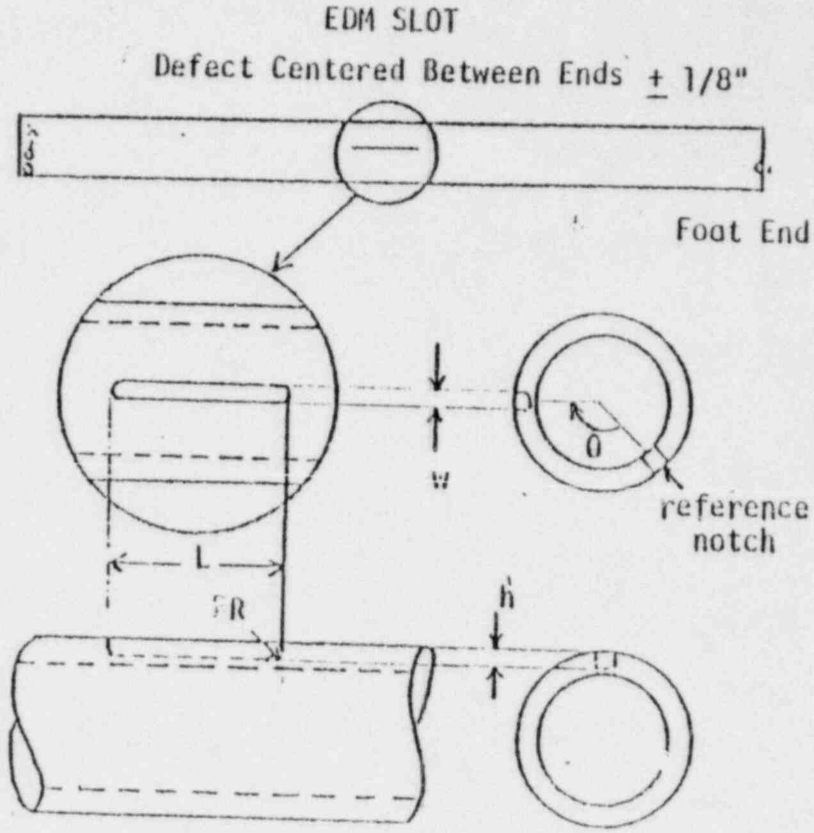


FIGURE 2. EDM Slot
Specimen Geometry

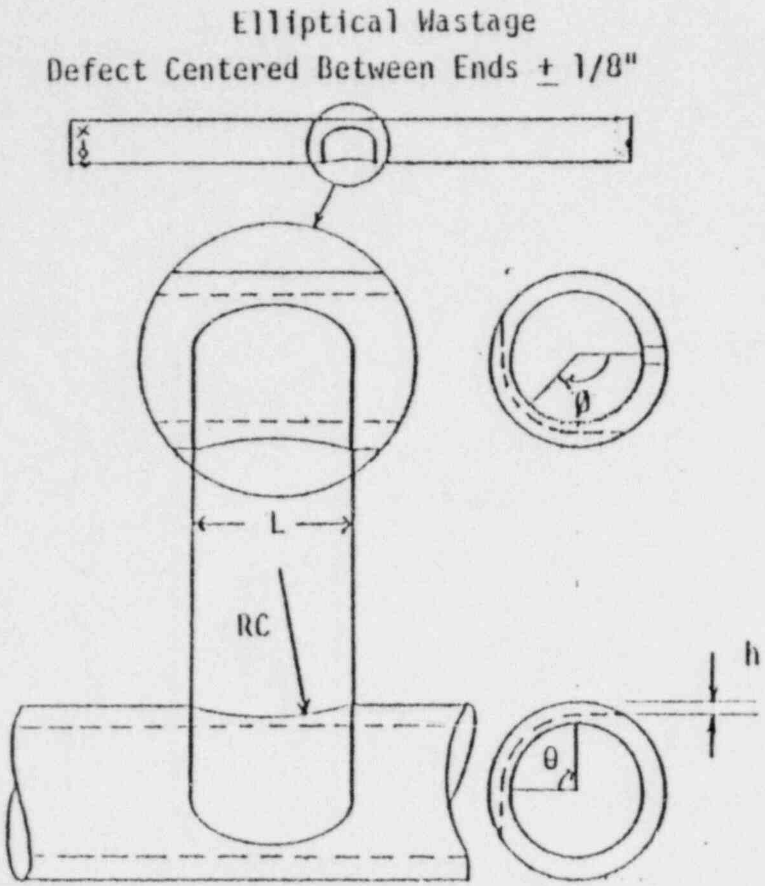


FIGURE 3. Elliptical Wastage Specimen Geometry

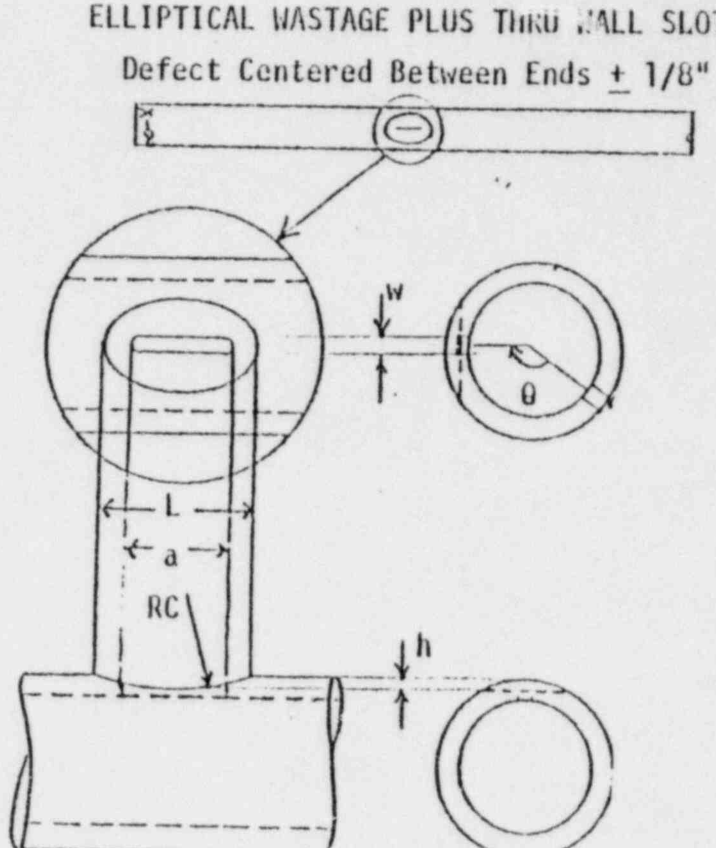


FIGURE 4. Elliptical Wastage Plus Through-Wall Slot Specimen Geometry

DENTING

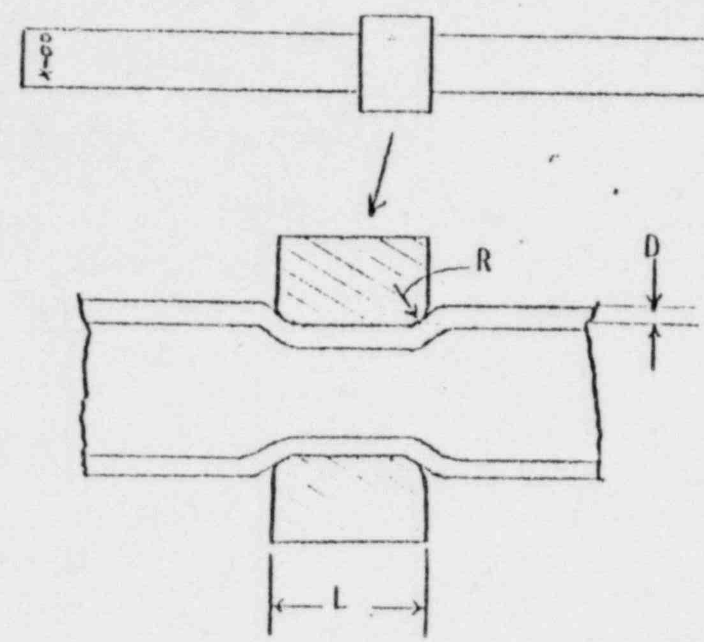


FIGURE 5. Denting Specimen Geometry

RANGE OF DEFECT DIMENSIONS

EDM SLOTS

DEPTH	25-30%, 55-60%, 85-90%
LENGTH	1/4 IN., 1/2 IN., 1 1/2 IN.
WIDTH	0.003 IN. — 0.010 IN.
END RADIUS	0.01 IN. — 0.02 IN.

ELLIPTICAL WASTAGE

DEPTH	25-30%, 55-60%, 85-90%
LENGTH	≈ 1 1/2 IN.
CUTTER RADIUS	6 IN., 12 IN., 24 IN.
WRAP ANGLE	0°, 45°, 135°

UNIFORM THINNING

DEPTH	25-30%, 55-60%, 75-80%
LENGTH	3/16 IN., 3/4 IN., 1 1/2 IN.
END RADIUS	1/16 IN.

DENTING

DENT DEPTH	0.040 IN. — 0.050 IN.
DENT LENGTH	3/4 IN.

FIGURE 6

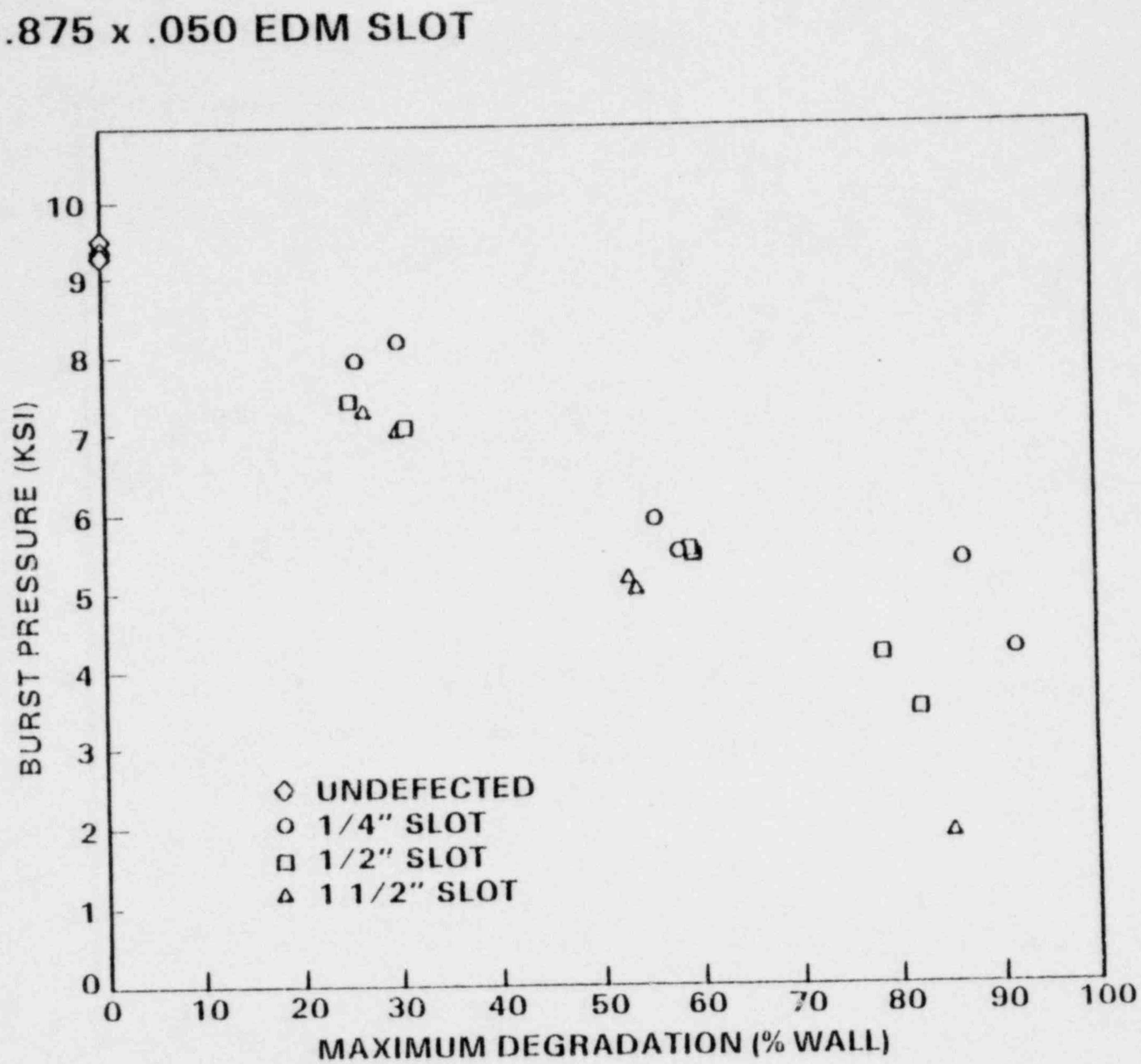


FIGURE 7. Burst Pressure as a Function of Defect Depth - EDM Slots

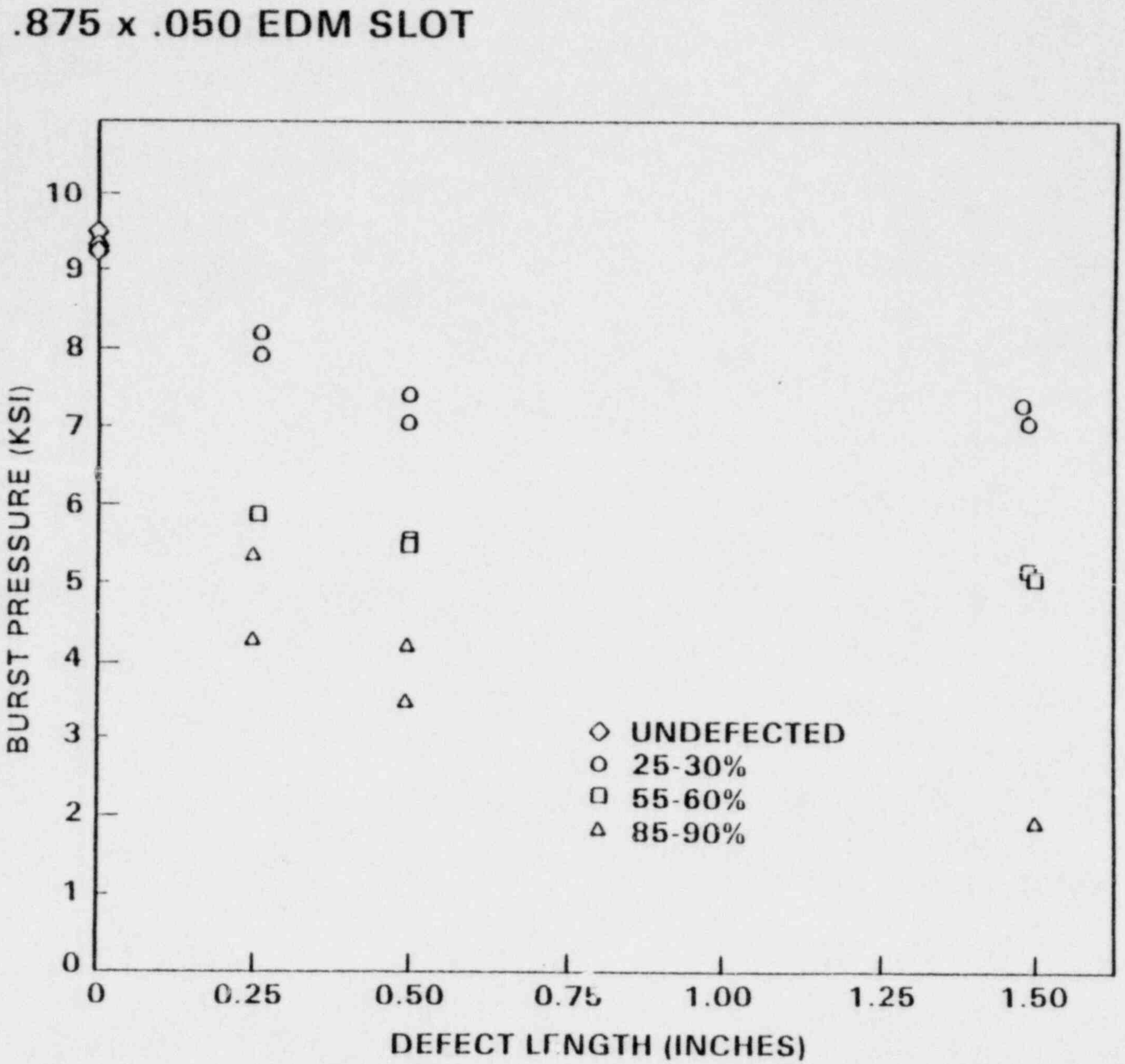


FIGURE 8. Burst Pressure as a Function of Defect Length - EDM Slots

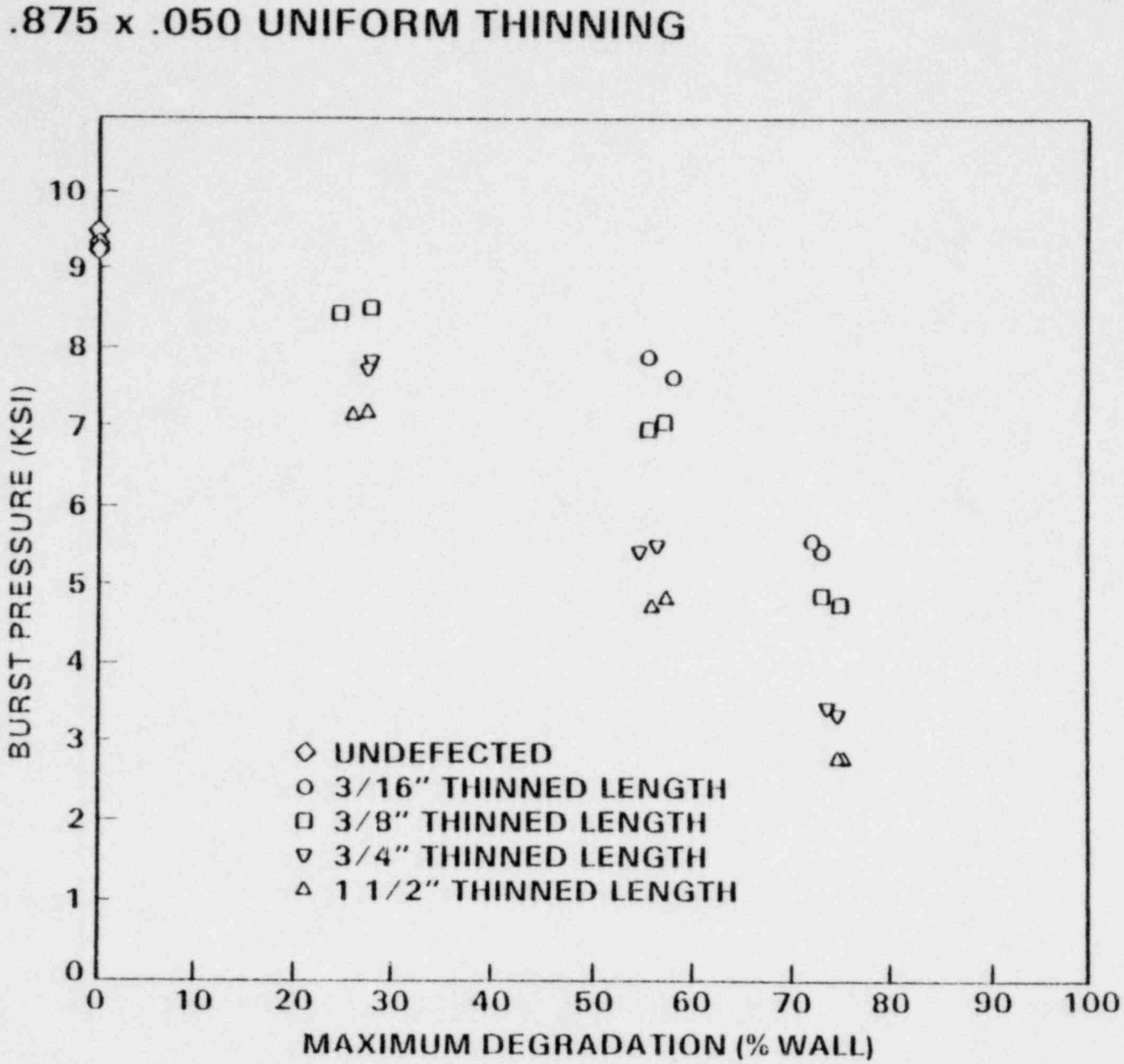


FIGURE 9. Burst Pressures as a Function of Defect Depth - Uniform Thinning

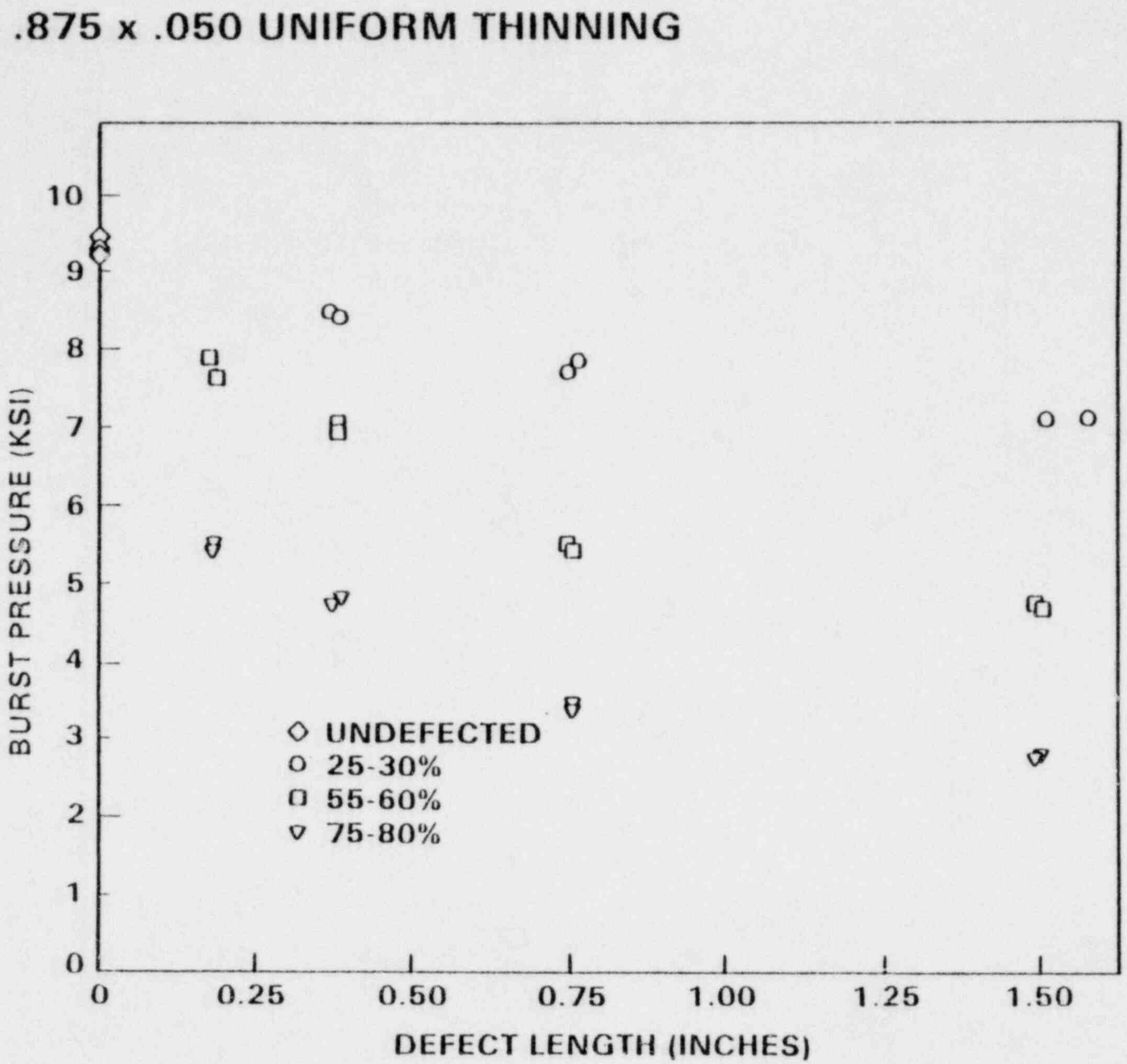


FIGURE 10. Burst Pressures as a Function of Defect Length - Uniform Thinning

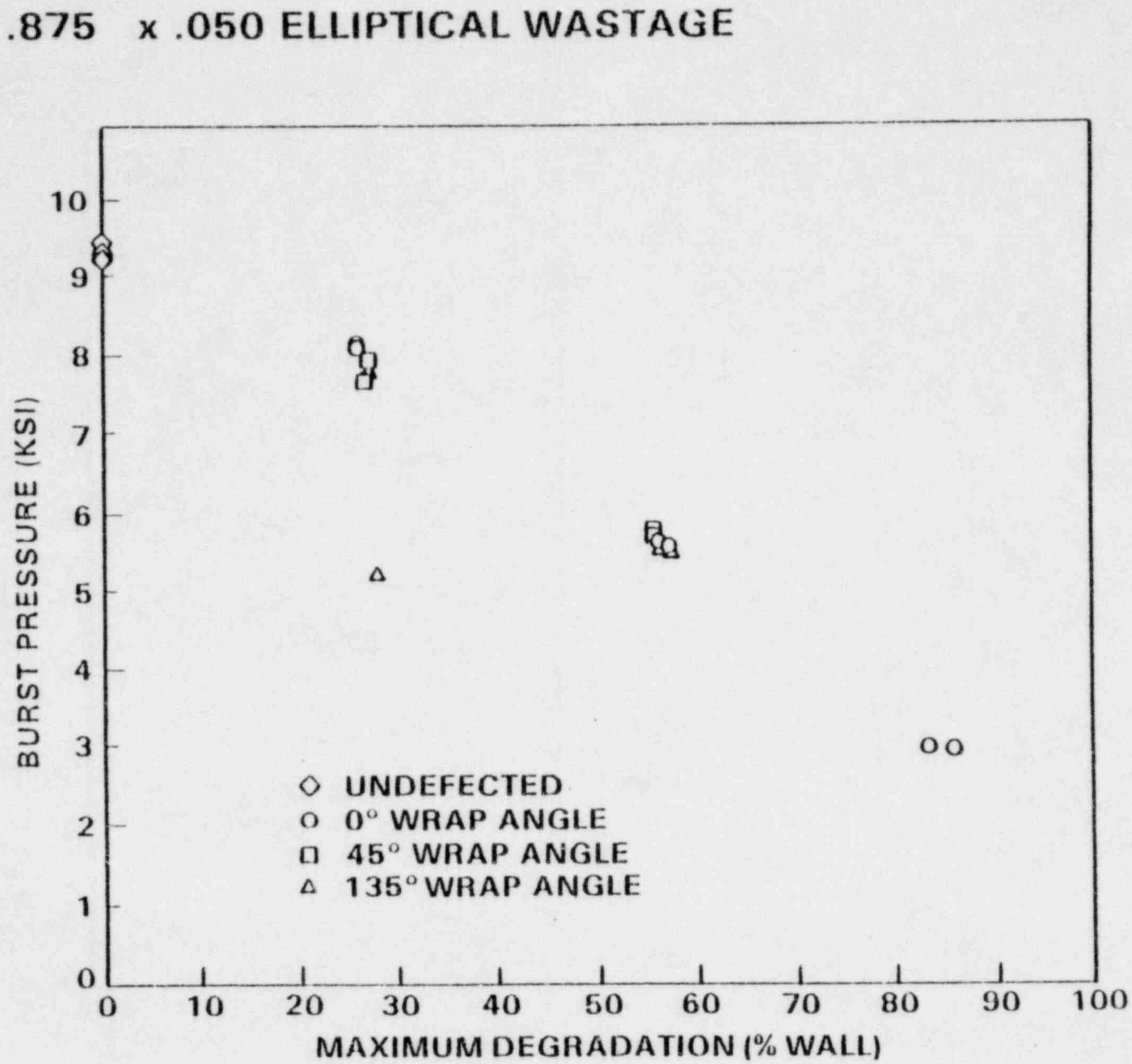
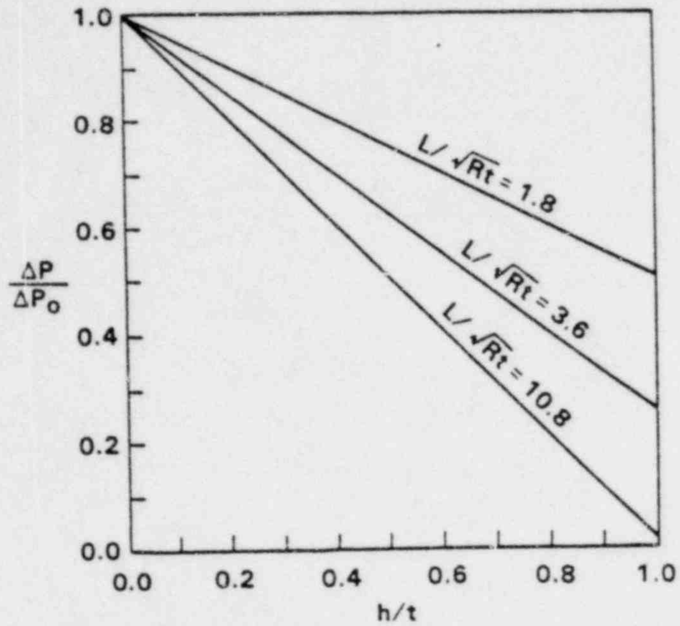


FIGURE 11. Burst Pressures as a Function of Defect Depth - Elliptical Wastage

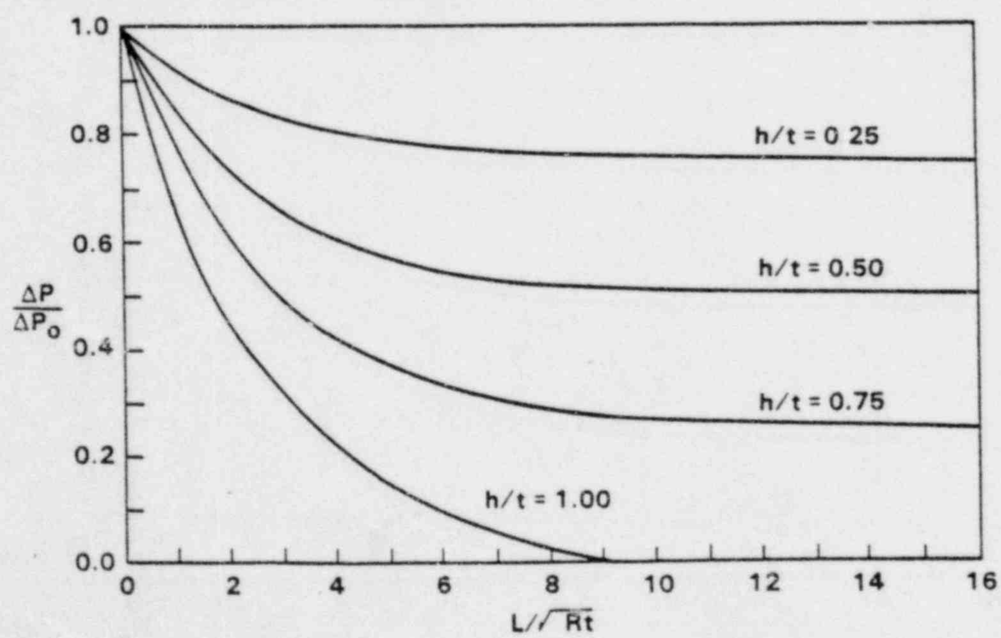
EDM SLOT BURST PRESSURE PREDICTION



$$\frac{\Delta P}{\Delta P_o}\ \text{(PREDICTED)} = 1 - \frac{h}{t} + \frac{h}{t}\, e^{-0.373 \frac{L}{\sqrt{Rt}}}$$

FIGURE 12

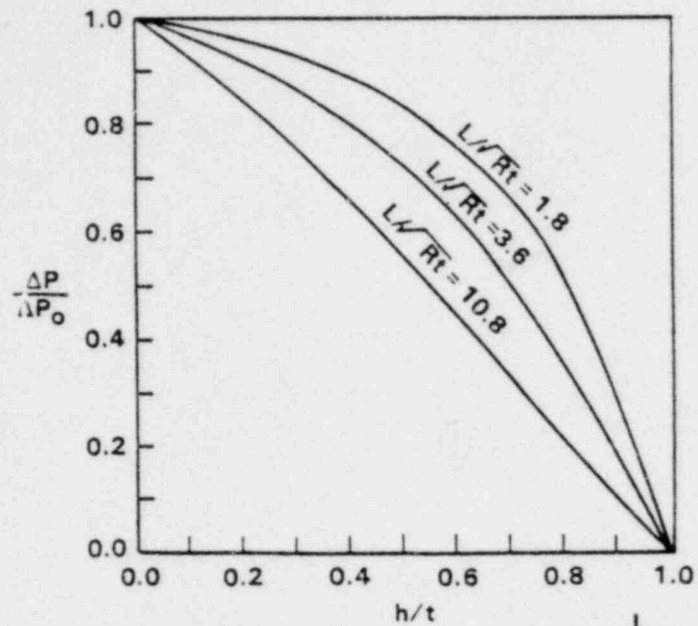
EDM SLOT BURST PRESSURE PREDICTION



$$\frac{\Delta P}{\Delta P_o}\ \text{(PREDICTED)} = 1 - \frac{h}{t} + \frac{h}{t}\, e^{-0.373 \frac{L}{\sqrt{Rt}}}$$

FIGURE 13

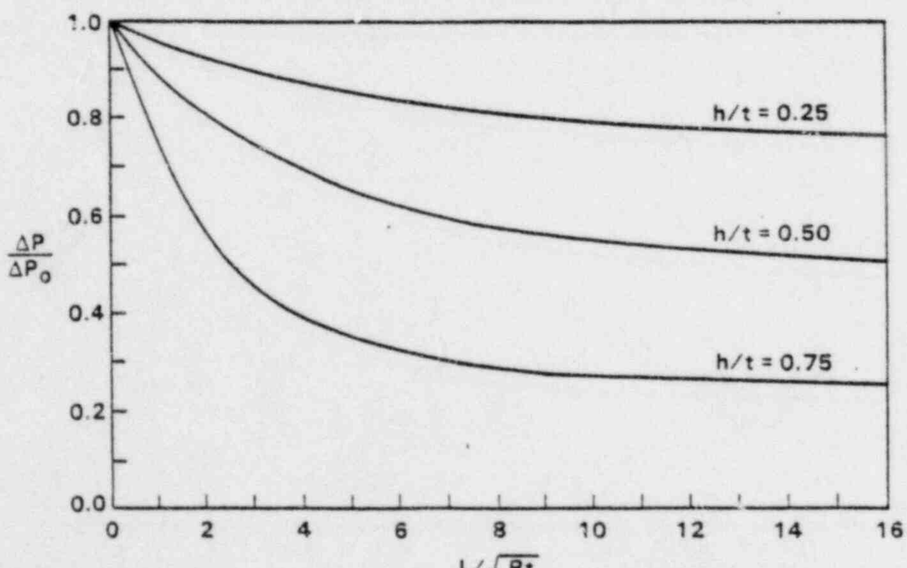
UNIFORM THINNING BURST PRESSURE PREDICTION



$$\frac{\Delta P}{\Delta P_o}\text{ (PREDICTED)} = \left(1. - \frac{h}{t}\right)^{\left(1-e^{-.13\frac{L}{\sqrt{Rt-h}}}\right)}$$

FIGURE 14

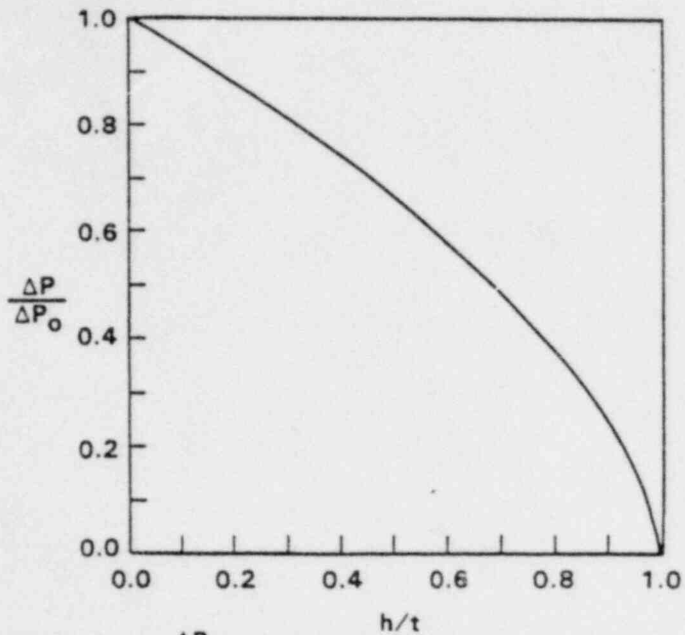
UNIFORM THINNING BURST PRESSURE PREDICTION



$$\frac{\Delta P}{\Delta P_o}\text{ (PREDICTED)} = \left(1. - \frac{h}{t}\right)^{\left(1-e^{-.13\frac{L}{\sqrt{R(t-h)}}}\right)}$$

FIGURE 15

ELLIPTICAL WASTAGE BURST PRESSURE PREDICTION



$$\frac{\Delta P}{\Delta P_o}\text{(PREDICTED)} = \left(1 - \frac{h}{t}\right)^{0.604}$$

FIGURE 16

ELLIPTICAL WASTAGE EMPIRICAL CORRELATION VERIFICATION

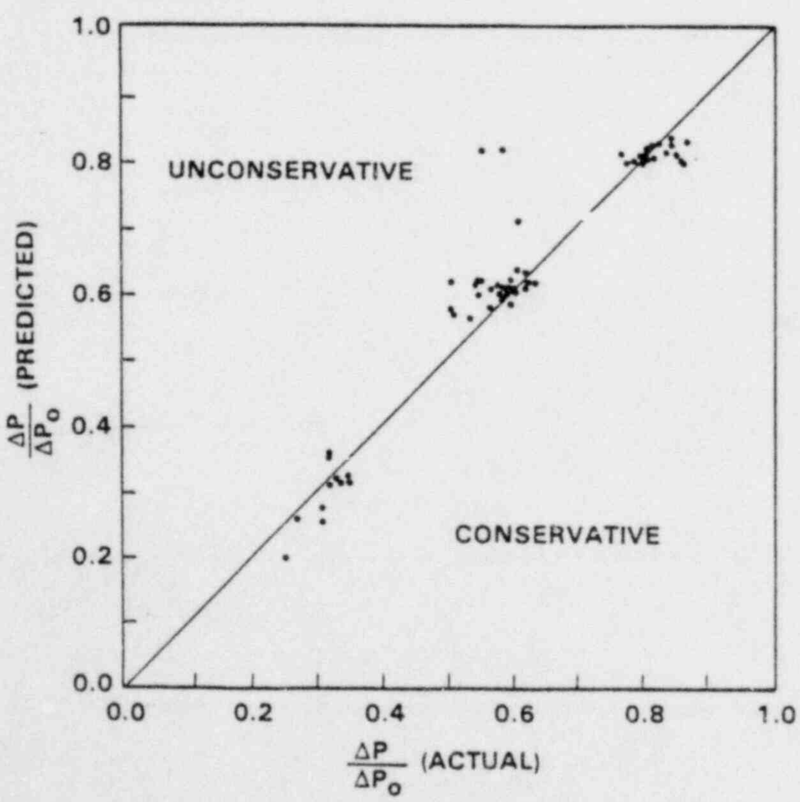


FIGURE 17

EDM SLOT EMPIRICAL CORRELATION VERIFICATION

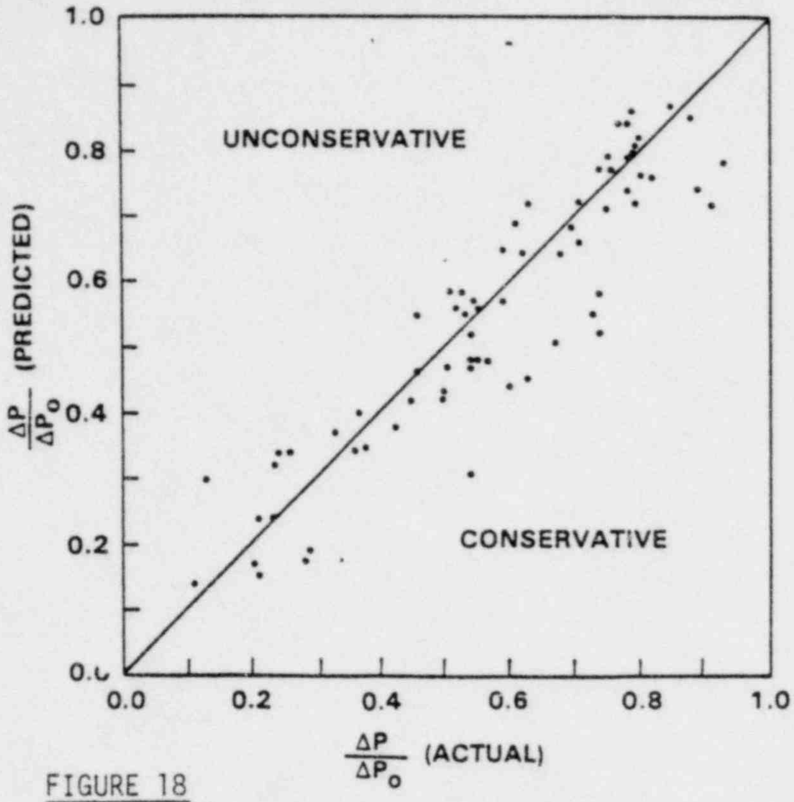


FIGURE 18

UNIFORM THINNING EMPIRICAL CORRELATION VERIFICATION

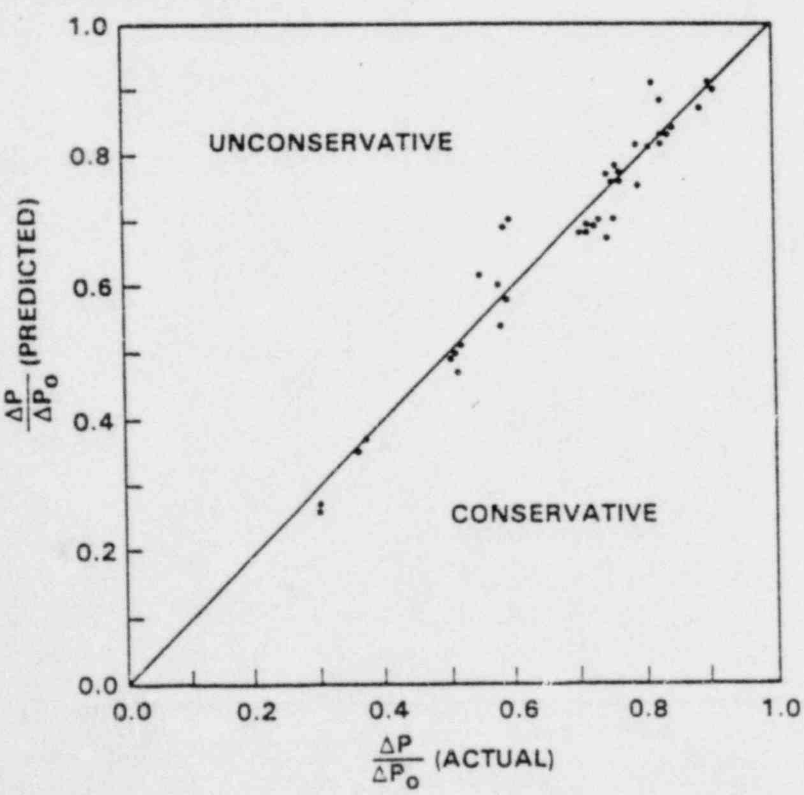


FIGURE 19

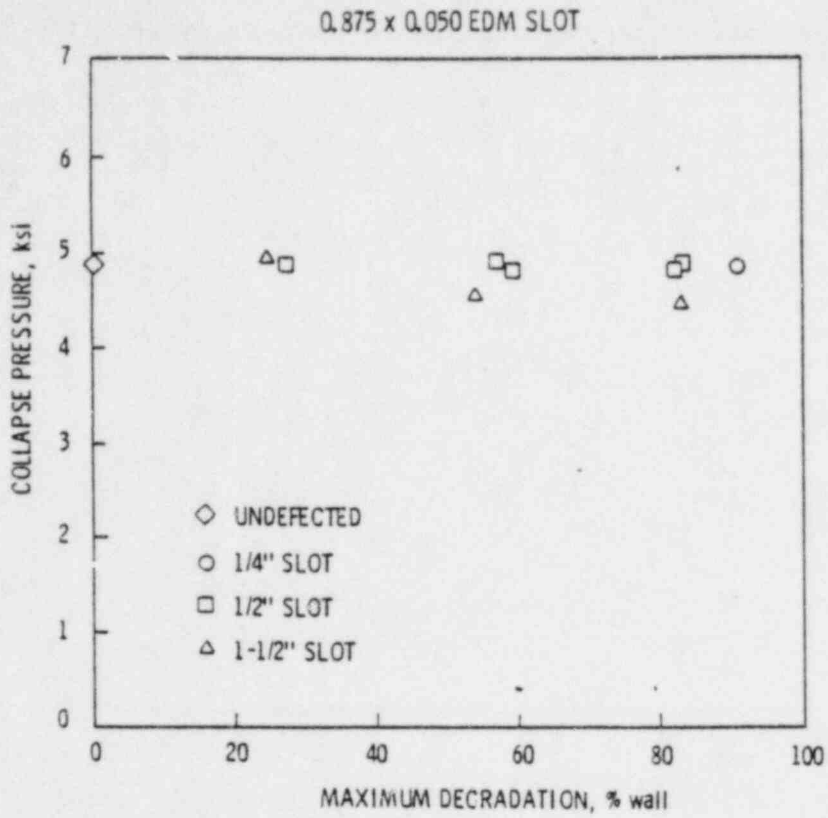


FIGURE 20

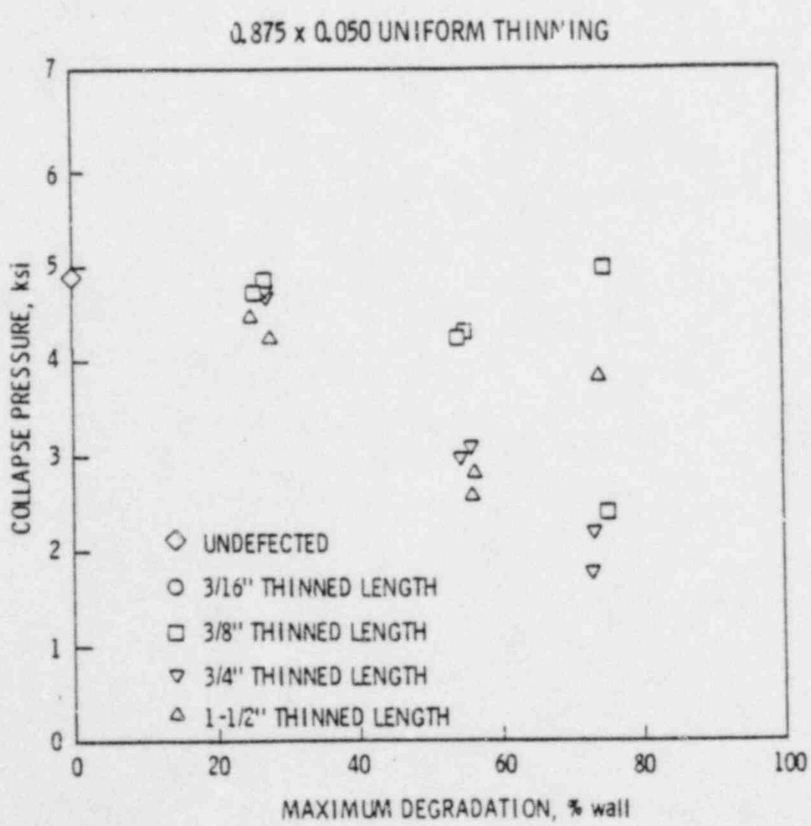


FIGURE 21

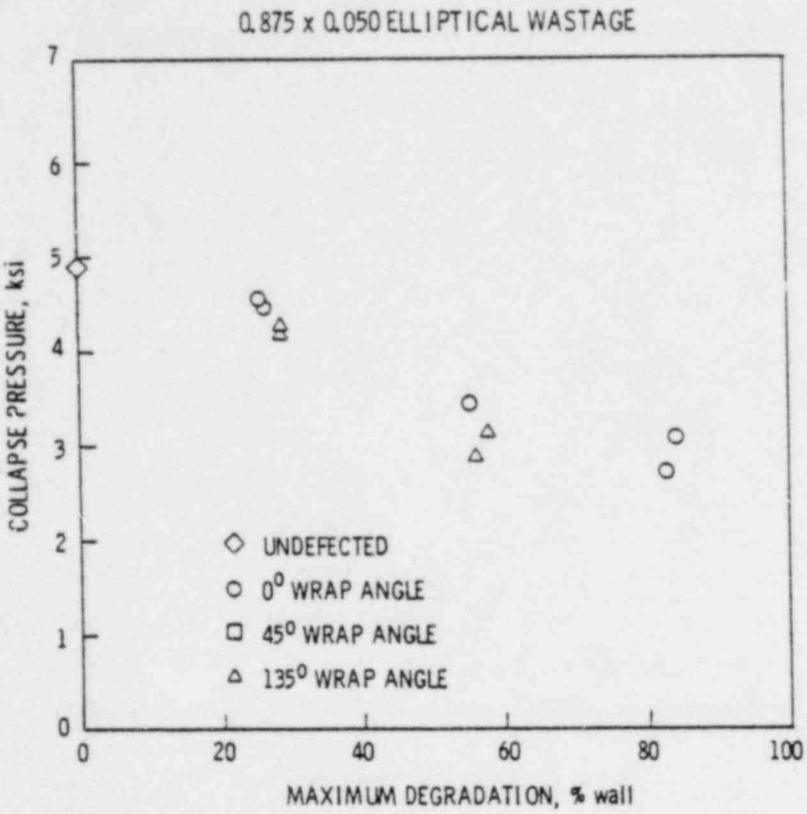

0.875 x 0.050 ELLIPTICAL WASTAGE
COLLAPSE PRESSURE, ksi
MAXIMUM DEGRADATION, % wall
0
1
2
3
4
5
6
7
0
20
40
60
80
100
UNDEFECTED
0° WRAP ANGLE
45° WRAP ANGLE
135° WRAP ANGLE

FIGURE 22

HARTZMAN'S PREDICTION OF CRITICAL PRESSURE

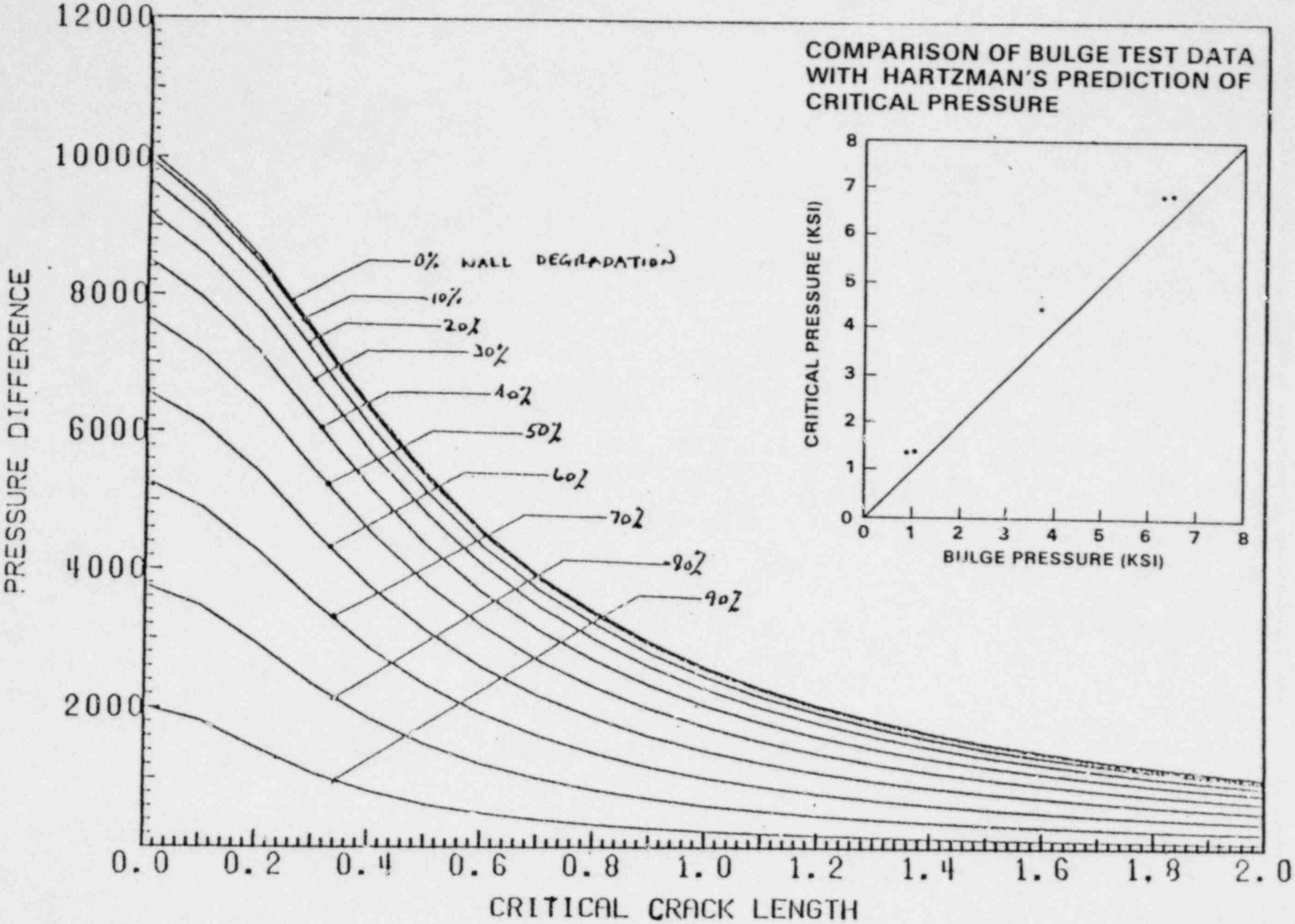


FIGURE 23

EDM SLOTS

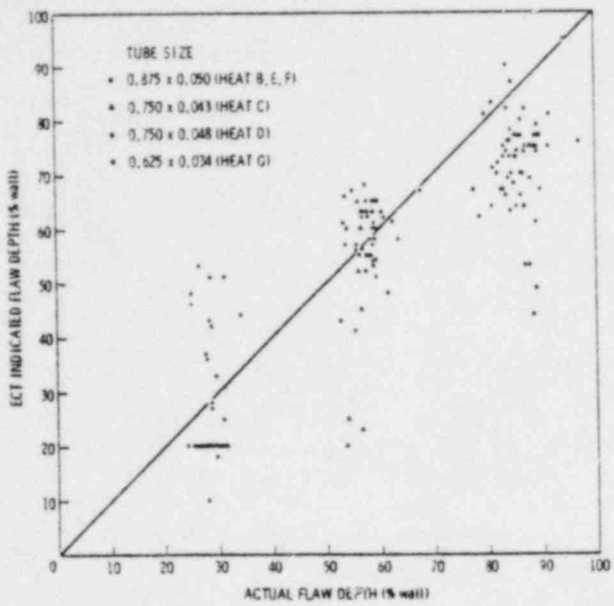


FIGURE 24

UNIFORM THINNING

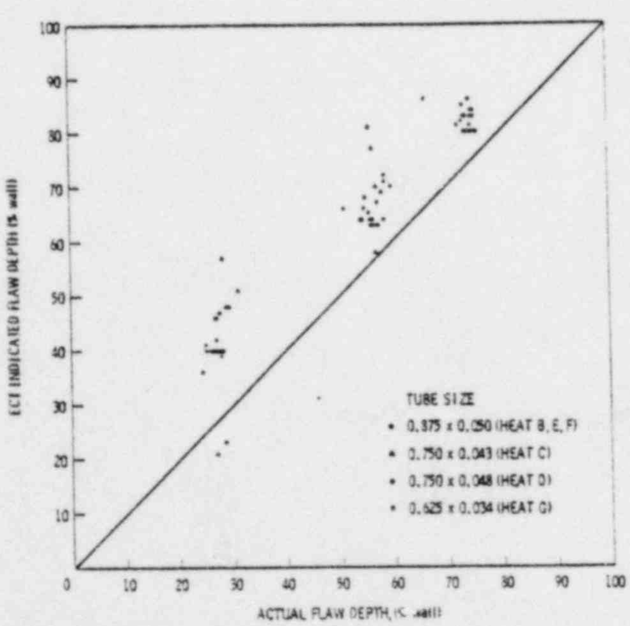


FIGURE 25

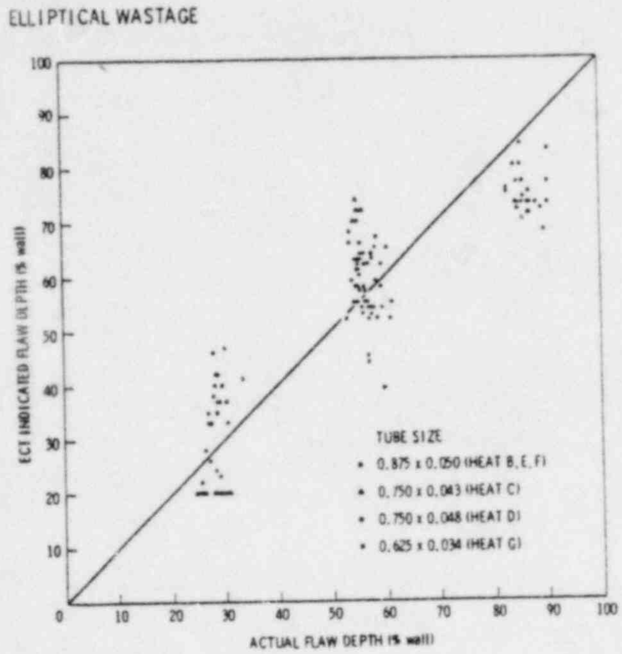


FIGURE 26

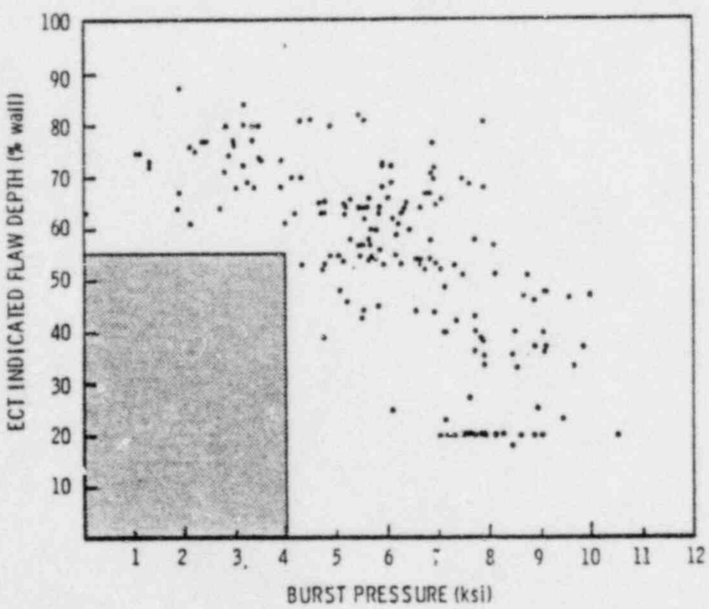


FIGURE 27