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STRUCTURAL ANALYSIS OF SHIPPING CASKS
VOL. 3. EFFECTS OF JACKET PHYSICAL PROPERTIES AND CURVATURE ON PUNCTURE RESISTANCE
(Thesis)

H. A. Nelms

This material was submitted to the Graduate Council of the University of Tennessee in partial fulfillment of the requirements for the Master of Science Degree.

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JUNE 1968

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Abstract

An experimental investigation was made of the puncture resistance of lead-shielded steel-jacketed shipping casks, and the results are reported here. This investigation was concentrated upon determining the effects of the material properties and the curvature of the cask jacket upon puncture resistance. An empirical equation for prismatic casks was developed to relate the thickness of the jacket material necessary to resist puncture to the ultimate tensile strength of the jacket material and the weight of the cask. The equation developed was then compared with data previously obtained from tests with a prototype cask. A procedure for selecting the jacket thicknesses of cylindrical casks was also outlined.

CHAPTER I

THE PROBLEM AND METHODS USED FOR ITS STUDY

The transporting of radioactive materials has become a common occurrence because of the widespread use of radioactive isotopes by industrial and research institutions and because of the increasing number of research reactors whose spent fuel elements must be transferred to facilities remote from the reactor for reprocessing. The rapidly expanding nuclear power industry with its need for locating nuclear power stations near population centers is introducing the shipment of radioactive materials into a completely new and potentially more hazardous era. The location of nuclear power stations near population centers will necessarily result in the shipment of fuel elements through or near those population centers. Thus, the general public would be exposed to a potentially severe hazard should an accident involving the transporting vehicle occur and should the container of the radioactive material be ruptured as a result of that accident.

As a result of its interest in all factors affecting safety in the nuclear field, the Atomic Energy Commission has formulated regulations pertaining to the design and performance of the containers in which radioactive material is shipped. One of these regulations is related to the puncture resistance of the outer shell (the jacket) of shipping casks, and the effects of the curvature and material properties of the jacket on the puncture resistance of lead-shielded steel-jacketed shipping casks are studied in this report in an attempt to devise a method of showing compliance with this regulation.

I. STATEMENT OF PROBLEM

The regulations governing the design and performance of shipping casks for radioactive materials proposed by the Atomic Energy Commission appear as Part 71 of Title 10 of the Code of Federal Regulations (1)*. One of these regulations includes a set of hypothetical accident conditions for which a shipping cask must be designed. The conditions of the hypothetical accident related to puncture are stated below.

> A free drop through a distance of forty inches striking, in such a position as to suffer maximum damage, the top end of a vertical cylindrical mild steel bar mounted on an essentially unyielding horizontal surface. The bar shall be six inches in diameter, with the top horizontal and its edge rounded to a radius of not more than 1/4 inch, and of such a length as to cause maximum damage to the package, but not less than eight inches long. The long axis of the bar shall be normal to the package surface.

An evaluation of what constitutes "maximum damage" and "a position as to suffer maximum damage" must include for consideration those limitations imposed by the regulation on the reduction of shielding and loss of radioactive materials. However, it seems that the governing consideration in an evaluation of the results of a cask impacting on a punch will in many cases be the hypothetical accident condition to which the cask must be subjected immediately after the punch impact

*Numbers within parentheses in the text refer to items in the List of References in this thesis.

test. This test is intended to measure the ability of a cask to withstand exposure to a fire. The conditions of this test are stated as follows.

> Exposure for thirty minutes within a source of radiant heat having a temperature of 1475 degrees F. and an emissivity coefficient of nine-tenths, or equivalent. For calculational purposes, it shall be assumed that the package has an absorption coefficient of eight-tenths. The package shall not be cooled artificially until after the thirty-minute test period has expired and the temperature at the center of the package has begun to fall. (1)

Therefore, those casks with shielding material that might melt during the fire could lose this material if the jacket of the cask were punctured prior to the fire. Resistance to puncture would therefore seem to be at least a minimum requirement for those casks whose shielding material has a melting temperature below 1475 degrees F. Lead-shielded casks, which are the most common type, would seem to be particularly vulnerable in fires if the jacket of the cask is damaged to the point where molten lead could escape the confines of the jacket.

To determine the position of impact that will produce the maximum damage, consideration must be given to closure components, handling and transportation tie-down accessories, and the internal structure of the cask that might limit the flexibility of the jacket of the cask. These factors vary from one cask design to another, and for that reason, they will probably assume varying degrees of importance.

For lead-shielded steel-jacketed casks, a measure of the resistance of the cask to puncture can be made by evaluating the case in which the cask impacts in an area that is free from structural constraints and in a manner such that the line of action of the punch intersects the center of gravity of the cask. With these impact conditions, it appears that the jacket of the cask would absorb a maximum amount of energy prior to actual puncture. The objective of the work reported here was to evaluate the effect of the material properties and the curvature of the jacket upon the puncture resistance of lead-shielded steel-jacketed shipping casks that impact with the test punch in an area of the cask free of internal or external structures which might limit the flexibility of the jacket of the cask.

II. METHODS OF STUDYING PROBLEM

Both experimental and analytical methods have been used to evaluate the puncture resistance of shipping casks. However, no generally accepted analytical solution has been developed, and full-scale testing has not been economical because only a few casks of any particular design are usually built. Because of unfavorable economics associated with full-scale testing and the difficulties encountered in purely analytical evaluations, the experimental approach of testing models of shipping casks is receiving strong support. This approach has been shown to be promising by the work reported by Clarke (2), Shappert (3), and Spaller (4). The work reported by Spaller and some of that reported by Clarke and Shappert dealt directly with the puncture resistance of shipping casks. Because of the success of the work reported by these investigators, the method chosen to study the effects of material properties and curvature of the jacket on the puncture resistance of shipping casks was one of experimental investigation involving the use of models.

The first step in setting up an experimental testing program for models was to review the literature on the subject, and the results of this review are reported in Chapter II. In general, it was found that the studies conducted to evaluate puncture resistance of casks have been directed toward prismatic casks and give only the type of material used for the cask jacket. The work reported here was undertaken to increase the scope of the available information related to prismatic casks to include data on properties of jacket material and to obtain model data for cylindrical casks that can be used along with the data on prismatic casks to predict the puncture resistance of full-size cylindrical casks. The parameters of the test program were then selected, and these are reported in Chapter III. The procedures for and the results of the tests on models of both prismatic and cylindrical casks are given in Chapter IV, the data are correlated in Chapter V, predictions for incipient puncture of the prototype casks are made in Chapter VI, and the summary, conclusions, and recommendations are presented in Chapter VII.

CHAPTER II

REVIEW OF LITERATURE

The resistance of plates to puncture by flat-ended cylindrical punches is of interest in several fields of endeavor. Two such areas of interest discovered in the review of literature are where the containment of projectiles generated by the failure of pressurized equipment is of concern and where the punch-and-die operation is used in the manufacture of perforated plate. Obviously, there are major differences between the processes of puncture in these two fields and in the field where the puncture of shipping cask jackets is of concern. One such major difference is in the restraints on the flexibility of the plate being punched. However, it appears that the significant variables other than flexibility restraints are the same.

I. PUNCHING WITH CYLINDRICAL PROJECTILES

The penetrating capacity of projectiles has been studied rather extensively, but the projectiles considered generally have velocities of such a magnitude that the penetration process is significantly different from that encountered in the puncture of shipping casks. The result of the change in the penetration process is a change in the energy required for a particular punch to penetrate a given plate. The fact that the energy to produce puncture with a relatively high-speed projectile is different from the energy required by a punch of the same dimensions that is forced through a plate with a hydraulic press was demonstrated in the work done at the Stanford Research Institute related to the containment of missiles. (5, 6) This alone seems to eliminate the possibility of directly applying the equations for high-speed projectile penetration to the puncture of shipping casks. However, the significant variables necessary to describe the relatively high-velocity penetration process studied at the Stanford Research Institute are of interest.

The data reported by Stanford Research Institute were obtained by using steel projectiles whose velocity varied from 70 feet per second to 350 feet per second. The equation that was reported to describe these data is

$$E_p = \frac{SD_p}{46,500}(16,000T_p^2 + 1,500 \frac{W}{W_s} T_p) , \qquad (1)$$

where

E_p = critical kinetic energy, foot-pounds,

S = ultimate tensile strength of the plate being punched, pounds per square inch,

D_p = diameter of projectile, inches,

T_p = thickness of plate, inches,

W = length of side between rigid supports (for a square plate), inches, and

W_s = length of standard width = 4 inches.

No mathematical correlation was given for the test conducted where the projectile (punch) was forced through a plate, which was reported as a "semi-static" test. However, the data seemed to fit a smooth curve plotted by using the variables in Equation 1 as the coordinates of the plot. Puncture in the semi-static test was reported to occur with an expenditure of approximately one-half the energy required in the projectile test.

Another equation for the puncture of plates with cylindrical steel projectiles that has been reported (7) is

$$E_p = 17{,}400 k^2 D_p^{3/2} T_p^{3/2}, \qquad (2)$$

where k = a constant dependent upon the grade of the steel and it is usually $\simeq$ 1. Equation 2 was reported as being applicable for use in determining the puncture resistance of steel shells for reactor containment, but no limits on its range of application were specified. Equations 1 and 2 seem to be significantly different but this difference might be understood easily if the range of application of Equation 2 were known.

A method of applying Equations 1 and 2 directly to the problem of predicting the puncture resistance of a shipping cask jacket is not apparent. However, Equations 1 and 2 are of interest for two reasons: their simplicity and their formulation on an energy basis. It is encouraging that only a few easily measured variables are necessary for the formulation of mathematical expressions that describe the projectile puncture process, particularly since these same variables appear to be among the significant ones affecting the puncture resistance of shipping casks. The semi-static tests conducted at Stanford

Research Institute (6) also appear to have the same principal variables, and this is more significant because these tests were conducted with punch velocities that are more nearly comparable with the impact velocities of the cask than are the velocities of the projectiles for which Equation 1 is valid and possibly Equation 2. It was evidently possible to correlate the projectile puncture data on an energy basis for at least a moderate velocity range. This is of particular interest because it is easier to vary the impact energy of a model cask by varying the impact velocity versus varying the weight of the model. This is discussed in greater detail in Chapter IV of this report.

II. MACHINE TOOL PUNCHING

Perforating plate with cylindrical punches has been a routine manufacturing operation for many years, and the manufacturing techniques used have been reported thoroughly. However, the question of how much energy must be expended to effect the puncture of a plate with a cylindrical punch has received little space in the literature, and if available, this information would be of value in understanding the problem of puncture of shipping cask jackets. The probable reason for neglecting the precise energy requirements for plate perforation with machine tools is the ease of circumventing this difficult problem by using peak punch force considerations.

The maximum (peak) force necessary to effect the puncture of a plate with a flat-ended cylindrical punch in a punch-and-die operation,

$$F_p = \pi d T_p S_s \ , \tag{3}$$

where

F_p = maximum shear force, pounds,

d = diameter of punch, inches,

T_p = thickness of plate, inches, and

S_s = ultimate shear strength of the plate material, pounds per square inch (generally assumed to be 0.75 times the ultimate tensile strength for annealed steel and aluminum).

If a punch press is designed to deliver the peak force given by Equation 3 and if the design provides punch strokes in excess of the thickness of the plate to be punched, puncture of the plate is assured without considering the exact energy necessary to effect puncture. The peak force given in Equation 3 can be reduced by beveling the working end of a punch to effect a progressive shearing operation, but an increased working stroke is necessary so that the energy expended in the punching process is essentially unchanged. (8)

In machine tool punching of plate and in punching lead-backed steel-jacketed casks, it is not necessary for the punch to shear through the full thickness of the plate to effect complete puncture, as may be seen in Figure 1. In punching operations, the depth of punch penetration required to effect complete puncture is defined as the critical penetration. When the critical penetration has been attained in any particular case, little additional progress by the punch is required to induce the remaining thickness of plate to fracture. (8) If the force exerted by a punch when it has reached the critical penetration for complete puncture is defined as F_f, the

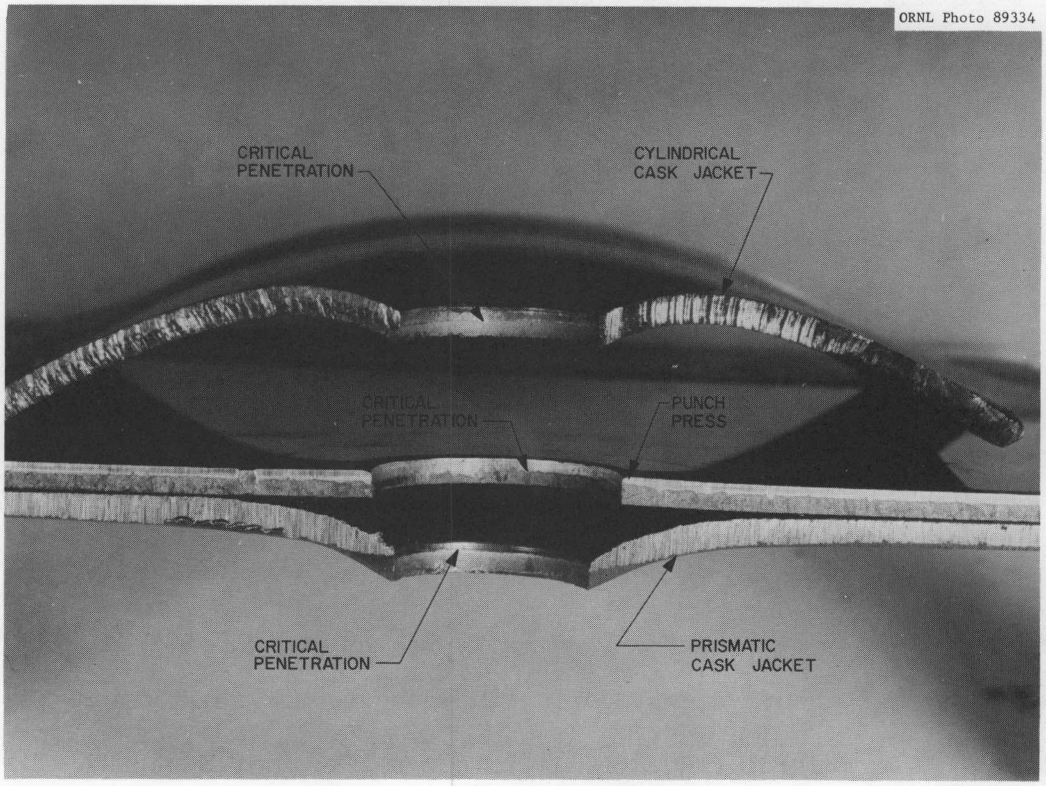

Figure 1. Plate punched with a power punch compared with plates punched in cask model tests.

energy to effect complete puncture in a punch-and-die operation using flat-ended cylindrical punches,

$$E_d = \frac{F_p + F_f}{2} P = \frac{\pi d T_p S_s + F_f}{2} P , \qquad (4)$$

where

E_d = energy to produce complete puncture in a punch-and-die operation, inch-pounds,

E_f = punch force at critical penetration, pounds,

P = critical penetration, inches,

and where it is assumed that the punch force decreases linearly from F_p to F_f.

If Equation 4 accurately defines the energy required to produce puncture in a punch-and-die operation and can be solved readily, it might provide a beginning point in an effort to isolate the various mechanisms that absorb energy during the puncture of shipping cask jackets. Unfortunately, Equation 4 is not easily solved because little information is available concerning the variables F_f and P. The variable P appears to be a function of the ultimate strength of the plate material (8) and the initial plate thickness (9), and it appears that F_f is a function of the unsheared thickness at the critical penetration and the material properties of the unsheared material. Therefore, it appears that the variables F_f and P will have to be investigated experimentally before Equation 4 can be used effectively.

III. REVIEW OF CASK PUNCTURE TESTS

The puncture tests that have been conducted to date have ranged in scope from punch and no-punch tests for specific cask designs to systematic studies aimed at producing general information suitable for routine shipping cask designs. Several tests have been conducted to evaluate the feasibility of using inexpensive models of full-size casks to predict puncture resistance and other performance capabilities. A comprehensive list of reports on the subject of puncture of shipping cask jackets is included in a bibliography of shipping cask literature produced by Shappert and Burns. (10)

In general, studies that have been conducted to evaluate the puncture resistance of shipping casks have been oriented toward prismatic casks and have reported only the type of jacket material used and not the properties of that material. Since shipping casks frequently are cylindrical in shape and since there are a number of materials that are of interest for use as jackets, it has not been possible to develop general design data from the data in the existing literature.

A number of such factors as the velocity of impact, radius of punch edge, smoothness of surfaces, properties of lead shielding material that backs the jacket, and the gaps between the jacket and the shielding material have received consideration by various investigators and are discussed in the reports included in the bibliography produced by Shappert and Burns. (10) The effects of internal and external constraints on the flexibility of a cask jacket, the effects of an impact where the line of action of the punch does not intersect the center of gravity of the cask, the effects of impact upon closure components, and the possibility of modes of failure other than puncture apparently have not been evaluated experimentally.

CHAPTER III

SELECTION OF TEST PARAMETERS

The regulations (1) proposed by the Atomic Energy Commission for the design and performance of shipping casks for radioactive materials have fixed several of the variables affecting the puncture resistance of cask jackets by requiring the use of a six-inch-diameter punch and specifying that the long axis of the punch is to be normal to the surface of the cask at impact. Further, the velocity at impact and the total energy available for any particular cask are fixed by the requirement for a 40-inch drop height. For steel-jacketed lead-shielded casks, there are obviously additional significant parameters. A review of the work done with shipping casks and in the areas of missile containment suggests that the incipient puncture energy of a steel-jacketed lead-shielded cask might be adequately predicted by an analytical expression of the form

$$E = f(S, t, d) \quad , \tag{5}$$

where

E = incipient puncture energy,

S = ultimate tensile strength of jacket material,

t = thickness of jacket, and

d = diameter of punch.

The incipient puncture energy is the maximum energy that can be absorbed by a cask jacket and the lead backing the jacket without effecting a complete puncture. As previously mentioned, it is not necessary to shear completely through a plate to effect complete puncture; it is only necessary for a punch to attain the critical penetration with some finite but relatively insignificant additional capacity to do work. Therefore, the incipient puncture energy of a cask is the energy required to just attain the critical penetration with all available energy expended. A shipping cask must be able to absorb an energy equal to the product of the weight of the cask and the 40-inch drop height.

I. MATERIAL PROPERTIES

The material properties of both the jacket and the lead shielding have been shown to affect the puncture resistance of lead-backed steel-jacketed casks. (4, 11) The evaluation of the effects of the material properties of both the lead and the jacket upon the puncture resistance of casks would be ideal. However, since chemical lead is commonly used as a shielding material for casks, chemical lead ASTM* B29-55 was used in all tests reported here and emphasis was placed on evaluating the effects of the material properties of the cask jacket.

It appears that the major energy absorption processes that affect the puncture resistance of casks are the shearing of the jacket, the deformation of the jacket, and the deformation of the lead material backing the jacket. Obviously, the hardness, ductility, ultimate

*American Society for Testing and Materials tensile strength, and ultimate shear strength of the jacket material will influence each of these processes of energy absorption. Even if possible, attempting to evaluate each of these characteristics by varying one and holding the others constant does not appear too practical. This is particularly true for ductile materials because the hardness and the ultimate shear strength can be related to the ultimate tensile strength at least approximately. Therefore, the test program for evaluating the effect of the material properties of the jacket was set up to evaluate several materials whose ultimate tensile strengths varied over the range of interest, and no controls were placed on the hardness, ductility, and ultimate shear strength characteristics of the materials. A listing of the materials tested is given in Table I.

II. CYLINDRICAL MODELS

The model of the cylindrical cask used in the test program is shown in Figure 2, and the cylindrical model holder is shown in Figure 3. The objective of the cylindrical model test program was to obtain, if possible, data on simple modifying factors that could be used with the data for prismatic models to predict the puncture resistance of full-size cylindrical casks. To isolate the effects of the cylindrical shape upon puncture resistance, the thickness and type of material of the jacket and the lead shielding were held constant. The diameters of both the cask model and the punch were varied.

TABLE I

JACKET MATERIAL TESTED

Sample Number	Description of Material	Thickness (in.)	Ultimate Tensile Strength[a] (p.s.i.)	Yield Strength at 0.2% Offset[a] (p.s.i.)	Per Cent Elongation for 1-in. Gage Length[a]
1	304L SST,[b] ASTM-A240 annealed	0.078	85,120	42,460	68
2	304L SST,[b] ASTM-A240 annealed	0.030	86,570	40,680	66
3	301 SST,[b] MIL-S-5059 half hard	0.031	175,610	119,810	33
4	ASTM-A366 carbon steel	0.120	46,480	27,910	49
5	ASTM-A366 carbon steel	0.038	43,030	22,190	41
6	304 SST,[b] annealed	0.076	93,840	47,130	62
7	304 SST,[b] annealed	0.028	94,620	44,020	69
8	ASTM-A245, carbon steel	0.107	54,390	36,210	44
9	Low carbon, hot rolled steel	0.031	43,710	23,040	45
10	Low carbon, hot rolled steel	0.063	45,450	23,720	50
11	316 SST,[b] ASTM A240-58T	0.074	87,250	47,140	54
12	321 SST,[b] AMS-5510-F	0.078	90,640	37,410	63
13	Brass, ASTM-B-121-#4	0.127	66,200	54,550	23
14	Copper, ASTM-B152	0.123	34,550	28,330	44
15	Tool steel, AISI type 01 annealed	0.031	97,150	78,770	22
16[a]	Tool steel, AISI type 01 annealed	0.065	97,150	78,770	22
17	430 SST,[b] annealed	0.073	70,320	53,100	21

[a]Except for Sample 16, these results represent the average of four tests. In each case, two specimens were taken from the parent material in the direction of rolling and two were taken perpendicular to the direction of rolling. No tests were conducted on Sample 16, and its values were assumed to be the same as the values for Sample 15, which is the same type material.

[b]The term SST is used to denote stainless steel.

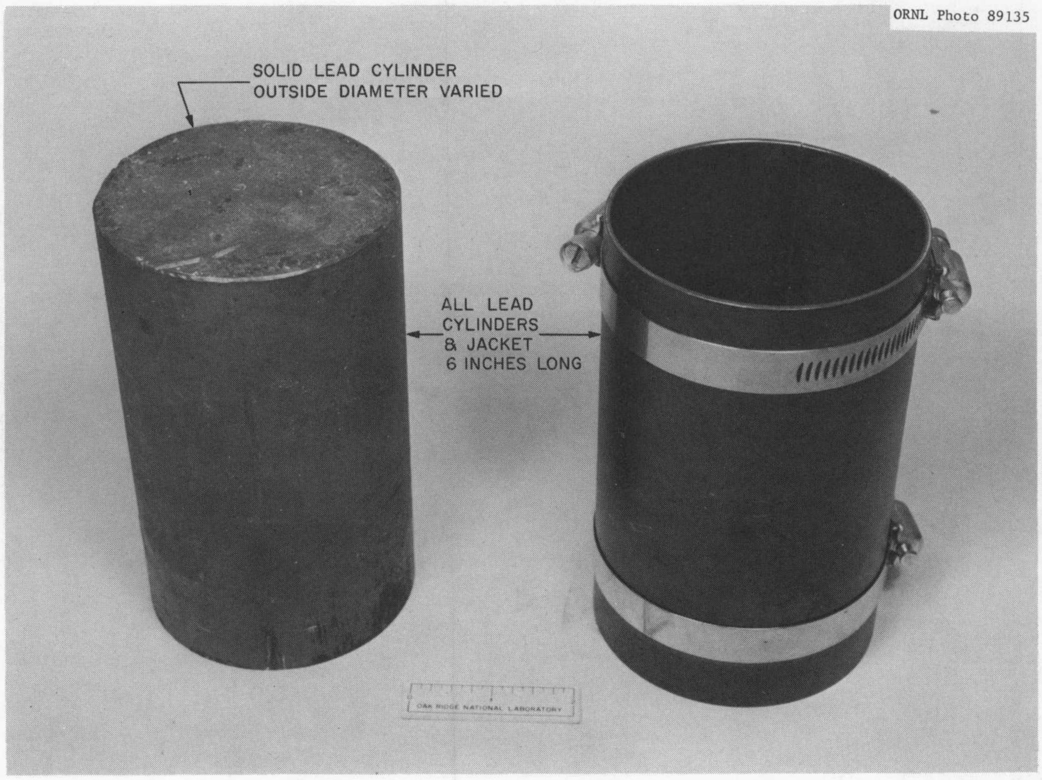

Figure 2. Model of cylindrical cask used in test program.

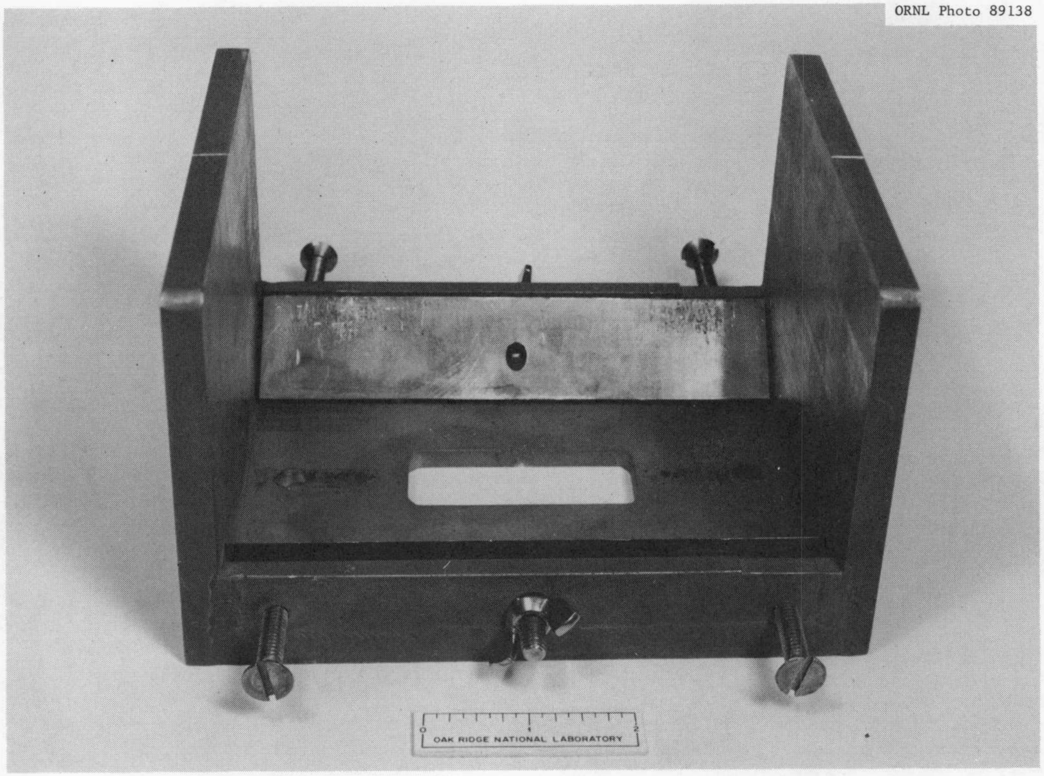

Figure 3. Cylindrical model holder used in test program.

CHAPTER IV

TEST PROGRAM

The test program was divided into two separate phases. The first phase involved the determination of the incipient puncture energy for several jacket materials used on prismatic models. The second phase of the test program involved the determination of the incipient puncture energy for jackets used on cylindrical models of various diameters. The type and thickness of the jacket material for the cylindrical models were held constant.

I. PROCEDURE FOR PRISMATIC MODEL TESTS

A scale model of the prismatic cask used in the puncture tests is shown in Figure 4. The model cask consists of a frame, test plate, lead brick, and backup plate. The disassembled test cask is shown in Figure 5. This cask model was used with the drop frame shown in Figure 6 to determine the energy (product of the weight of test cask and the drop height) required to produce incipient puncture in the test plates of different jacket materials.

An approximation of the exact incipient puncture energy for each material used for the jacket of the prismatic model was made by averaging the minimum puncture energy and maximum no-puncture energy values that resulted from several drop tests for each set of conditions. The jacket material and thickness and the size of the punch were held

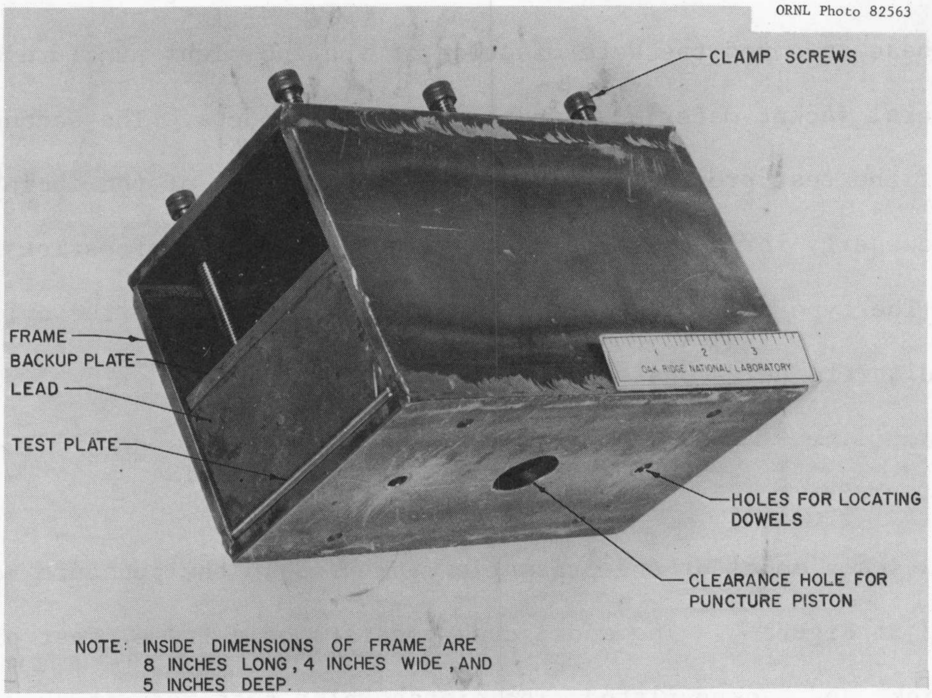

Figure 4. Scale model of the prismatic cask used in the puncture tests.

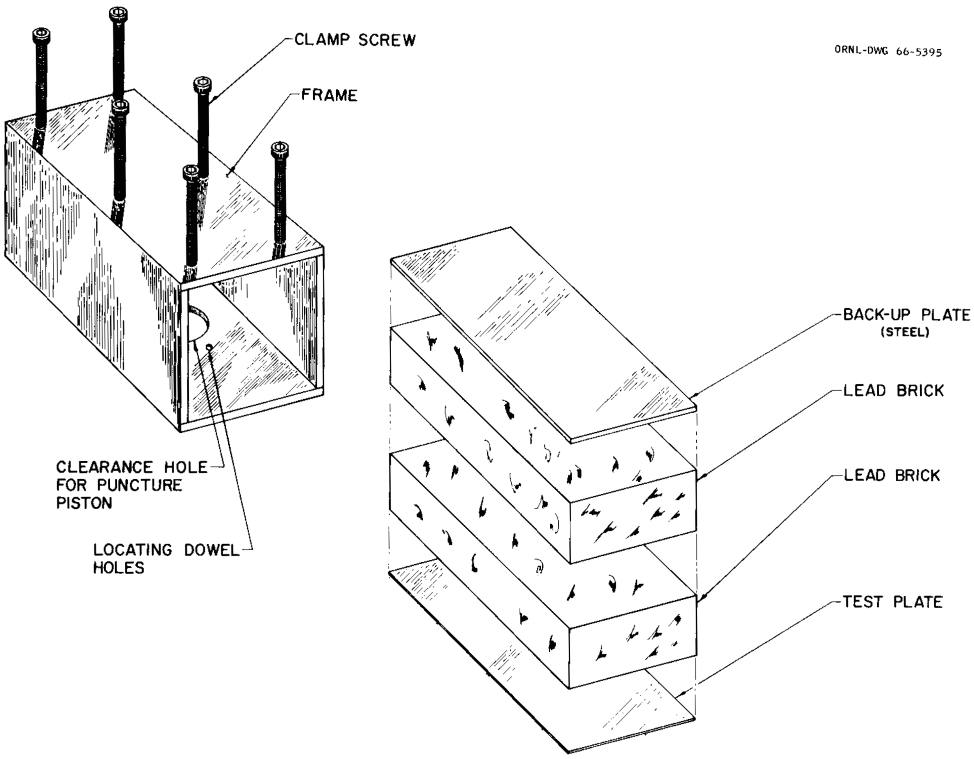

Figure 5. The disassembled test cask used for the prismatic model tests.

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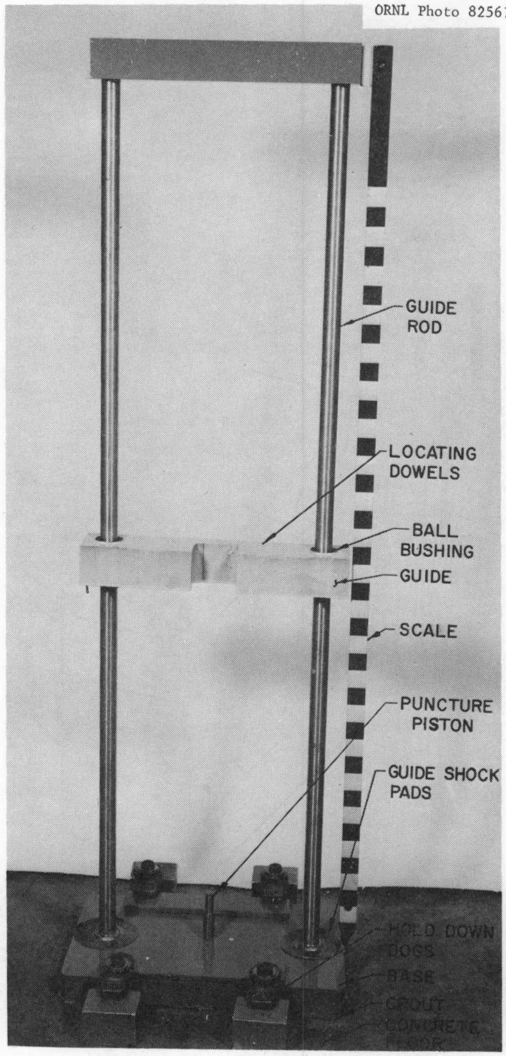

Figure 6. Drop frame used with the test cask in the prismatic model tests.

constant. Puncture and no-puncture energy values for each set of conditions were obtained by varying the weight of the model from 36 to 66 pounds and/or the drop height of the model from 8 to 40 inches. After puncture and no-puncture energy values were obtained for particular jacket and punch conditions, only the drop height had to be varied to narrow the difference between the puncture and no-puncture energy values that were averaged to find an approximate incipient puncture energy. Varying the drop height obviously varies the impact velocity, but for the range of drop heights used, the effect of impact velocity upon puncture energy has been shown to be negligible. (4) About five test drops were made to obtain each data point (incipient puncture energy). Initially, from six to eight test drops were required, but as a basis for estimating the incipient puncture energy developed, only three to five test drops were required.

The test drops were conducted by using the drop frame, the prismatic test cask, and either a 0.5-inch-diameter or a 0.6-inch-diameter punch. The punches used are illustrated in Figure 7. They were made from hot-rolled steel bar stock that had a hardness value of about Rockwell B-70. The sequence of the events necessary for each drop test was as follows.

1. The diameter of the punch was measured and the punch was placed in the drop frame. A new sharp-edged punch was used for each test drop.

2. The thickness of the jacket plate was measured and the test rig was assembled. Each jacket plate of the same material and

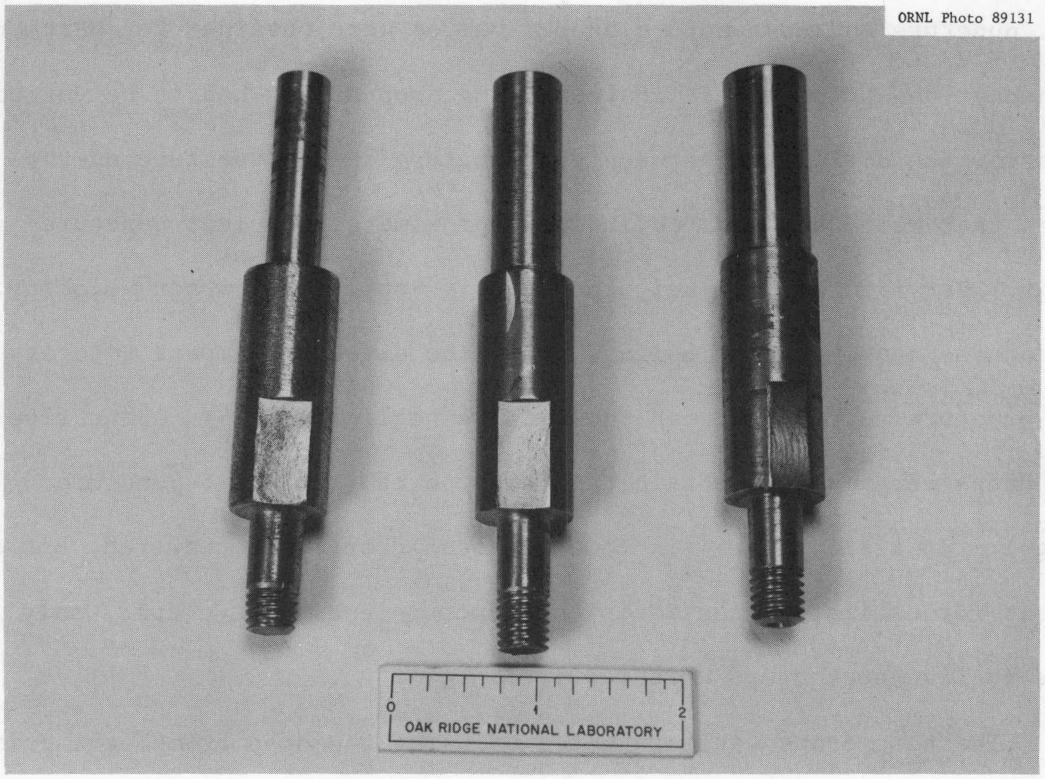

Figure 7. Punches used in cask model test program.

thickness was obtained from a single sheet of stock material whose physical properties were determined prior to the puncture test.

3. The test rig was weighed and positioned on the guide bar of the drop frame.

4. The test rig was raised to a height that was estimated to be near the height required to produce puncture and then it was dropped and the impact energy data were recorded.

5. The damaged jacket was inspected for puncture, and the indentations and damage conditions were recorded.

This test sequence just described was repeated for a particular type jacket (thickness and material) and punch size until sufficient data were obtained to determine an approximate value for the incipient puncture energy. Generally, testing of a particular type jacket was terminated when the difference between the drop height for a puncture and a no-puncture case at a particular weight was about 1 inch.

Examples of jacket plates for prismatic models that have been tested near their incipient puncture energy are shown in Figures 8, 9, and 10. A fracture line is clearly visible on the plate shown in Figure 8, and a cross-sectional view of a completely punctured test jacket is shown in Figure 9. The reverse side of a jacket plate for a prismatic model that was tested near its incipient puncture energy is shown in Figure 10. It was possible to obtain results of this quality with the test equipment used, and most of the data included in this report represent such results. However, in order to reduce the number of test drops, it was necessary to consider the results of tests in

Figure 8. Punctured jacket plate for prismatic model with clearly visible fracture line.

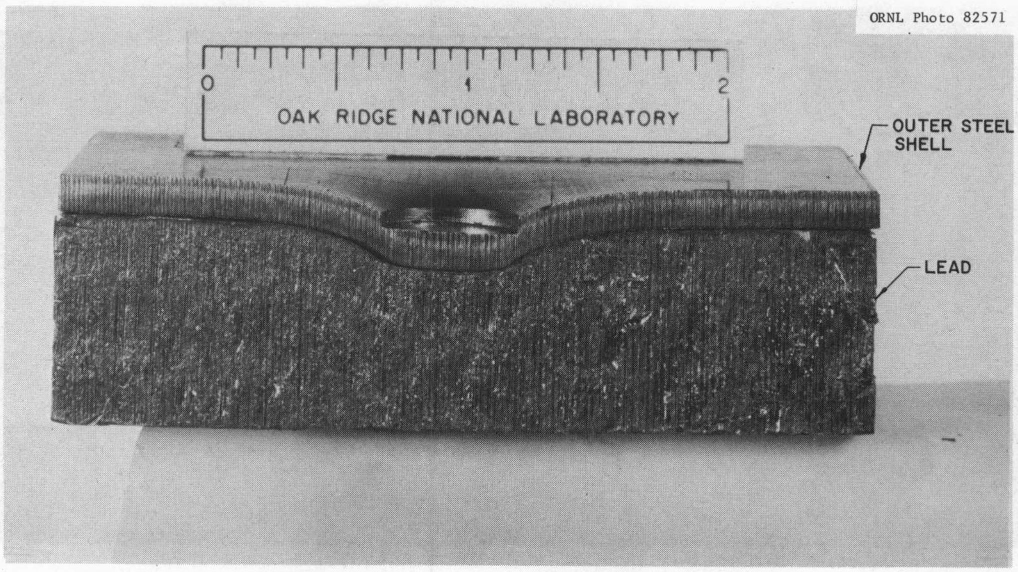

Figure 9. Cross-sectional view of a completely punctured test jacket.

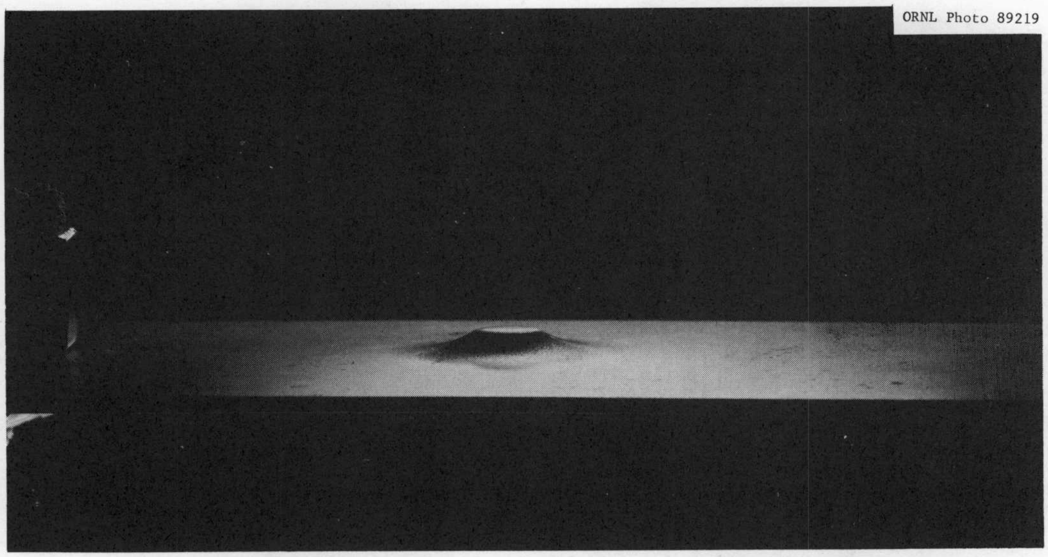

Figure 10. Reverse side of a prismatic model jacket plate tested near the incipient puncture energy.

which there was other than no puncture or complete puncture; that is, where the length of the fracture line on the reverse side of the jacket was less than 100 per cent of the circumference of the punch.

As pointed out earlier, the peak force required to effect complete puncture in a punch-and-die operation can be reduced by beveling the working end of the punch. A similar condition exists when a cask or a model of a cask strikes a test punch in such a manner that the long axis of the square-ended punch is not perpendicular to the surface of the cask. If the line of action of the test punch does not pass through the center of gravity of the cask, the cask rotates and the beveled-punch effect is likely to occur. Therefore, in order to obtain test results in which the indentation of the punch is symmetrical about the center line of the punch, it is necessary to maintain a very high degree of alignment between the cask and the punch.

Because of the flexibility of the vertical guides on the drop frame and the clearances in the bearings of the guide bar, maintenance of the required degree of alignment between the cask and the punch at impact was difficult. The test data were completely rejected for test drops where gross misalignment occurred. However, for test drops that produced a fracture line whose length was less than or about 10 per cent of the circumference of the punch, a no-punch condition was generally assumed. For test drops that produced a fracture line whose length was in excess of 75 per cent of the circumference of the punch, a puncture condition was generally assumed to have been attained.

Categorizing test results as puncture or no puncture based upon the length of the fracture line produced in the test plate was considered reasonable. The basis for this is that little additional energy is expended to effect complete puncture once the critical penetration has been attained in a case where the punch squarely strikes the surface of the plate being punched. Also, the beveled-punch effect reduces the peak force necessary to initiate puncture when the punch does not strike squarely.

II. RESULTS OF PRISMATIC MODEL TESTS

Tests with the prismatic model test rig were conducted with test plates of all the types of material given in Table I. However, some of these materials are not likely to be used as jacket material for shipping casks. Test data for those materials that are likely to be used for cask jackets or that cover the range of ultimate tensile strengths of possible jacket materials are given in Table II. The test data for those materials that are not considered candidates for use as cask jackets are given in Table III. The data of Table II are represented graphically in Figure 11, and the data of Table III are illustrated graphically in Figure 12.

The coordinates of Figure 11 include one variable that has generally been held constant or neglected in previous investigations. This variable is the ultimate tensile strength of the jacket material. Two types of jacket material were considered in an investigation conducted by Spaller (4), and a different mathematical correlation was

TABLE II

PRISMATIC MODEL TEST DATA OBTAINED WITH CANDIDATE JACKET MATERIALS[a]

Sample Number[a]	Jacket Thickness (in.)	Punch Diameter (in.)	Minimum Puncture Energy (in.-lb.)	Maximum No-Puncture Energy (in.-lb.)	Incipient Puncture Energy[b] (in.-lb.)	Jacket Indentation at No-Puncture Energy[c] (in.-lb.)	Jacket Indentation at Puncture Energy[c] (in.)
1	0.078	0.5	1723	1613	1668	0.185	0.280
4	0.120	0.5	2129	1892	2011	0.184	0.216
5	0.038	0.5	385	289	337	0.075	0.102
6	0.076	0.5	2031	1762	1897	0.180	0.225
8	0.107	0.5	1790	1696	1743	0.167	0.260
9	0.031	0.5	308	250	279	0.072	0.093
10	0.063	0.5	809	732	771	0.121	0.175
11	0.074	0.5	1892	1625	1759	0.184	0.223
13	0.078	0.5	1871	1742	1807	0.196	0.227
1	0.078	0.6	2540	2520	2520	0.210	0.260
2	0.031	0.6	652	621	637	0.101	0.112
4	0.120	0.6	2590	2474	2532	0.215	0.293
5	0.038	0.6	462	424	443	0.081	0.093
7	0.027	0.6	646	536	591	0.103	0.115
8	0.107	0.6	2540	2477	2509	0.148	0.150
9	0.031	0.6	385	308	347	0.064	0.088
10	0.063	0.6	1046	900	973	0.120	0.150

[a]Jackets with equal thicknesses are not necessarily the same material. Sample numbers correspond with those given in Table I, page 18.

[b]Incipient puncture energy $= \frac{\text{maximum no-puncture energy + minimum puncture energy}}{2}$.

[c]Depth of indentation was measured from the undeformed surface of the jacket plate.

TABLE III

PRISMATIC MODEL TEST DATA OBTAINED WITH NON-CANDIDATE JACKET MATERIALS[a]

Sample Number[a]	Jacket Thickness (in.)	Punch Diameter (in.)	Minimum Puncture Energy (in.-lb.)	Maximum No-Puncture Energy (in.-lb.)	Incipient Puncture Energy[b] (in.-lb.)	Jacket Indentation[c] At No-Puncture Energy (in.)	Jacket Indentation[c] At Puncture Energy (in.)
13	0.127	0.5	1474	1114	1294	0.107	0.183
14	0.123	0.5	1501	1441	1471	0.197	0.225
15	0.031	0.5	456	344	400	0.086	0.125
16	0.065	0.5	1300	975	1138	0.124	0.179
17	0.073	0.5	1105	968	1037	0.136	0.155
3	0.031	0.6	803	578	691	0.078	0.238
13	0.127	0.6	2121	1818	1970	0.157	0.191
14	0.123	0.6	2129	1965	2047	0.213	0.235

[a]Jackets with equal thicknesses are not necessarily the same material. Sample numbers correspond with those given in Table I, page 18.

[b]Incipient puncture energy $= \dfrac{\text{minimum puncture energy + maximum no-puncture energy}}{2}$.

[c]Depth of indentation measured from the undeformed surface of the jacket plate.

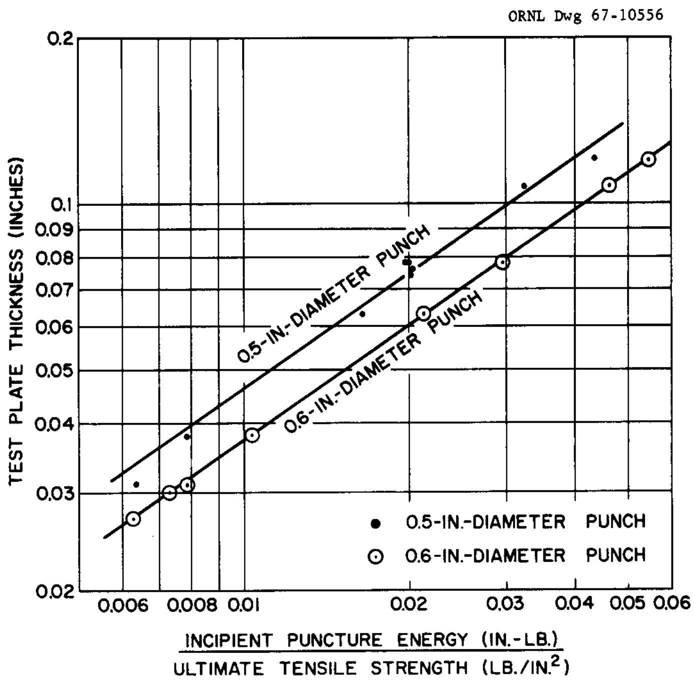

Figure 11. Jacket thickness versus the ratio of incipient puncture energy to ultimate tensile strength of the material for the candidate jacket materials.

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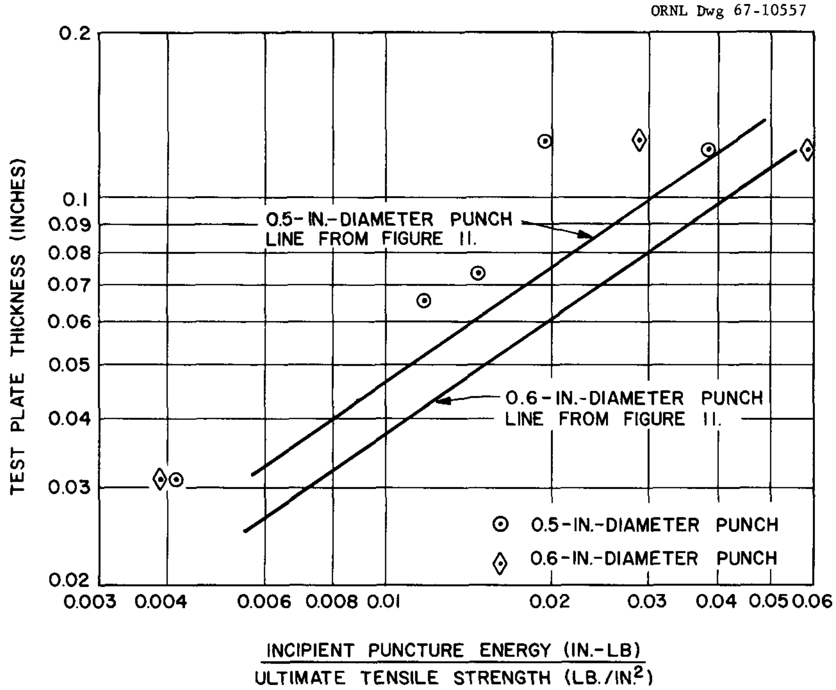

Figure 12. Jacket thickness versus the ratio of incipient puncture energy to ultimate tensile strength of the material for non-candidate jacket materials.

obtained for each type of material. In order to compare the results of that work with the results of the work reported here, the material properties of several of the model jackets were obtained. The results of this reevaluation are given in Table IV and plotted in Figure 13.

The general nature of the damage that occurs when models of prismatic casks are impacted onto a punch has been illustrated in Figures 8, 9, and 10. In general, the diameter of the region that sustained permanent deformation as a result of the cask impacting upon a punch was from 2.5 to 3 times the diameter of the punch. For jacket materials with elongations of less than 40 per cent in a 1-inch gauge length, there was a noticeable permanent deformation over the entire surface of the test plate and local deformation similar to that illustrated in Figures 8, 9, and 10 was superimposed over the general deformation. The diameter of the region in which this local deformation occurred was about 2 times the diameter of the punch.

The jacket materials with elongations of less than 40 per cent in a 1-inch gauge length exhibited less resistance to puncture than those materials with equal thicknesses and ultimate tensile strengths but more than 40 per cent elongation in a 1-inch gauge length. Except for Sample 14, the data given in Table III and illustrated in Figure 12 represent the results of tests made with materials whose elongation in 1 inch is less than 40 per cent. Sample 14 is copper and it is the material with the lowest strength that was tested. Sample 14 had 44 per cent elongation in a 1-inch gauge length, and the puncture

TABLE IV

PRISMATIC MODEL DATA FROM PREVIOUS TESTS RECORDED IN REFERENCE 4

Test No.[a]	Jacket Thickness (in.)	Punch Diameter (in.)	Incipient Puncture Energy (in.-lb.)	Jacket Material Ultimate Tensile Strength[b] (p.s.i.)	g(d)[c]
1	0.0495	0.3115	258	41,900	
2	0.072	0.3115	471	47,800	0.393
3	0.117	0.3115	1,063	47,100	
4	0.0495	0.375	332	41,900	
5	0.072	0.375	619	47,800	0.516
6	0.117	0.375	1,345	47,100	
7	0.072	0.4365	750	47,800	0.625
8	0.072	0.450	814	47,800	0.679
9	0.051	0.500	522	41,900	
10	0.0595	0.500	708	47,100	
11	0.072	0.500	943	47,800	0.786
12	0.110	0.500	1,875	60,100	
13	0.1183	0.500	2,095	47,100	
14	0.136	0.500	2,595	62,000	
15	0.072	0.552	1,107	47,800	
16	0.0495	0.625	784	41,900	0.993
17	0.072	0.625	1,409	47,800	1.175
18	0.031	0.500	489	84,200	
19	0.050	0.500	829	84,200	
20	0.0625	0.500	1,328	84,200	
21	0.074	0.500	1,950	84,200	

[a]The jacket material for Tests 1 through 17 was ASTM A-245 Grade A, structural quality, hot-rolled steel. For Tests 18 through 21, the material was type 304L stainless steel, ASTM A240, bright-cold rolled, No. 2B finish.

[b]Two specimens of the jacket materials used in Tests 9 through 14 and 20 were tested. The average value of the values determined from the tests is recorded. For the remainder of the tests where A-245 material was used, the value recorded is the value for the thickness actually tested that is nearest to the particular thickness used in the test. All thicknesses of type 304L stainless steel were assumed to have the same ultimate tensile strength.

[c]The function of the diameter of the punch,

$$g(d) = 39.8E_F/S,$$

where E_F = incipient puncture energy for jacket of prismatic cask and

S = ultimate tensile strength of jacket material.

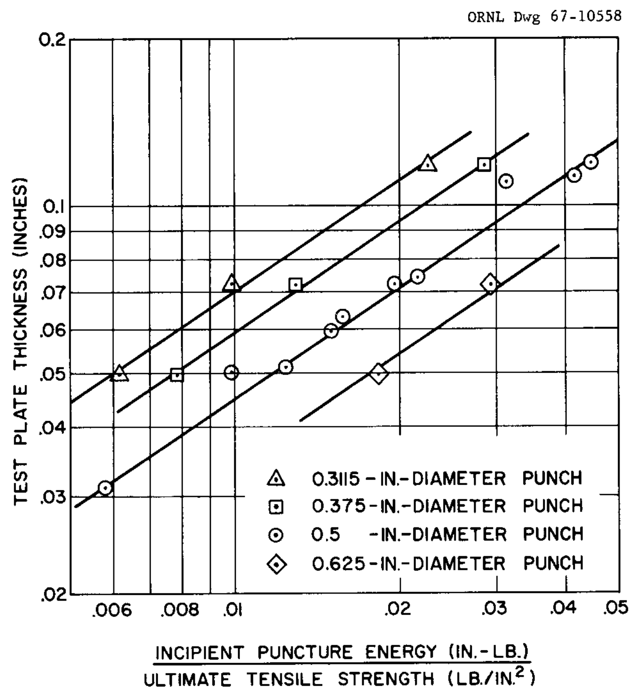

Figure 13. Thickness of jacket material versus the ratio of the incipient puncture energy to the ultimate tensile strength of the material for data obtained in previous tests (Reference 4).

characteristics of this test plate material were similar to those of steel test plates of comparable thickness, strength, and elongation values.

III. EVALUATION OF CYLINDRICAL MODELS

The three cylindrical models shown in Figure 14 were considered for use in the cylindrical model test program. These three models differed only in the manner in which their jackets approximated a complete ring. From the left, the jacket of the first model in Figure 14 has a welded joint, the jacket of the second model has a flange joint, and the jacket of the third model has a banded joint. The first or Type 1 model is an accurate typification of cylindrical casks but more expensive than the second, Type 2, and third, Type 3, models because of the welding. The procurement time for the Type 1 model is also greater than that for the Type 2 and Type 3 models because the lead shielding material must either be cast directly into or machined to fit a previously fabricated jacket.

Samples of each of the three types of models were fabricated and tested to determine whether or not the depth of jacket indentation varied significantly with the types of joints used in the jackets. If not, the less expensive and more readily available models could be used in the test program. The results of these tests are given in Table V. Since the indentations that occurred in the Type 3 model did not appear to differ significantly from those that occurred in the Type 1 model,

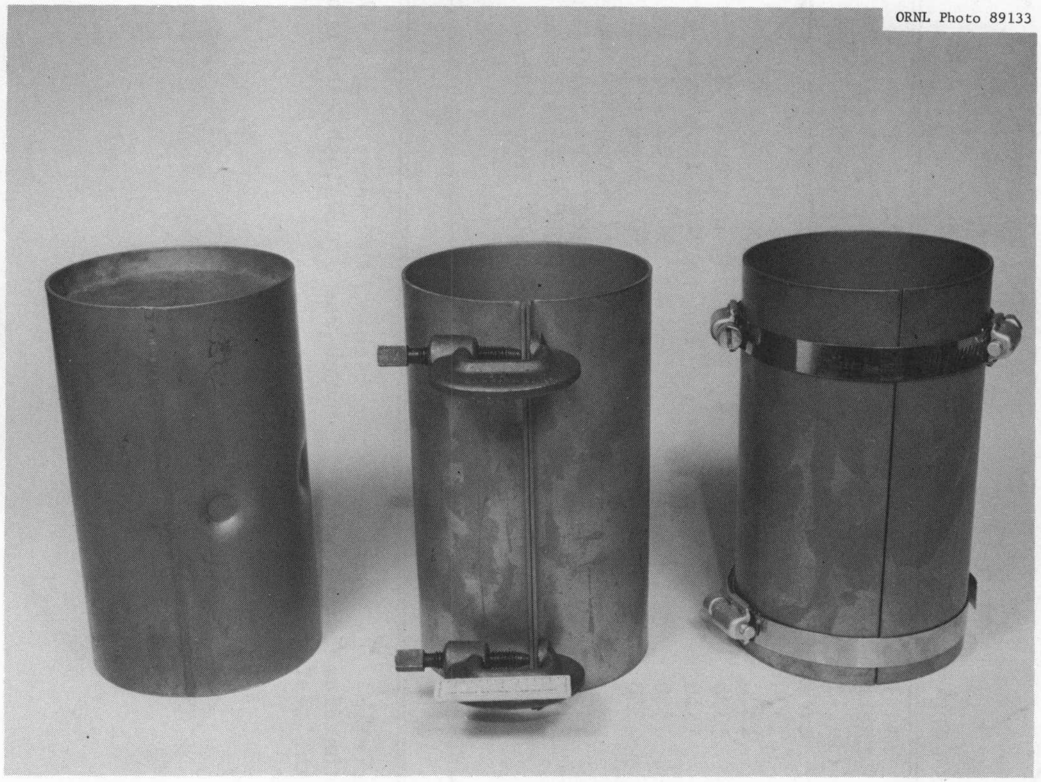

Figure 14. Cylindrical models considered for use in the test program.

TABLE V

RESULTS OF TESTS MADE TO EVALUATE CYLINDRICAL MODELS[a]

Model Test No.	Model Type No.	Model Weight (lb.)	Drop Height (in.)	Impact Energy (in.-lb.)	Depth of Indentation (in.)	Comments
1	1	32.5	40	1300	0.160	
2	1	32.5	40	1300	0.156	
3	1	32.5	40	1300		Did not hit punch squarely
4	3	33.75	40	1350	0.165	Impact 180° from slit in shell
5	3	33.75	40	1350	0.160	Impact 90° from slit in shell
6	3	33.75	40	1350	0.175	Impact 90° from slit in shell, did not hit punch squarely
7	2	33.75	39	1316	0.146	Impact 180° from slit in shell
8	2	33.75	39	1316	0.153	Impact 90° from slit in shell
9	2	33.75	40	1350	0.155	Impact 90° from slit in shell
10	1	32.75	39	1277	0.156	
11	1	32.75	40	1310	0.152	
12	1	32.75	38	1238	0.135	

[a]For all of the tests, the diameter of the model was 4.17 inches, the jacket was 0.0725-inch-thick stainless steel ASTM A240, the diameter of the test punch was 0.600 inch, and puncture of the jacket did not occur in any of the tests.

the Type 3 model with the banded jacket was selected for use in the test program. The Type 3 model is only slightly easier to fabricate than the Type 2 model, but the area of the Type 2 model that can be tested is restricted by the flanges necessary for clamping the jacket joint.

IV. TEST PROCEDURE FOR CYLINDRICAL MODELS

The procedures used in the test program for the cylindrical models were essentially the same as those used for the prismatic cask models. Prior to each test drop, the diameter and weight of each cask model, the thickness of the jacket, and the diameter of the punch were recorded. Test drops with each cask model were then made until enough puncture and no-puncture data were obtained to determine the approximate incipient puncture energy by averaging the maximum no-puncture and minimum puncture energies. An average of about six test drops was required for each size punch to determine the incipient puncture energy for each size cask model.

As in the tests with the prismatic models, categorizing the results of each test of a cylindrical model as either puncture or no puncture was accomplished by inspecting the inside surface of the jacket for the presence of fracture lines. However, the length of the fracture line was not used as the only criterion for categorizing the results of the tests with cylindrical models. It was necessary to classify as puncture only those cases where the fracture lines were approximately symmetrical about the line of action of the punch because of the small variation in incipient puncture energy over the range of the sizes of models tested.

When a cylindrical cask impacts on a flat-ended square-edged punch with sufficient impact energy to puncture the jacket, the fracture that occurs after the critical penetration has been attained starts at two points along the long axis of the cask and grows until the fracture lines meet if enough energy is available. Several stages of this process are illustrated in Figure 15. Therefore, if the impact energy available is only slightly in excess of that required to attain the critical penetration, two fracture lines of equal length will appear when a cylindrical cask impacts in such a manner that the line of action of the punch passes through the center of gravity of the cask and the long axis of the cask is perpendicular to the long axis of the punch. Thus, in evaluating the results of test drops with cylindrical models, the results of a test were disregarded where only one fracture line appeared with a length in excess of about 10 per cent of the circumference of the punch used in the test. If two fracture lines with approximately equal lengths appeared, a state of puncture was assumed.

V. RESULTS OF CYLINDRICAL MODEL TESTS

The tests of cylindrical models were made with models whose diameters varied from approximately 4 to 7 inches. Punch sizes of 0.4 inch, 0.5 inch, and 0.6 inch were used. The shielding material in the model was chemical lead and the jackets were fabricated from

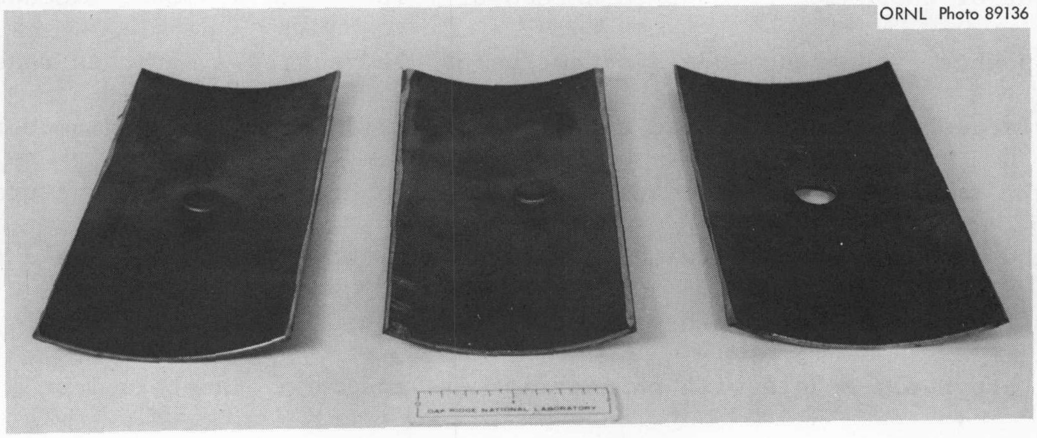

Figure 15. Jackets of cylindrical models tested at several impact energies to show different stages of fracture.

0.075-inch-thick hot-rolled carbon steel, ASTM A245. The results of the tests are given in Table VI and illustrated in Figure 16.

The range of the sizes of the model casks that were tested was influenced by the weight of the large-diameter models, the alignment that could be maintained between the model and the punch at impact, and the minimum size cask whose jacket could be penetrated entirely. The weight of those models much in excess of 7 inches in diameter exceeds 100 pounds, and these models cannot be handled easily. For this reason, the largest model tested had a diameter of 7.18 inches. The diameter of the smallest cask model tested was 4.19 inches. Complete puncture of the jackets of models with diameters less than 4.19 inches could not be effected with the punch sizes and jacket thicknesses used in this test program. Models with thinner jackets and with diameters less than those used could have been tested but were not because it became progressively more difficult to maintain the proper cask-to-punch alignment as the diameters of the cask models were decreased.

The ASTM A245 hot-rolled carbon steel was selected as the jacket material for the cylindrical models because of its availability in thicknesses that could be completely punctured with the size punches used in the test program. The use of a jacket material with an ultimate tensile strength much larger than that of the material used would have required the use of thinner materials, smaller punch diameters, or a reduction in the range of model diameters that were tested.

TABLE VI

RESULTS OF CYLINDRICAL MODEL TESTS

Model Diameter[a] (in.)	Punch Diameter (in.)	Minimum Puncture Energy (in.-lb.)	Maximum No-Puncture Energy (in.-lb.)	Incipient Puncture Energy[b] (in.-lb.)	Indentation[c] At Puncture Energy (in.)	Indentation[c] At No-Puncture Energy (in.)
4.19	0.400	909	844	877	0.167	0.161
4.65	0.400	889	847	868	0.175	0.161
5.20	0.400	882	844	863	0.171	0.153
6.16	0.400	859	848	853	0.175	0.154
4.19	0.500	1232	1194	1213	0.195	0.178
4.66	0.500	1243	1160	1202	0.192	0.158
5.15	0.500	1250	1146	1198	0.175	0.160
6.17	0.500	1246	1117	1181	0.181	0.161
6.65	0.500	1260	1086	1173	0.183	0.155
7.18	0.500	1192	1140	1166	0.192	0.166
4.65	0.600	1494	1470	1482	0.183	0.187
5.22	0.600	1590	1354	1472	0.183	0.154
6.65	0.600	1460	1442	1451	0.181	0.171
6.9	0.600	1456	1433	1444	0.179	0.172

[a]The jacket material for all the tests was 0.075-inch-thick hot-rolled carbon steel, ASTM A245, with an ultimate strength of 51,300 p.s.i.

[b]The incipient puncture energy = $\frac{\text{minimum puncture energy + maximum no-puncutre energy}}{2}$.

[c]The indentation of the cylindrical jacket was measured radially from the undeformed surface.