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RADIOGRAPHIC INSPECTION AND DENSITOMETRIC EVALUATION OF CP-5 REACTOR FUEL

by

J. F. Staroba and T. W. Knoerzer

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Nondescructive Assay Section
Special Materials Division

February 1978

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ABSTRACT

This report covers the radiographic and densitometric techniques used as part of a quality verification program for CP-5 reactor fuel by the Nondestructive Assay Section of the Special Materials Division. Other nondestructive tests used were ultrasonic and gamma-ray spectrometry. The main objectives were to perform a one-hundred percent radiographic inspection of the fuel tubes and to derive a quantitative relationship between fuel thickness and film density with the use of fabricated fuel step wedges. By the use of tangential X-ray techniques, measurements were made of fuel peaks or "hot spots" that protruded above the main fuel line. Other general problems in radiographic inspection and solutions for the upgrading of the total radiographic inspection program are also discussed.

I. INTRODUCTION

The CP-5 fuel elements[1] are tubular, and each contains three concentric fuel tubes. Table I gives specifications for dimensions and ^{235}U content for each size fuel tube.

Previously, CP-5 fuel-tube radiographic inspections[2] had been limited to a spot check on one of every six fuel tubes for aluminum end-cap and fuel-length verification. In addition, an X-ray on polaroid film was taken of the marked ends of all outer fuel tubes to ensure that the top end had

Table 1. Dimensions and ^{235}U Content of Fuel Tubes

	Inner	Intermediate	Outer
Cladding thickness, in.	0.015 ± 0.003	0.015 ± 0.003	0.015 ± 0.003
Core thickness, in.	$0.032^{+0.004}_{-0.003}$	$0.032^{+0.004}_{-0.003}$	$0.020^{+0.004}_{-0.003}$
Wall thickness, in.	0.062 ± 0.003	0.062 ± 0.003	0.050 ± 0.003
Avg outside dia., in	2.236 ± 0.005	2.640 ± 0.005	3.000 ± 0.005
Avg inside dia, in.	2.112 ± 0.005	2.516 ± 0.005	2.900 ± 0.005
Roundness, in. (max. O.D. - min. O.D.)	0.010	0.010	0.014
Bow, max., in.	0.025	0.025	0.025
Core length			
1) Minimum thickness	21-13/16	21-13/16	21-13/16
2) Maximum thickness	26-5/16	26-5/16	26-5/16
Tube length, in.	27-9/16 ± 1/16	27-9/16 ± 1/16	32-5/32 ± 1/16
End filler length, min., in.	1/2	1/2	1-3/8 Top 3-7/8 Bottom
^{235}U content, grams	62.0 ± 3.0	73.0 ± 3.0	35.0 ± 3.0
^{235}U content of a matched set, grams		$170.0^{+6.0}_{-2.0}$	

(1 in. = 2.54 cm; 0.0397 in. = 1 mm)

been properly identified. These polaroid shots also ensured that the minimum aluminum end-cap lengths for the outer fuel tubes were not less than the specifications called for.

Measurement of the fuel-core length of any fuel tube had been done by x-raying a portion of each end of the fuel tube and then computing the fuel length by subtracting the sum of the lengths of the ends from the overall fuel-tube length. Full radiographic examination of the entire length of the fuel tube and core thickness/density measurement was not done.

The radiographic program was designed to gather more meaningful data concerning: (1) core thickness over the entire length of the fuel; (2) uranium-aluminum alloy segregation sizes, thickness, and location; (3) characteristic buildup of fuel in the transition zone from fuel to aluminum at the tube ends ("dog-bone" effects); (4) accurate fuel-length measurement.

II. HANDLING PROCEDURES

Handling procedures for fuel-tube radiography required that clean, lintless gloves be worn, and that all contacting surfaces be free from oil, dirt, and grit. In addition, extreme care was taken during both setup and radiography that there should be no possible direct contact of the fuel tubes with the lead shielding or with the lead identification letters. Because the aluminum outer cladding could easily be damaged by careless handling or by bumping, all sharp corners and edges of surrounding and/or neighboring apparatus were padded with flexible, lead-impregnated rubber medical shielding to eliminate accidental marring of the fuel-tube surfaces.

The fuel tubes were paper-wrapped for added protection and were stored in an adjacent building. Individual tubes in their paper wrappings were carefully transported from the storage area to the radiographic inspection area, and the paper was removed only after all setup had been accomplished.

III. RADIOGRAPHIC PROCEDURE

For the overall static exposures, four 36" lengths of Kodak Type M industrial X-ray film, 2-3/4" wide, were used on each fuel tube. The 36" length ensured ample space for step wedge placement on the film off the end of the fuel tube at its top, and for coverage of its bottom end. The 2-3/4" width provided sufficient overlap from film to film, regardless of fuel-tube size. For the outer, or largest, size fuel tube, the film overlapped about 1/4" on each side, and for the smallest, or inner, fuel tube, the film overlapped about 1/2" on each side.

The exposure parameters were as follows:

Picker 150 X-Ray Machine	0.3 mm focal spot
Target to film distance	77"
Kilovoltage	90
Milliamperes	5
Time (outer tubes)	95 seconds
Time (inner and intermediate)	175 seconds
Kodak X-OMAT Processer	81° F

The fuel tubes were backed by flat lead shielding to eliminate radiation back-scatter. In addition, the collimator on the Picker 150 X-Ray unit was adjusted to define a beam (Fig. 1) just somewhat larger than the fuel element and the film to reduce scattered radiation. The film was held tightly in place against the inner surface of the fuel tube by soft sponge-rubber segments. The appropriate step wedge and identification were placed on the portion of the film which protruded from the top (numbered) end of the fuel tube, and which was backed directly by a formed cylinder of medical shielding to reduce X-ray scattering effects to the standard step wedge (Fig. 2).

Another important consideration was the placing of the fuel tube and the film perpendicular to the X-ray tube axis (that is, the fuel-tube axis was placed along the 0° line) to minimize the "toe and heel" effect of the X-ray tube (Fig. 3). Nevertheless, geometric factors, due to the spread

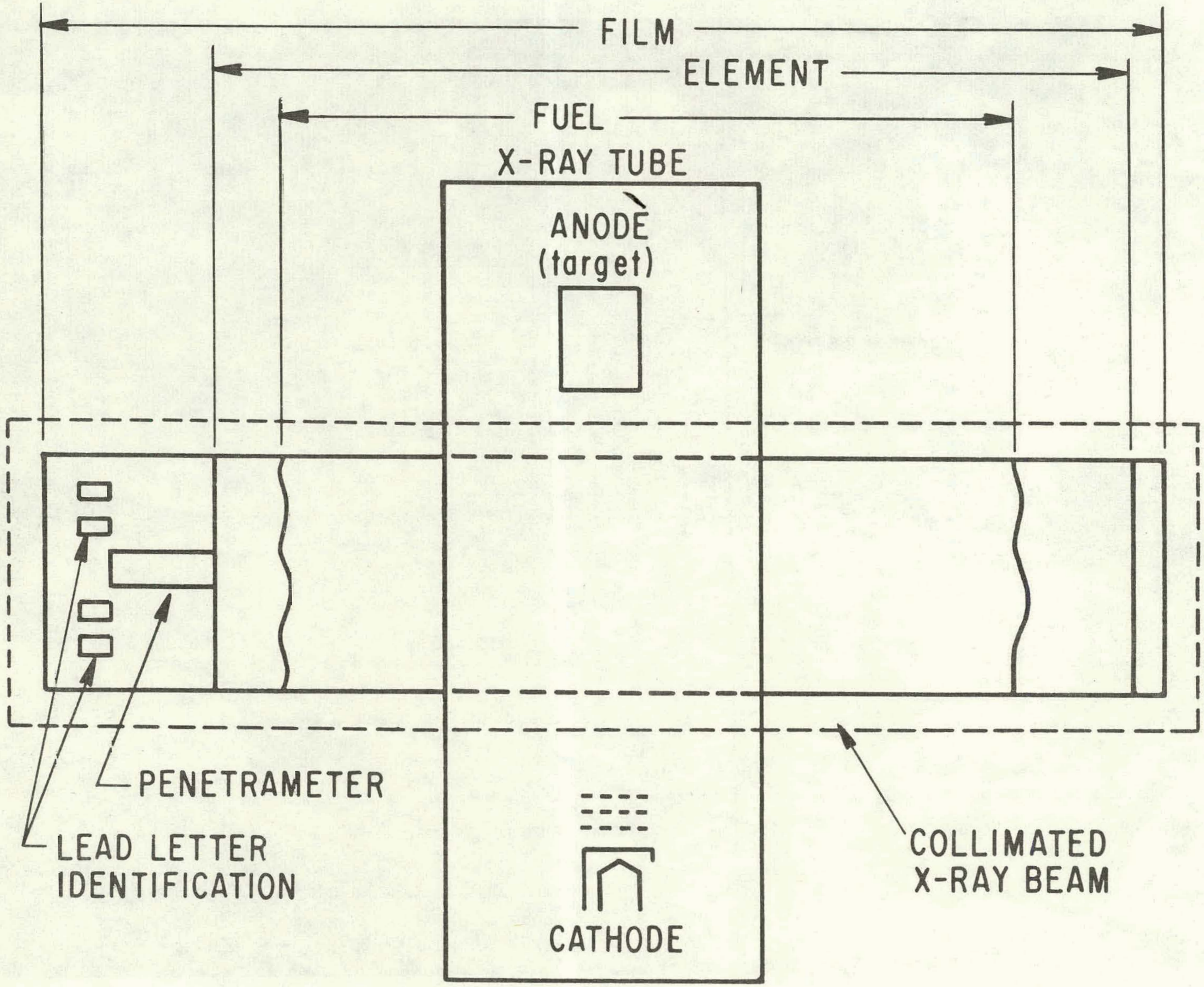


Fig. 1. Diagram of exposure setup.

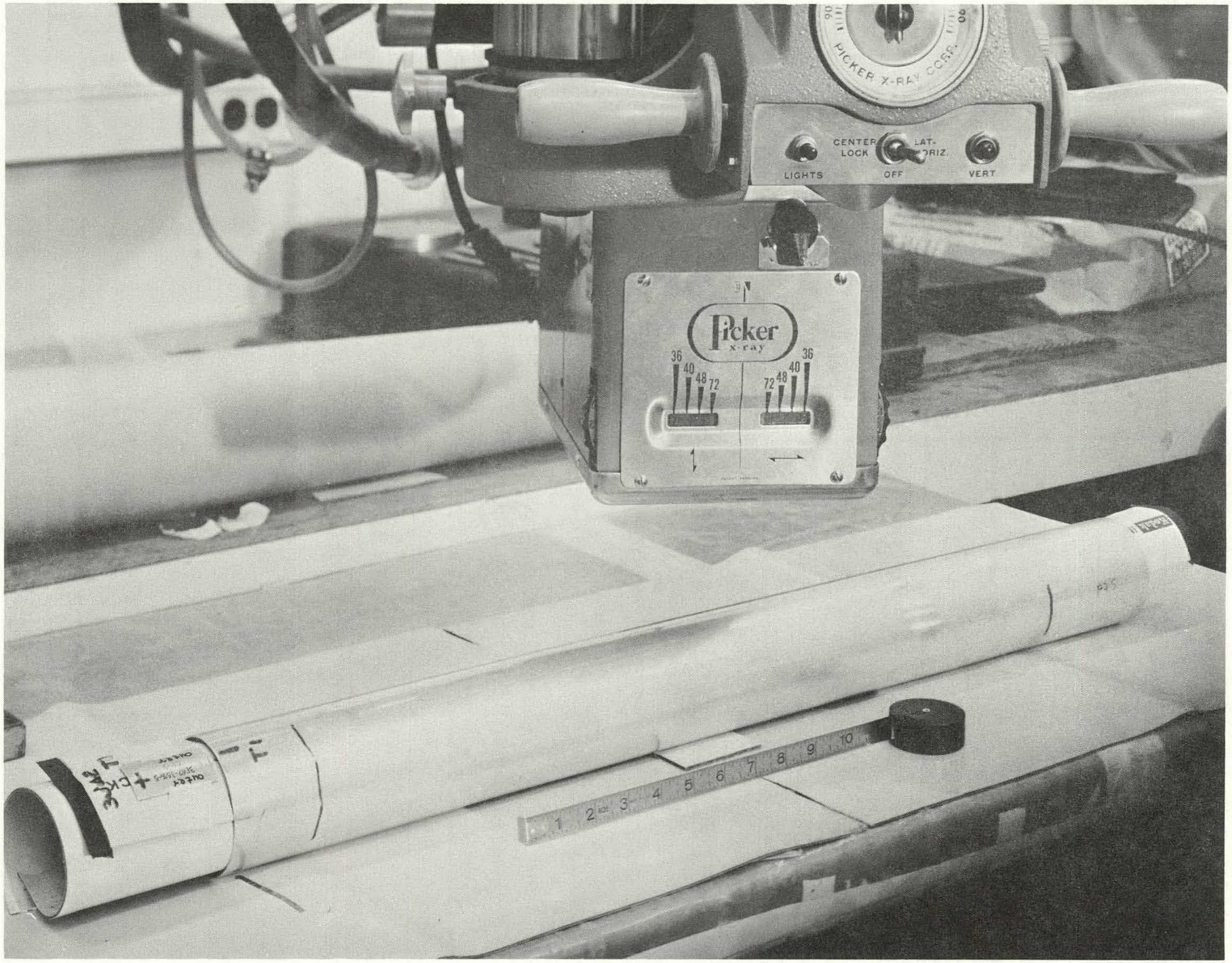


Fig. 2. Equipment and setup.
ANL Neg. No. 150-575.

of the X-ray beam from its central axis to each end of the fuel tube, yielded a decreasing density that also had to be considered. A plain film was exposed without using a specimen; the variation in density on the film was measured, and this measurement was used to obtain a normalized density for actual tube radiographs (Fig. 4). In practice, it was assumed that there was no variation in density over the middle 8" of fuel. The remaining length of fuel on each side, and the fabricated fuel step wedge standard at the top end of the fuel tube required an addition, depending on the location of the measurement, of up to 0.10 density units to the actual density measurement.

The films were developed in a Kodak Model B X-OMAT automatic processor at 81° F. Development time (dry to dry) was 11 minutes. The 36" lengths of film could be fed directly into the processor without being attached to a leader.

IV. FUEL LENGTH MEASUREMENT

One great advantage of radiographing on one piece of film is that both maximum and minimum fuel lengths and minimum aluminum end-cap lengths can be accurately determined by measurement. Previously, a portion of both ends of each fuel tube was radiographed, and the fuel length computed by subtracting the sum of the two ends from the total tube length. Under the new fuel inspection program, four films taken of adjacent areas of each tube can be aligned, attached to each other, and viewed together so that the entire tube can be seen at once.

The maximum core length was defined,[3] and was determined on the radiographs as the distance between the extreme locations of core material measured parallel to the tube. The minimum core length was defined, and also determined on the radiographs as the axial distance between points where the radiographic density is equal to that of the proper step of the standard step wedge. This was specified as the 0.029" step for the inner and the intermediate fuel tubes, and as the 0.017" step for the outer fuel tubes.

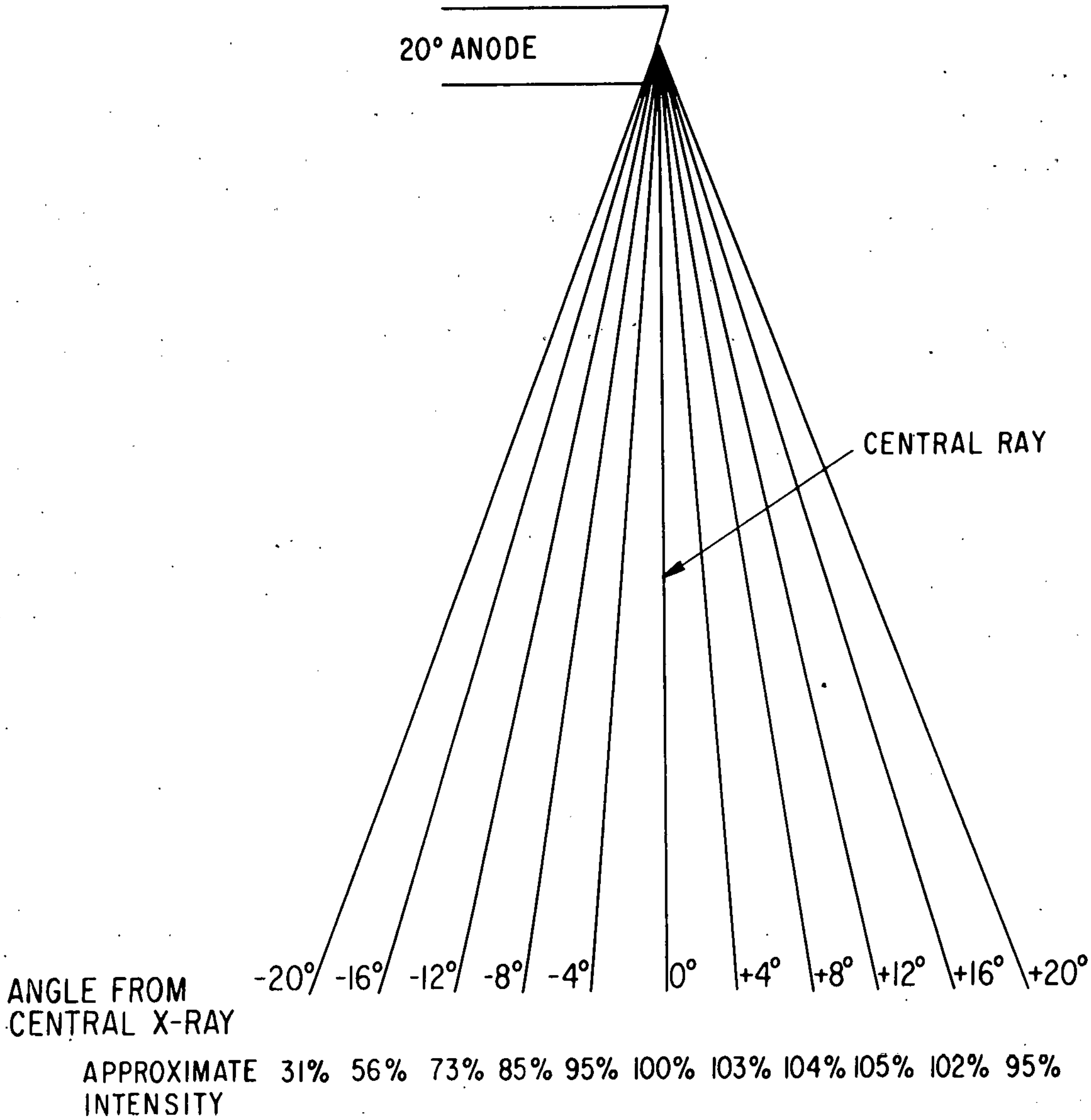


Fig. 3. Diagram showing variation in intensity of the x-ray beam along the longitudinal axis of the x-ray tube.

CENTRAL X-RAY

12"	10"	8"	6"	4"	2"	0"	2"	4"	6"	8"	10"	12"
2.67	2.70	2.72	2.74	2.74	2.74	2.76	2.75	2.76	2.76	2.73	2.70	

2.70	2.71	2.73	2.74	2.76	2.75	2.76	2.76	2.76	2.74	2.72	2.69
11"	9"	7"	5"	3"	1"	1"	3"	5"	7"	9"	11"

Fig. 4. Optical density vs distance from central axis of x-ray beam.

The CP-5 fuel-tube inspection sheet No. 2 (Fig. 5) end-cap measurement columns refer only to minimum aluminum end-cap lengths. Another important consideration in the minimum end-cap length measurements was the assurance that there must be enough pure aluminum material for welding purposes. Adequate guarantees had to be provided that no welding would be done through a portion of the fuel core. In Fig. 6, "A" and "X" are regarded as minimum end-cap lengths on a representative fuel tube.

In actual practice, the determination of the minimum core length involved a search and measure operation using the densitometer at both fuel ends. The fuel core characteristics were such that, at each transition zone, there were sometimes abrupt changes from fuel core to pure aluminum, while other adjacent areas displayed gradual changes from fuel core to pure aluminum. There were usually several areas that could qualify as points of measurement, and, consequently, all points were measured and compared before a final decision could be made.

In many cases, the maximum fuel length "peaks" did not line up axially (Fig. 6). This was also true for a number of "valleys", in the search for the minimum fuel length. Both of these cases required a careful axial measurement on each of the four films for every fuel tube, and then the longest and the shortest fuel lengths from the four films were selected and reported.

As a matter of interest, and for verification, the maximum and minimum fuel lengths were also computed by the "difference method"; that is, the subtraction of the sum of both maximum end-cap lengths from the known overall fuel-tube length yielded the minimum fuel length. Conversely, subtraction of both minimum end-cap lengths yielded the maximum fuel length. This was done on each of the four films required for each fuel tube, and only the smallest and the largest measurements from the four films were recorded. The results from this subtraction method yielded a somewhat different conclusion. In effect, the minimum effective fuel length was defined by the cylinder created when the distance between the maximum top and bottom points of the aluminum end caps was swept out along the circumference of the tube; that is, between these extreme points, fuel exists over the entire

CP-5 FUEL TUBE INSPECTION SHEET NO. 2
NON-DESTRUCTIVE EXAMINATION

Fuel Tube Identification: ____________________ Fuel Tube Type: ____________

1. CORE CHARACTERISTICS AS DETERMINED BY RADIOGRAPHY

A. Core and End Cap Length

	SPEC LIMIT	ANL VALUE	MFG VALUE
Aluminum End Cap Length, Numbered End	Type 1 & 2 – 1/2 Type 3 – 1-3/8		
Aluminum End Cap Length, Opposite End	Type 1 & 2 – 1/2 Type 3 – 3-7/8		
Fuel Length, Maximum	26-5/16		
Fuel Length, Minimum	21-13/16		
Fuel Length, Mean (completed by RRO)	23-13/16		

Fuel core length as specified: ________ (yes or no)
Fuel tube marked as specified: ________ (yes or no), Type 3 only
Remarks: ____________________

Date: ____________
Inspector: ____________

B. Core Thickness and Homogeneity (visual)

Does core thickness appear uniform: ________ (yes or no)
Does core need full length densitometry: ________ (yes or no)
Are there signs of U-Al segregation: ________ (yes or no)
Remarks (note signs of "dog-boning" and approximate size and location of U-Al segregation):
____

Date: ____________
Inspector: ____________
RRO Rep: ____________

C. Core Thickness as Determined by Densitometry

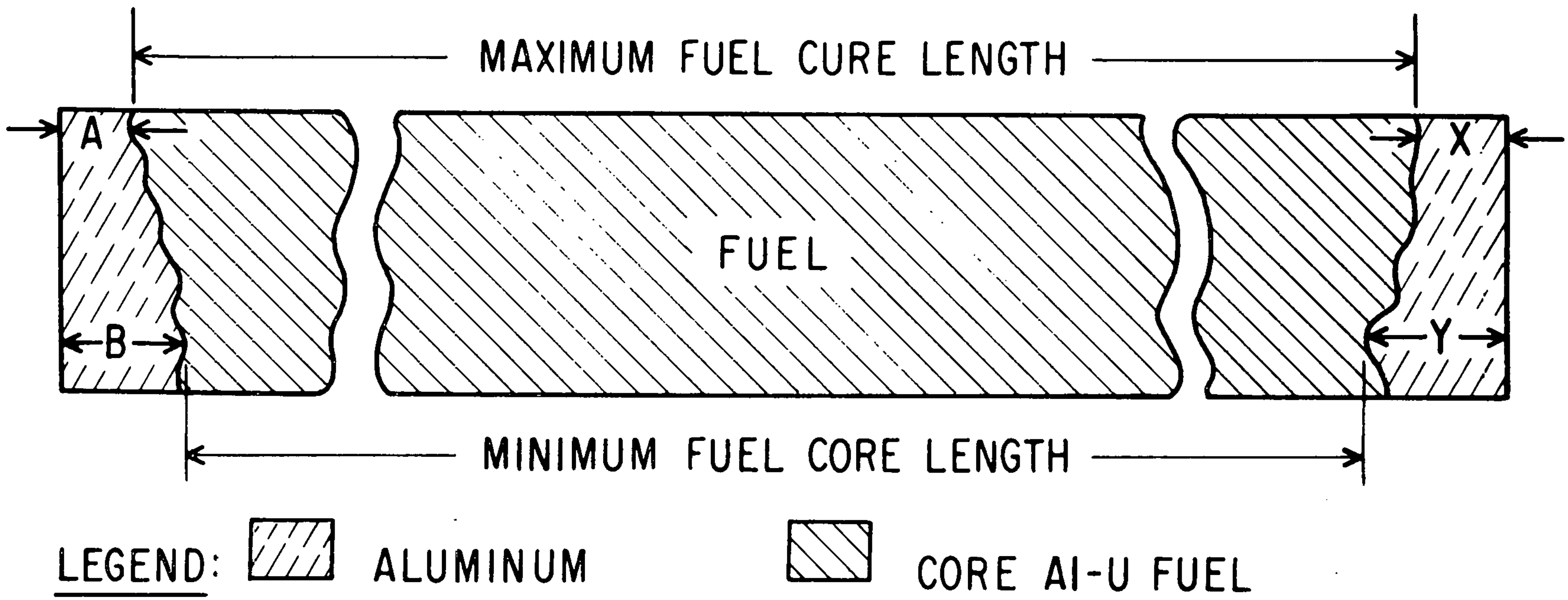
	OPTICAL DENSITY UNITS			
	T_1 (0°)	T_2 (90°)	T_3 (180°)	T_4 (270°)
Transition, Top, Max. Thickness				
Core 6" from Top				
Core 12" from Top				
Core 18" from Top				
Transition, Bottom, Max. Thickness				
STEP WEDGE				
At inch Step				
At inch Step				
At inch Step				
At inch Step				
At inch Step				

Date: ____________
Inspector: ____________

Remarks: ____________________

RRO Approval: ____________

Fig. 5. Fuel tube radiographic inspection report.



A = MINIMUM END CAP LENGTH (TOP END)

B = MAXIMUM END CAP LENGTH (TOP END)

X = MINIMUM END CAP LENGTH (BOTTOM END)

Y = MAXIMUM END CAP LENGTH (BOTTOM END)

Fig. 6. Fuel-length determination diagram.

area of the core.

Nevertheless, these results done by "difference" compared remarkably well with measurements done strictly axially. This was attributed to the fact that the ratio of fuel length (∿ 24") to film-viewing width (∿ 1.75") was large, making the non-axial measurements approach real axial dimensions.

V. STANDARD STEP-WEDGE FABRICATION AND ANALYSIS

In order to obtain quantitative information about optical film density as a function of fuel-core thickness, five fuel-core step wedges were fabricated as standards for each type of fuel tube.

A slab of uranium-aluminum alloy was carefully machined to form a step wedge and was mated to an equally carefully machined aluminum outer and inner sleeve. The ends were then welded, and the aluminum side inserts were put in and bonded. Figure 7 shows fabrication and assembly details. Tables II and III depict dimensions and core characteristics. The finished standards measured ∿ 1" x 1-3/4", with the radius of curvature equal to that of an an actual fuel tube along the 1" dimension.

All standards were carefully x-rayed and compared to each other. One standard step wedge was selected for each fuel-tube type on the basis of

1. fuel core homogeneity and uniformity,
2. consistent average density readings, and
3. highest $\Delta D/\Delta T$,

where

ΔD = change in film density, and
ΔT = change in fuel core thickness.

Figure 8 shows a plot of fuel-core thickness versus the optical film density of standard step wedge #3E42-5, which was selected as the standard for use with all outer fuel tubes. Indicated is a ± 10% change, or ± 0.002",

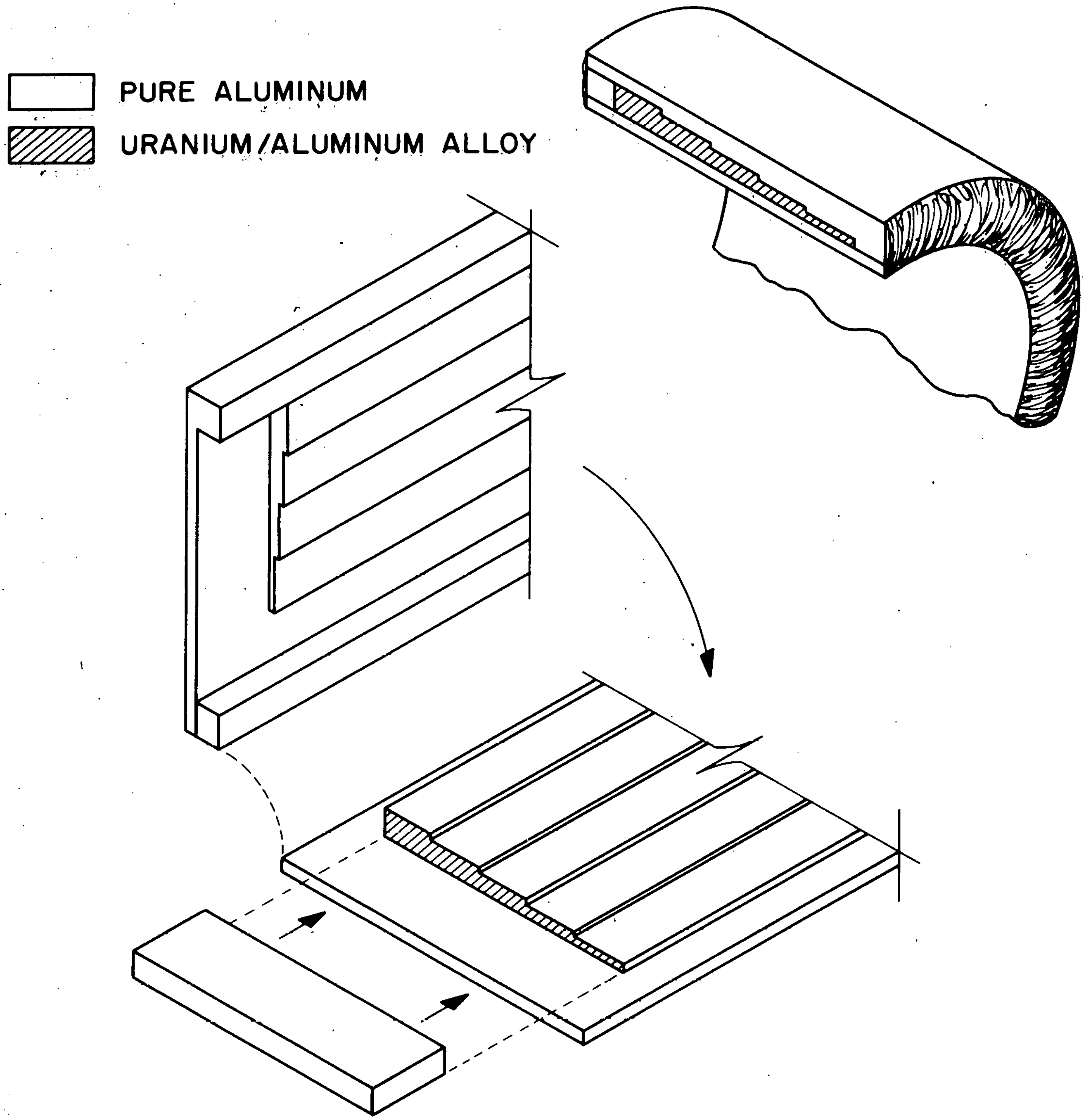


Fig. 7. Standard step-wedge assembly details.

Table II. Standard Step Wedge for CP-5 Fuel X-radiography

Step Wedge No. 3E42-5

Uranium-Aluminum Core Alloy

Width	Net Alloy	W/% U	SS	W/% Enr.	^{235}U
1.020"	2.037 g	16.18	0.329 g	93.14	0.306 g

Dimensions of Alloy and Cladding

Step #	Alloy	I.D. Clad	O.D. Clad	Total Thickness
1 *	0.0305"	0.0085"	0.0080"	0.0470"
2	0.0230	0.0085	0.0160	0.0475
3	0.0190	0.0085	0.0203	0.0478
4	0.0170	0.0085	0.0230	0.0485
5	0.0145	0.0085	0.0243	0.0473

*From left to right when reading identification.

Material:

Clad = 606IT6 Aluminum
Bond = Shell epon resin #820 - curing agent "A"

(0.0397 in. = 1 mm)

Table III. Standard Step Wedge for CP-5 Fuel X-radiography

Step Wedge No. 1B33-4

Uranium-Aluminum Core Alloy

Width	Net Alloy	W/% U	SS	W/% Enr.	^{235}U
1.010"	2.637 g	23.35	0.615 g	93.18	0.573 g

Dimensions of Alloy and Cladding

Step #	Alloy	I.D. Clad	O.D. Clad	Total Thickness
1 *	0.0395"	0.0090"	0.0092"	0.0577"
2	0.0330	0.0090	0.0143	0.0563
3	0.0295	0.0090	0.0183	0.0568
4	0.0268	0.0090	0.0214	0.0572
5	0.0235	0.0090	0.0242	0.0567

*From left to right when reading identification.

Material:

Clad = 6061T6 Aluminum
Bond = Shell epon resin #820 - curing agent "A"

(0.0397" = 1 mm)

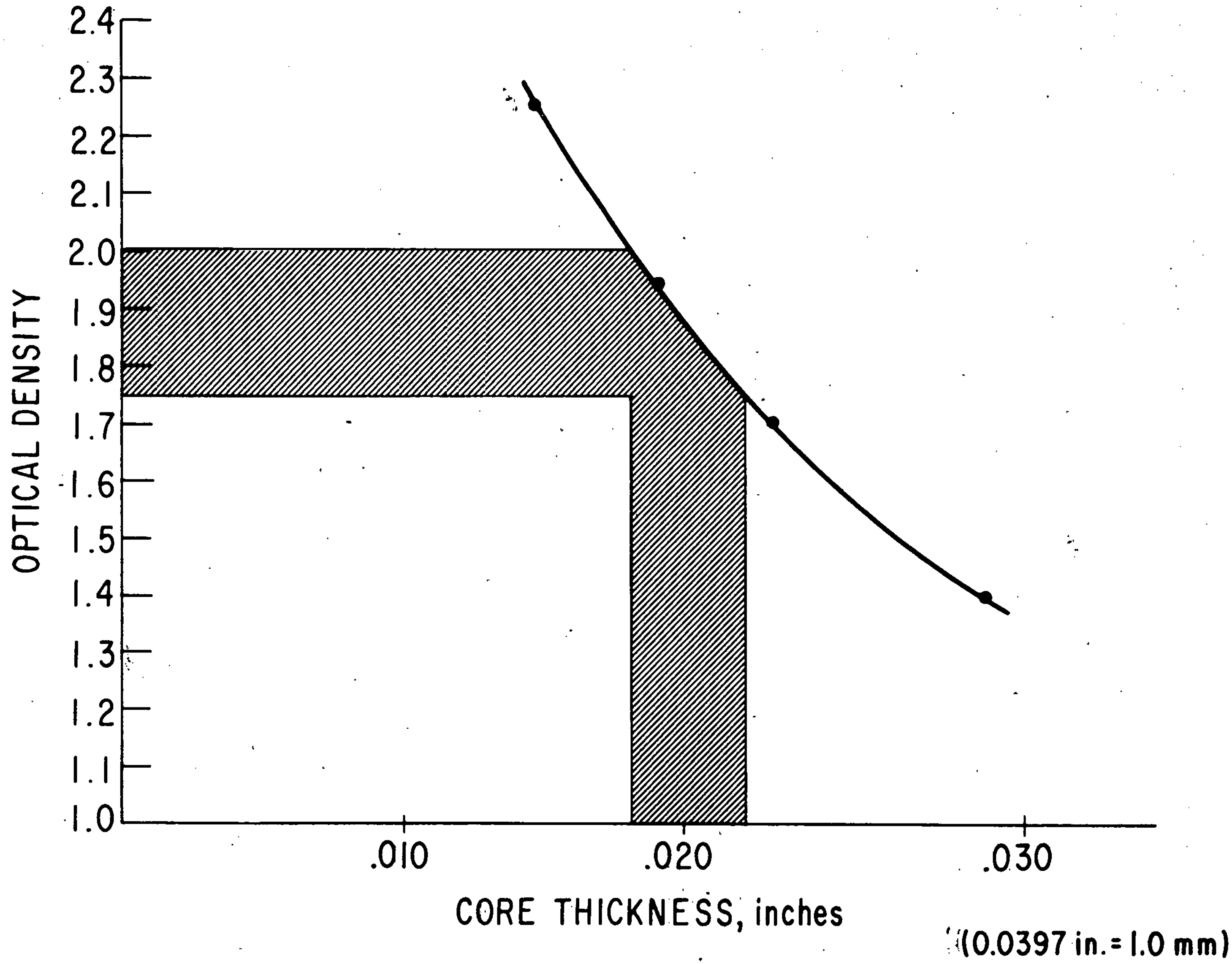


Fig. 8. Fuel-core thickness vs optical density.
Standard Step Wedge #3E42-5.

deviation from the nominal 0.020" fuel-core thickness, with the attendant change of 0.24 density units. Thus, an 0.001" change in fuel core yields an 0.06 change in density.

Similarly, Fig. 9 shows a plot of fuel-core thickness versus the optical film density of standard step wedge #1B33-4, selected for use with all inner and intermediate fuel tubes. Here, a change of ± 10%, or ± 0.0032", deviation from the nominal 0.032" fuel-core thickness gave a net change of 0.32 density units. In this case, a change of 0.001" in fuel core gave an 0.05 change in density.

These density differences are not very large, but they are sufficient for monitoring at least a 10% change in core thickness. As the densitometer employed was accurate to ± 0.02 density units over the entire range of measurable densities, the actual determinable lower limit of change in core thickness was probably on the order of 4 or 5 percent. Good averaging of readings in the measurement area on both the standard step wedge and the fuel tube was necessary to average out granularity and nonhomogeneity of the fuel.

Because these step wedges could only be placed directly on the film off the end of each fuel tube, careful densitometric corrections for the x-ray beam spread had to be made, as discussed in Sections III and VII.

VI. URANIUM SPOT MEASUREMENT

The characteristics of this particular coextrusion manufacturing process for CP-5 fuel became quite evident after the first few full-length fuel-tube radiographs were taken. The graininess of the uranium-aluminum core was seen to vary greatly from tube to tube. Also encountered were fuel-core striations, stringers, and individual unalloyed uranium spots of various lengths and sizes.

Many of these areas could not be measured densitometrically, because: (1) when the uranium spot or stringer was smaller than the 5/32" aperture

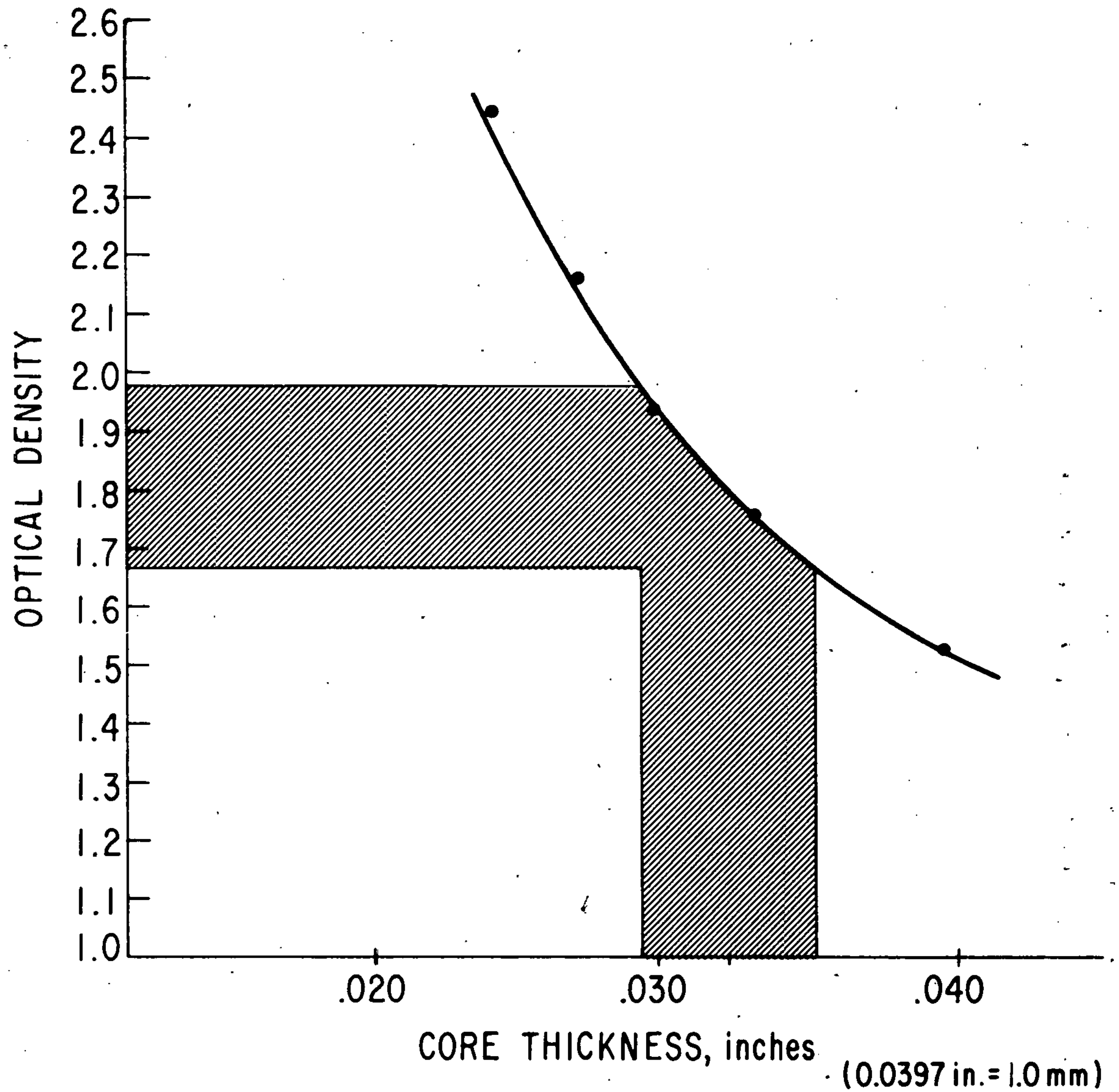


Fig. 9. Fuel-core thickness vs optical density.
Standard Step Wedge #1B33-4.

of the densitometer, various neighboring densities contributed unevenly to the overall measurement; and (2) when the uranium spot or stringer was larger than the 5/32" aperture of the densitometer and its apparent thickness was considerably more than the thickness of the thickest step of the standard step wedge, the optical density approached the ordinary background density of a developed unexposed film.

The total areas of the various uranium spots and stringers were nevertheless measurable by using an X-ray film comparator with graduated circles. The larger uranium spots and stringers were measured by using a ruler and then computing the area. Many irregularly shaped stringers were described by number, length and largest width. Reactor operations personnel inspected visually the films of the most severe stringers and the large uranium-alloy segregation areas.

Being able to have an overall view of the complete fuel core in one radiograph increased confidence in rejecting or accepting fuel tubes that displayed any irregularities, especially when this view was correlated with the results from the ultrasonic, nonbond inspection.

VII. DENSITOMETER OPERATION AND MEASUREMENTS

Readings were done with a MacBeth-Ansco Model 12-A densitometer; the aperture used was 5/32". After a proper warm-up (45 minutes), the instrument was calibrated against an NBS film strip standard. Three density readings were taken on each step of the standard step wedge and averaged. Three density readings were then taken at points 6", 12", and 18" from the top end of each tube and averaged. Readings were also taken at each end of the fuel in the transition zone, at points of maximum fuel buildup, in search of minimum core lengths. Minimum fuel-core lengths required densitometric measurement, whereas maximum core length was determinable visually, because even the smallest speck of uranium contrasted greatly against a pure aluminum background.

Before the averaged density readings were recorded on the inspection sheet (Fig. 5), adjustments were made to reflect the changing intensity of the x-ray beam at the outer edges, as determined by prior measurement (Fig. 4). Adjustments were also made to the standard step wedge readings. Then, straightforward comparison yielded data by which the decision could be made whether to accept or to reject a fuel-tube core thickness.

After a short familiarization period, density measurements became easy, rapid, accurate, and somewhat routine.

VIII. TANGENTIAL "HOT SPOT" RADIOGRAPHY

Some of the fuel tubes exhibited heavier buildup of core material in certain areas, or of segregated uranium in very small areas. These areas, in most cases, were smaller than the 5/32" aperture on the densitometer and appeared quite dense. Consequently, some indication was needed of how close these potential "hot spots" came to the outer surface.

Approximate location of such an area or peak was first determined from the core-thickness radiographs. Then, with careful alignment of the central ray over the edge of the fuel tube (Fig. 10), and with a low X-ray dosage (5-10 sec), a tangential radiograph was obtained of the buildup area showing the exterior of the main fuel line and the aluminum cladding (Fig. 11).

Low exposure was necessary for the aluminum cladding surface to be distinguished from film exposed directly to X-rays--in other words, control of exposure to show contrast on the film between the infinitely thin aluminum at the tube surface and the bare film. The uranium, being very opaque to low energy X-rays, showed great contrast against aluminum at most exposures.

The distance between the fuel peak above the main fuel line and the remaining aluminum cladding was measured by two equally accurate methods. One method employed a simple, scaled optical comparator which could be placed in actual contact with the film, simultaneously enlarging the images of the scale and of the measured objects. Measurements could be made to

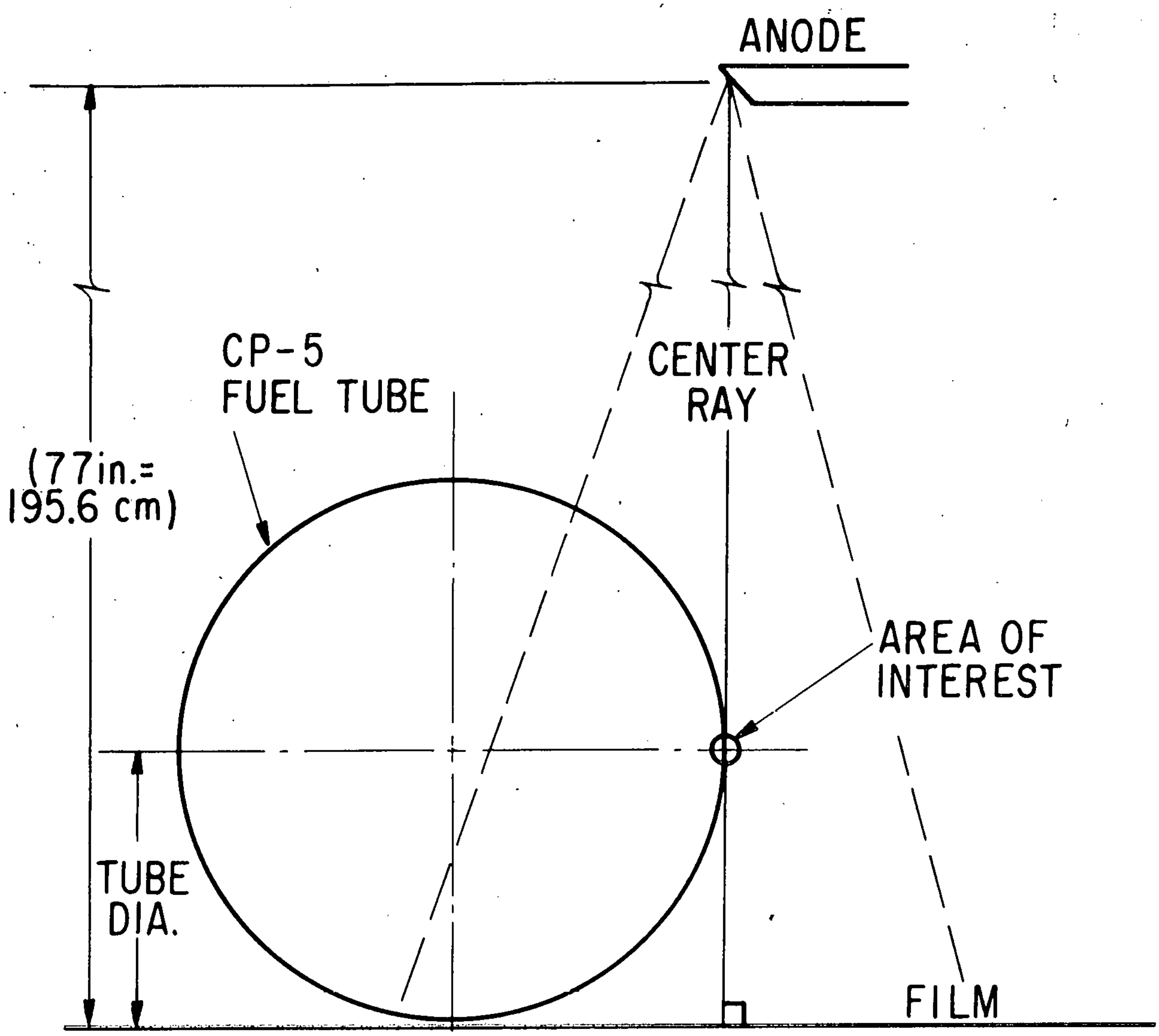


Fig. 10. Tangential alignment diagram.

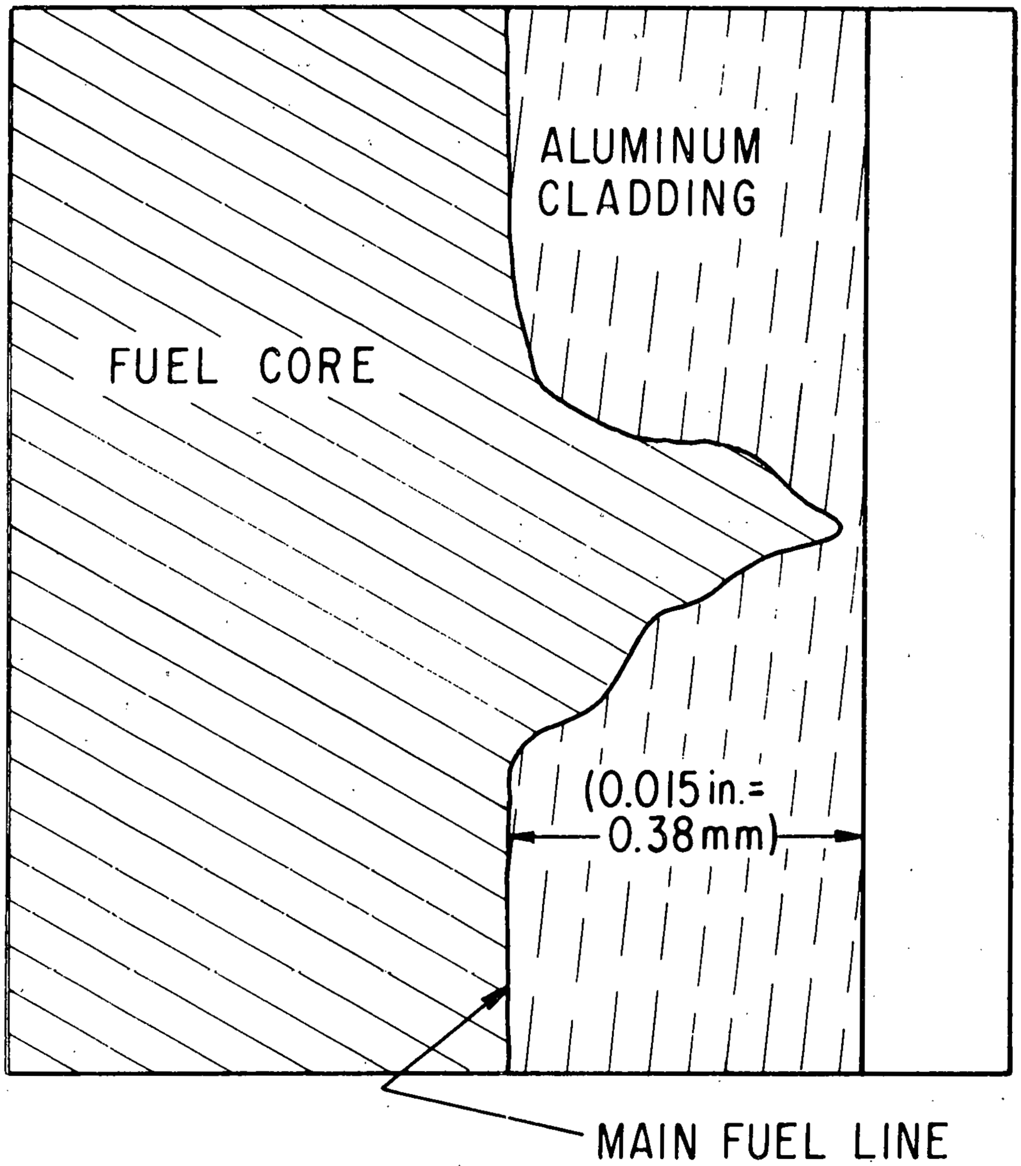


Fig. 11. Magnified fuel-peak details.

an accuracy of 0.0005" with this instrument. Several fuel tubes were rejected when this analysis showed some areas of fuel buildup came to within 0.002" of the outer surface.

The other method employed a profile projector with a magnification of 50X. Accuracy obtained with this instrument was also 0.0005". As this method required more time, owing to alignment and focusing procedures, most measurements were done by using the optical comparator routinely, with occasional use of the profile projector as a check.

Encountered occasionally were indications of heavier fuel buildup that could not be located and measured by this tangential technique. This was because the fuel buildup projected toward the inner surface, with no projection toward the outer surface, and therefore could not be seen or measured because of the masking of this fuel-buildup area on the film by the rapidly increasing thickness of the fuel core due to the curvature of the fuel tube.

IX. CONCLUSION

Through this improved radiographic inspection program, substantial additional information was obtained that helped in deciding the acceptability of CP-5 fuel tubes. Information on CP-5 fuel-core thickness, on fuel length, and on uranium-aluminum segration sizes and their locations can now be routinely obtained with very little added to the overall cost of X-ray inspection.

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