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Behaviour of Wood Filled Impact Limiters during Fire Test

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Abstract

Packages for the transport of radioactive material are often equipped with impact limiters consisting of wood, encapsulated by steel sheets. These impact limiters shall ensure the transport cask meets the mechanical and thermal IAEA regulatory test requirements. After damage caused by the mechanical tests the package has to withstand a severe fire scenario. According to the regulations during and following the thermal test, the specimen shall not be artificially cooled and any combustion of materials of the package shall be permitted to proceed naturally.

Corresponding to results of the French institute IRSN combustion and smouldering of wood inside the impact limiter occurred during and after the fire test. An additional energy supply from a pre-damaged impact limiter to the cask could be the consequence for the safety assessment of the containment.

BAM started a first test phase to examine the issue of combustion for such kind of package components. The goal was to understand the phenomena under the consideration of relevant regulatory boundary conditions. Several metal buckets were filled with wood and equipped with thermocouples. The test specimens have been prepared with different damage arrangements to take the influence of the mechanical tests into account. This paper shows the experimental setup and the conduction of the tests. The first test shows that pre-damaged metal encapsulations can lead to smouldering of the wood and with this to a supplement energy release after the end of the 30 minute fire. BAM is in the preparation process for a second test phase. A thermal test will take place with a wood filled test specimen weighing about 2Mg.

Introduction

Packages for the transport of radioactive material are often equipped with impact limiters made out of wood, encapsulated by steel sheets. These impact limiters shall ensure that the package meets the safety requirements of the IAEA mechanical test [1]. After damage caused by the mechanical test the package has to withstand a thermal test which is defined in the IAEA regulations [1] and its advisory material [2]. The thermal test comprises three phases. The first phase is the initial phase; after that the fire phase starts and is followed by the cooling down phase. In the initial phase the package is in a thermal equilibrium with defined boundary conditions, e.g. an ambient temperature of 38°C. In the second phase, the package has to be fully engulfed with an 800°C fire for a period of 30 minutes. After that the cooling down phase starts. The damaged package is exposed again to an ambient temperature of 38°C in combination with solar insolation. According to [2], the package shall not be artificially cooled and any combustion of materials of the package shall be permitted to proceed naturally after the fire. The cooling down phase has to last until temperatures in the package decrease everywhere.

Tests by the French institute IRSN have shown that after the fire phase an additional energy supply from a pre-damaged impact limiter should be taken into account due to continuous combustion and smouldering of wood [3].

Significant effects on the leak tightness of the sealing system and consequently on cask containment efficiency due to thermal effects like shown in [4] might result due to thermal impact of smouldering processes in impact limiters. The influence of heating to the widening between the lid and body flange surfaces has to be taken into account. This widening can amongst others result from the different thermal expansion of lid and cask body material due to different coefficients of thermal expansion or inhomogeneous heating under thermal impact. These effects of thermal impact which might result in an elevated activity release are mentioned in [5] and [6].

BAM started a first test phase to examine the issue of combustion for constructions with regard to typical package impact limiter designs. The goal was to understand the phenomena under the consideration of relevant regulatory boundary conditions. Three closed conical metal pails were filled with wood and equipped with thermocouples. The test specimens have been prepared with different damage arrangements to take into account the influence of the mechanical tests. This paper shows the experimental setup and the conduction of the tests.

At the moment, BAM is in the preparation process for a second test phase. An impact limiter with a diameter of about 2.3 m will be build and exposed to an IAEA fire at the open air test facility at BAM Test Site Technical Safety (TTS) [7]. The thermal test will be conducted with a wood filled impact limiter test specimen weighing about 2Mg. The general experimental setup planned will be shown in this paper.

First Test phase

In the following the first test phase with the conical metal pails filled with wood will be described and discussed. The first test phase is described more detailed in [8].

Test specimens

Figure 1: Test specimen 3

For the tests, 3 conical metal pails were filled with spruce wood and prepared with different pre-damage as shown in figure 2. The pails were all of the same size, made from tin sheet and had a lid closure system. Figure 1 shows test specimen 3 as an example. The test specimens had a diameter of about 330 mm, and an extent of about 390 mm and were filled with 12 spruce wood layers. These wood planks had a thickness of about 30 mm. The wood planks were manufactured as semi-discs and inserted each rotated by 90 degrees. Three test specimens were prepared with different pre-damage.

Test facility

A furnace was used for the tests. The furnace has a volume of 1 m³ with equal lengths of the edges. The furnace has two oil burners each generating spurts of flame entering the furnace chamber. As the flames have a higher temperature than required of IAEA regulations and as they are strongly turbulent, the test specimen was placed with an offset to the flames. So the test specimen was exposed to the heat fluxes resulting from the furnace environment temperature which was over 800°C for at least a period of 30 minutes, and the radiation of the furnace walls. Three thermocouples were placed in direct vicinity of the test specimen to monitor the environmental temperature.

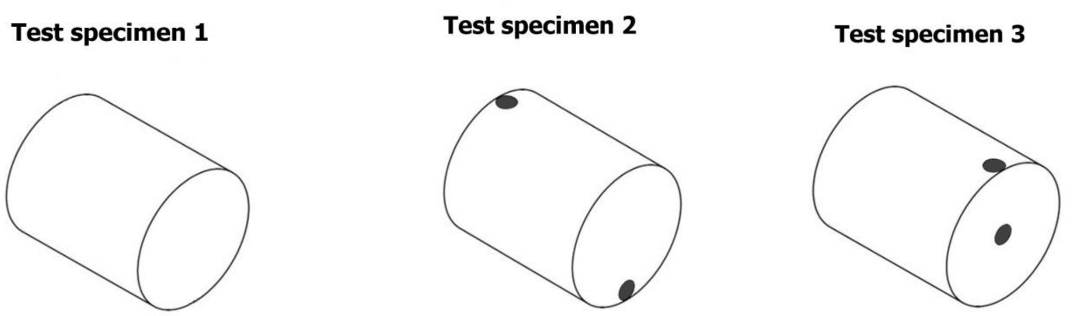

Figure 2: Specimens with no pre-damage (left) and two kinds of pre-damage

Observations after the fire test

During the fire test with specimen 1 a swelling of the lid could be observed. The inner pressure, the change of strength and the expansion of the lid may have lead to the buckling. After extinction of the burner, spurting flames with high speed at the pressure equalization holes were observed. After opening and discharging test specimen 1 it was discovered that a 30 mm to 60 mm thick area in the

Figure 3: Test specimen 1 and test specimen 3 after opening

outer edges was charred (figure 3, left). The test specimen lost about 4.5 kg during the thermal test which would theoretically correspond to a total loss of about 20 mm of wood in the boundary layer. On the left side of figure 3 test specimen 1 is shown after removal of the lid and the completely charred first wood layer. From the second layer one semi-disc of wood has been removed on this figure. The charring depth in the wood is visible. The small pressure equalization holes were too little to obtain sufficient oxygen supply for a continuing smouldering of the wood.

Spurting flames could be observed at the damage holes of test specimens 2 and 3 after extinction of the fire. They remained stable for a few minutes. During the cooling down period test specimens 2 and 3 showed smoke leaving the upper damage hole. Therefore, the upper hole can be defined as gas outlet and the hole in the bottom of the specimens can be defined as air inlet. Figure 3 also shows test specimen 3 on the right-hand side after removal from the furnace and opening of the specimen. Continuing smouldering processes in the test specimen lead to a loss of weight of about 11 kg. Calculating with a heating value of about $4.3\ \frac{\text{kWh}}{\text{kg}}$ for spruce wood, around 47 kWh were set free. The heat generation in the test specimen 3 dropped sharply after about 36 hours which can be seen in figure 4. The heat generation of test specimen 2 dropped after about 53 hours with an almost equal loss of weight. This difference in time may be caused by the different arrangement of the initial damage. A first estimation is that the pressure loss coefficient between the inlet and the outlet of test specimen 3 is lower than the comparable pressure loss coefficient of test specimen 2. This might occur during the whole test period. In the beginning, when no wood is charred, this can be attributed to the difference of the flow path length which naturally still exists during the test period. During the fire phase and the cooling down phase the pressure loss coefficient between the inlet and the outlet decreases even more in test specimen 3 due to buckling of the lid, cracking of the first wood layer and its continuous burning. Therefore, the oxygen supply might be higher during the whole time of smouldering and leads to the mentioned difference of heat generation time which has to be shown in further tests.

In figure 3 (right), a remaining ring of charred wood in test specimen 3 can be observed. Due to the smouldering process in the test specimen during the cooling down phase the outer area of the test specimen might be cooler than the inner area. This might lead to the incomplete combustion of the layered wood. The surface/volume ratio may be a parameter influencing this phenomenon.

Furthermore, this volume has been heated up during the fire phase without being in contact with sufficient oxygen for a continuing smouldering process as one can see on the results of test specimen 1. So this area lost pyrolysis gases which might be relevant for a continuing smouldering process at a later time when sufficient oxygen can be supplied. This might lead to a thermal insolation layer which exists during the whole fire test period under the outer surface of the impact limiter.
Furthermore, comparison of a simulation taking into account heat transfer only the test in [8] shows a strong difference in the characteristics of the temperature development. Only heat conduction does not seem sufficient to describe heat transfer in the test specimens during the thermal test. A transport of hot gases from the verge region to the center of the test specimen seems to occur and transports energy into the cooler areas of the system. This energy heats up the specimen and is not considered by calculation with heat conduction only.

Progress of combustion

As discussed above, different periods for the combustion of almost all wood of test specimens 2 and 3 could be observed. For test specimen 3 different thermocouples could be evaluated, showing a heat wave in the test specimen. Figure 4 shows some temperature developments during the thermal test. Thermocouples have been arranged in different layers in direct vicinity of the rotation axis of test specimen 3. The distance from the lid is indicated in figure 4. Especially after reaching the peak temperature it cannot be guaranteed that the thermocouples are still in place due to the vanishing of the wood. Additionally, the diagram shows the environmental temperature in the furnace during the fire period which was between 800°C and 1050°C for about 30 minutes. The curves show a proceeding smouldering process beginning at the bottom of the test specimen where the initial damage is located. The temperature curves in figure 4 show clear temperature peaks with strong increase of temperature before and a strong decrease after it. The propagation speed of the heat wave from one thermocouple at the time of its peak temperature to the following thermocouple at its peak temperature was measured with a value of about $13 \pm 2.5\ \frac{\mathrm{mm}}{\mathrm{h}}$. Such a clear structure could not be observed in the fire test of test specimen 2. Unstructured oxygen supply due to continuously changing flow might be the reason.
Regarding the safety assessment, the overall thermal energy released from the burning or smouldering wood in an impact limiter may be an important value and has to be considered in relation with time. The amount of thermal energy and the time the energy will be released may vary depending on size, design and geometry of the wood filled impact limiter plus the extent and location of mechanical damage. The maximum of thermal energy released of an impact limiter during the cooling down phase may overlap with the energy wave coming from the package surface and reaching the closure system of the package. Therefore the speed of progress of combustion might be an important parameter for the assessment regarding combustion of wood encapsulated in steel sheets during thermal test.

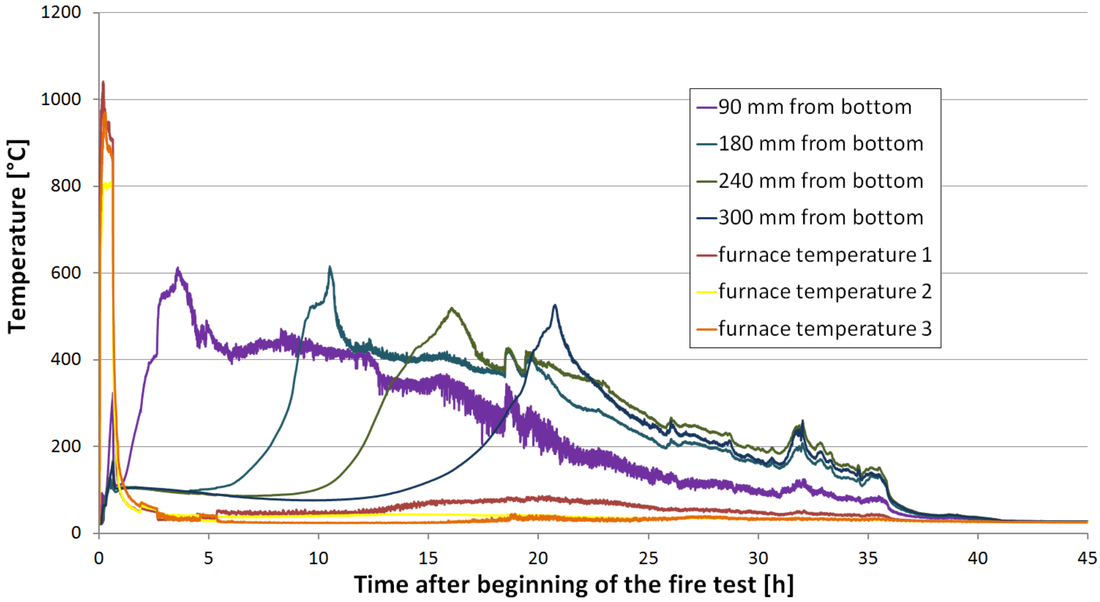

Figure 4: Temperature development in different wood layers of test specimen 3 during and after fire test

Limits of tests

Too small numbers of tests have been made to get reliable results. However, the tests showed that it might be possible to generate additional thermal energy during a thermal test due to smouldering wood in impact limiters.

Compared to a pool fire the **furnace** is a partly divergent environment. The advisory material [2] considers the difference one has to take into account while performing a furnace test. Due to the combustible material in the test specimens, special attention had to be paid to the oxygen supply. During and especially after the 800°C phase the oxygen level must be sufficient to ensure a naturally proceeding combustion. Additionally, the inner space of the furnace must be large enough to allow free convection, which ventilates a combusting area and supplies it with oxygen. Corresponding to [2], tests with combustible specimens can be carried out in a pool fire or other possible test environments like an open air burner system operating with liquefied petroleum gas as available at the BAM fire test facility [7]. This might minimize the above mentioned uncertainties. Nevertheless a continuing smouldering process can be expected in a pool fire for this kind of test specimen under the proper IAEA fire test conditions.

Regarding the size of the test specimen, the advisory material [2] states that the performance of thermal tests using **scale models** is problematic. It might be applied under special circumstances for conservative temperature results in the fire test if no fundamental change in the thermal behaviour of the components occurs [2] which is not the case for wood packed impact limiters. The regulatory states that the calculation of heat transfer or the determination of physical and chemical changes of a full size package based on the extrapolation of the results from a thermal test of a scale model may be impossible without many different tests [2]. Heat transfer mechanisms were shown above which might depend on non-scalable, dimensionless parameters. Parameters like the surface/volume ratio influence the smouldering process and the heat transfer. Oxygen supply depends, besides other parameters, on pressure loss coefficients from the inlet to the embers and from the embers to the outlet which are not scalable for such a test. However, the tests could show heat transfer mechanisms and smouldering processes which should be assessed in non-scaled safety analyses. The regulations states that the efficiency of a heat shield, or of an impact limiter acting in this role, could be most readily demonstrated by a test of this component with a relatively simple body beneath it [2] which should be the goal after the outcome of the IRSN test [3] and the here shown first test phase. Therefore BAM is going to carry out a second test phase with an impact limiter of a size which is based on existing impact limiter designs. The current state of planning will be shown in the following.

Further Tests planned – Second Test phase

The above shown results of the first test phase with small scale tests and the discussion shows the necessity to perform a test with an impact limiter of representative size. The energy transferred into the package over time is of importance for the assessment of the safety of the packages. Furthermore the process of smouldering should be analyzed for unscaled impact limiter. The scope of the second test phase is to develop and expand methods for the assessment of the behaviour of wood filled impact limiters. It is projected to perform a fire test corresponding to [1] with a representative impact limiter design. The planned design of the experimental setup is shown in figure 5 and figure 6.

Test specimen

The test specimen for the second test phase will have a circular design as shown in figure 5. It will have a diameter of about 2.3 m and it will be filled with spruce wood. The impact limiter will be equipped with thermocouples to monitor the process of smouldering.

Pre-damage have been chosen with regard to the regulatory requirements [1] which says, that the specimen shall be subjected to the cumulative effects of the mechanical tests and the thermal test. The chosen pre-damage is representative for typical damage of impact limiter after mechanical tests. Corresponding to [2] it is required that the attitudes of the package for both the impact and the pin drop tests be such as to produce maximum damage, taking into account the thermal test. The advisory material [2] says that any damage which would give rise to increased radiation or loss of containment, or affect the confinement system after the thermal test, should be considered.

Examples for damage of impact limiter after a 9 m drop test can be seen in [9], [10] and [11]. The penetration of the bar for the 1 m pin drop test mentioned in [12] for scaled models. Drop tests and pin drop tests have shown, that many different damage of the outer shell of impact limiters are possible. Damage of the outer shell can be different in quantity, geometry, size and location. The chosen pre-damage on the top of the test specimen (figure 5) will represent the result of the 1 m pin drop test. Three pre-damage in the lower area of the impact limiter will represent the damage of the 9 m drop

test. They will be implemented in different size and simulate tearing of welding seams.
The outer metal shell of the impact limiter will be pre-damaged at different locations as shown in figure 5.
More research has to be done to develop models to examine the effects of smouldering impact limiters on the containment of packages for the transport of radioactive material. Small scale tests should be performed to examine the influence of different parameters like the size of the test specimen, surface/volume ratio of the test specimen, the oxygen supply relative to the size of the test specimen and initial pressure loss coefficient between two locations of pre-damage.

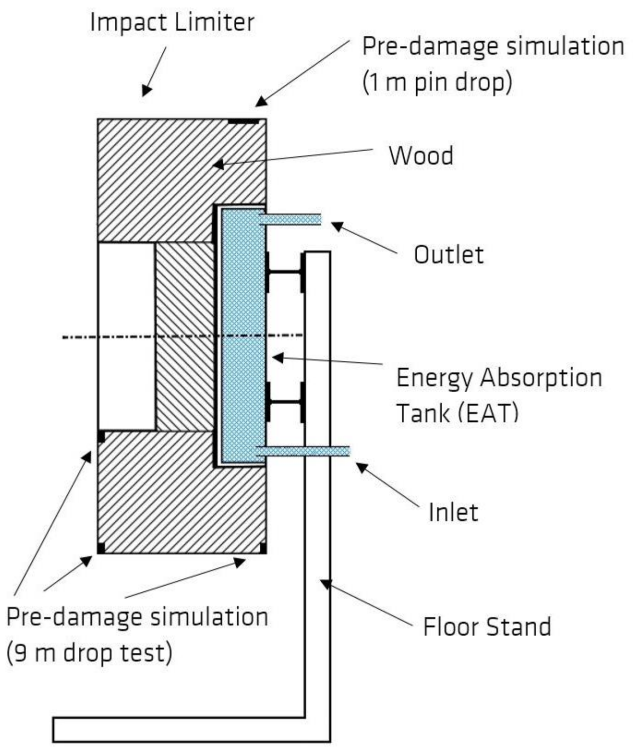

Figure 5: Experimental setup with impact limiter

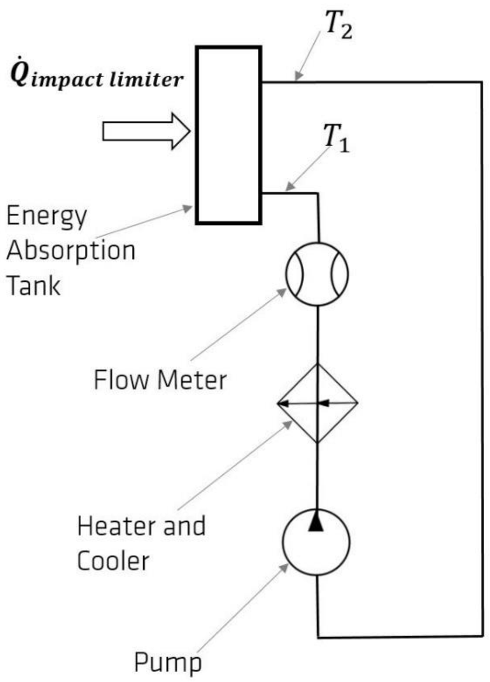

Figure 6: Schematic layout of the experimental setup

Construction of test facility

The fire test is planned to take place at the BAM fire test facility at BAM TTS. The test facility is based on the principle of a ring burner fed by liquid Propane designed for testing packages for radioactive material. The test facility is described more precisely in [7]. The general experimental setup is shown in figure 6 schematically.
The above described impact limiter will be mounted on an energy absorption tank (EAT) simulating the transport package (figure 5). During the thermal test, water will flow through the EAT. The temperature level at the inlet of the EAT (figure 5) will be hold constant at about 85°C. The temperature of the water flow will be measured at the inlet and the outlet of the EAT. With the additional

measurement of the flow rate with a flow meter, the energy absorbed by the EAT can be quantified. A regulated pump will ensure the water flow in the system. Furthermore the experimental setup will be equipped with a heating and cooling unit. The cooling system in combination with the regulation of the pump ensures the system not to heat up over a defined temperature of about 95°C. The heating system will ensure the inlet temperature not to fall under a certain level of about 85°C.
For the initial phase, realistic initial temperature gradient will be obtained in the impact limiter due to the heater in the experimental setup. The heater will heat the water flow up to a constant temperature and hold it until a steady state temperature field is reached in the impact limiter. So the heater can simulate the decay heat out of the ongoing nuclear reactions of the spent fuel for the initial phase by holding the temperature constant. As the system is temperature controlled, during the transient phases – the fire phase and the cooling down phase – the simulation of the decay heat will not be met. Due to the cooling medium the system has to be temperature controlled as the vaporisation temperature should not be reached.
The EAT will be mounted on a floor stand as shown in figure 5. So the impact limiter can be fully engulfed by the fire during the fire phase.
During the cooling down phase it is expected that smouldering processes will take place in the impact limiter. The inside of the impact limiter is equipped with several thermocouples to monitor the process of smouldering and burning over time. The highest heat flow to the EAT is expected in this phase.

Conclusion

The test set-up for determining the combustion of wood encapsulated in steel sheet during the fire test was shown in this paper. The conduction of the tests was described and the results were presented.
Even though limits of tests have been located and described the behaviour of wood encapsulated in metal sheet could be examined with regard to the issue of combustion in the thermal test. Three major outcomes arise concerning the design and the assessment of wood filled impact limiters:

1. Pyrolysis gas and water vapour generated during the thermal test may lead to a rising pressure in the impact limiter which should be considered for the design.

2. Heat conduction only does not seem sufficient to describe heat transfer into layered wood during the thermal test. A transport of hot gases from the verges to the centre of the test specimen seems to occur and transports energy into the centre of the system. This energy heats up the specimen and should be considered in the thermal assessment.

3. The small scale tests showed that wood encapsulated in metal sheet may generate additional thermal energy by smouldering and burning out completely during the IAEA thermal test. Different parameters could be located in the tests which have to be assessed in the safety

analyses of packages for the transport of radioactive material. The exact determination of the additional amount of energy in dependence of the time may be important for a proper safety analysis, as a safety-related heat flux from a burning impact limiter into the closure system could overlap with the energy wave reaching the closure system. Parameters influencing the characteristic of smouldering and burning are the geometry of the steel encapsulation, the geometry of wood, the oxygen supply which involves the geometry and the arrangement of mechanical pre-damage.

4. Experimental tests with original size of impact limiters should be conducted to examine the behaviour of wood filled impact limiter during fire test. A first experimental setup was developed at BAM.

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