A NEW APPROACH TO PUNCTURE RESISTANCE OF SHIPPING CASKS

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SUMMARY

A new approach has been devised in this work, to deal with the problem of finding puncture resistance of lead shielded shipping casks. This work gives new formats in design of the casks with which the outer shell thickness of the lead shielded shipping cask can be provided much reliably than what used to be with the conventional empirical equation design procedure. The approach will be more realistic to model the hypothetical accident sequences of puncture and involvement in fire of the shipping casks and can be a useful tool in the hands of cask designers trying to show the compliance of the cask to the regulations without having to go for full scale testing.

INTRODUCTION

Drop of the cask from 1m height on a punch, kept on an unyielding surface is the crucial test, that determines the thickness of the outer shell in case of lead shielded casks. This drop test is followed by a thermal test in which the cask is subjected to 800°C fire. Pressurisation of the space between inner and outer shells in the fire test may open a crack generated in the drop test. During thermal test, molten lead between inner and outer shell can come out of the cask, through the crack generated in outer shell, resulting in loss of radiation shielding. Compliance of the cask design to the stipulated regulations can be shown by full scale testing, which may call for a number of tests. For larger casks, it invariably becomes cost prohibitive.

The equations developed for puncture resistance by various researchers, are shown validated with prototype testing, though the tests programs were not general enough. All the work has been targeted to determine the puncture resistance relationships which account for resistance to total puncture of the steel shell on impact in one go. In most situations, the outer shell may not get fully penetrated but may get partially damaged. Little information can be derived as to what happens if the damaged cask, after 1m drop on punch, was to get involved in a fire. If the damage to the cask shell is not large enough to permit molten lead to come out during thermal test, then the cask can still said to be complying with the regulations. There can be situations in which the pressure retaining capacity of the cask outer shell may get reduced due to localised reduction in thickness of the shell. Even a crack produced in the cask shell can open up due to rise in pressure effected by molten lead, during thermal test. These aspects pose limitations on the equations which are being used for deciding upon the cask shell thickness. So there is a need for the new approach based on damage consideration. This work is an attempt to develop a methodology to attack the problem of finding puncture resistance of lead shielded cask shell in 1m drop on punch, keeping in view the thermal test which follows the puncture test.

BACKGROUND

Typically, the analytical methods involve development of correlation based upon extensive laboratory-scale or field-scale experiments. These correlation may be expressed as a normalised incipient puncture energy versus a dimensionless design parameter such as shell thickness divided by punch diameter. A summary of available experimental puncture data at low velocity was prepared by Larder and Arthur in a research program conducted for U.S. Nuclear Regulatory Commission.

A promising method of demonstrating the puncture resistance of steel shell without having to do costly destructive testing is by testing scale models. Several model puncture tests have been carried out by H. C. Clarke and are reported by Shappert. This work has indicated that puncture resistance is a scaleable quantity. Spaller et. al. also conducted large number of laboratory as well as field scale impact studies in an attempt to develop puncture resistance relationship for showing compliance with the regulations and concluded that puncture resistance of steel plates backed by lead is a scaleable quantity.

Even though the equations developed for puncture resistance are shown validated with the prototype testing, the test programs were not general enough. The linear scaling method used with the thickness of the shell being taken as the characteristic length that determined the scale factor resulted in an equation that did not consistently predict data obtained from tests with cylindrical cask prototype. It appears that the thickness of the shell and possibly the material also may have to be varied to produce general equation for puncture resistance.

All the work stated in literature has been targeted to determine the puncture resistance relationship, which account for the total puncture of the steel shell on impact on punch in one go. The relations developed, or being used currently give upper bound margin on the incipient puncture energy, on very conservative side, that a particular thickness of steel shell can sustain, after impacted on the 150 mm diameter punch. No information can be derived as to what happens if the damaged cask gets involved in a fire. The damage to the steel shell due to impact of a heavy cask on the punch will be considerably high, even though it may not puncture.

INVESTIGATION APPROACH

The suggested procedure to find the puncture resistance of the shipping cask is indicated in the flow chart. (Chart No. 1) It consists of carrying out dimensional analysis followed by experimental analysis, for evaluation of puncture resistance and the damage characteristic parameters namely, 1. Pressure Retaining Capacity and 2. Leak Tightness of the cask shell. Dimensional analysis provides the basis for the equation and also simplifies the experiments by reducing the number of parameters to study. The experimental analysis is used to study the puncture resistance phenomenon combined with the thermal test.

Dimensional analysis is carried out to derive an expression for estimating the incipient puncture energy required for a specific shell thickness. Pressure retaining capacity parameter (P/P_d) represents the ratio of reduced pressure retaining capacity, after the impact on punch with energy less than the incipient puncture energy vs. original pressure retaining capacity of the cask shell. Similar to the pressure retaining capacity the cask should not loose its leak tightness. Leak tightness retaining capacity is the parameter which represents the reduced leak tightness with respect to the cask design parameter.

The above two damage parameters help in modelling the combined behaviour of the cask in the punch test followed by a thermal test. This approach is selected basically, to study the effect of punch test, on the pressure retaining capacity and on the leak tightness. For a lead shielded cask the two parameters together are important rather than only resistance to puncture. The work is focused more or less to obtain a puncture resistance relationship and design curves which ensure that the cask will retain the required leak tightness as well as pressure capacity even after punch test followed by thermal test. These relations and design curves can be used to show the compliance of the cask design to the IAEA safety regulations.

PARAMETERS AFFECTING RESISTANCE TO PUNCTURE

The following are the parameters which affect puncture resistance :

a. Material of the outer shell	d. Geometry of the cask	h. Strain rate
b. Backing material	f. Drop energy (Weight of the cask)	i. Temperature.
c. Geometry of the punch	g. Relative hardness of punch and shell	e. Punch Material

The material of the outer shell plays an important role as the resistance to puncture depends upon the yield strength, ultimate strength, toughness and percentage elongation. To have maximum impact energy absorbed without damage, ductile materials such as SS 304 are used. Lead, which is the most common shielding material, is selected for the investigation here. In lead shielded casks, the mode of failure is annular shear fracture in the plates near the circumference of the punch. In no case does the fracture propagates to the rear surface of the lead.

DIMENSIONAL ANALYSIS

Out of the parameters listed above, the parameters selected here for dimensional analysis to establish the equation for finding incipient puncture energy are -

I. Geometrical -

t - thickness of the shell. d - diameter of punch. H-height of impact.
r - corner radius of the punch. D - diameter of the specimen shell.

II. Constitutive -

σ_{ys} - yield strength of shell material σ_{us}- ultimate strength of shell material.

σ_{yp} - yield strength of lead. σ_{up}- ultimate strength of lead.

III. Energy -

W- Cask weight. E_P- W*H - Drop energy/Puncture energy.

Velocity of impact as a parameter is not included since, the energy of impact is important than velocity of impact, which is again function of height of drop.

Derivation of Π-Terms :

By inspection we can write following non-dimensional Π-Terms ...

$\Pi_1 = t/d$; $\Pi_2 = D/d$; $\Pi_3 = r/d$; $\Pi_4 = \sigma_{ys}/\sigma_{us}$; $\Pi_5 = \sigma_{yp}/\sigma_{us}$; $\Pi_6 = \sigma_{up}/\sigma_{us}$;

The variables which remain to form the further Π- Terms are - W,H,d,σ_{yp} & E.

Applying Buckingham's Π- theorem, we get three additional Π- Terms ...

$\Pi_7 = H/d$; $\Pi_8 = \sigma_{us}.d^2/W$; $\Pi_9 = E/W.d$.

If we divide Π_9 by Π_8 we get additional Π- Term ...

$\Pi_{10} = (W/\sigma_{us}.d^2) * (E/W.d)$ or $\Pi_{10} = (E/\sigma_{us}.d^3)$

Hence, $(E/\sigma_{us}.d^3) = f(\Pi_1, \Pi_2, \Pi_3, \ldots, \Pi_9)$

or, $(E/\sigma_{us}.d^3) = f(t/D, D/d, r/D, \sigma_{ys}/\sigma_{us}, \sigma_{yp}/\sigma_{us}, \sigma_{up}/\sigma_{us}, \ldots)$ ...... **(1)**

This is a general relationship. Particular relationship is to be found out by experiments and by plotting the respective non-dimensional energy **($\bar{E} = E/\sigma_{us}.d^3$)**

Analytical Treatment :

Energy required to puncture a outer shell can be expressed as - $E = E_{st} + E_{pb}$ ...... **(2)**

where, E_{st} - component of energy absorbed by steel shell.

E_{pb} - component of energy absorbed by lead backing.

Also, the energy absorbed in steel shell can be written as - $E_{st} = E_{shear} + E_{global}$ ...... **(3)**

where, E_{shear} - energy absorbed in shearing of shell.

E_{global} - energy absorbed in global deformation of shell.

Shear stresses induced due to load applied on shell by a punch of diameter d -

$\tau = W/\pi dt$ ...... **(4)**

$\tau_s = (k\sigma_{ys}/2)$ .... k- constant (between 1 to 2)

Therefore, energy required for shearing ,

$E_{shear} = (1/2).W.t = (1/2).(\tau\pi dt).t$

$= (1/4).(k\sigma_{ys}.\pi dt^2)$ ...... **(5)**

E_{global}, given by Jones N. et. al. -

$(E_{global} / k\sigma_{ys}.d^3) = A\,(D/d)^{\alpha}\,.\,(t/d)^{\beta}$

therefore, $E_{global} = k\sigma_{ys}.dt^3\,.\,A\,(D/d)^{\alpha}\,.\,(t/d)^{\beta}$ ...... **(6)**

Thus from equation 3,5 and 6,

$E_{st} = (1/4).(k\sigma_{ys}.\pi dt^2) + k\sigma_{ys}.dt^3\,.\,A\,(D/d)^{\alpha}\,.\,(t/d)^{\beta}$

or, $(E_{st} / \sigma_{us}.d^3) = (k\sigma_{ys}/\sigma_{us})\,.\,[(\pi/4)\,(t/d)^2 + A\,(D/d)^{\alpha}\,.\,(t/d)^{\beta}]$ ...... **(7)**

To find E_{pb},

let us assume - $(E_{pb}/k.\sigma_{yp}.d^3) = B\,(D/d)^{\gamma}$

therefore, $E_{pb} = k.\sigma_{up}.d^3\,.\,B\,(D/d)^{\gamma}$ ...... **(8)**

Total puncture energy -

From equation 2,7 and 8,

$(E/\sigma_{us}.d^3) = (k\sigma_{ys}/\sigma_{us})\,.\,[(\pi/4)\,(t/d)^2 + A\,(D/d)^{\alpha}\,.\,(t/d)^{\beta}] + (k.\sigma_{yp}/\sigma_{us}).B.(D/d)^{\gamma}$ ...... **(9)**

Above equation can be considered as the empirical equation with non-dimensional terms -

1. $\overline{E} = (E/\sigma_{us}.d^3)$ ..... the incipient impact energy,
2. σ_{ys}/σ_{us} ; 3. σ_{yp}/σ_{us} ; 4. t/d ; and 5. D/d.

The constants α, β, γ and A, B can be found out through experiments, once the values of E, σ_{ys}, σ_{us} , σ_{yp}, d, t, & D are known.

EXPERIMENTAL ANALYSIS

The cask shell thickness designed using empirical equation (9) assures that the steel shell will not get penetrated, in punch test. But because of impact, shear stresses are induced in the shell at the impact location and area surrounding the circumference of the punch. The impact causes large local deformation on the cask shell and reducing the thickness of the shell. This causes reduction in pressure retaining capacity (P/P_d) of the cask shell. Hence in the experimental analysis, we shall evaluate the pressure retaining capacity of the test specimens which has undergone impact test with impact energy less than incipient puncture energy and followed by thermal test. The pressure retaining capacity of undamaged cask (P_d) and for damaged cask (P) is evaluated by carrying out hydrotesting. The leak tightness of the test specimens will be evaluated after each punch test and during hydrotesting.

Test Procedure :

Initially few drops over lead backed steel plates with different punches need to be carried out to know approximately the height of drop for the penetration of a specific shell thickness with specified size of punch. The initial height of drops in subsequent experiments is based on these preliminary tests.

a. For determining puncture resistance against complete penetration : The instrumented test specimen (Fig.1) and test punch (Fig.2) are placed in the drop test facility. The punch is fixed to the ram with special fixture. The test specimen is held rigidly over the base plate of the test facility. The ram along with punch is hoisted to a specified height. An accelerometer is mounted on the punch holder for measurement of deceleration of ram/punch during impact. (Fig.3) The ram is dropped from the specified height onto the test specimen. The accelerometer signal is acquired and stored in computer for further analysis. The deformed geometry of the punch and the lead backed plate of test specimen are noted down. The exercise is repeated for various test specimens having different shell thickness, impacted with different sizes of punches.

b. For determination of the damage characteristics, the pressure retaining capacity and the leak tightness : The same test specimens are used for carrying these tests. This time around each test specimen undergoes 2 to 3 drops with same size of punches dropped from different heights. Each time the height of drop is maintained just below the height of drop required for complete penetration for the concerned shell and punch combination. The height of drop required for complete penetration is estimated based on the earlier drops mentioned in para, a. In these tests also the accelerometer output is recorded. After the drop test is carried out the lead inside the test specimen is taken out by heating the test specimen at a temperature of about 400°C. Helium leak testing is carried out on each test specimen to know if any of the indented locations are punctured. The leak rate at the indented locations are noted. Hydro testing of the test specimens is carried out by applying pressure inside. Pressure is applied inside test specimen until any of the damaged location. breaks open. Pressure corresponding to breakage is noted. Disk welding is applied at the opened location on the test specimen and again hydro test is repeated till the next damaged test location breaks out. This exercise is repeated for combination of different sizes of punches and test specimens having shells of various thicknesses. Some of the test specimens may be hydro tested at elevated temperature, to study the effect of temperature.

Data Reduction : The force vs. displacement curve for the punch/plate drop can be generated once the accelerometer data is known. Thus in case of the drops mentioned in para, a, the exact value of penetration energy can be calculated by integrating the area under the force vs. displacement curve unto the point where the maximum value of force occurs. This point can be considered as the point where penetration occurred.

The damage characteristics are formulated in two non dimensional parameters as -

Ratio of pressure capacity of specimen after damage to the pressure capacity of the test specimens before damage: The pressure capacity of undamaged test specimens is found out by carrying hydro test on some of the test specimens. The pressure capacity of the damaged test specimens after drop test and thermal test is known for various heights of drops (various impact energies), for the specified combination of punch and plate sizes after the tests mentioned in para, b, are carried out. The ratio of the pressure retaining capacity can be plotted as a function of ratio of applied energy to penetration energy for various d/t ratios.(Fig.4a) The pressure retaining capacity can be thus represented on the graph of non-dimensional puncture energy vs. t/d.(Fig.4b) Thus the relation between these parameters can be obtained, which can be used for determination of shell thickness which will maintain its pressure retaining capacity until a specified limit of pressure, after a specified drop test and followed by thermal test.

Leak tightness: The ratio of the leak rate at the test location where the test specimen is impacted with energy less than the incipient puncture energy to the leak rate at the test location where the test specimen is impacted with energy equal to incipient puncture energy, is the leak tightness parameter. This parameter indicates the intensity of the drop test. The leak tightness parameter Vs. ratio of applied energy to penetration energy can be plotted for various d/t ratios.(Fig.5a) Consequently the leak tightness parameter can be represented over the graph of non-dimensional puncture energy vs. t/d.(Fig.5b) Thus in this case also a relation can be obtained, which can be used for determination of thickness of the lead shielded cask shell, which will remain leak tight after a specified drop test and followed by thermal test.

CONCLUDING REMARKS

The empirical equation developed here takes into account the energy absorbed by lead in case of punch test of lead shielded cask. It is much more realistic and estimates the puncture resistance of steel shell more accurately than any of the empirical equations available, for determining the shell thickness. An altogether new approach has been devised, which takes into account both the punch test and the thermal test for estimating the shell thickness of the lead shielded casks. The damage characteristics evolved in this work - the pressure retaining capacity and the leak tightness parameter, closely model the combined phenomenon of the drop on punch and the thermal test. Finally it can be concluded that the puncture resistance and the damage characteristics are scaleable quantities and a simple experimental study as presented in this work can be conducted to generate a reliable tool for the safe design of the shipping casks using lead as shielding material.

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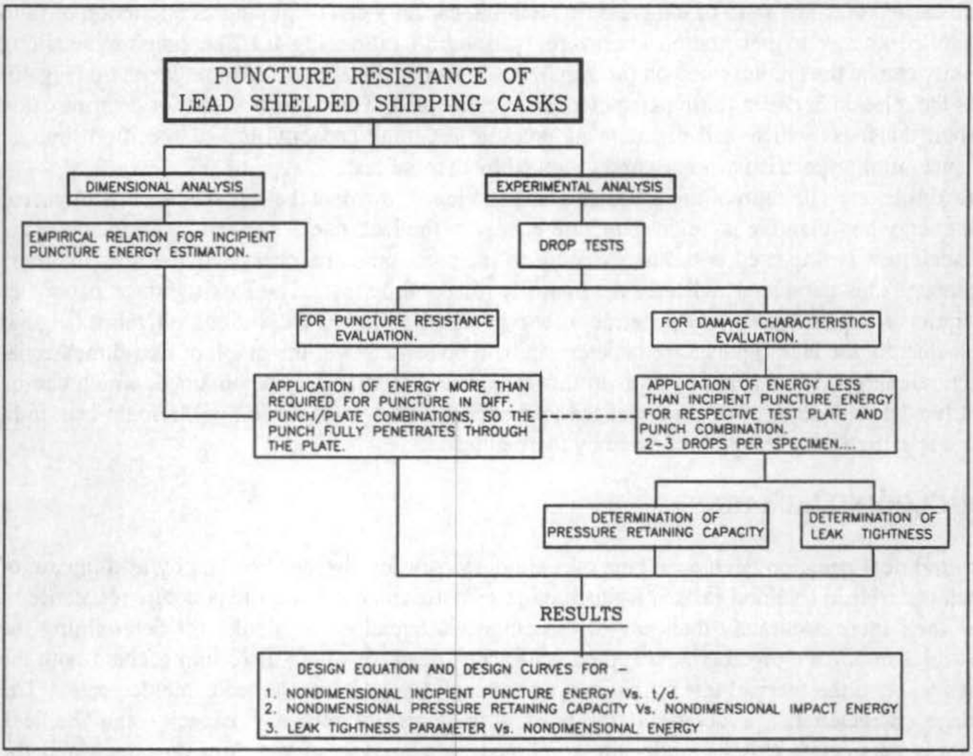

CHART 1

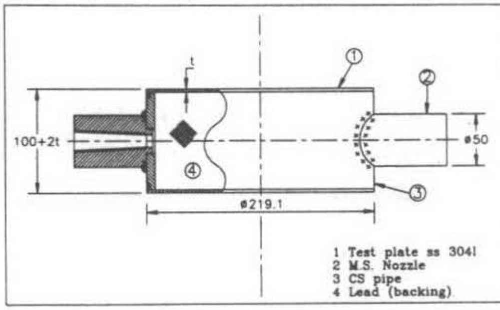

FIG.1 TEST SPECIMEN

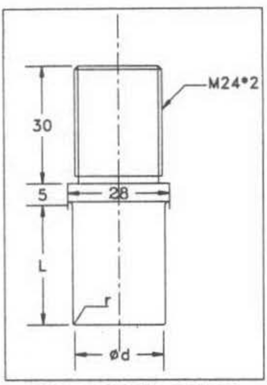

FIG.2 TYPICAL PUNCH

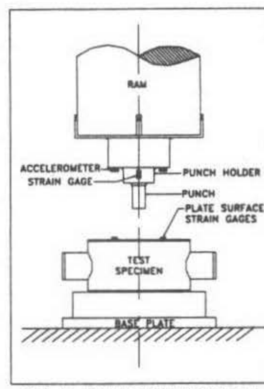

FIG.3 INSTRUMENTATION

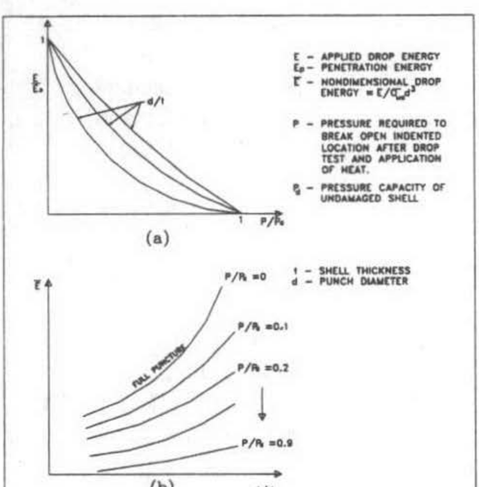

FIG.4 REPRESENTATION OF DAMAGE CHARACTERISTICS
1.NONDIMENSIONAL PRESSURE RETAINING CAPACITY

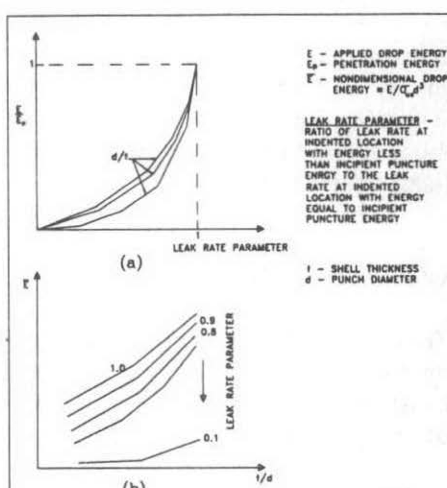

FIG.5 REPRESENTATION OF DAMAGE CHARACTERISTICS
2. LEAK TIGHTNESS PARAMETER