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Development of Innovative Solutions for High Performance Impact Limiters on Transport Casks

KALCK Charlotte
AREVA TN International

NEFFATI Amine
AREVA TN International

ISSARD Hervé
AREVA TN International

Abstract

In reference to IAEA safety recommendations, regulations demand that transportation casks resist to acceleration effects occurring in conditions of transports, without the reduction of the closure system efficiency. The integrity of the whole package must be maintained without giving rise to a significant release of radioactivity. One of the tests is 9m drop test of the package onto an unyielding surface. Impact limiters are a key safety component of the casks allowing to meet the integrity requirement. Their function is to absorb drop energy and limit the g-load, in order to ensure structural integrity.

Up to now, the wood is the main shock absorber material, equipping the majority of heavy transportation or dual-purpose casks.

AREVA TN with its more than 50 years of expertise in cask, design, license, manufacturing and operations has an extensive knowledge of this material.

Data base on wood performance is quite significant as many industrials use this material. Wood presents a lot of advantages especially with its very high specific energy absorption, and considering its light weight.

The industry is facing challenges to deal with the increasing constraints required by authorities and several solutions could be adequate alternatives without being influenced by environmental parameters such as humidity and temperature.

To continue improve the safety performance and also economic performance of the casks, AREVA TN evaluated these different alternatives.

Other efficient shock absorber materials are assessed and developed by AREVA TN. As an example, Honeycomb is an efficient technology quite well known in industry. This solution shows low dispersion with temperature when structural components are assembled by welding.

Among other solutions, polymer foams show interesting mechanical features, with low dispersion at ambient temperature and influenced by moisture and temperature. Alveolar metallic solutions with high energy absorption capacity is also another alternative which can be “tailor-made” manufactured to integrate the regulatory requirements and the specific needs of our customers without being sensitive to environment effects.

Research and development activities of AREVA TN on this critical component are focusing on the development of efficient solutions for energy absorption.

This paper will present a description of the evaluation and performance results performed to improve performance and provide efficient solutions to customers.

Introduction

Transportation casks of radioactive materials must comply with regulatory safety requirements defined in TS-R-1. Regulations define hypothetical accident conditions as well as normal conditions of transport.
Accident conditions are the following:

- 9 meters freefall onto an unyielding surface;
- 1 meter fall onto a pointed steel rod;
- Direct exposure to fire generating an average ambient temperature of 800°C for 30 minutes;
- Immersion in water at a depth of 200 meters.

After all those tests, casks must remain sealed and shielded, and must be able to remove the heat released by the radioactive content. In other words, the casks must remain sub-critical.

Shock absorbers, essential components for safety, are placed around and on both sides of casks to protect the contents by absorbing the kinetic energy of the cask stored during a drop and then limit deceleration on the contents. The diversity of international customers and thus the variety of nuclear authority requirements has led AREVA TN to develop and propose a large range of solutions for shock absorbers to satisfy customer needs.
Considering the strict regulations, shock absorbers requirements are also very stringent. Those impact limiters shall have a high specific energy absorption capacity. The influence of temperature and humidity on the properties shall be limited. And the cost must be limited.
Amongst other significant developments, AREVA TN has been working on the development of new shock absorber materials. AREVA TN conducts many research programs with academic partners and with suppliers.

AREVA TN is a leader in design and manufacturing of casks for storage and transportation of nuclear materials. AREVA TN has more than 50 years expertise in design of casks and of impact limiters.

This paper outlines a short and quick overview of few different shock absorber materials used in AREVA TN casks to meet customer needs including balsa and oak wood and welded honeycomb. Their features, benefits and limits are introduced. AREVA TN is also working on two recent innovative solutions for impact limiters for casks. These new technologies, carbon foam and metallic foam, and their advantages are also discussed.

Wood

AREVA TN uses several wood species in its casks. This study focuses on only two species, balsa wood and oak wood, which are the most frequently used by AREVA TN casks for their goods shock absorbing properties.

Test conditions

For each type of wood used in AREVA TN casks, clear-grained large blocks without knots and splits were selected. Cylindrical samples were selected to avoid structural and geometrical effects, the ratio value between the length and the diameter was fixed to 1. This ratio enabled the observation of large strains in the samples. A typical wood specimen was 40 mm in diameter and height. To carry out the compressive crushing characteristics of the wood, test specimens inserted into an unyielding steel pipe to maintain high constraint. These compressive tests were conducted with a 250 kN testing machine, in quasi-static conditions at a rate of 1 mm/min. The compressive behavior of the wood species was studied according to the temperature and the crushing direction (parallel 0° and perpendicular 90° to the fiber). For each group of tests, 25 samples have been tested. All compressive curves were represented by the mean curve on each figure. The test matrix is shown in Table 1.

Table 1 Test Matrix for wood specimens

Wood Species	Fiber direction	Temperature (°C)	Density (kg/m^3)
Oak	0°	- 40°C	700
		20°C	
		140°C	
Balsa		- 40°C	300
		20°C	
		140°C	
Oak	0°	20°C	650
	90°		
Balsa	0°		200
	90°		

Figure 1 : Wood specimen tested

The tested temperatures here are compliant with the AIEA requirements for the minimum and the maximum temperatures which could be encountered in an impact limiter of a type B cask (-40°C and 140°C).

Test results

Figures 2 and 3 show stress–strain curves. Wood properties are strongly dependant on the temperature of the test. This trend is similar for all species in different ranges of impact. Globally, the compressive strength of the wood at -40°C increased and the strength of the wood at 140°C decreased compared with the strength at room temperature in the direction parallel to fiber [2].

Figures 4 and 5 show that compressive strength strongly decreased with the fiber direction. The ratio between crushing parallel to the fiber and perpendicular to the fiber could be up to 1:5. Wood is a cellular and porous material with a pronounced anisotropy. The geometry of wood cells is elongated and preferentially oriented in the longitudinal direction, as a honeycomb structure. Thus, the mechanical properties are stronger in this preferential direction.

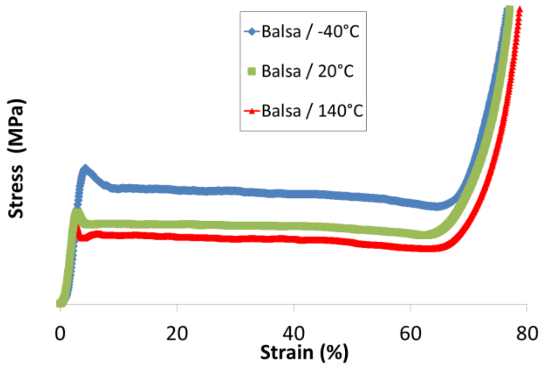

Figure 2: Strain – stress curves for balsa vs temperature

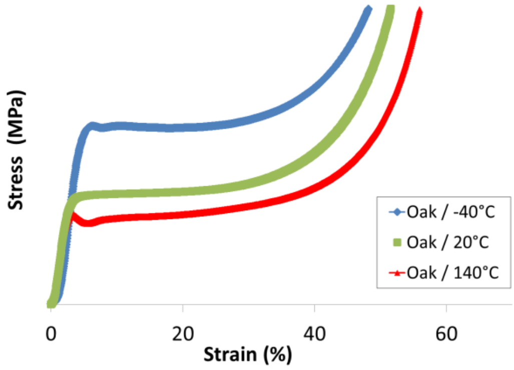

Figure 3: Strain – stress curves for oak vs temperature

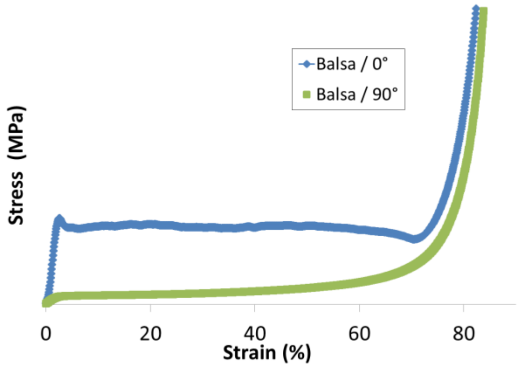

Figure 4: Strain – stress curves for balsa vs direction of fiber (0° & 90°)

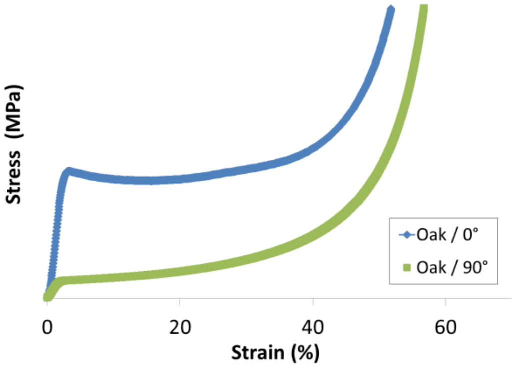

Figure 5: Strain – stress curves for oak vs direction of fiber (0° & 90°)

Welded Honeycomb

Honeycomb cellular structures are used in many industrial applications because of their light weight, rigidity (bending) and high energy-absorbing capability. They are especially used as a sandwich composite in aircraft components.

Extensive studies have been conducted for many years by AREVA TN on this family of material, glued and welded honeycomb. In this paper, only results – for welded honeycomb will be shown. This material with very high energy absorption capacity is already used in several AREVA TN casks.

Test conditions

One kind of honeycomb is shown in this paper. The sample is a metallic parallepiped of 100 mm, 50 mm in height in stainless steel, with density above 600 kg/m^3. Compressive tests without lateral constraint were performed with a 600 kN testing machine. The uniaxial compressive tests conducted here were performed in quasi-static conditionsat a rate of 1 mm/min. The test matrix is shown in Table 2

Table 2 Test Matrix for welded honeycomb specimens

Material	Solicitation	Temperature (°C)
Welded honeycomb	Axial	20°C
		150°C

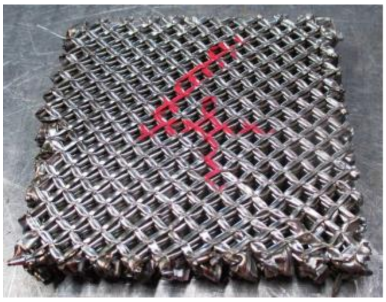

Figure 6 : Welded honeycomb specimen after compressive test

The temperature influence on the honeycomb behavior was studied and the repeatability of the behavior is carefully analysed. The tests were performed at range temperature (20°C) and above the maximum temperature experienced potential in impact limiters of ours transport casks, 150°C.

For each group of tests, 4 samples were tested. The average curve is shown. All compressive curves are represented by the mean curve on each figure.

Test results

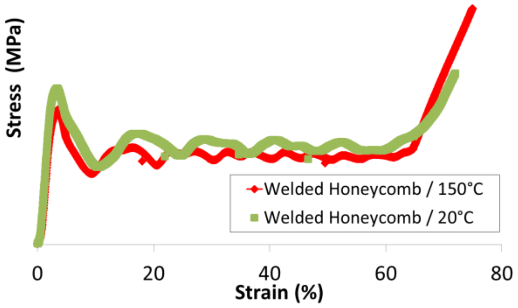

Figure 7: Strain – stress curves for welded honeycomb vs temperature

The energy ratio proved that the temperature has an influence on the behavior of the honeycomb. In figure 7, the presence of a relatively high initial stress peak can be observed, often giving rise to peak g-loads regardless of the severity of the impact. This peak can be mitigated, if needed, by applying a pre-crush load to the honeycomb structure to initiate the deformation. Thus, with this material and for this structure, the compressive curve is less affected by high temperature in comparison to wood. From 20°C to 150°C, the structure lost 10% of its ability to absorb kinetic energy. The advantage of this kind of welded honeycomb is that it can be used at high operating temperature, for type B transport cask.

Carbon Foam

Carbon foam is widely used in many industrial applications because of its physical and thermo-mechanical properties such as low density, low thermal conductivity and high fire resistance. In addition of these properties, this kind of foam has some interesting mechanical properties that could be a good compromise between low density and good mechanical performances compatible with absorbing energy applications. AREVA TN has been studying this kind of material for years and will show shortly some results in this article including the sensitivity of mechanical behavior to temperature, direction load and moisture.

Test conditions

To obtain the compressive crushing characteristic of carbon foam, test specimens were placed into an unyielding steel pipe to maintain high constraint. As for the wood, cylindrical samples were selected to avoid structural and geometrical effects. The size of the specimen was 40 mm in diameter and 40 mm in height. The samples are constrained by an unyielded steel pipe. These compressive tests were performed with a 250 kN testing machine. The uniaxial compressive tests are performed in quasi-static conditions. The compressive behavior of this carbon foam is also studied under varying conditions: crushing direction, foaming direction, humidity rate and temperature. The test matrix is shown in Table 3.

Table 3 Test Matrix for carbon foam specimens

Material	Foaming direction	Humidity rate (%)	Temperature (°C)
Carbon foam	0°	<10%	-40°C
		<10%	140°C
		<10%	20°C
		25%	
		103%	
	90°	<10%	

Figure 8: Carbon foam specimen tested

The experienced temperature here are compliant with the AIEA requirements for the minimum and the maximum temperature which could be experienced in an impact limiters of a type B transport cask (-40°C and 140°C).

For each group of test, 5 to 10 samples were tested. Density values may vary between 300 and 400 kg/m3 for carbon foam showed here. All compressive curves are represented by the mean curve on each figure.

Test results

Temperature Influence

In figure 9, the stress-strain curve obtained during the confined compression test reveals the elastic-brittle behavior of this kind of foam. Although this elastic brittle behavior, with lateral restrictions as in our shock absorber, three zones can be highlighted in the stress-strain curve. We observed a short elastic range with a brittle failure, followed by a slight increase of the stress as a crushing plateau and a quick increase in stiffness and stress due to the densification of the material.

Strain-stress curves perfectly overlap for these extremes temperatures. Thus, it can be concluded that this parameter has **no influence on the foam compressive behavior**. which can, on the other hand, be explained by the inert properties of the foam.

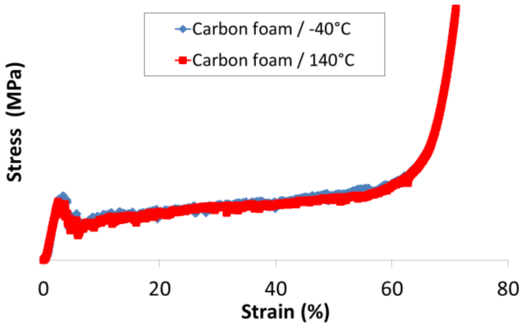

Figure 9: Strain – stress curves for carbon foam vs temperature

Humidity rate and Direction load influence

As for the wood, humidity must be studied because it could have a significant influence on the foam behavior. Tests were conducted with different humidity rates at several temperature. Tests whose curves are shown in figure 10 were carry out in extreme operating conditions of transport cask. Our reference curve shows a humidity rate obtained at the equilibrium in the foam (less than 10%). The second group of samples were placed at relative humidity of 90% for 14 days and with a humidity rate in the samples an average of about 25%. Compressive tests were performed at -40°C. As figure 10 shows, the humidity rate is null. **The foam behavior is insensitive to this parameter.**

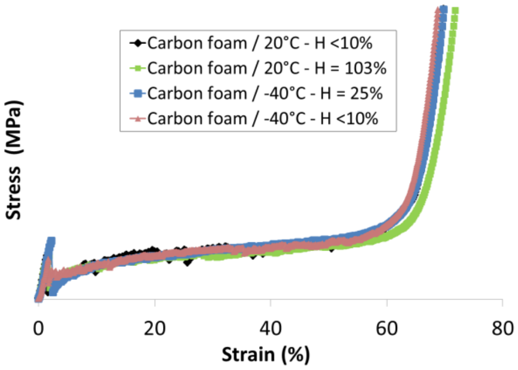

Figure 10: Strain – stress curves for carbon foam vs moisture

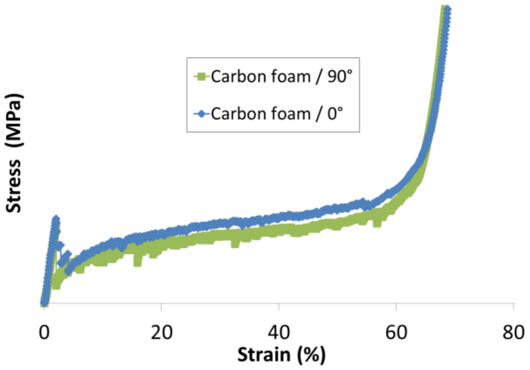

Figure 11: Strain – stress curves for carbon foam vs direction

As displayed in figure 11, the influence of direction load on the mechanical properties is noteworthy. The ratio of compressive stress between the direction of foaming and the perpendicular direction is nearly 20%. Due to the manufacturing process, the microstructure of this material is slightly elongated in the foaming direction. This explains the slight anisotropy observed during the tests.

Metallic foams

Metallic foams have a high specific energy absorption capacity. In addition, they can be made with different metallic materials (steel, aluminium, copper…). Porosity rates can be adjusted between 70% and 95% in order to adapt compression properties of the structures to will be used as shock absorbers for a given application, depending on the cask features and on the requirements.

Test conditions

Compression behavior of different kinds of foams was studied in quasi-static and dynamic conditions, at lower and higher temperatures. Aluminium foams samples dimensions were approximately about 150x150x150 mm^3. Steel foams samples dimensions were 150x150x100 mm^3.

Table 4 Test Matrix for metallic foam specimens

Material	Strain rate	Temperature (°C)
AlSi10Mg	QS	20°C
	13 m/s	-30°C
		120°C
304L	13 m/s	-30°C
		120°C

Test results

In the framework of this study, steel foams were tested in dynamic conditions. Firstly, a limited scattering can be observed between mechanical properties. For a similar density, the disparity is about 16%. The strengthening effect due to dynamic conditions (higher strain rates) depends on the constitutive metal of the foam. The strengthening effect is insignificant for aluminium foams. Indeed for a similar density of about 572 kg/m^3, the plateau stress is about 11 MPa in dynamic conditions, for both testing temperatures. For steel foams, the strengthening effect of plateau stress values is a little bit more important as we can see in figure 12.

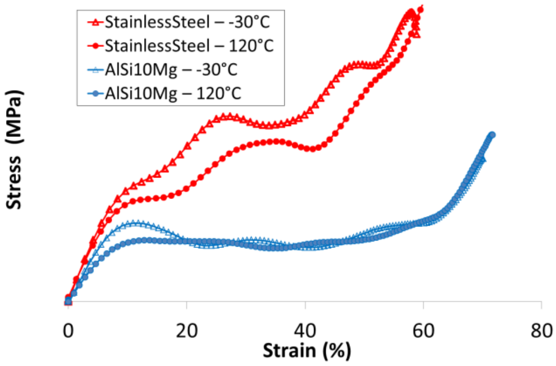

Figure 12 : Dynamic strain – stress curves for stainless steel and aluminium foams

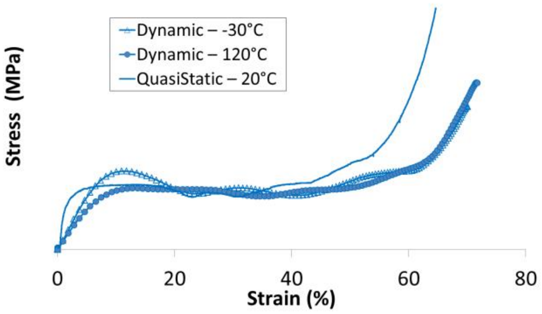

Figure 13 : Strain – stress curves for aluminium foams in dynamic and quasi-static conditions

The major benefit of isotropic behavior is to eliminate concerns with oblique impacts and the necessity of orientating the material inside the cover.

In figure 13, the plateau stresses of foams are very similar in quasi-static conditions and in dynamic conditions. Thus, it seems that there is no strengthening in steel foams behavior linked to dynamic effects at ambient temperature and at 120°C. Nevertheless, we can notice a strengthening of steel foams behavior at -30°C. Moreover, the strengthening is more significant for higher densities: the increase in plateau stress is about 12% for foam density of about 1170kg/m^3 and about 25% for foam density of about 1310 kg/m^3. The tendency is similar for energy absorption capacity.

Other parameters are of a great importance when choosing a shock absorber. The designer must take into account the cost, the availability and the supply, the thermal behavior in operating conditions and the long-term life.

Comparison

To compare these different solutions, a ratio between the absorbed energy and the density of the material was used. The energy is defined as the energy absorbed by the material before the densification which appears when there is a sudden increase of the stress in the compressive curve. Figure 14 shows different ratios between these materials.

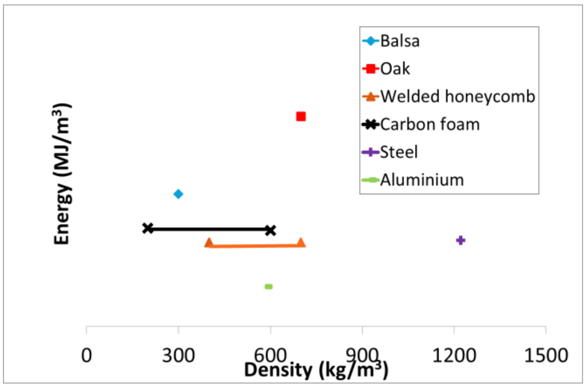

Figure 14: Comparison between materials

Figure 14 seems to conclude that actual materials used in AREVA TN shock absorbers have a low density and a great energy absorption capacity which is why they have been selected them. Even though, the innovative solutions presented in this paper may have a higher density, or a low energy absorption capacity, but they have numerous advantages for the design of casks. Low influence of environmental parameters (moisture, temperature, anisotropy, fabrication dispersion, …) on the mechanical performances is a huge advantage increasing efficiency for the same volume of the impact limiters.

Such is the conclusion if only mechanical performance without any environmental effect (temperature, humidity, anisotropy, fabrication dispersion, etc) is considered.

Conclusion

AREVA TN’s extensive knowledge of material and large panel of solutions to fulfils IAEA safety recommendations, especially 9 m drop test to ensure the safety of the nuclear materiel we carry in our transport and storage casks [3]. This paper has provided a glimpse of AREVA TN existing solutions such as wood and welded honeycomb, as well as some innovative solutions that might be use in future impact limiters.

AREVA TN invests in resources to qualify all the solutions and to characterize properties required to fulfil our customers' needs (for transport and storage casks) and in compliance with safety regulations.

To summarize, the differences between the various impact limiters presented here are the following:

- Actual solutions used in AREVA TN casks and approved by Safety Authorities :
    - Woods are very anisotropic, their mechanical properties are sensitive to temperature and to humidity rate,
    - Welded honeycomb is anisotropic and has lower sensitivity to high temperature,
- Recent Innovative solutions :
    - Carbon foam has a quasi-**isotropic** behavior, its properties are **insensitive** to temperature and to humidity,
    - Metallic foam has an almost **isotropic** behavior, its properties are quasi-**insensitive** to temperature and can be designed and adapted to any specific customer needs,

These two last solutions are highly performant in terms of the ratio energy/density and are suitable to be used in future AREVA TN impact limiters. In addition to their high performance, they have some additional advantages compared to current actuals solutions which are repeatability, restricted range of strengths for fabrication dispersion, facility of manufacture by any metallic foam supplier.

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