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DETERMINATION OF INERTIA LOADS WHICH THE FUEL CELLS IN THE FUSELAGE OF THE COMET MODEL 4 AIRPLANE MAY BE CAPABLE OF WITHSTANDING WITHOUT RUPTURE DURING CRASH CONDITIONS

FOR LIMITED DISTRIBUTION

by

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SUMMARY

In this report an analysis is presented giving the inertia loads which the flexible, nonmetallic type of fuel cells in the fuselage of the Comet Model 4 airplane might reasonably be expected to withstand in a crash without rupture. Comments also are presented on the close proximity of the cells to the bottom fuselage skin and on the necessity for using proper fittings and accessories with the cells as these factors may affect the over-all crash-fire protection afforded by the tank installation.

INTRODUCTION

During the meeting of the Preliminary Type Certification Board on the Comet Model 4 airplane at Hatfield, England, August 20 to 22, 1956, it was suggested by the powerplant representative of the Civil Aeronautics Administration that The DeHavilland Aircraft Company, Ltd., give consideration to the installation of fuel tanks in the fuselage which could comply with an airworthiness regulation then being proposed by CAA for inclusion in Part 4b of the Civil Air Regulations. The proposal with supporting discussion follows:

Fuel Tank Construction

4b.420 Fuel System Construction and Installation (General)

Specific Proposal.

> Add 4b.420 (f) to read, "Fuel tanks located within the fuselage contour shall be capable of resisting rupture and retaining the fuel in a crash condition producing a 35 G fuel loading on the tank contents in the direction of the maximum fuel head; in addition, these tanks shall be located in a protected position so that exposure of the tank to scraping action with the ground will be unlikely."

Supporting Discussion.

> The intent of this proposal is to provide a means of carrying fuel in the fuselage area with a reasonable level of safety. Fuel carried in this area in conventional fuel tanks is hazardous to the passengers and crew of aircraft if the aircraft experiences an accident or forced landing. Fuel from a ruptured tank in this area can spread quickly to all portions of the fuselage, and if ignited it may cause great loss of life in an otherwise survivable accident. This proposal is offered as a means by which fuel can be carried in this area in lieu of a previous proposal to forbid any fuel in the fuselage.

In response to CAA's suggestion, DeHavilland subsequently submitted drawings on the fuel-tank installation to the Office of Flight Operations and Airworthiness. That office forwarded the data to the Technical Development Center (TDC) of CAA for analysis. Samples of two fuel-cell materials proposed for use in the airplane by DeHavilland were submitted for testing on TDC's compressed-air gun.

In submitting the data and samples of fuel-cell materials to TDC for testing on the compressed-air gun, the Office of Flight Operations and Airworthiness requested that if the fuel cells did not comply with the 35 G inertia loading specified in the proposed regulation, calculations be made to show the inertia loading with which they would comply.

The techniques used in the analysis are those derived from the results of previous work on the development of crash-resistant fuel tanks for aircraft.[1,2,3,4]

[1] Technical Development Center paper, "Crash-Resistant Fuel Tanks for Fuselages of Aircraft," dated August 8, 1956.

[2] Minutes of the Crash-Resistant Fuel Tank Conference, Technical Development Center, Indianapolis, Indiana, June 5 and 6, 1956.

[3] Technical Development Center paper, "Development of Crash-Resistant Fuel Tanks for Wings of Aircraft," dated July 31, 1956.

[4] Richard N. Motsinger, Melvin F. Miller, and Robert J. Schroers, "Some Physical Properties of a Number of Proposed Constructions of Materials for Nonmetallic Crash-Resistant Aircraft Fuel Tanks," CAA Technical Development Report No. 220, December 1953.

ANALYSIS

Material Strength Requirements.

A schematic sketch of the bladder-cell arrangement for the Comet Model 4 aircraft is shown in Fig. 1. This tank consists of four interconnected cells positioned in the lower fuselage section between the wing spars. Individual cells of this tank are surrounded by structure of appreciable strength. Because of this structural strength, each cell has been considered separately for the application of the "one-third rule."[5] Sketches of the individual cells, with dimensions scaled from DeHavilland drawings, are shown in Figs. 2, 3, 4, and 5.

All cells are interconnected in the longitudinal direction of the airplane. In this analysis, therefore, the fuel head is the resultant diagonal head of all cells located to the rear of the cell under consideration. (See Fig. 1.)

The assumed structural openings, based on the one-third rule, are shown in Figs. 2, 3, 4, and 5 for the four cells. Because all work at TDC on the burst-testing of fuel-cell material samples to obtain data for the design of crash-resistant fuel cells in accordance with the one-third rule has been confined to rectangular shapes, certain compromises have been necessary to the extent that some panels of the fuel cells have been considered to be rectangles even though the actual areas are not of this exact shape.

The effect of structural-opening size and shape on the maximum allowable burst pressure of fuel-cell materials of known tensile strength is shown in Fig. 6. The size and shape of the structural opening is defined by the ratio D/A; where D is the diagonal length of the rectangular area of unsupported fuel-cell material, in inches, and A is the area of the same unsupported fuel-cell material, in square inches.[6]

The results of calculations made to determine the fuel-cell material strength required to withstand the fuel pressures resulting from a 35 G loading are shown in Table I. The calculations are based on a fuel

[5]The one-third rule is defined as meaning one-third of the total dimension of the particular fuel-cell panel in question.

[6]See Technical Development Center paper, "Crash-Resistant Fuel Tanks for Fuselages of Aircraft," dated August 8, 1956. It should be noted that Fig. 6 of this report has been revised somewhat from Fig. 3 of that paper.

density of 43 pounds per cubic foot. Sample calculations showing the determination of the required tensile strength for fuel cell No. 1 are presented after Table I.

TABLE I

REQUIRED TENSILE STRENGTH OF MATERIAL IN FUEL CELLS FOR A LOAD FACTOR OF 35

Cell No.	Critical D/A (1/inches)	Required Tensile Strength* (pounds per inch of width)**
1	0.0765	900
2	0.077	770
3	0.070	680
4	0.0816	490

*See discussion under "Design Safety Factor."
**Tensile strength as determined by burst tests on compressed-air gun.

Sample Calculations for Fuel Cell No. 1.

The crosshatched areas shown in Fig. 2 are the assumed areas of failure of the structure surrounding fuel cell No. 1. The smaller dimensions of these areas are based on the one-third rule. Areas of three panels are involved; namely, areas A, B, and C. The ratio D/A is determined for each of the crosshatched areas, also called "design areas." The D/A values of each of these design areas are shown in Fig. 2. The maximum hydrostatic pressure in fuel cell No. 1 resulting from a loading of 35 G is determined as follows:

Hydrostatic pressure (in pounds per square inch) = maximum fuel head (in feet) x fuel pressure per foot of head per unit load factor (in pounds per square inch) x load factor (1)

Where

Maximum fuel head for fuel cell No. 1 = 187.2 inches (see Fig. 1).
Fuel density = 43 pounds per cubic foot.
Load factor = 35.

Substituting these values in Equation (1) yields the following:

$$\text{Maximum hydrostatic pressure} = \frac{187.2}{12} \times \frac{43}{12 \times 12} \times 35 = 163 \text{ pounds per square inch.}$$

With the design values of D/A known, and with a hydrostatic pressure of 163 pounds per square inch, values of tensile strength of fuel-cell material are obtained from Fig. 6. Of the three design areas, the maximum tensile strength of 900 pounds per inch of width is obtained for area C which has a D/A value of 0.0765. This value of tensile strength is considered to be the required tensile strength for the material in fuel cell No. 1.

BURST TESTS

Compressed-air gun burst tests were conducted on samples of Marlite MM 263/C and Flexelite 66/20/25/C materials. Both of these fuel-cell materials have been proposed for use in the Comet Model 4 airplane. The load-elongation data for these materials are shown in Figs. 7 and 8. The results of these tests indicate a tensile strength of 160 pounds per inch of width for the Marlite material and 53 pounds per inch of width for the Flexelite material. It should be pointed out that these values are based on the results of two tests only, and they may not be completely reliable. Experience shows that a minimum of five tests generally is necessary to establish reliable strength values.

Allowable Inertia Loading of Fuel Cells.

Based on the burst-test results, the inertia loadings which the fuel-cell materials are capable of withstanding without rupture when used in the four cells are shown in Table II. Because the allowable loading of a cell of any given size and shape is directly proportional to tensile strength of the fuel-cell material, the results shown in Table II were determined as follows:

$$\text{Allowable load factor} = \frac{\text{Available Material Strength}}{\text{Required Material Strength for a Load Factor of 35}} \times 35$$

The allowable load factors given in Table II are based on an amount of failure of the structure surrounding the fuel cells corresponding to the one-third rule. This rule, described in TDC paper, "Crash-Resistant Fuel Tanks for Fuselages of Aircraft," dated August 8, 1956, originally was derived from examination of simulated wing structures which in impact tests had experienced inertia loading in the order of 35 G. For inertia loading less than 35 G, it is reasonable to expect that the amount of failure of the surrounding structure often may be less than that prescribed by the one-third rule. For this reason, therefore, the cells actually may be capable in some instances of surviving loadings considerably higher than those given in Table II. Also, in some crashes it is probable that the structure itself, without benefit of the fuel cells, may afford protection which surpasses some of the loadings given in the table.

TABLE II

ALLOWABLE LOAD FACTOR FOR
MARLITE AND FLEXELITE MATERIALS

Cell No.	Allowable Load Factor* Marlite MM 263/C	Flexelite 66/20/25/C
1	6.2	2.05
2	7.3	2.4
3	8.2	2.7
4	11.5	3.8

*See discussion under "Design Safety Factor."

The amount of structural failure in actual crashes is not always directly proportional to load factor experienced in the crash. This is particularly true of fuselages. Experience shows that severe damage often may be done to lower fuselage structure by ripping and tearing action with the ground, accompanied by severe damage to the adjoining higher structure, even though load factors may be extremely low. For this reason it is considered unwise to allow any appreciable reduction in area of unsupported bladder-cell material below that prescribed by the one-third rule. Actually, the one-third rule is merely a means of estimating an amount of damage to the supporting structure which is reasonable but adequate for fuel-cell design purposes.

Although the allowable load factors given in Table II may be unduly low for some types of crash conditions, they are considered to represent the upper limit of what the cells can withstand without rupture in those types of crashes in which appreciable damage to the surrounding structure occurs.

TANK LOCATION

Fuel tanks in the lower fuselage which might be considered to be "protected," as specified in the CAA proposal, should be located high enough above the bottom fuselage skin so that it is unlikely that they will be exposed to scraping action with the ground. How high this should be probably varies somewhat from one aircraft design to another. An evaluation of each particular design should be conducted and the tanks should be located accordingly. In any case the bottom surface of the tanks should be located well above the lower flange of the wing's front spar, the higher the better. This is substantiated by the work of the National Advisory Committee for Aeronautics (NACA).[7]

It appears that the close proximity of the cells to the lower surface of the fuselage in the Comet Model 4 airplane might expose the cells to scraping action with the ground during crash conditions. Although specific figures on tank location cannot be recommended at this time, it appears that the tank installation does not comply with the intent of the CAA proposal with respect to tank location.

FITTINGS AND ACCESSORIES

Although stronger fuel cells undoubtedly will afford greater protection than weaker ones under certain conditions, in order to furnish maximum protection against crash fires, crash-resistant fuel cells should be equipped with fittings and accessories which will not tear them or otherwise detract from their crash-resistance. In crashes, forces exist which tend to move the cells in any direction relative to each other. The amount of shifting and resulting tearing of the cells by the fittings probably is proportional to the severity of crash impact. On the other hand, instances are known in which fittings have torn the cells in even relatively minor crashes, resulting in subsequent fire and loss of part or all of the aircraft.

Each of the fuel cells in the fuselage of the Comet Model 4 airplane is surrounded and supported by structure which appears to be unusually rugged. Undoubtedly this, as well as the over-all general arrangement of the cells, will do much to help increase the level of crash-fire protection afforded by the tank installation. It must be emphasized, however, that without proper fittings and accessories the level of safety afforded by the cells is most unpredictable.

[7] "NACA Conference on Airplane Crash-Impact Loads, Crash Injuries and Principles of Seat Design for Crash Worthiness," NACA Report, Lewis Flight Propulsion Laboratory, Cleveland, Ohio, April 17, 1956.

DESIGN SAFETY FACTOR

Studies and tests are being conducted to establish a safety factor for the design of flexible, nonmetallic-type fuel tanks. These studies indicate that this factor may be as low as 1.45 or as high as 1.75. This is a multiplying factor of safety. A safety factor increment of 0.45 is necessary to cover possible variations in the strength of fuel-cell materials due to variations in strength of the basic fabric, tank manufacturing tolerances, aging, and exposure to fuel. It is estimated that loss of strength and/or energy-absorbing properties under extreme conditions of temperature and humidity may require an additional safety factor increment of as much as 0.30. This would raise the total multiplying factor to 1.75. Tests are being conducted to determine whether the additional factor of 0.30, in fact, does constitute reasonable compensation for the effects of extreme temperature and humidity.

The values of material strength given in Table I should be multiplied by a safety factor to assure adequate resistance to rupture under 35 G loading conditions. Likewise, the loadings in Table II should be divided by a safety factor to derive final allowable load factors for the cells.

CONCLUSIONS

The results of an analysis of the fuel-cell arrangement, study of the surrounding structure, and the results of tests on materials proposed for fuel-cell construction for the Comet Model 4 airplane may be summarized as follows:

1. Fuel-cell design procedures employing the concepts of the one-third rule indicate that the cells fabricated of either Marlite MM 263/C or Flexelite 66/20/25/C materials will rupture under an inertia loading of much less than 35 G.

2. The fuel cells appear to be surrounded by strong structure, a factor which should do much to help prevent their exposure to scraping action with the ground during crash conditions. The fuel-tank installation, because of its close proximity to bottom fuselage structure, is not considered to comply with the intent of the proposed CAA regulation with regard to location in a "protected position."

3. The general arrangement of the cells, as well as the strong structure surrounding them, should help to increase the level of crash-fire protection afforded by the tank installation. Without proper fittings and accessories, however, the level of safety is most unpredictable.

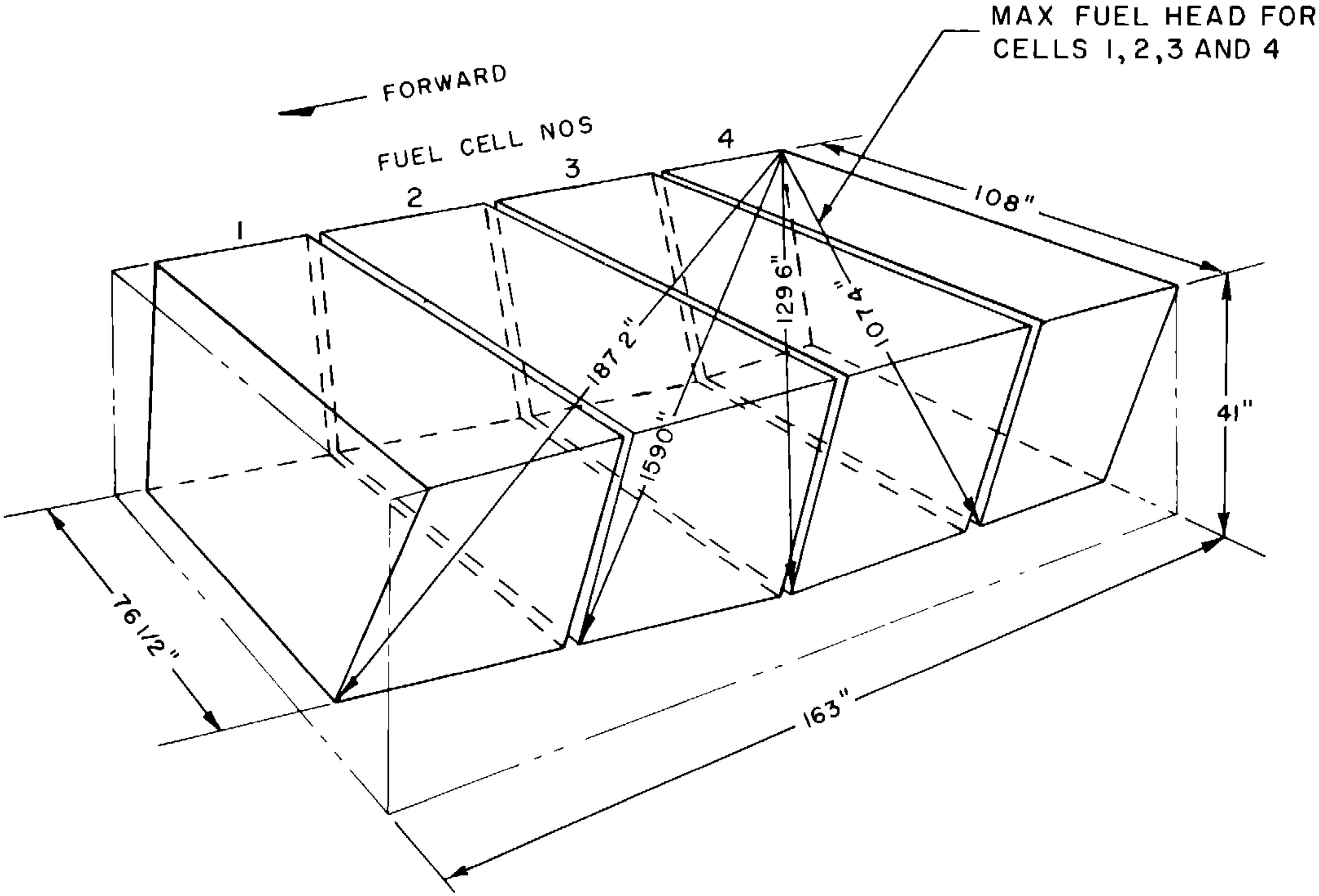

FIG 1 FUEL CELL ARRANGEMENT COMET 4 AIRCRAFT

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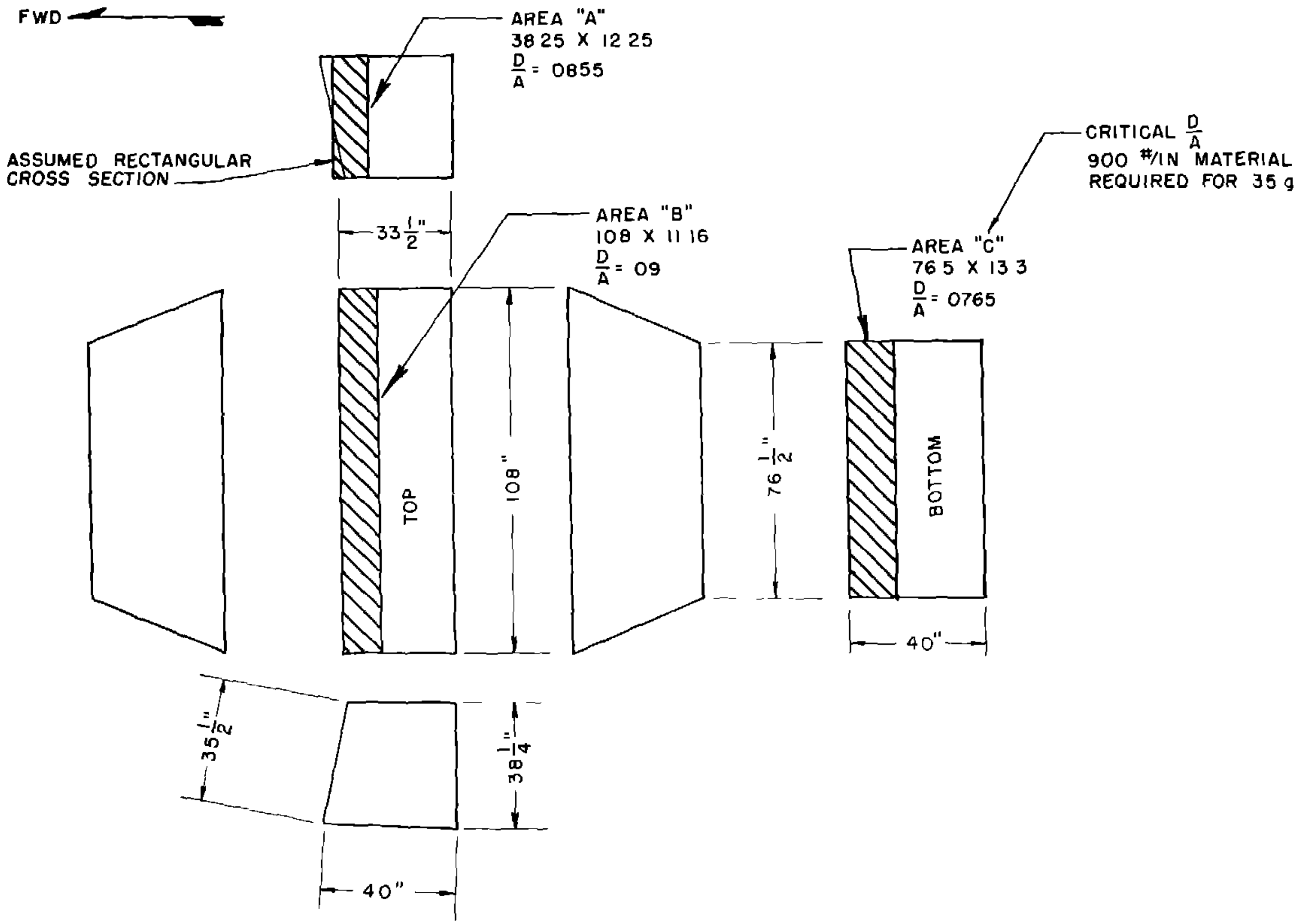

FIG 2 FUEL CELL NO 1

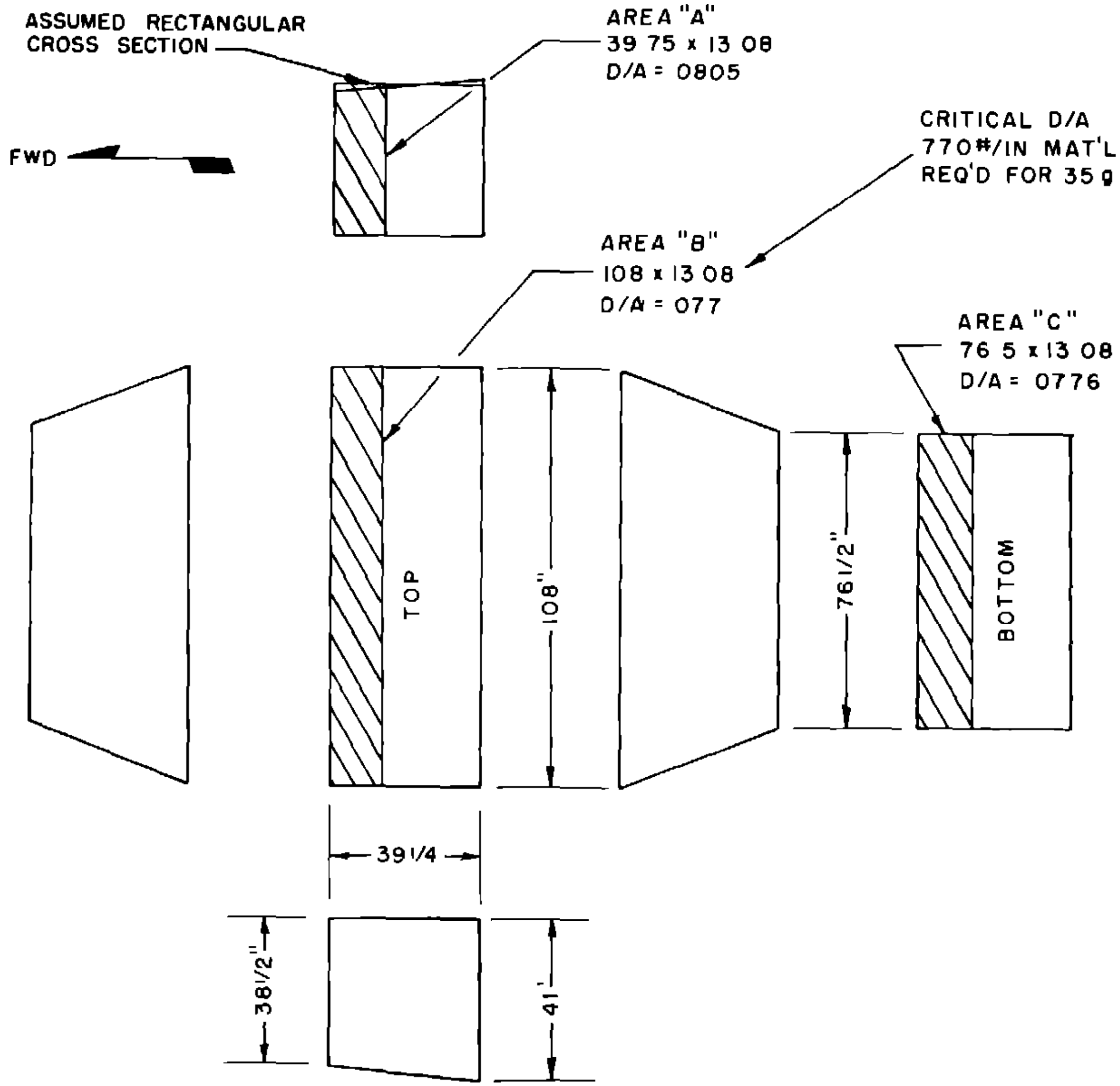

FIG 3 FUEL CELL NO 2

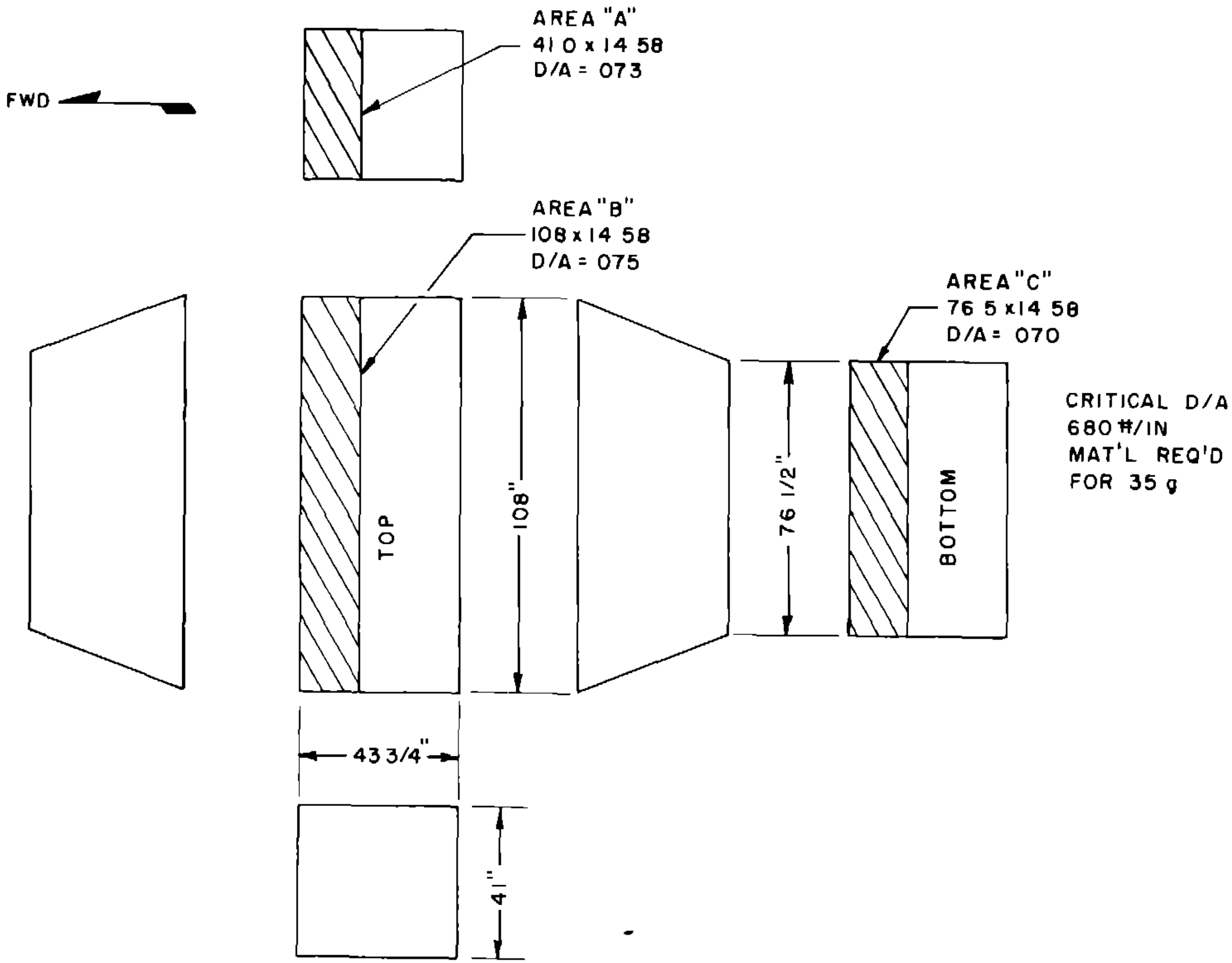

FIG 4 FUEL CELL NO 3

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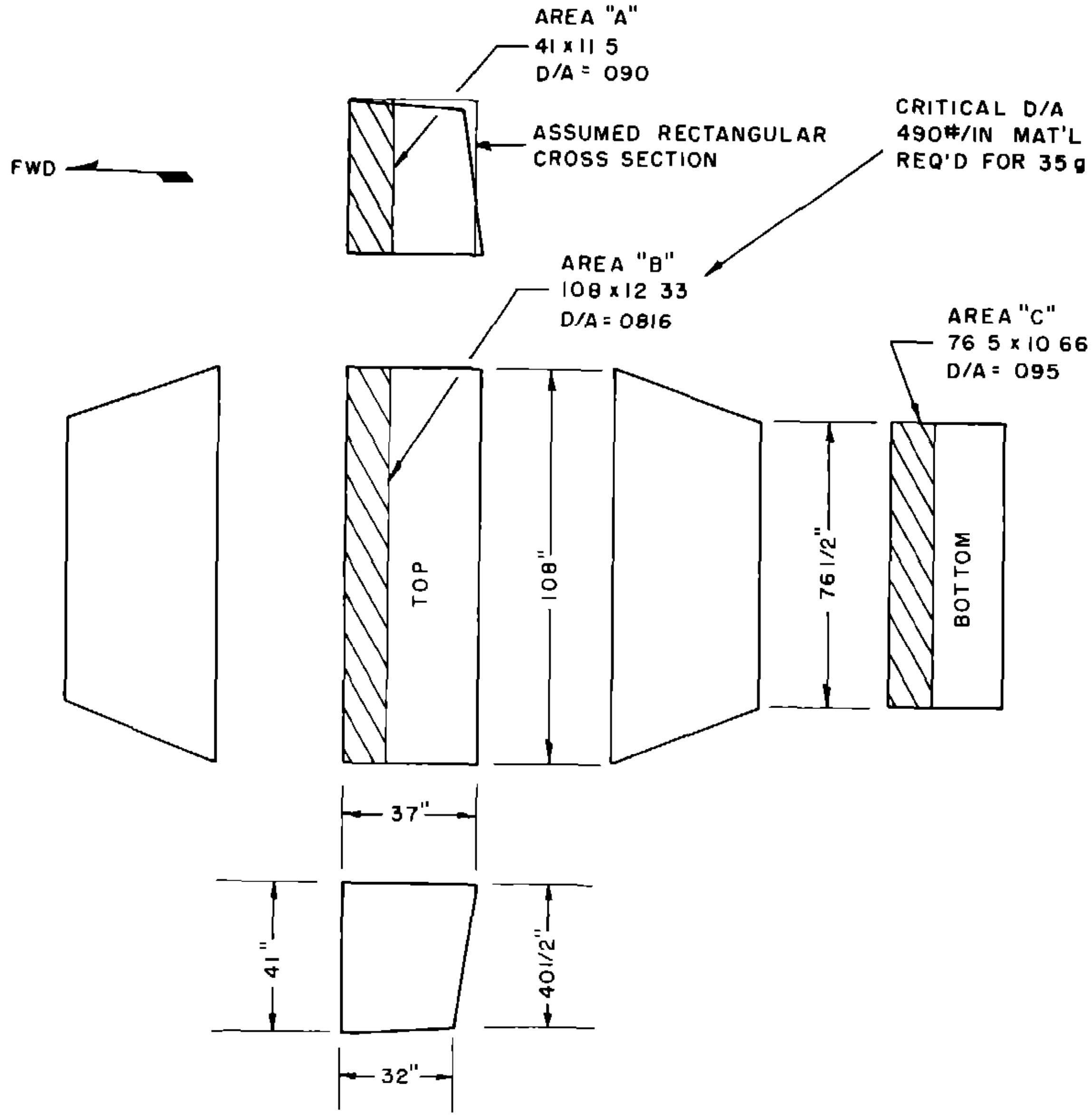

FIG 5 FUEL CELL NO 4

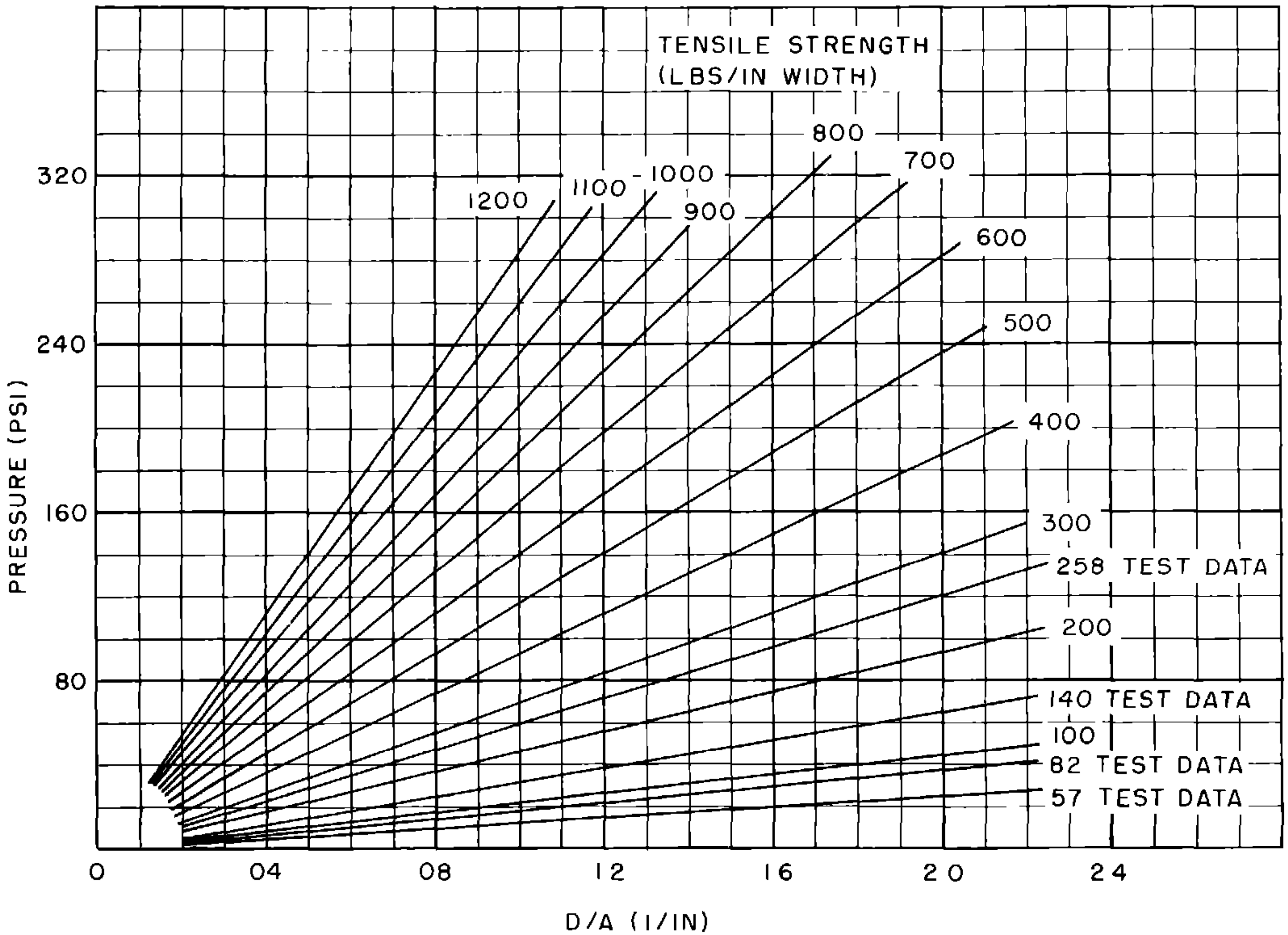

FIG 6 RESULTS OF A COMPRESSED AIR GUN TEST ON FLEXIBLE RECTANGULAR PANELS. REVISED DEC, 1956

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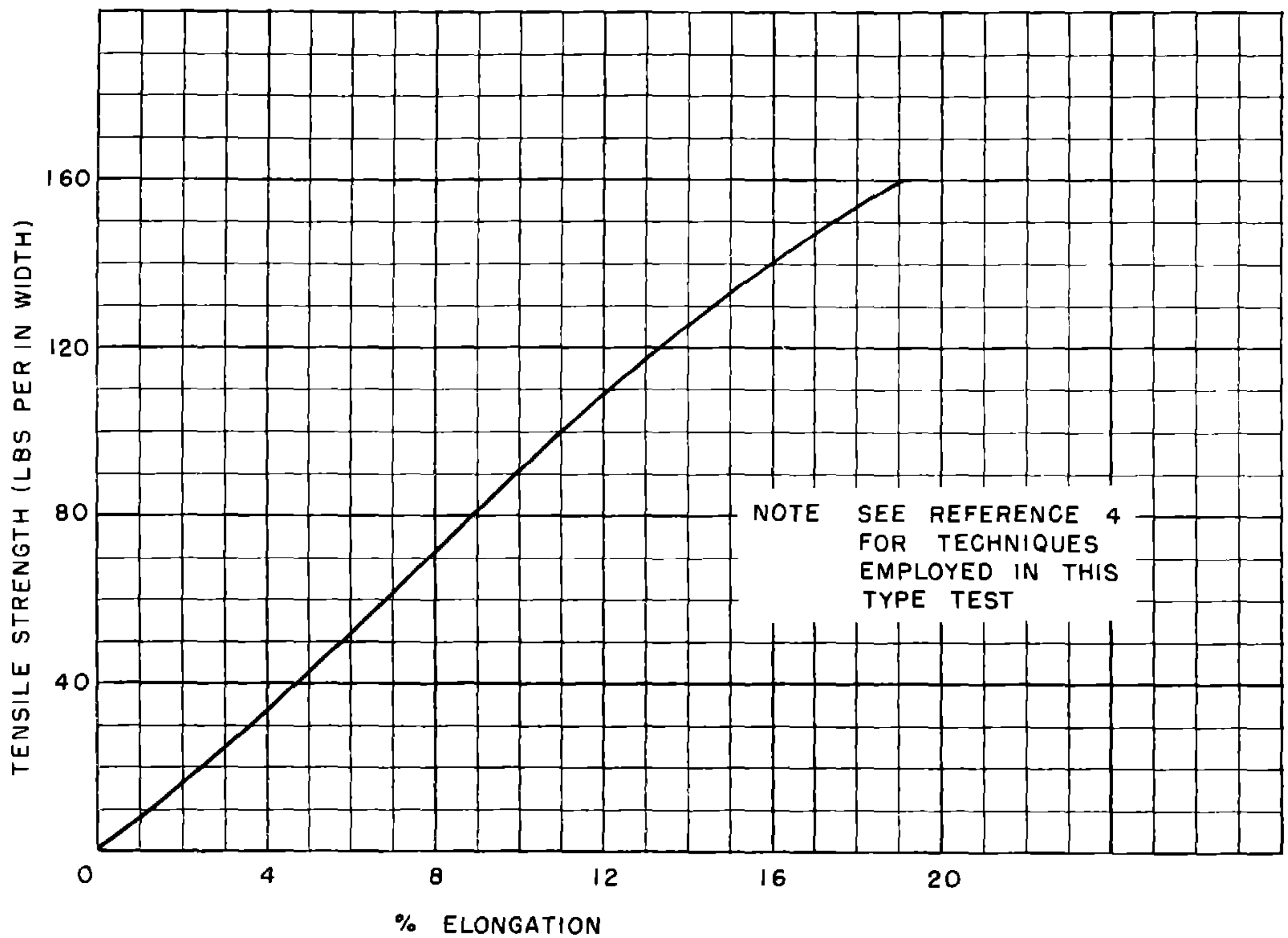

FIG 7 COMPRESSED AIR GUN TEST RESULTS OF BRITISH MATERIAL MM 263/C

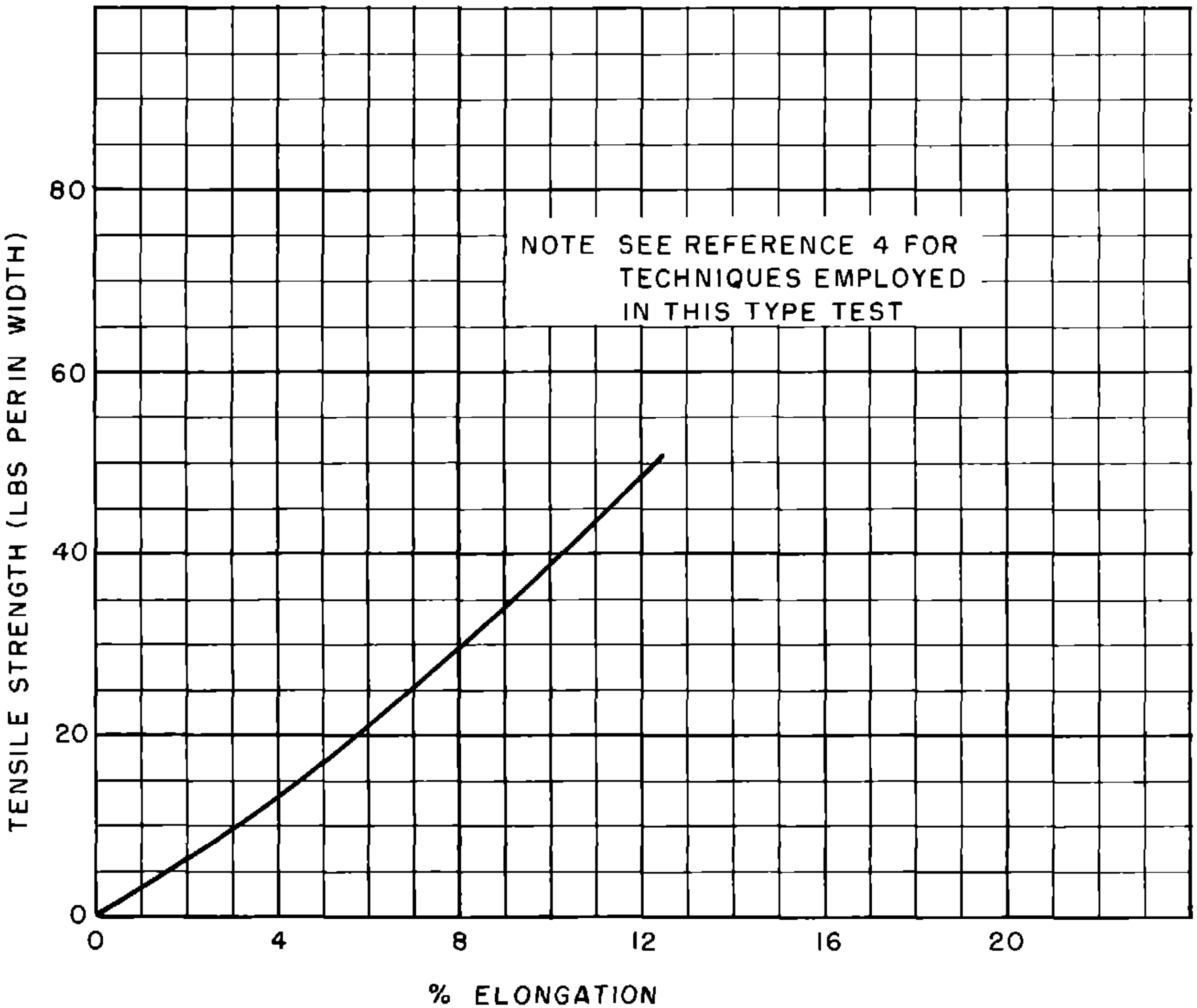

FIG 8 COMPRESSED AIR GUN TEST RESULTS OF BRITISH MATERIAL 66/20/25/C