diameter, and it seems reasonable that this would significantly affect the mode of failure.

The amount of test data for large cylindrical casks is limited, but a comparison of the data that is available with the results predicted by the model test is of interest. This comparison can be made by scaling up the cylindrical model test data with the jacket thickness used as the characteristic length that determines the scale factor. Taking the jacket thickness as the characteristic length, the scale factor,

$$f = T/0.075 \ , \tag{29}$$

where

f = scale factor between model and prototype cylindrical cask,

T = thickness of jacket for prototype cask, inches, and

0.075 = jacket thickness of the model, inches.

To apply Equation 24 to casks with any jacket thickness but within the D/d and D/t ranges tested, each variable must be divided by an appropriate power of the scale factor. For linear scaling, lengths must be divided by the first power of the scale factor and energy must be divided by the cube of the scale factor. Thus, Equation 24 becomes

$$E_{cc}/f^3 = 3040(d/f) - 256 - 16(D/f) \ . \tag{30}$$

Multiplying both sides of Equation 30 by f^3,

$$(E_{cc})_P = 3040df^2 - 256f^3 - 16Df^2 \ , \tag{31}$$

where the subscript P is used to indicate that Equation 31 applies to the prototype cylindrical cask.

If it is now assumed that the incipient puncture energy of a cylindrical cask is directly proportional to the ultimate tensile strength of the jacket material, Equation 31 can be written as

$$(E_{cc})_P = (S/51{,}300)(3040df^2 - 256f^3 - 16Df^2) \ . \qquad (32)$$

Substituting the value of f given by Equation 29 into Equation 32,

$$(E_{cc}/S)_P = (10.5d - 0.0554D)T^2 - 11.8T^3 \ . \qquad (33)$$

The results of several tests of prototype casks (3, 13) are given in Table VII along with the incipient puncture energy predicted by Equation 33. The incipient puncture energies that would be predicted by scaling up the prismatic model data using the punch diameter as the characteristic length that determines the scale factor are also given in Table VII. Only three of the cases listed in Table VII, Cases 4, 5, and 6, had D/d and D/t ratios that are within the range covered by the model test. The Case 2 cask had a D/d ratio well below the range of the model tests, and for that reason, the results of the test with that cask would have been valuable here had the impact energy not been so far below the value of incipient puncture energy predicted by Equations 26 and 33.

In all of the cases listed in Table VII except Cases 1 and 2, the jacket of the cask was reported to have been punctured. However, it must be noted that a complete description of the conditions of deformation is not available. In Case 4, it is known that the line of action of the punch was not perpendicular to the surface of the cask, but similar information is not available for the other cases.

TABLE VII

RESULTS OF PROTOTYPE CYLINDRICAL CASK TESTS COMPARED WITH RESULTS PREDICTED FROM CYLINDRICAL MODEL TESTS

Case No.	Punch Diameter (in.)	Jacket Thickness (in.)	Cask Diameter (in.)	D/d	D/t	Jacket U.T.S.[a] (p.s.i.)	Cask Weight (lb.)	Test Impact Energy[b] (in.-lb.)	Incipient Puncture Energy Predicted By: Equation 33 (in.-lb.)	Incipient Puncture Energy Predicted By: Equation 16[c] (in.-lb.)
1	6	0.5	30	5	60	62,300	11,350	817,200	844,000	920,000
2	6	0.312	18	3	57.7	53,500	2,600	156,000	305,000	390,000
3	4	0.375	30	7.5	80	55,000	11,350	204,300	277,000	288,000
4	2	0.375	30	15	80	55,000	11,350	68,100	113,000	94,500
5	2	0.312	18	9	57.7	53,500	2,600	62,400	85,000	73,200
6	1.43	0.312	18	12.6	57.7	53,500	2,600	62,400	54,300	56,400

[a]Ultimate tensile strength values obtained from one specimen taken from each jacket thickness. Jacket material was mild steel.

[b]Puncture occurred in all cases except Cases 1 and 2. In Case 1 the punch penetrated 1/8 inch into the 1/2-inch shell, indicating that the test impact energy was near the incipient puncture energy. In Case 4 the penetration was not symmetrical about the line of action of the punch.

[c]Equations scaled up from Equation 16 for
6.0-inch punch, $E/S = 39t^{1.4}$;
4.0-inch punch, $E/S = 20.7t^{1.4}$;
2.0-inch punch, $E/S = 6.74t^{1.4}$; and
1.43-inch punch, $E/S = 5.37t^{1.4}$.

In Cases 1 and 6, the values of incipient puncture energy predicted by both methods used differed by less than 13 per cent from the test impact energies. In Cases 3, 4, and 5, the jacket of the cask was punched at significantly lower values in each case than was predicted by either method used. However, in Case 4, it is known that the line of action of the punch was not perpendicular to the surface of the cask, and this resulted in unsymmetrical punching.

In view of the lack of consistent agreement between the results of the prototype cylindrical cask tests and the results predicted by scaling up the cylindrical model test data, it appears that until more data are obtained, the design of jackets for cylindrical casks might best be based upon the data for the prismatic casks. Because the equations for prismatic casks predicted incipient puncture energies greater than the values observed in several of the cases listed in Table VII, a correction factor must be applied to the values obtained with these equations. Further, because the maximum difference between the observed and predicted values given in Table VII was 29 per cent (Case 3), using Equation 28 with a corrected cask weight equal to 1.3 times the true weight of the cask appears to be a reasonable method of selecting a safe jacket thickness for cylindrical casks whose diameters are from 18 to 30 inches. For casks whose diameters are greater than 30 inches, the weight correction factor must for the present be left to the judgment of the cask designer. The penetration of the punch in Case 1 of Table VII was 1/8 inch into a 1/2-inch-thick jacket, indicating that the impact energy for that case was very close to the incipient puncture energy.

Judging from that case, it seems reasonable to assume that the incipient puncture energy for a cask whose diameter is in excess of 30 inches would be predicted within a close percentage by Equation 28.

CHAPTER VII

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

I. SUMMARY

Prismatic and cylindrical models of steel-jacketed lead-shielded shipping casks for radioactive materials were tested to obtain information concerning the puncture resistance of prototype casks. The model tests for prismatic casks included tests on several types of material that are likely to be used for cask jackets and several other types of material with mechanical properties in the range of those of materials that might possibly be used for jackets. The thickness of the jacket material and the diameter of the punch were varied in the tests of prismatic models. The shielding material used in the cask models was chemical lead for both the prismatic and the cylindrical model tests. In the model tests for cylindrical casks, the jacket material and thickness were held constant while the diameters of the models and the punches were varied.

A correlation of the data obtained in the prismatic model tests produced the equation

$$E_F/S = 2.4d^{1.6}t^{1.4} , \tag{15}$$

which appears to adequately represent the model test data reported here and that reported by Spaller. (4) A separate correlation for the test data with the 0.5-inch-diameter punch was also obtained. This correlation is expressed by Equation 16, which also included data from Reference 4.

$$\left(\frac{E_F}{S}\right)_{5c} = 0.7t^{1.4} \quad . \tag{16}$$

Equation 16 was scaled up geometrically to the equation

$$\left(\frac{E_F}{S}\right)_{P} = 39t^{1.4} \quad , \tag{26}$$

which appears to be applicable for use in predicting the incipient puncture energy of the prototype prismatic cask. Equations 15 and 26 were compared graphically in Figure 22 with the results of prototype prismatic cask tests reported by Spaller (4), and Equation 26 was found to be in good agreement with the test data for the prismatic cask.

A correlation of the data resulting from the cylindrical model tests produced the equation

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

Equation 24 is applicable for only one jacket material and thickness, and it was compared with the prismatic model test data to obtain the ratio of the incipient puncture energy for cylindrical models to the ratio of the incipient puncture energy for prismatic models. This ratio,

$$E_r = \frac{3040d - 256 - 16D}{2260d^{1.6}} \quad . \tag{25}$$

Within the range of parameters tested, Equation 25 shows that the models of cylindrical casks are most difficult to puncture.

To evaluate the extent to which the cylindrical model test data can be used to predict puncture of prototype cylindrical casks, Equation 24 was scaled up by using the jacket thickness as the characteristic length that determines the scale factor and by assuming that the incipient puncture energy of cylindrical casks is directly proportional to the ultimate tensile strength of the jacket material. The result of scaling up Equation 24 was

$$\left(\frac{E_{cc}}{S}\right)_P = (10.5d - 0.0554D)T^2 - 11.8T^3 \ . \tag{33}$$

The results of several tests made with cylindrical prototype casks that have been reported (3, 13) were compared with the results predicted by using Equation 33 and with the results predicted by scaling up the data obtained from the prismatic model tests. Neither method used to predict the results of the tests made with cylindrical prototype casks provided conservative results consistently. However, in the tests made with cylindrical prototype casks that were reported as having resulted in punctured jackets, no general description of the jacket deformation was given and no specific indication that the resulting deformation was symmetrical about the center line of the punch was made. Therefore, it was suggested that a method based on the equations for prismatic casks be used in predicting the necessary jacket thicknesses for cylindrical casks.

II. CONCLUSIONS

The principal objective of this study was to determine the influence of the curvature and the material properties of jackets upon the incipient puncture energy of steel-jacketed lead-shielded shipping casks. With regard to these two aims, five conclusions may be drawn from the results of the tests.

1. For jackets of prismatic casks made of steel materials with between 41 and 69 per cent elongation in a 1-inch gauge length, the incipient puncture energy of the jacket is directly proportional to the ultimate tensile strength of the jacket material.

2. It is not conservative to select jacket thicknesses for cylindrical casks with diameters of less than 30 inches by using the data for prismatic casks per se.

3. The puncture data obtained from the cylindrical model tests were well ordered but the test program was not general enough. The linear scaling method used with the thickness of the jacket being taken as the characteristic length that determined the scale factor resulted in an equation that did not consistently predict existing data obtained from tests with the cylindrical cask prototype. It appears that the thickness of the jacket and possibly the type of material must be varied to produce a general equation for puncture.

4. There is good agreement between the test results for prismatic models and the prismatic cask prototype. Since the test data obtained for the cylindrical model were well ordered, it seems