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Contractor Report ARPAD-CR-89002

STICK PROPELLANT X-RAY INSPECTION

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Ron Akre
IRT Corporation
3030 Callan Rd.
San Diego, CA 92121

Harry Chu
Project Engineer
AMCCOM

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A line scan x-ray transmission technique has been developed for the stick propellant automated inspection. The system has high reliability and is cost effective. This report documents the results of testing the stick propellant x-ray inspection system to measure the outer diameter, perforation diameter, web thickness, and density of M31A1E1 propellant sticks.

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FIGURES

1. INTRODUCTION

This report contains the results of testing the Stick Propellant X-Ray Inspection System, designed and built by IRT Corporation, San Diego, California, to measure the outer diameter, perforation diameter, web thickness, and density of M31A1E1 propellant sticks. Slot width and porosity of the stick were also observed during testing.

1.1 SYSTEM OVERVIEW

The Stick Propellant X-Ray Inspection System is designed to measure the outer diameter, perforation diameter, web thickness, and density of M31A1E1 stick propellant. The inspection system uses x-ray transmission and a linear diode array detector to collect information needed to accurately determine the required parameters. The system can be broken down into four sections, the x-ray unit, the stick handling sub system, linear array detector and interface, and the main computer.

1.2 PRINCIPLES OF OPERATION

The function of the four subsystems are described in this section. The system interconnect schematic is shown in Figure 1-1. The test bench with x-ray source, stick handling system and detector are shown in Figure 1-2. The x-ray system consist of four components: x-ray tube, high voltage generator, x-ray controller and water cooler. The system is capable of an output of 100 kV at 15 mA. During testing the best results were obtained using a high voltage setting of 40 kV and the large focal spot, 15 mA. The water cooler is used to prevent the tube from overheating and must be turned on before the x-ray generator and left on 5 minutes after the generator is turned off. This will prevent damage to the tube. The x-ray control unit controls the high voltage generator and monitors and stabilizes high voltage and current. Safety interlocks can be connected to the control unit to cause the x-ray system to turn off when a door is open. The x-ray source controller is also equipped with a timer to turn off x-rays after a preset time.

X-rays passing through the stick propellant are detected by a linear diode array. The linear diode array is light sensitive and is used with a scintillator attached to the front of it. The scintillator emits light when struck by x-rays and also protects the linear diode array from x-rays. The light emitted by the scintillator is collected on the linear diode array. A charge is built up which is proportional to the incident light. The build up of charge is reset when the diode arrays are read. In order not to saturate the diodes the exposure time should be kept less than 0.6 s. The linear diode array is also sensitive and can be damaged by moisture. Dry air or gas is used to purge the detector array to keep it free of moisture while running. The air should be turned on at least 5 minutes before turning on the detector interface. The detector interface supplies the detector with operating voltage and reads the diode array. The detector interface is controlled by the main computer through a GPIB port. Commands are sent by the computer to set up and operate the detector interface. The status of the detector interface and data from the linear diode array can be read by the computer.

The stick handling system consists of two motion control units. One unit runs a single-stepper motor for rotation of the stick. The other motion control unit runs two stepper-motors in parallel to translate the stick into and out of the inspection area. The motion control units receive commands from the computer through the serial port to control position of the stick.

The computer controls the detector interface, used to run the detector, and the motor interfaces, used to run the stepper-motors which rotate and translate the stick. A printer is also connected to the computer to supply the operator with hard copies of data in the form of numbers or graphs. The data from the detector array transferred to the computer is stored in 10 arrays set up in the computer memory. These data are then analyzed to determine the parameters of the stick.

The analysis of the stick to find the outer and inner diameter, web thickness, and density at a point along the stick axis takes about 45 s. The stick is first rotated and 18 images taken, one every 10 degrees. The images are analyzed to see if the slit is present in the center of the image. Once the position of the slit is determined (after all 18 sets of data are analyzed) the stick is then rotated into the position where the slit is located in the center of the image, parallel to the x-rays. A 5 s count is then taken on the stick. Curve fitting is done to the square of the data to determine the outer and inner diameter and web thickness. The stick is then rotated 90 degrees and another 5 s count taken. From this count the attenuation of the x-rays at the center of the stick is obtained.

The web thickness determined from the first count is the distance x-rays pass through the stick near the center. The density is calculated from the amount of attenuation through the measured distance.

2. SYSTEM PERFORMANCE

Results of measurements of system characteristics are discussed in this section. These results are parameters of the gauging system, and are independent of stick propellant measurements.

2.1 DARK CURRENT STABILITY

The dark current of the detector seems to drift in the first five minutes of system operation. After this the dark current seems to be very stable. Fifty counts were taken with the dark current and the average and standard deviation calculated for each of 450 array elements. The average of the 450 elements average and standard deviation are given below for 0.5-second and 5-second counts.

	Average	Sigma	Percent (Sigma x 100/Average)
0.5 Sec Count	563.8	0.069	0.0108
5.0 Sec Count	5641	0.268	0.0054

The 0.5 s count is a single count, whereas the 5.0 s count is a sum of ten 0.5 s counts. In both cases the integration time of the diode array is 0.5 s.

To check the long-term stability of the dark current, two 50 s counts were taken 14 days apart. The average of 450 elements was used to check stability. The average dark current dropped by 1.6 percent. This was an overall drop in signal level, since the standard deviation of the difference between counts was only 0.13 percent. The variation in dark current over long periods of time does show that the dark current of individual diodes will change. The change in individual diodes is not as noticeable as the shift in dark current of the entire array. Even a shift in dark current of 2 percent will not noticeably affect the system measurement due to the normalization algorithms used.

2.2 SIGNAL-TO-NOISE RATIO

To test the gain between diodes, data were taken and plotted for various x-ray voltages. Each diode seems to have about the same gain, as can be seen in Figure 2.1, by the plots being relatively flat. Near the edge of the array the signal may drop off due to partial shielding of the detector from the x-ray beam by the collimator. This part of the diode array is not used for measurements.

The system was set up to take ten 0.12 s counts, for a total integration time of 1.2 s. Fifty such 1.2 s counts were taken, and the average and standard deviation for 450 diodes were calculated. The average for the 450 diodes of the fifty run averages for individual diodes and the average of the standard deviation of the fifty runs is given in the table below.

	Average	Sigma	Percent (Sigma x 100/Average)
Dark Current	2023	18.8	0.93
20 kV	4.10	44.3	1082.0
30 kV	276.3	54.3	19.6
40 kV	1492.2	51.2	3.4
50 kV	3919.7	249.9	6.4

Operation of the system below 30 kV is not practical due to the low signal levels as compared to the dark current. The level of dark current can be lowered by additional cooling of the detector if lower x-ray energies are desired.

During examination of stick propellant, a large amount of attenuation caused by the propellant is desirable. The percent of attenuation caused by the stick propellant is given below.

X-Ray Energy	Count Rate - Dark Current		Ratio
	With Stick	Without Stick	
50 kV	12984	16358	0.794
40 kV	4287	5789	0.741
30 kV	612	948	0.646

A lower energy would give more attenuation, but the dark current noise limited the minimum energy at which the system could be operated. An energy of 40 kV was selected because of low signal-to-noise ratio and reasonable attenuation.

2.3 RESOLUTION WITH LIGHT AND WITH X-RAYS

The detector array has diode elements spaced at 1.0 mil. With a light source the resolution of the detector system seemed to be very close to 1 mil. Figure 2.2 shows an image of a dark band placed across the detector array. The image was taken with a light source illuminating the diode array with the scintillator removed. The slope of the curve at the edge of the band could be from the band not being exactly perpendicular to the diode array. If the object were off by 12 degrees this would result.

Imaging an object with x-rays degrades the sharpness of the edges. This can be seen in Figure 2.3 where a thin sheet of tungsten was rotated in front of the detector. The long curving edges are believed to be from x-ray scattering within the scintillator. With the use of curve fitting, the edges can still be found to within 1 mil.

A stainless steel wire 1.2 mils in diameter was imaged to get an approximation to the point spread function. Two images were taken between which the wire was rotated 180 degrees. Displacement of the wire in the two images was used to find the pixel which represents the center of rotation. The half max is about 3 mils, and the pixel at the center of rotation is number 673 as shown in Figure 2.4

Although resolution of the system is dependent upon x-ray scattering in the scintillator, edges and other similar features can be located very accurately by use of algorithms in the data analysis.

2.4 NORMALIZATION OF DATA

To normalize the data the dark current is subtracted from the image of the object and from an image of the unattenuated x-ray beam. The ratio of the two images is then used to form a normalized image. This process adjusts the data for offset and linear gain of each diode. The actual equation used for normalization also inverts the data and scales the data to 10000 full scale. The equation is given below.

NORM = (I0-DK)/(I-DK)*10000-10000

where:

DK = Dark Current Measurement
I0 = Unattenuated x-ray Measurement
I = Measurement With Object In Beam

3. STICK GAUGING SENSITIVITY

The routine to evaluate the stick parameters first rotates the stick to locate the slot. This is done by rotating the stick 180 degrees and taking an image every 10 degrees. For each image a ten-point sliding integral is used to find the two edges of the inner diameter, local maxima. A local minimum between the two local maxima is next found using a five-point sliding integral. The difference of the sum of the two local maxima and four times the local minimum is used as a reference value for the slot. After all 18 images have been taken and analyzed, the angle at which the reference value is greatest is then calculated and rotated to. The slot is now parallel to the x-ray beam.

With the slot parallel to the x-ray beam the inner diameter outer diameter and web thickness can be measured. The stick is then rotated 90 degrees, and an integral taken in the center (along the diameter) of the stick. The value of this integral and the thickness of the web the radiation is passing through, known from the last measurement, are used to calculate the density. The methods are discussed in the following sections.

3.1 OUTER DIAMETER

To find the outer diameter, the two points of half maximum are first found in the normalized data. These two points are shown in Figure 3.1. The data are then squared and a straight line is fitted to 21 points centered at the half maximum points. The intercept of each line with the base line determines the location of the outer edge of the stick. The diameter is found from scaling the difference between these two intercept points at the two sides of the curve. The scaling factor used is dependent on the density of the object, and for stick propellant is 0.907.

Using this method, the outer diameter is determined with a standard deviation of 0.12 percent or 0.30 mil on a stick of 244 mils outer diameter.

3.2 PERFORATION DIAMETER

After the outer diameter edges have been found, the edges of the perforation are next located. This is done by finding the two local maxima and then fitting curves to the nearby points. Twenty-one points on the outer side of each local maximum are fitted to a second-order polynomial. Twenty-one points on the inner side of the local maximum are fitted to a third-order polynomial. The point at which the two curves intersect is taken as the edge of the perforation. The second- and third-order curve fits are shown in Figure 3.2. The inner diameter is found by scaling the difference of the two edges of the perforation. The scaling factor used for stick propellant is 0.915.

Using this method for finding the perforation diameter, the diameter is found with a standard deviation of 1.30 percent, or 1.14 mils on a stick of 87.9 mils inner diameter.

3.3 WEB THICKNESS

The web thickness is obtained from location of the outer diameter edges and edges of the perforation. The difference between the outer diameter edge and the perforation edge is the web thickness. The web thickness on both sides is determined, and the average of the two values displayed.

The accuracy of the web thickness is dependant on the outer and inner diameter measurements. The web thickness is found with a standard deviation of 0.69 percent, or 0.54 mil on a stick with a web thickness of 78.7 mils.

3.4 DENSITY

Once the web thickness is known in the present view, the stick is rotated 90 degrees and a measurement taken in the center (along the diameter) of the stick. A twenty-one point integral is used to determine the attenuation of the x-ray beam. The integral is taken through the area in which the web thickness was measured in the previous view. The equation used to determine the density is given below.

DENSITY = LOGe(INTEGRAL X CAL1 / 10000) / WEB X CAL2

where:

CAL1	= First calibration factor
CAL2	= Second calibration factor
INTEGRAL	= Twenty-one point integral
WEB	= Total Web thickness, sum of both sides
LOGe	= log base e

For stick propellant CAL1 is 0.65, and CAL2 is 711.

Results of 9 sets of 50 runs show the density is measured with a standard deviation of 0.86 percent, or 0.0142 gm/cm^3 on a stick with a density of 1.647 gm/cm^3.

3.5 SLOT WIDTH

The slot width is determined from the image in which the slot is parallel to the x-ray beam. The area in the center of the image between a parabola fitted to the perforation and the actual data is proportional to the slot width. Figure 3.3 shows three different slot widths, 5, 10 and 15 mils. The area used to determine slot width is shaded and the integrals of the shaded area given. The data show that slot widths of 5, 10 and 15 mils can be easily distinguished from one another.

3.6 POROSITY

In Figure 3.4 the square of the data is fitted with a straight line near the outer edge of the stick. The difference of the data from the line is an indication of porosity. The graph shown in Figure 3.4 is stick propellant data squared with a small slit in the side to simulate porosity.

4. CONCLUSION

A summary of the system gauging capabilities are given in Table 4.1.

Table 4.1. Stick Propellant X-Ray Inspection System Sensitivity Results

Measurements	Average		Standard Deviation		Error (%)
Outer Diameter	243.7	mils	0.30	mil	0.12
Perf. Diameter	87.9	mils	1.14	mil	1.30
Web Thickness	78.7	mils	0.54	mil	0.69
Density	1.647	gm/cm^3	0.0142	gm/cm^3	0.86

These results demonstrate that the system determines quickly and accurately the dimensions and density of M31A1E1 stick propellant. The sensitivity of the system is well within the required values for both spatial resolution and density gauging. The resolution of the system is sufficient to measure more complex geometries than the one studied.

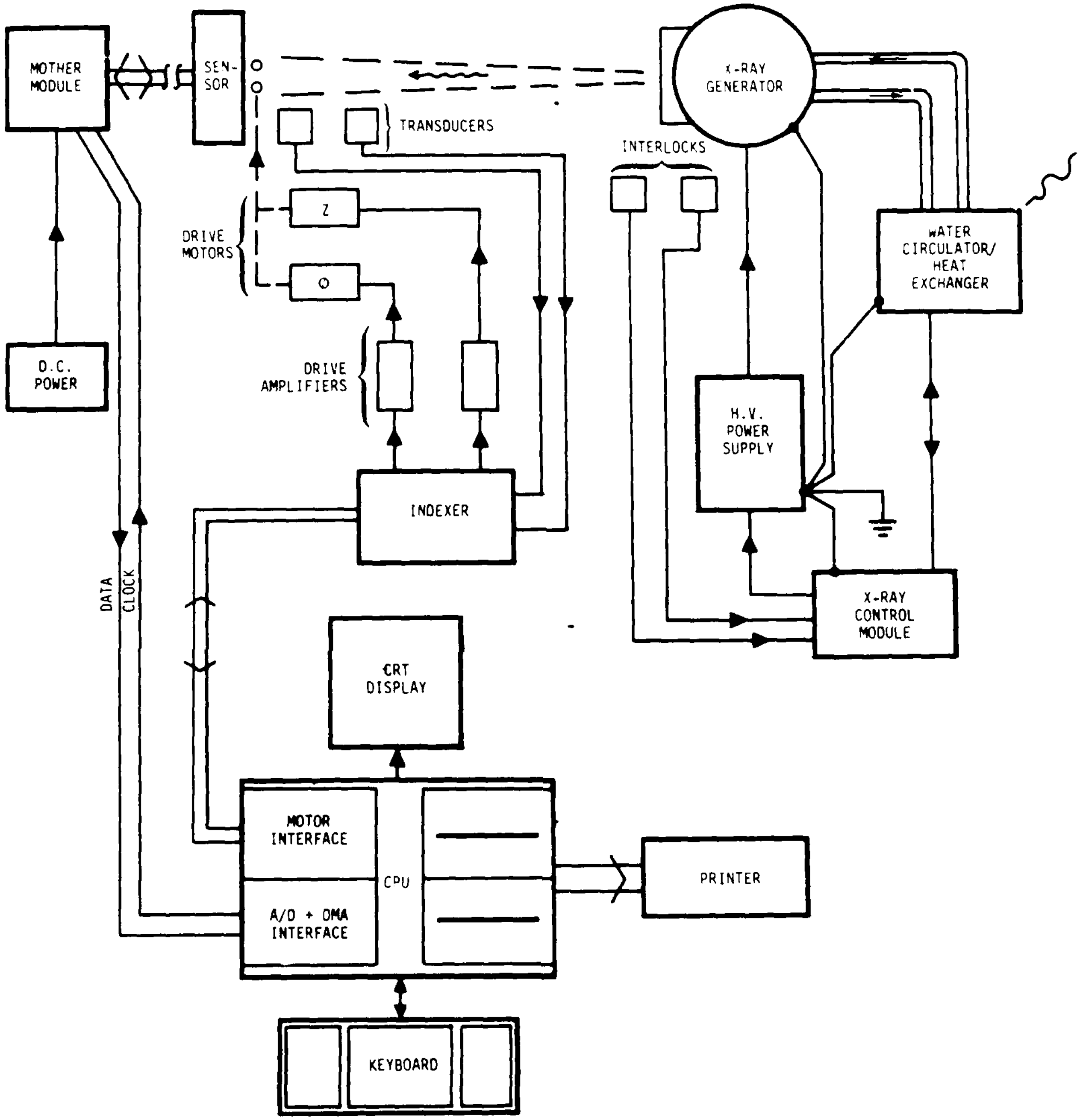

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Figure 1-1. System interconnect schematic

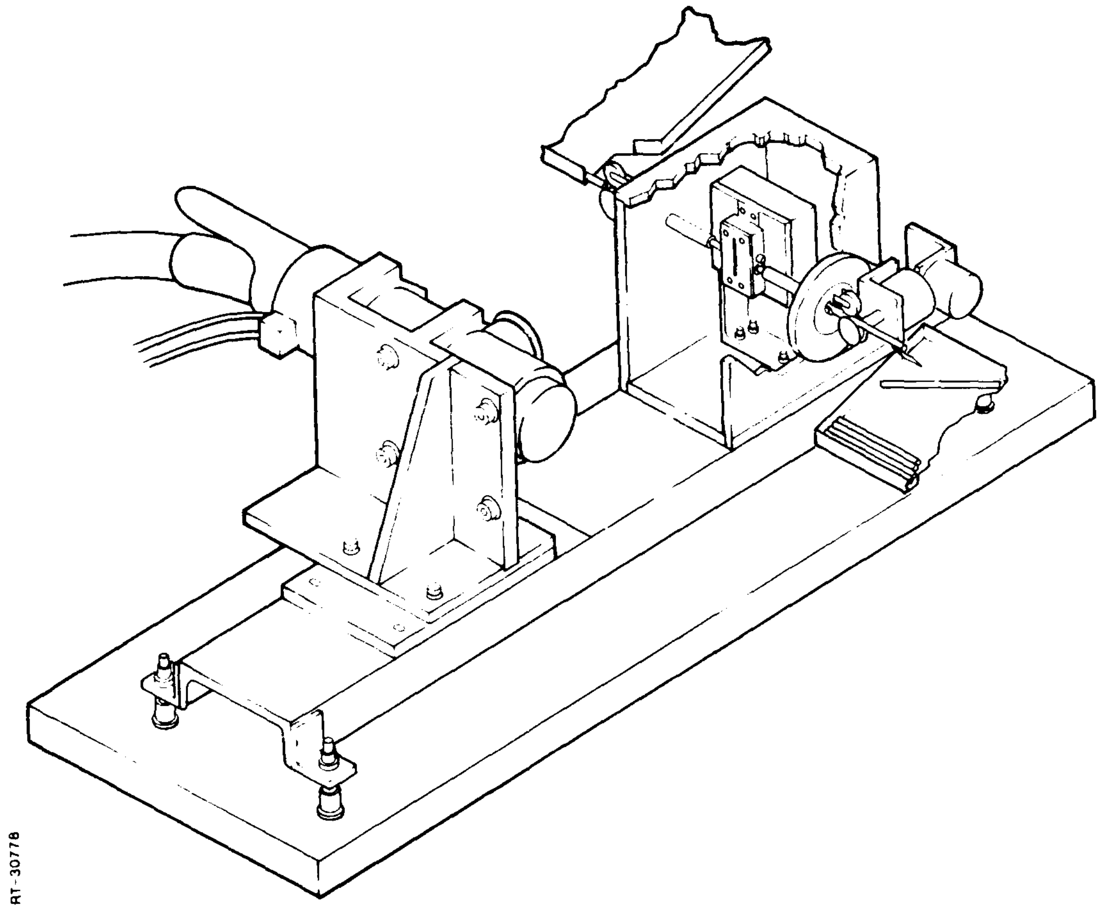

Figure 1-2. Artist's concept of the Stick Propellant System

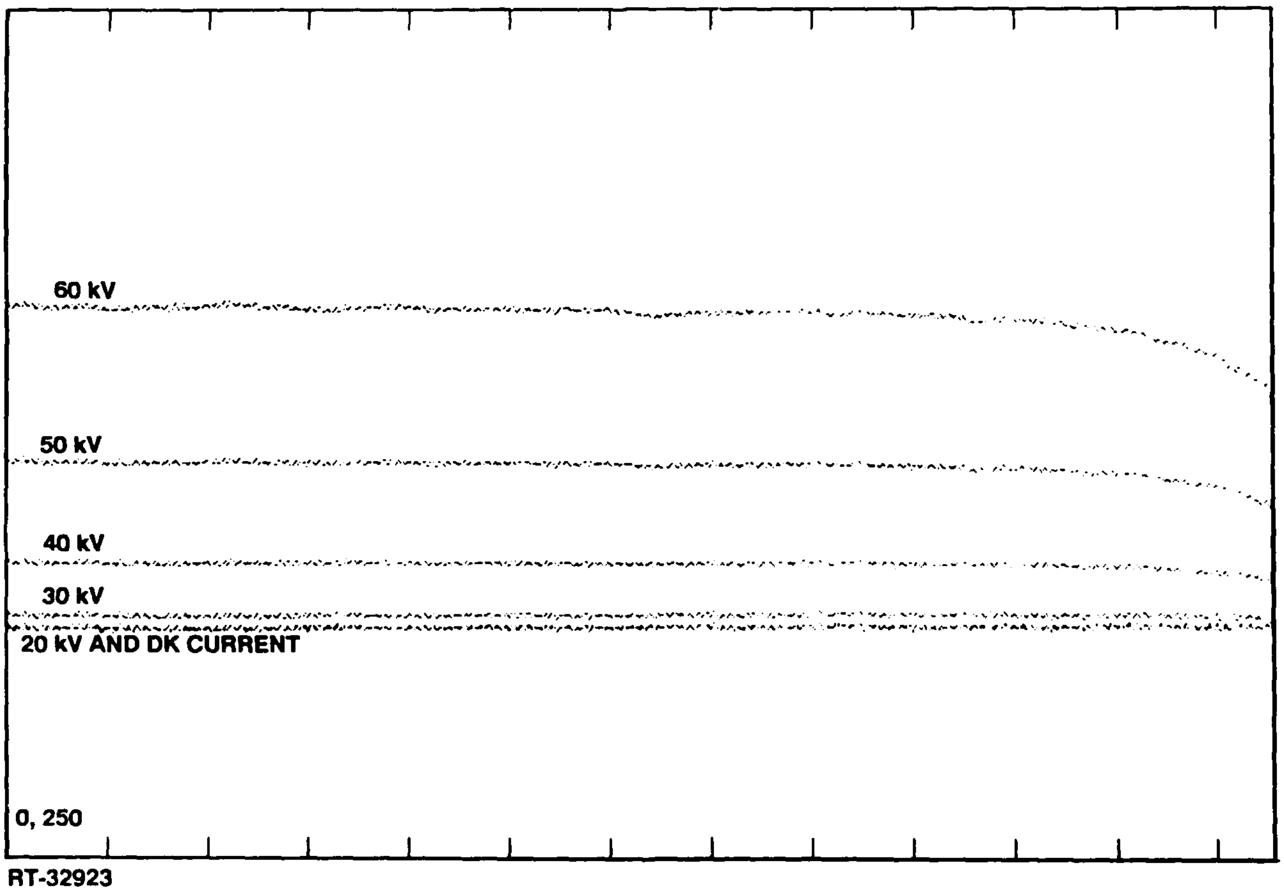

Figure 2.1. Diode counts at various voltages

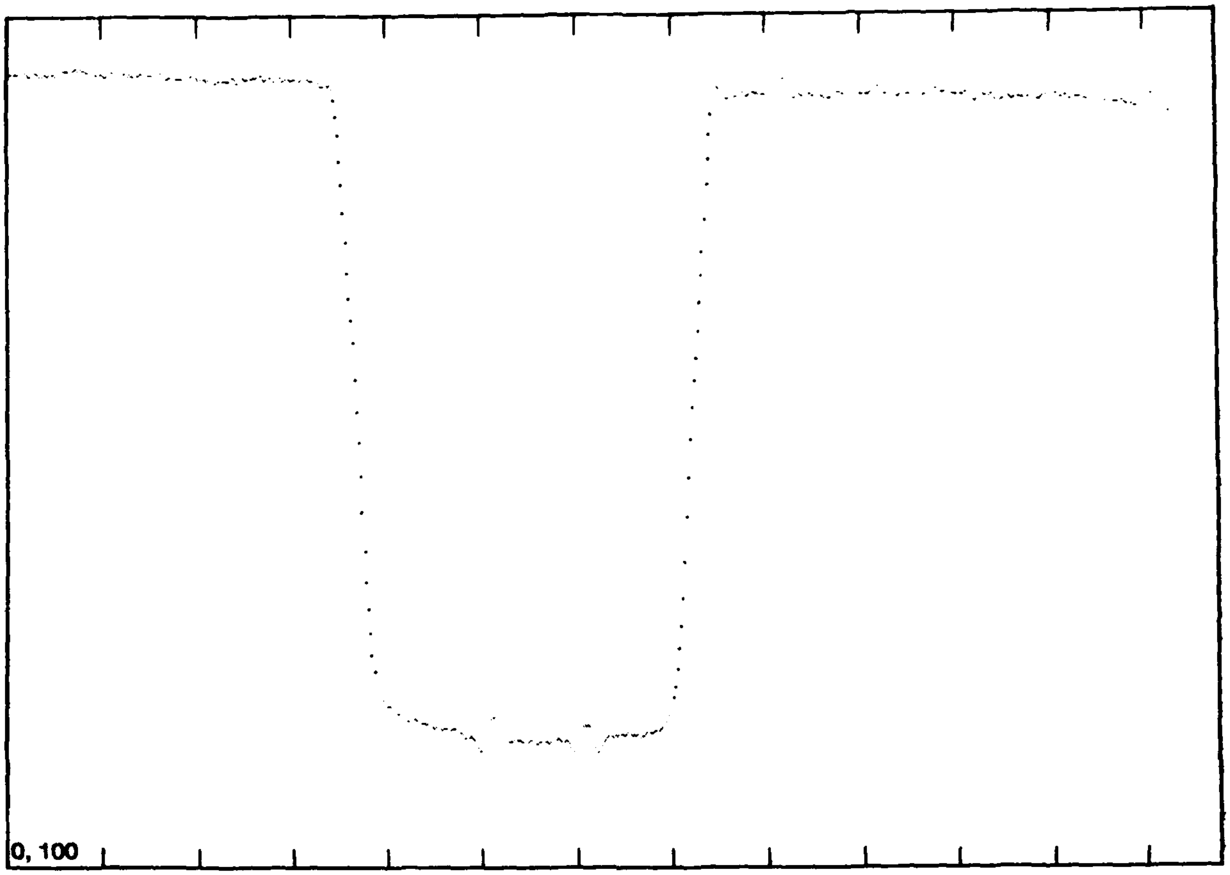

Figure 2.2. Opaque band across diode array illuminated with light

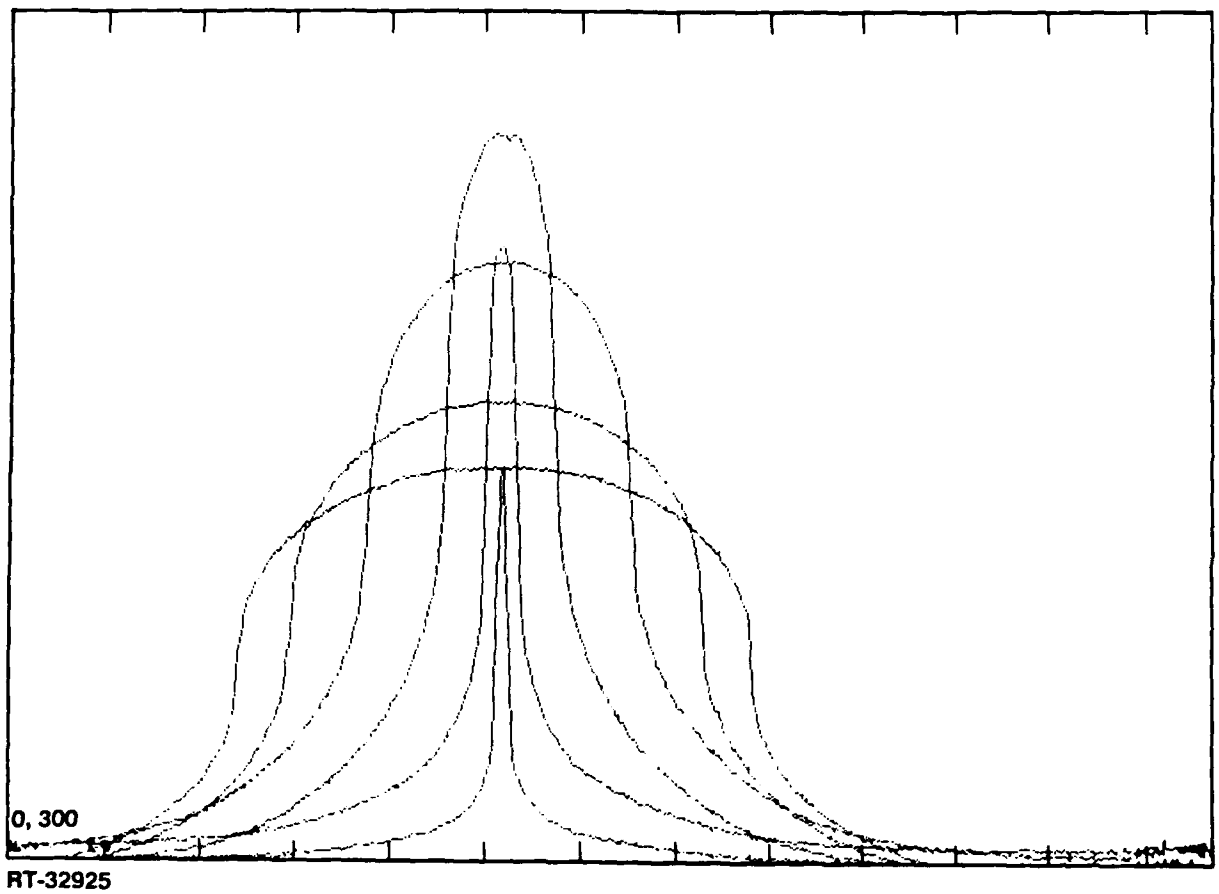

Figure 2.3. Tungsten band rotate perpendicular to diode array

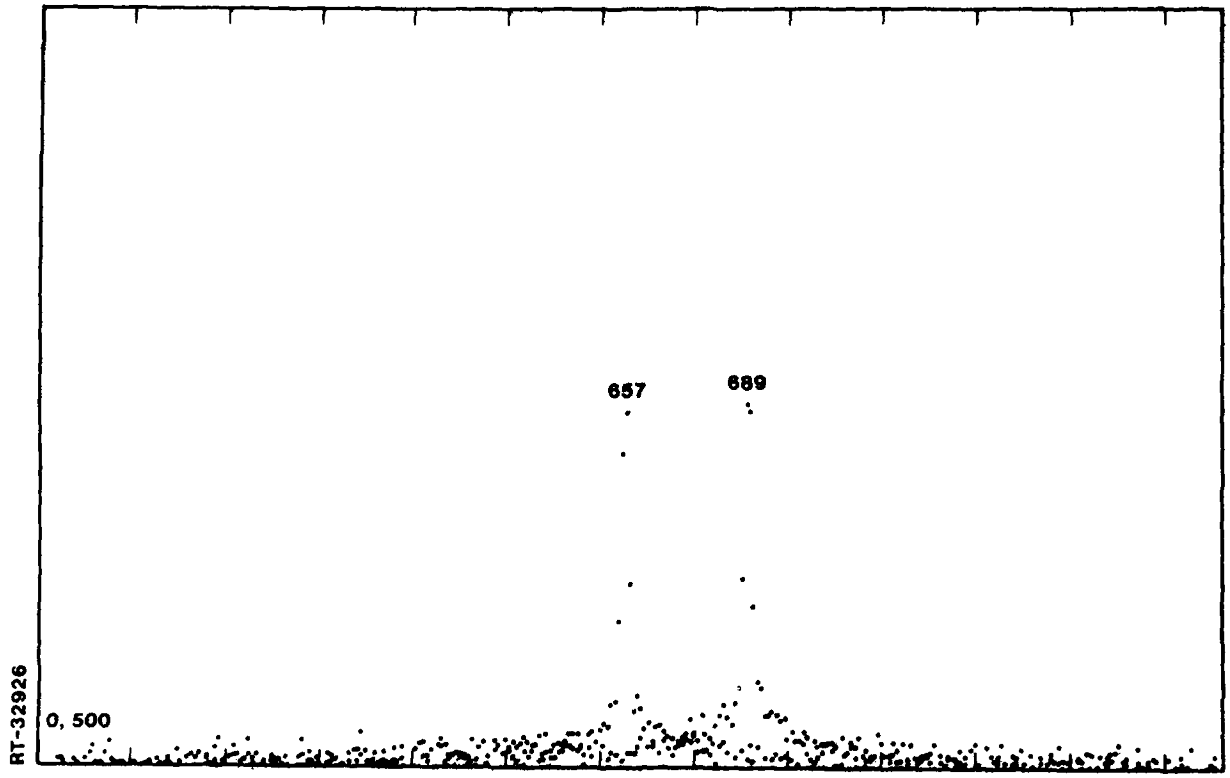

Figure 2.4. 1.2 mil stainless steel wire

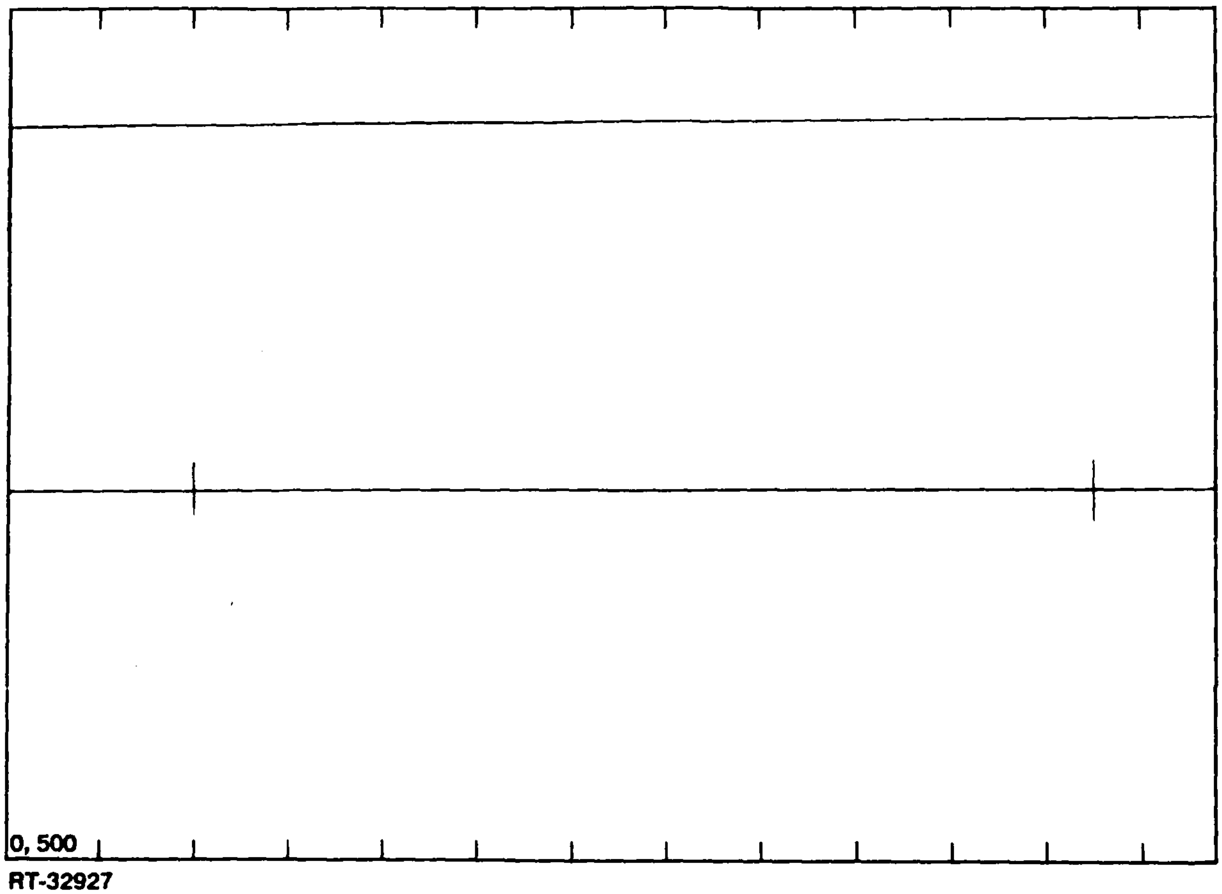

Figure 3.1. Normalized data for M31A1E1 stick propellant

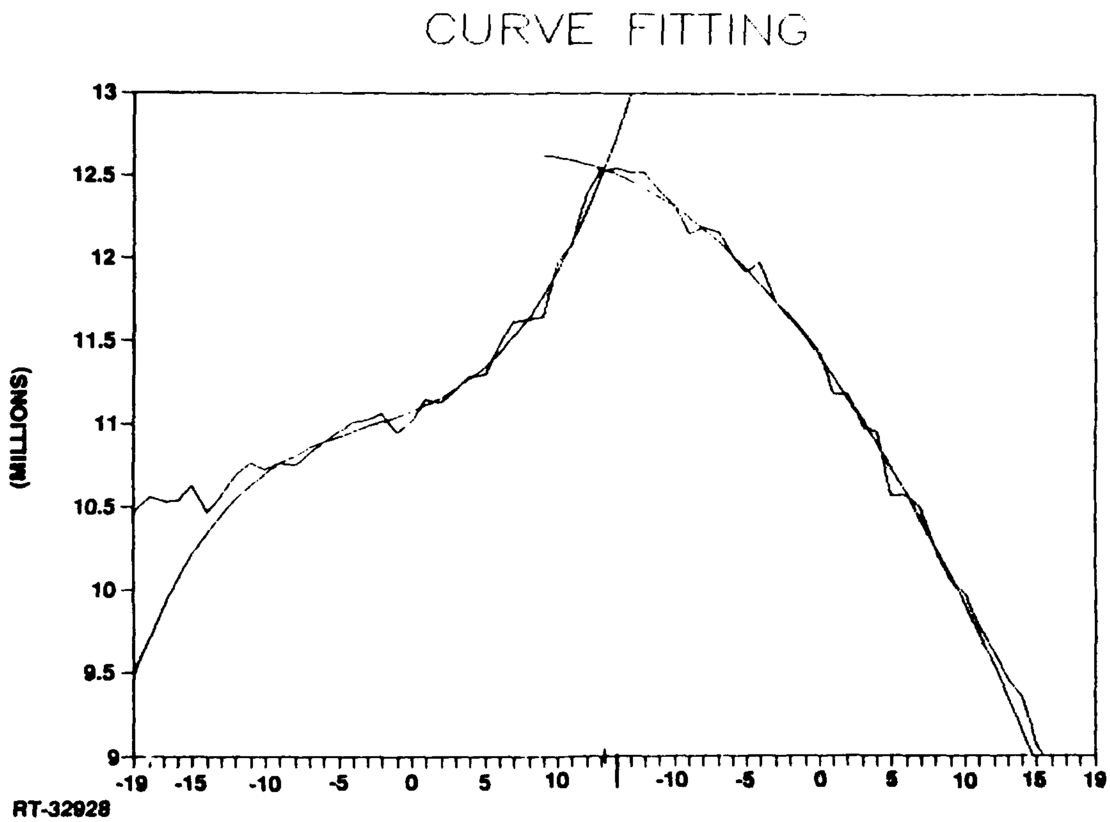

Figure 3.2. Second and third degree curve fits used to locate edge of inner perforation

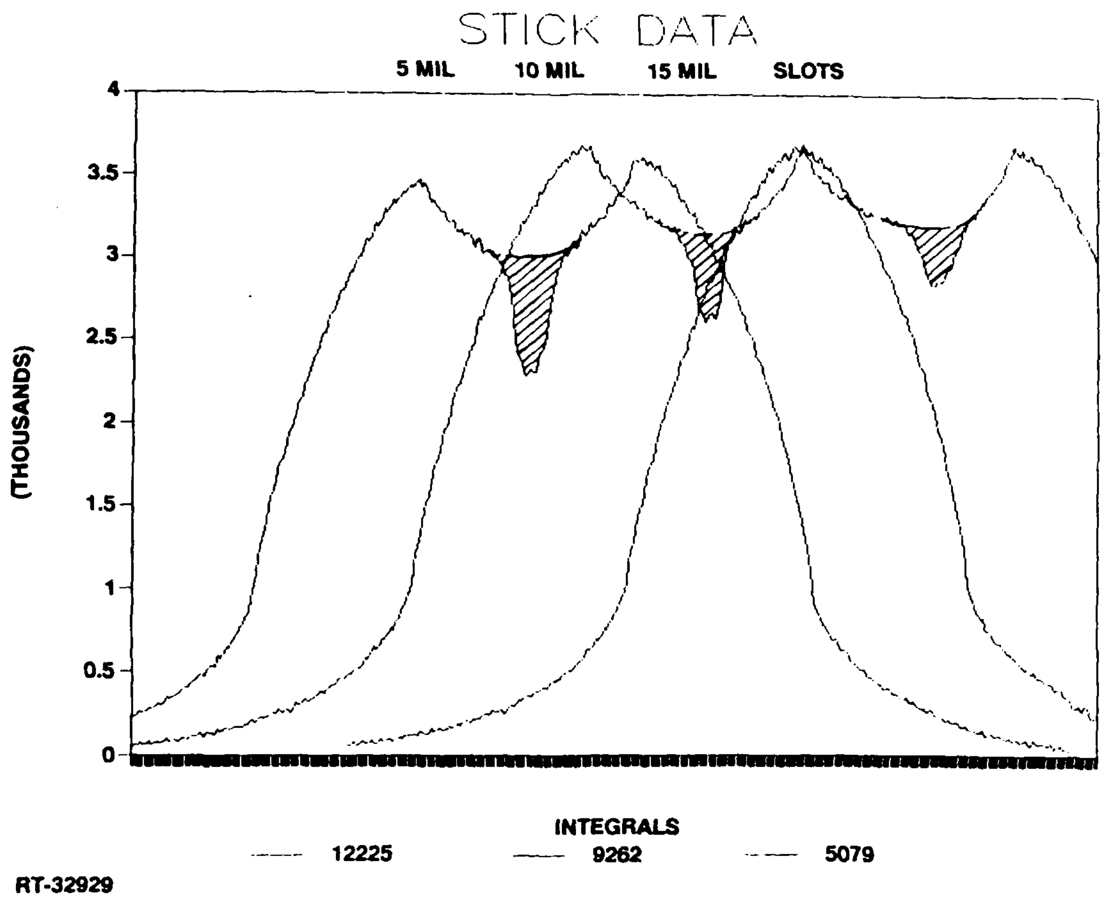

Figure 3.3. Normalized stick image of sticks with 5 mil, 10 mil and 15 mil slot widths

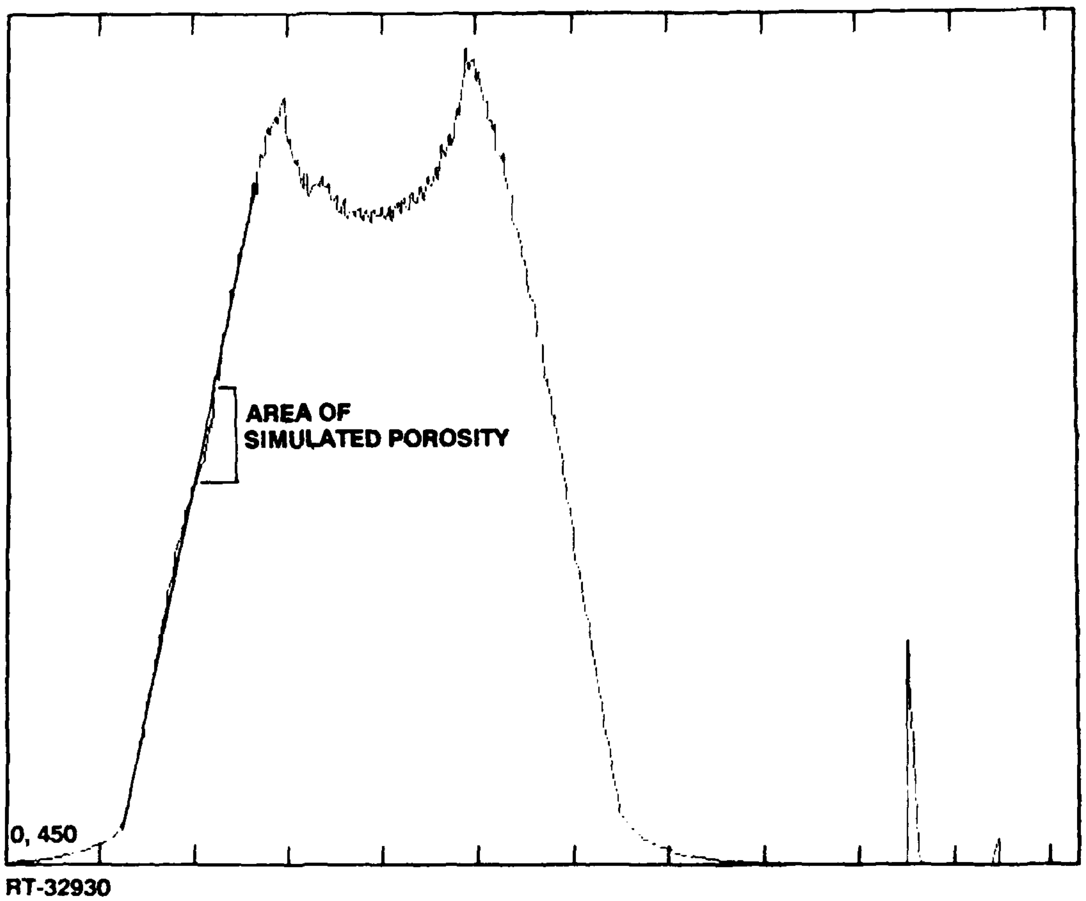

Figure 3.4. Straight line fit to edge of stick with simulated porosity

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