10 per cent or less, and only two of the data points differ by more than 15 per cent from the value predicted by using Equation 15.

One additional relationship that is of interest in comparing the test data with values obtained by using Equation 15 and also as a basis for scaling up the model test data to predict results with full-scale casks is the correlation of the combined data for the 0.5-inch-diameter punch from Tables II and IV. The correlation for these data obtained by using the method of least squares is given in Equation 16.

$$(E_F/S)_{5c} = 0.74t^{1.4} \quad , \tag{16}$$

where the subscript 5c refers to the combination of the data given in Tables II and IV for the 0.5-inch-diameter punch.

Equation 16 represents 50 per cent of the combined data listed in Tables II and IV. The coefficient 0.74 differs by about 6 per cent from the value that could be obtained by substituting a value of 0.5 inch for d in Equation 15.

II. CORRELATION OF DATA FOR CYLINDRICAL MODELS

The objective of the cylindrical model tests was to evaluate the effect of curvature of the jacket upon puncture resistance of casks by obtaining a modifying factor or factors that could be used with the test data for the prismatic models to predict the puncture resistance of full-size cylindrical casks. A plot of the data taken in the cylindrical model tests shown in Figure 16 suggests a relationship for a given punch size of the form

$$E_c = C_1 - C_2 D \ , \tag{17}$$

where

E_c = incipient puncture energy for a cylindrical jacket, inch-pounds,

C_1 = a constant,

C_2 = a constant, and

D = the outside diameter of the cask jacket, inches.

Using the method of least squares, the following relationships were obtained.

$$E_4 = 950 - 16D \ , \tag{18}$$

$$E_5 = 1280 - 16D \ , \tag{19}$$

and

$$E_6 = 1560 - 16D \ , \tag{20}$$

where the subscripts 4, 5, and 6 refer to the punch diameters 0.4, 0.5, and 0.6 inch, respectively, for which the equations apply. Equations 18, 19, and 20 are applicable for a 0.075-inch-thick jacket with an ultimate tensile strength of 51,300 pounds per square inch. This value for the ultimate tensile strength is the arithmetic mean of six values obtained with two specimens from each of three models with different diameters. The maximum variation from this mean value for any of the six values obtained was about 2 per cent.

An inspection of Figure 16 and Equations 18, 19, and 20 suggests a general relationship for all the data for cylindrical models of the form

$$E_{cc} = f(d) - 16D \ , \tag{21}$$

where f(d) is a function of the size punch in inches and where the subscript cc refers to the combined data for cylindrical models. A plot of the diameter of the punch versus the intercepts in Equations 18, 19, and 20 is shown in Figure 20. This plot indicates that the term f(d) in Equation 21 can be adequately defined by a relationship of the form

$$f(d) = C_3 + C_4 d \ , \tag{22}$$

where C_3 and C_4 are constants and d is the diameter of the punch in inches.

Using the method of least squares to fit the data plotted in Figure 20,

$$f(d) = -256 + 3040d \ . \tag{23}$$

Substituting the value of f(d) given by Equation 23 into Equation 21,

$$E_{cc} = 3040d - 256 - 16D \ , \tag{24}$$

where the range of application is for

$7.55 \leq D/d \leq 15.5$,

$55 \leq D/t \leq 95$,

jacket thickness, t, of 0.075 inch, and

ultimate tensile strength of jacket material, S, of 51,300 pounds per square inch.

If Equation 24 is divided by Equation 15 and the values of t = 0.075 and S = 51,300 are inserted, the result is

$$E_r = \frac{E_{cc}}{E_F} = \frac{3040d - 256 - 16D}{3260d^{1.6}} \ , \tag{25}$$

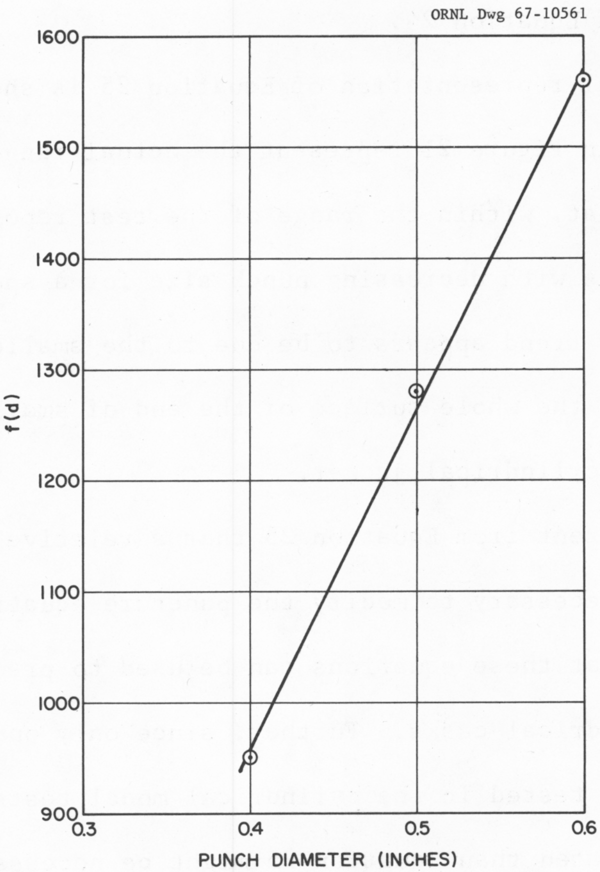

Figure 20. Derived values of f(d) as a function of the punch diameter for the cylindrical model test data.

where the range of application of Equation 25 is limited to the range of application of Equation 24.

A graphical representation of Equation 25 is shown in Figure 21. The solid lines in Figure 21 represent the actual range of the test. It is apparent that, within the range of the test reported here, the E_r value increases with decreasing punch size for a specific cylindrical jacket. This trend appears to be due to the smaller deflections required to bring the whole surface of the end of smaller punches into contact with the cylindrical jacket.

It is apparent from Equation 25 that a relatively complicated general term is necessary to modify the puncture equations for prismatic casks so that these equations can be used to predict incipient puncture of cylindrical casks. Further, since only one jacket material and thickness was tested in the cylindrical model tests, a relationship more complicated than Equation 25 might be necessary. If the material and thickness of jackets for cylindrical casks must be considered, a more direct approach to the problem of predicting the incipient puncture energy of jackets for cylindrical casks seems to be indicated.

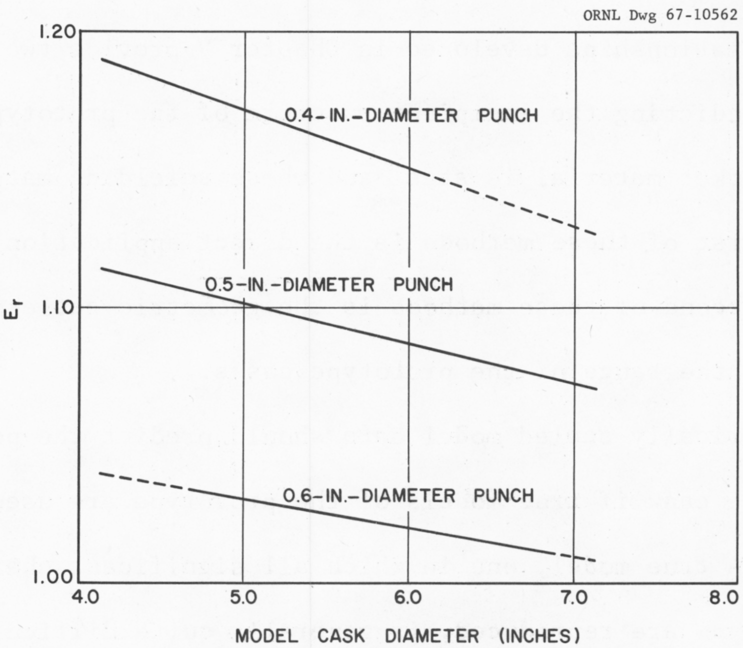

Figure 21. Ratio of incipient puncture energy for cylindrical models to the incipient puncture energy for prismatic models (E_r) versus the diameter of the cylindrical models.

CHAPTER VI

PREDICTION OF INCIPIENT PUNCTURE OF THE PROTOTYPE CASKS

I. PRISMATIC CASKS

The relationships developed in Chapter V provide two possible methods of predicting the incipient puncture of the prototype shipping cask whose jacket material is steel and whose shielding material is lead. The first of these methods is the direct application of Equation 15, and the second of these methods is the geometric scale-up of the model data to the range of the prototype casks.

Geometrically scaled model data should predict the performance of a prototype cask if true models of the prototype are used in the model test. A true model, one in which all significant characteristics of the prototype are reproduced, is generally quite difficult to produce and is not necessarily required if the prediction of only one characteristic of the prototype is desired. (12) Thus, if the models of the prismatic casks included those characteristics of the prototype casks that significantly affect the incipient puncture energy of the prototype casks, then a scale factor based on a characteristic length such as the diameter of the punch should relate the incipient puncture energy of the models to that of the prototype casks.

If the diameter of the punch is taken as the characteristic length in scaling up the model cask data, the scale factor is 12 for the data taken with a 0.5-inch-diameter punch because a punch diameter of 6.0 inches is the standard for prototype casks. Therefore, all linear dimensions of the model cask must be scaled by a factor of 12, and the weight of the model (or energy at impact) must be scaled by a factor of $(12)^3$ or 1728. Thus, Equation 16 scaled up to predict the incipient puncture energy of prototype casks becomes

$$\left(\frac{E_F/1728}{S}\right)_P = 0.74\left(\frac{t}{12}\right)^{1.4} ,$$

$$\left(\frac{E_F}{S}\right)_P = 39t^{1.4} . \qquad (26)$$

Equations 15 and 26 predict slightly different values for the incipient puncture energy of the prototype casks. A comparison of these two equations is shown in Figure 22 along with three data points that were taken for the results of the tests made with the prototype cask that were reported in Reference 4.

Since Equation 26 appears to predict the results of tests with prototype casks reasonably well, it seems worthwhile to arrange that equation in a more convenient form. The energy of a cask upon impact,

$$E = Wh \qquad (27)$$

where

W = weight of the cask, pounds, and

h = height from which the cask is dropped

= 40 inches to satisfy the requirements of Reference 1.

Combining Equations 26 and 27,

$$t = (W/S)^{0.71} . \qquad (28)$$

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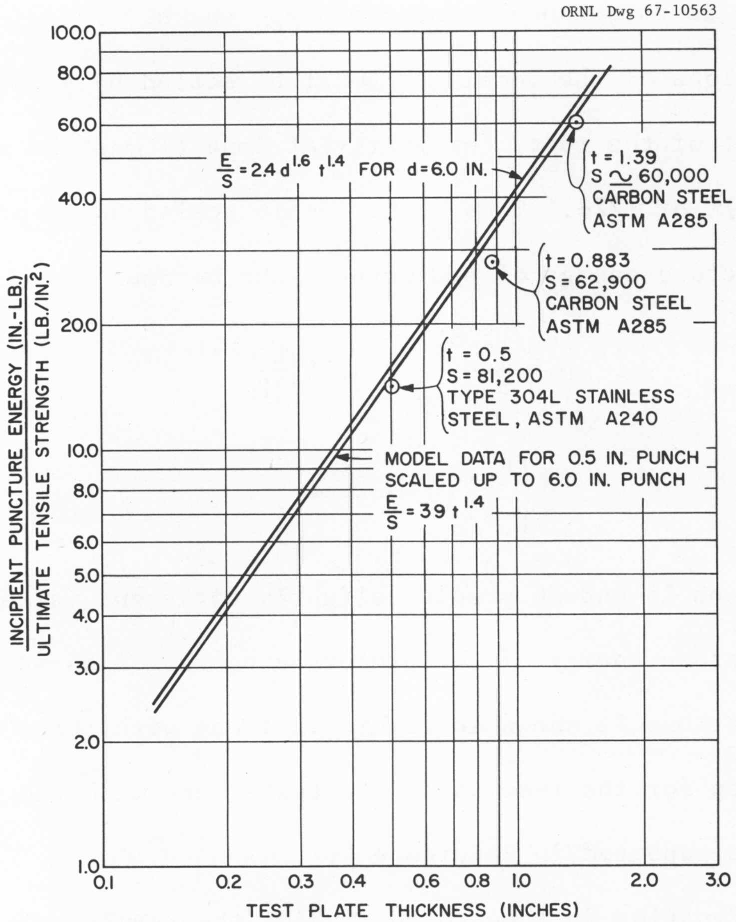

Figure 22. Results of tests made with prototype prismatic cask compared with the results predicted from the prismatic model test data.

A plot of Equation 28 for various values of the ultimate tensile strength of jacket materials is shown in Figure 23 to further increase the ease of determining the jacket thickness for which puncture is imminent.

II. CYLINDRICAL CASKS

The results of the cylindrical model tests show that in the range of the variables tested, the models of cylindrical casks are more difficult to puncture than those of prismatic casks of equal weight when the thickness and strength of the jackets are the same. For D/d and D/t ratios greater than those evaluated, the incipient puncture energy for the cylindrical models should approach the values obtained with prismatic models since the cylindrical surface approaches a flat surface as a limit. For D/d and D/t ratios smaller than those evaluated, the change in puncture resistance as these ratios are decreased is not clear. For decreasing D/t ratios, the puncture energy should increase because the cask is approaching the limiting case of

$$D/t = \frac{D}{D/2} = 2 \ ,$$

which is the D/t value for a solid steel cask. For decreasing D/d ratios, the puncture energy may or may not increase, depending upon the ease with which the cylindrical jacket deforms locally to bring the whole surface of the punch in contact with the jacket. For a cask with a small diameter, the length of the cask might be much greater than its

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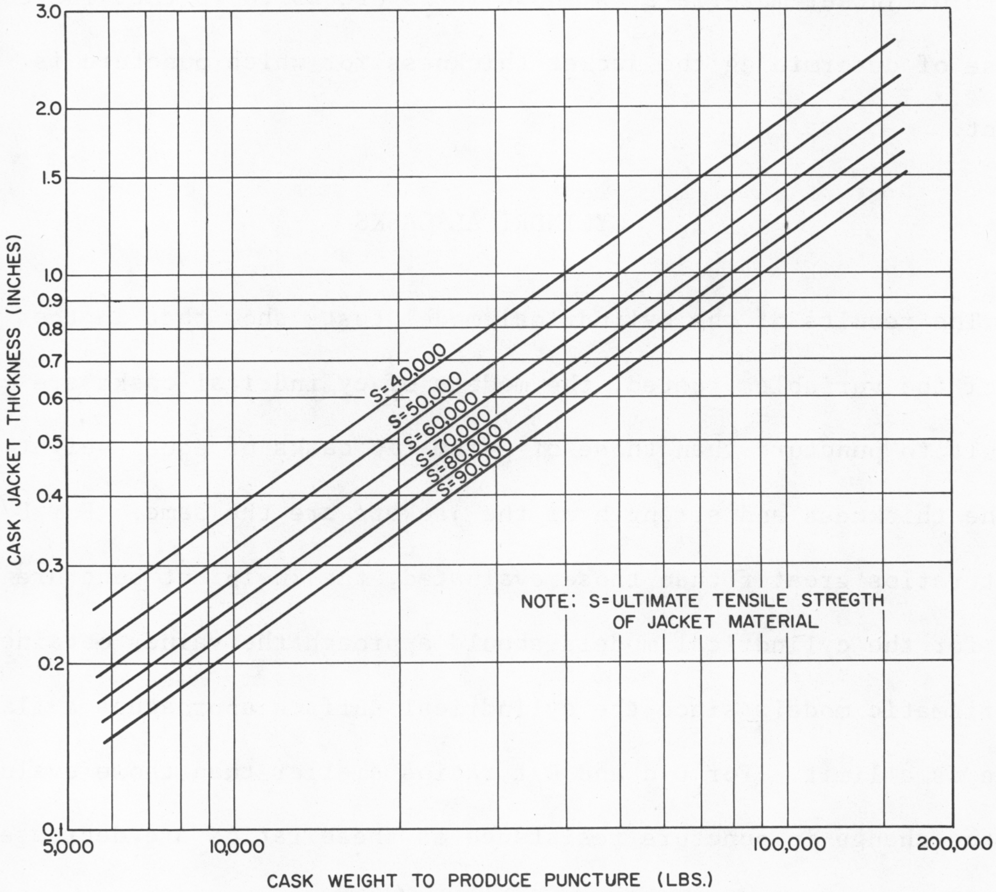

Figure 23. Thickness of jacket versus weight of cask to produce puncture for various ultimate tensile strength values for jacket materials.