Candidate Materials to Prevent Brittle Fracture – (186)

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ABSTRACT

For heavy transport or dual purpose casks, selecting the appropriate materials for the body is a key decision. To get a Type B(U) approval, it is necessary to demonstrate that the mechanical strength of the material is good enough at temperature as low as –40°C so as to prevent the cask from any risk of brittle fracture in regulatory accident conditions. Different methods are available to provide such a demonstration and can lead to different choices.

It should be noted also that the material compositions given by national or international standards display relatively wide tolerances and therefore are not necessarily sufficient to guarantee a required toughness. It is therefore necessary to specify to the fabricator the minimum value for toughness, and to verify it.

This paper gives an overview of the different methods and materials that are used in several countries. Although the safety is strongly linked to the choice of the material, it is shown that many other parameters are important, such as the design, the fabrication process (multi layer, cast or forged body), the welding material and process, the ability to detect flaws, and the measured and/or calculated stress level, including stress concentration, in particular when bolts are used.

The paper will show that relying exclusively on high toughness at low temperature does not necessarily deliver the maximum safety as compared with other choices. It follows that differences in approaches to licensing by different competent authorities may bias the choice of material depending on the country of application, even though B(U) licenses are meant to guarantee unilaterally a uniform minimum level of safety.

INTRODUCTION

In order to be transported, spent fuel assemblies as well as high level wastes require a strong gamma shielding . For this reason heavy casks have to be considered and large quantities of metal are necessary. Thus, in most cases, gamma shielding is provided by the containment vessel which is generally made of carbon steel, stainless steel, or ductile cast iron. Typical thickness for such vessels is around 250 mm and the total mass exceeds 50 tonnes . For cask vendors, it is therefore a major concern to select the appropriate materials that combines safety assurance and cost effectiveness.

When a type B(U) approval is needed, then the cask must survive severe accident conditions even when the ambient temperature is as low as –40°C. It is thus necessary to demonstrate that the mechanical strength of the material is good enough so as to prevent the cask from any risk of brittle fracture. The different methods currently available to provide such a demonstration are summarized hereafter.

Brittle fracture assessment methods

Three methods are used today.

1st method

Use of materials which remain ductile and tough throughout the required service temperature range, including down to –40°C.

This is the easy way from a licensing point of view, since in this case, no specific assessment is necessary. The safety relies only on the ductility of the material, and does not rely on limiting stress levels, flaw sizes and fracture toughness.

Typically, this method leads to use austenitic stainless steel, such as ASTM 304 L , which are known to remain ductile at temperature much lower than –40°C. However , due to the high price and low thermal conductivity of such materials, multilayer designs are usually preferred : lead is encased in a double wall containment vessel made of stainless steel. Thus the stainless steel provides the mechanical strength while most of the gamma shielding is provided by the lead or, in some cases, depleted uranium. For large thicknesses,the behaviour of lead in drop test conditions has to be demonstrated against the risk of settling. In addition, lead behaviour under regulatory fire conditions also has to be studied because of its low melting point.

2nd method

Evaluation of ferritic steels using nil-ductility transition temperature (NDTT) measurements correlated to fracture resistance.

The basis for determining the NDTT is the highest temperature at which brittle fracture does not run in the parent material from a brittle weld bead in the standard drop weight test. This can be thought of as the minimum of the transition temperature curve either for propagation/crack arrest or for dynamic initiation from small initial cracks.

Typical example of use of the NDTT approach is described in the US Nuclear Regulatory Commission (US NRC) regulatory guides. For thick wall containment vessel high nickel carbon steel such as ASTM A 508 gr 4N cl 3 can be used.

This second method has also the benefit of not relying on limiting stress levels or flaw sizes. Thus the licensing process remains quite smooth and the Non Destructive Examination (NDE) in fabrication less demanding.

3rd method

Assesment of fracture resistance based on design evaluation using fracture mechanics.

In this case, the designer has the latitude of material selection together with the ability to determine stresses and NDE requirements such that fracture initiation and brittle fracture are precluded.

The mechanical property that characterizes the material resistance to crack initiation from pre-existing crack-like defects is its initiation fracture toughness. According to the stress level and stress-strain conditions, several criteria are used :

- for linear-elastic stress-strain conditions, the stress intensity factor (K_I),
- for elastic-plastic stress-strain conditions, the energy line contour integral J_I, or the critical level of the crack tip opening displacement (CTOD) δ.

With this third method, the licensing process is quite tougher because there are more parameters involved in the demonstration :

- calculation or measurement of the stress level in the most stressed area of the package,
- maximum flaw size guarantied by the NDE during fabrication.

This method has been widely used in Europe and especially for those cask vendors having designs using ASTM A 350 LF 5 or Ductile Cast Iron.

CURRENT PRACTICES WORLDWIDE

As can be seen hereabove, according to the material selected, there is little choice concerning the method that can be used. The tougher the material, the easier the licensing. However, the tougher material is also the more expensive. The table below gives an overview of the situation worldwide concerning the different materials used.

USA*	EUROPE	JAPAN
ASTM 304 L Method 1 ASTM A 350 LF 3 Method 2	ASTM A 350 LF5 Method 3 Ductile Cast Iron Method 3 A 508 gr 4N cl3 Method 2	ASTM A 350 LF5 Method 3

* In the US the lowest regulatory ambient temperature is –29°C

The most commonly used materials being listed above, one can raise the following question :
are the designs made of the toughest materials, the safest ?

The answer is not so immediate and we try to illustrate this as follows.

First one has to remember that the safety relies on many parameters. Among these parameters we can quote the following.

Chemical composition of the material

The material compositions given by national or international standards display relatively large tolerances and therefore are not sufficient to guaranty a required toughness. It is therefore necessary to specify to the fabricator the needed value for toughness and to verify it.

Machining

Drilling and threading holes for bolting or inserting neutron shielding material will lead to stress concentration in the area. This has to be taken into account when calculating the stresses in accident conditions of transport.

Casting or welding

Manufacturing requires a good qualification to ensure the adequate mechanical properties uniformly and that the flaws remain within specification.

Stress calculation or measurement

Even in case of measurement, it is necessary to calculate the stresses in the cask to find the location where the maximum stresses are seen. Those calculations require a good knowledge of the deceleration (g loads) expected in accident conditions of transport. This analysis must take into account all local stresses and in particular those generated in the vicinity of the bolts of the closure and/or of the trunnnions.

Design

The choices made for the design itself are important too. To illustrate this we propose below several designs for a same need and will see how they compare from a mechanical viewpoint.

GENERIC DESIGN

Let us assume we have to design a cask having a cavity which length is 4000 mm, which usefull cavity diameter is 1000 mm and for which the gamma shielding is equivalent to 250 mm of carbon steel.

Therefore, based on the different characteristics listed in the table below we will define equivalent designs for the different materials.

+ Price -

Material	Density (kg/dm^3)	NDTT (°C)	$S_{y20°C}$ (MPa)	$S_{y100°C}$ (MPa)
304 L	7.9	N/A	190	145
A 508 gr 4N cl3	7.85	- 107°C	485	455
A 350 LF 5	7.85	- 60°C	260	238
Ductile Cast Iron	7.1	N/A	230	220

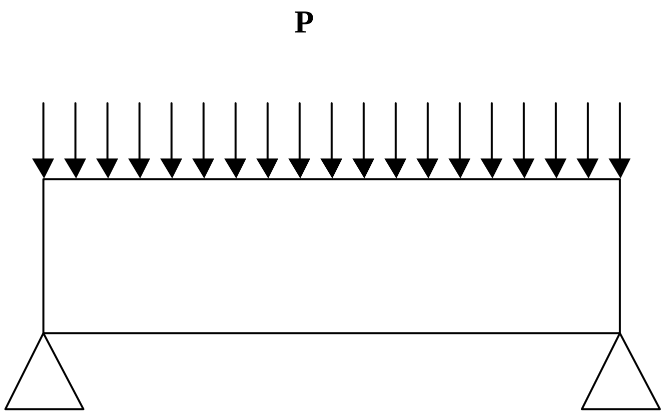
+ Toughness -

The different shells described in the table below have the same gamma shielding capability.

DESIGN	MATERIAL	SHELL THICKNESS (mm)	SHELL INERTIA (mm^4)	MASS (kg)
1	304 L	248	1.97 10^{11}	30 700
2	304L/LEAD/304L	60/80/60	8.50 10^{10}	27 600
3	A 508 gr43 cl3	250	1.99 10^{11}	30 800
4	A 350 LF 5	250	1.99 10^{11}	30 800
5	Ductile cast iron	276	2.35 10^{11}	31 400

We assume that the mass of the content is 8 000 kg, to be added to the mass of the shell to calculate the stresses in the shell in drop test conditions.

For a side drop test, with a 100 g load, we can calculate the maximum bending stress in the shell by using a simple beam model.



The results, for the different designs are summarized in the following table.

DESIGN	TOTAL MASS (kg)	Max bending moment (N.mm)	Max bending stress Sb (MPa)
1	38 700	$1.89\ 10^{10}$	72
2	35 600	$1.75\ 10^{10}$	144
3	38 800	$1.90\ 10^{10}$	72
4	38 800	$1.90\ 10^{10}$	72
5	39 400	$1.93\ 10^{10}$	64

This calculated stresses must be compared to the stress limit allowable for each material (Sa). For steel, the yield stress is widely accepted as a criterion for accidental conditions. For ductile cast iron, it is usually recommended not to exceed half of the yield strength (Sa=1/2Sy).

We can estimate the safety margin as being the ratio Sa/Sb. For the two temperatures (20°C and 100°C) the safety margins are summarized in the table below.

DESIGN	MATERIAL	Sb (Mpa)	Sa/Sb 20°C	Sa/Sb 100°C
1	304 L	72	2.64	2.01
2	304 L/LEAD/304 L	144	1.32	1.00
3	A 508 gr4N cl3	72	6.74	6.32
4	A 350 LF5	72	3.61	3.31
5	Ductile cast iron	64	1.79	1.72

Thus, the designs made of the material with the highest ductility (stainless steel) as well as the design made of the material with the lowest ductility (Ductile Cast Iron) show a much lower safety margin at 20°C and 100°C than the designs made of the material with the intermediate ductility (carbon steel).

CONCLUSION

COGEMA LOGISTICS carries out yearly approximately three hundred shipments of heavy casks loaded with spent fuel or high level waste. The very large majority of those transports take place with an ambient temperature higher than 0°C. In some cases the ambient temperature is less than 0°C but the heat content of the cask is such that the temperature of the steel shell is much more than 20°C.

For those transports, the basic calculations performed above show that the carbon steel is the material offering the highest safety margins compared to stainless steel or ductile cast iron.

In case of domestic tranportation, it is possible to seek for Type B(M) approval, which makes the licensing process smoother for carbon steel forged body : the use of method 2 can be extended to A 350 LF 5.

As concerns the dual purpose casks, for historical reasons, the different storage regulations often require a Type B(U) approval. For those casks, it is usually easy to demonstrate that for the storage duration (usually 40 to 50 years) the body of the cask remains at temperature above 0°C , due to internal heat load, even with an ambient temperature of –40°C. However, because of the interim storage sites unrealistic impositions, it is not possible to take advantage of this.

The consequence is that an almost nil probability event (i.e : uniform –40°C in the cask) may lead to selecting materials that offer lower safety margins for higher probability events.

Due consideration of probablilities should lead to increased storage site safety by :
- selecting realistic low temperature criteria in case of dual purpose systems,
- accepting a Type B(M) approval that takes into account –40°C as an ambient temperature and the minimum residual heat load at the end of the storage period, all other features being compliant with a Type B(U) approval.