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COMPARISON BETWEEN DIFFERENT PRINCIPLES FOR PACKAGING DESIGNS

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ABSTRACT

Over the past years, the continuous increase of burn-up of the used fuel has resulted in higher constraints for the design of transport or dual purpose casks. In the same time, the competition between cask vendors has put a high pressure on the prices. In this context, the cask designer has to make tricky choices to meet the stringent requirements of his customer and of the competent authority, while maintaining low prices.

Most heavy packages consist of three main components:
- a vessel,
- an internal arrangement,
- a set of shock absorbers.

The shock absorbers are mostly used to guaranty a low level of g load in accident conditions. They also often provide fire insulation.

The internal arrangement is key to the criticality safety (use of neutron poison, mechanical strength to guaranty the geometry), and to the heat transfer.

The vessel has to provide the containment, the shielding and the heat transfer.

The design of each component relies on two major choices:
- the materials,
- the type of assembly.

The materials available have intrinsic characteristics such has mechanical strength, thermal conductivity and shielding capacity. Some materials have very good performances in one domain and very bad performances in other domains. Other materials seem to be good compromises between the different constraints.

High performances can be obtained either by assembling several materials each of them having very good behaviour in one domain, or by assembling fewer materials being good compromises in several domains.

Thus, the cask designer has first to evaluate the performance of each material and its cost. Then, to decide which materials to choose, the cask designer needs to consider not only the performance of each material separately but also how they perform when assembled together.

The paper will focus on the vessel design. It will describe which materials, and which types of assembly are commonly proposed by the casks vendors and how they compare as far as safety and costs are concerned.

INTRODUCTION

Over the past decades, the need to increase the economic performance of the nuclear power plants has driven the increase of burn-up. The quantity of fuel elements used in the power plants has consequently been reduced. Thus the fuel elements discharged from each reactor are nowadays less numerous but with much higher activity and heat load. The cask vendors have been obliged to adapt their products to those new specifications.

We will detail hereafter the different solutions available and how they compare, as far as performance, safety and cost are concerned.

CASK PERFORMANCE

Most heavy packages consist of three main components:

- a vessel,
- an internal arrangement,
- a set of shock absorbers.

The shock absorbers are mostly used to guarantee a low level of g load in accident conditions. They also often provide fire insulation. The characteristics of the fuel have low influence on their designs.

The internal arrangement is key to the criticality safety (use of neutron poison, mechanical strength to guaranty the geometry), and to the heat transfer. Different kind of designs exists but in most cases they are made of an assembly of stainless steel plates or profiles for the mechanical strength, and of aluminium plates or profile for the heat transfer. Criticality control is achieved by use boron either in the stainless steel or in the aluminium.

The vessel has to provide the containment, the shielding and the heat transfer. It is key to the heat transfer performance, which is probably the most challenging aspect of the high burn-up fuels. We will focus our analysis on this component.

MATERIALS USED

Containment always relies on a metallic vessel made of carbon steel, stainless steel or cast iron. In case of use of carbon steel or cast iron, the internal part of the vessel is painted or coated by metallic spray or stainless steel liner.

Gamma shielding is mostly provided by high density metal such as iron, steel, copper, lead, uranium or by concrete. Neutron shielding usually requires additionally the use of hydrogenated material such as resin, polymer or concrete.

Heat transfer will typically be improved by the use of aluminium profiles or copper plates.

For each material listed we indicate below the relative performance as far as mechanical, thermal and shielding capabilities are concerned.

MECHANICAL PERFORMANCE

The table below summarizes the mechanical performance of the different materials listed above. Polymers and resin are not listed since no credit is taken for their mechanical resistance.

Material	Mechanical strength	Ductility at low temperature	Ductility at room temperature
Carbon steel	++	+	+
Stainless steel	++	++	++
Cast iron	+	o	o
Copper	+	++	++
Lead	o	++	++
Uranium*	n/a	n/a	n/a
Concrete	o	o	o
Aluminium	+	++	++

o average + good ++ very good

* Usually no credit taken for the mechanical strength of uranium

THERMAL PERFORMANCE

The table below summarizes the thermal performance of the different materials listed above.

Material	Thermal conductivity	Maximum operating temperature
Carbon steel	+	++
Stainless steel	o	++
Cast iron	+	++
Copper	++	++
Lead	+	+
Uranium	+	++
Concrete	o	o
Aluminium	++	+
Polymer/resin	o	o

o average + good ++ very good

SHIELDING PERFORMANCE

The table below summarizes the shielding performance of the different materials listed above.

Material	Gamma shielding	Neutron shielding
Carbon steel	+	o
Stainless steel	+	o
Cast iron	+	o
Copper	++	o
Lead	++	o
Uranium	++	o
Concrete	o	+
Aluminium	o	o
Polymer/resin	o	++

o average + good ++ very good

None of the material can efficiently fulfil all the required functions. It is therefore necessary to use several materials.

TYPICAL DESIGNS

We briefly describe below the most common designs available for transport and/or storage of spent fuel. They are characterised by the material used as the main gamma shielding.

Concrete designs

Concrete is the cheapest material listed, therefore it is worth investigating this kind of solution to transport and/or store spent fuel. Concrete provides the gamma shielding as well as the neutron shielding. Today, concrete designs are widely used for storage but very few, if any, designs have a transport license.

The main reason for this, is the relatively low specific gravity of concrete compared to metal, which leads to have very bulky designs hardly compatible with transport. Another concern is the very low thermal conductivity and operating temperature, which dramatically limit the heat load of the design.

Concrete designs are therefore the cheapest, but they do not fit the needs to transport high burnup fuel.

As far as safety is concerned, the main challenge is to properly characterize the material and to provide all guaranties for the properties.

Cast iron designs

Cast iron is the cheapest metal available for the containment vessel. It has rather high specific gravity and good thermal properties. Since it is cast, various shapes can be designed (for example fins can be directly obtained, without machining or welding).

Neutron shielding is usually made of polymer rods inserted in holes drilled in the vessel (see figure 1).

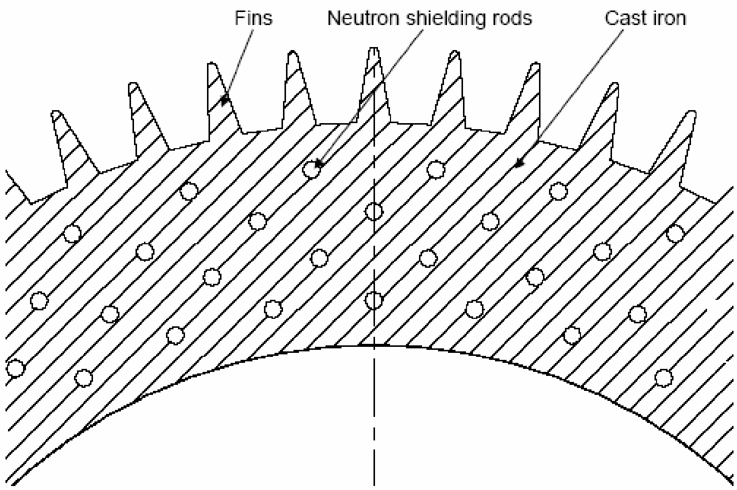


Figure 1

Today, cast iron designs are mostly used in Germany. The performances of those designs are limited by the shielding (specific gravity of iron is less than steel and it is difficult to add large quantities of neutron shielding). From a licensing point of view, there are countries were competent authorities will not issue B(U) approval for cast iron designs, due to the poor ductility of the material at low temperature.

Uranium designs

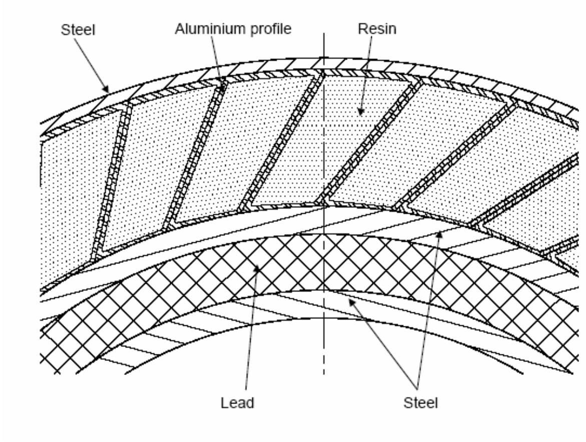
Uranium is a very high density metal which is of interest for its high gamma shielding capacity in a limited volume. Therefore uranium designs are, in theory, well adapted for the transport casks. However metallic uranium is very expensive, and machining requires specific equipments and know-how which are available only in few facilities and for small parts.

Today very few casks fabricated use uranium as a shielding material.

Lead designs

Lead is a cheap material with very high gamma shielding performance. It is usually poured in between two steel shells. Outside this multi-wall shell, mainly two kinds of configurations are used to fix the neutron shielding:

- polymer or resin encased in aluminium profile (see figure 2),
- resin poured in between two steel shells, usually with copper plates heat conductor (see figure 3) crossing the resin,



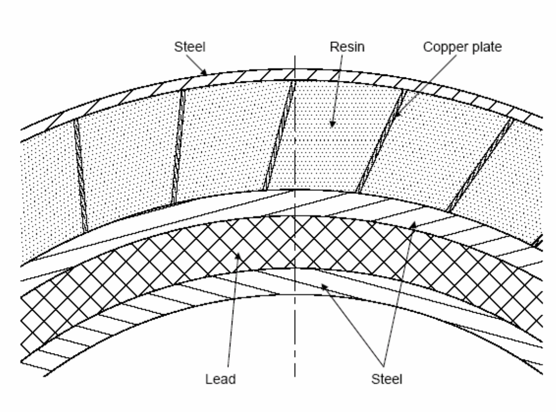


Figure 2 **Figure 3**

Lead designs have been widely used in the past, for designs with low heat load. They are much less used today because of the need for long cask to often use stainless steel with high mechanical strength to avoid the lead slump effect and guaranty the mechanical strength in accident conditions of transport, which increases significantly the price. Another difficulty is to master the gaps between lead and steel shells:

- large gaps decrease the thermal performance and create the risk of loss of shielding,
- narrow gaps generate high stresses in temperature in the steel shell, since the thermal expansion of lead is higher than the one of steel.

To fit the requirements for high burnup fuel, lead designs require the use of expensive materials (such as stainless steel, aluminium, copper,..) and complex assembly techniques which make them rather expensive.

The safety justifications are usually difficult because of many questions related to the gaps and to the behaviour of the lead (expansion, creeping, melting…).

Multi-wall steel designs

A few cask vendors have promoted multi-wall steel designs. In most cases they are made of carbon steel rolled plates (see figure 4). Typical thickness of the plates is two inches which leads to use five or even more plates.

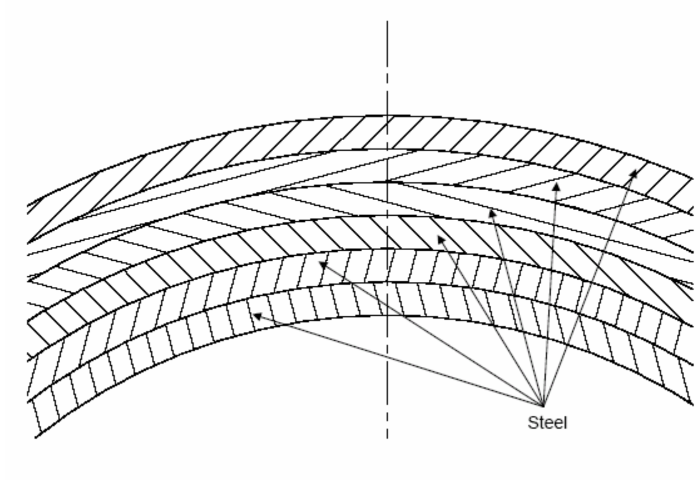


Figure 4

Those designs are easier to justify, as far as mechanical strength is concerned, than the lead designs. They are less complex and less expensive. However, in case of use of too many layers, the thermal performance will be quite low since there are significant increases of temperature across the gaps. Therefore, the challenge for these designs is to master the value of the gaps to avoid the use of too conservative assumptions (large gaps) in the thermal calculation provided to the Competent Authorities.

The assemblies used to fix the neutron shielding are similar to those described for the lead designs.

Forged steel designs

They are usually made of one or two carbon steel forged shells. In case of a two shell design, the containment vessel is made of high ductility carbon steel and the shell is typically two to four inch thick. This containment vessel provides the mechanical strength and is surrounded by a thick forged steel shell, with lower ductility, as the main gamma shielding.

In case of a one shell design, the carbon steel has good ductility at low temperature. The same shell provides the mechanical strength and the main gamma shielding.

Those designs are the easiest to justify from a mechanical point of view. They have the highest thermal performance since there is one or no gap. They are also quite expensive.

The assemblies used to fix the neutron shielding are similar to those described for the lead designs.

PERFORMANCES

From those brief descriptions we can derive a qualitative comparison of the different designs. This comparison includes the mechanical, thermal and shielding performances as well as a cost performance. Cost comparison does not include any consideration for the capacity of the cask or the heat load or fuel data of the payload, it should rather be considered as a price per ton of cask indicator.

Design	Mechanical performance	Thermal performance	Shielding performance	Cost performance
Concrete	o	o	o	++
Cast iron	+	++	+	+
Uranium	+	+	++	n/a
Lead	+	+	++	o
Multi-wall	+	o	++	+
Forged steel	++	++	++	o

o average + good ++ very good

CONCLUSIONS

The comparison made above confirms that the most performing designs are also the most expensive. Cost comparison does not include any consideration for the capacity of the cask or the heat load or fuel data of the payload, it should rather be considered as a price per ton of cask indicator.

The economic performance is most of the time the driving criterion to choose between different solutions.

To make the more performing designs attractive, it is therefore necessary to take into consideration savings that can be made in operations by:

- reduced number of transports (high capacity of the cask),
- reduced number of storage casks (high capacity of the cask),
- possibility to load high burn-up fuels, short cooled,
- easy re-licensing,
- possibility to get approvals in several countries,
- low costs of maintenance,
- …

As the consequence, the choice of a given technology will depend on a global analysis, which will take into account not only the cost to buy but also the cost to operate. The requirements of the competent authorities are also part of the decision making.

