Aspects of Assessment of Packages with Wood Filled Impact Limiters during Fire Tests-17191

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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 that the transport casks meet the mechanical and thermal IAEA regulatory test requirements. According to the accident conditions of transport it is mandatory to expose the specimens to a cumulative effect by mechanical and thermal impacts. The mechanical tests consist of a free drop from 9 m onto a flat unyielding target and a 1 m drop onto a puncture bar. After damage caused by mechanical test sequences the package has to withstand a severe fire scenario. Corresponding to the IAEA advisory material it is required that the impact attitudes for the 9 m drop test and for the puncture test have to be such as to produce maximum damage, taking into account the thermal test. Moreover, 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. 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.

Different works from the French Institute for Radiological Protection and Nuclear Safety (IRSN) and BAM show that additional energy supply from a pre-damaged impact limiter to the cask could occur. This effect should be considered within the safety assessment of the containment. Thermal effects at the closure system of the cask, which might result in an elevated activity release, have to be excluded. BAM conducted small scale tests with wood filled metal buckets showing continuing combustion processes during the cooling down phase. These test results are presented. As not much is known about smouldering processes in wood filled impact limiters, it is highly complex to define pre-damage of impact limiters, which are conservative, regarding the maximum damaging energy flow from the impact limiter to the containment system. 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. Aspects of assessment and its difficulties are shown.

BAM as a competent authority for the approval of transport casks for radioactive material in Germany operates the test facilities to examine the issue of mechanical damage, combustion and heat transfer for such kind of package systems. For this purpose, the knowledge from real drop tests with casks of a mass partly over 100 tons was transferred to a test application. A thermal test will take place with a wood filled test specimen with a diameter of about 2.3 meters. The aim is to understand the phenomena of smouldering under the consideration of relevant regulatory boundary conditions. The process of smouldering is described with regard to the requirements in the thermal assessment of safety of packages for the transport of radioactive material. Requirements concerning the pre-damage of packages for the maximum damage of impact limiters are discussed. Parameters influencing the smouldering process are identified.

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 also 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 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 phase. 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 of wood [3]. Effects on the leak tightness of the sealing system and consequently on cask containment efficiency might result due to thermal impact of smouldering processes in impact limiters [4]. The influence of heating on the widening between the lid and body flange surfaces has to be taken into account as well. This widening can amongst others result from the different thermal expansion of the lid and the cask body 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].

It is known that in common casks with impact limiters the peak temperature at the sealings of the lids is reached several hours after the fire period due to the heat wave from the body flange into the lid system. This heat wave could overlap with the heat wave of a burning or smouldering impact limiter.

BAM as the competent authority for the approval of packages for the transport of radioactive material in Germany 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. It could be stated that combustion processes can take place in these kind of constructions. It was also shown, that different locations of pre-damage might have an significant impact on the combustion process of the wood. At the moment, BAM is in the preparation process for a second test phase. A wood filled impact limiter with a diameter of about 2.3 m (weighing 2 Mg approx.) was built and will be exposed to an IAEA fire at the open-air test facility at BAM Test Site Technical Safety (TTS) [7]. For the arrangement of pre-damage the knowledge from real drop tests with casks of a mass partly over 100 Mg was transferred to this test application.

Aspects concerning the assessment of safety of packages for the transport of radioactive material concerning the thermal test and the mechanical tests with regard to the effect of smouldering and burning will be discussed.

ASSESSMENT OF MECHANICAL PRE-DAMAGE

The assessment of the damage parameters are based on the safety recommendations of the IAEA [1]. The thermal test is one part of a series of tests that need to be performed to fulfill the requirements under accident conditions of transport [1]. Therefor successively connected mechanical and thermal tests are designed to ensure that a severe accident does not affect the safety of the transport package. Before the transport package will be exposed to the thermal test, the specimen must be exposed to a series of different drop tests. These shall ensure that the package does meet the regulatory requirements at a large range of possible accidents. The loads of the mechanical tests can be classified broadly in three categories: impact, crush and puncture load. Analysis of accidents referenced in [2] have shown that these three test categories represent the majority of severe traffic accidents. The real challenge in the assessment of the mechanical tests are the circumstances that the IAEA regulations call for drop tests to produce maximum damage, taking into account the thermal test. Here the pin drop load also has to be performed to cause maximum mechanical damage. Corresponding to [2] it is required that the attitudes of the package for both the 9 m drop 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.

In many years of experience, BAM shows in [8 - 11] that drop tests lead to many types of damage depending on e.g. the package size or drop specification. The damage behavior of an impact limiter after a 9 m drop test can be seen in [8], [9] and [10]. The drop test of a cask with a mass up to 100 Mg shows that the wood of the impact limiter was ruptured at several points. At first sight fragmentations, displacements and buckling can be seen. Further investigations show penetration of the steel sheets by escaping wood. A drop test on a bar [1] is mentioned in [11] for scaled models. In this test sequence, the package drops on a bar with a length up to 1 m. The most damaging length of the drop bar and impact point depends on the cask and impact limiter design and is determined for the pin

Fig. 1: Test specimen 3

drop test. In accordance with the IAEA regulations [1] this test has to be performed to produce maximum damage.

Evaluations of BAM show that many different pattern of mechanical pre-damage on the impact limiters are possible. 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. Depending on the drop test, fiber direction of the wood but also the arrangement of the puncture test alternate damage forms could be shown. In order to achieve an adequate assessment of package design during the fire test according to IAEA guidelines, it is necessary to investigate the fire and smouldering behavior of the impact limiters to identify the damage with maximum impact. In addition, it is necessary to investigate the differences between damage configurations, fracture mechanics and different component forms regarding the fire and smouldering behavior of the impact limiter design. As not much is known about smouldering processes in wood filled impact limiters, it is sophisticated to define pre-damage of impact limiters, which are conservative, regarding the maximum damaging energy flow from the impact limiter to the containment system.

BAM started a first test phase to examine the issue of combustion and smouldering for constructions with regard to typical impact limiter designs. Here the influence of the mechanical pre-damage should be investigated taking into account the smouldering behavior. The test setup is described briefly in the following and more precisely in [12]. The general outcomes regarding the smouldering behavior is given in the next chapter. Three 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 and are shown in figure 2.

A furnace was used for the thermal tests. The furnace has a volume of 1 m^3 with equal lengths of the edges. The furnace has two oil burners each generating spurts of flame

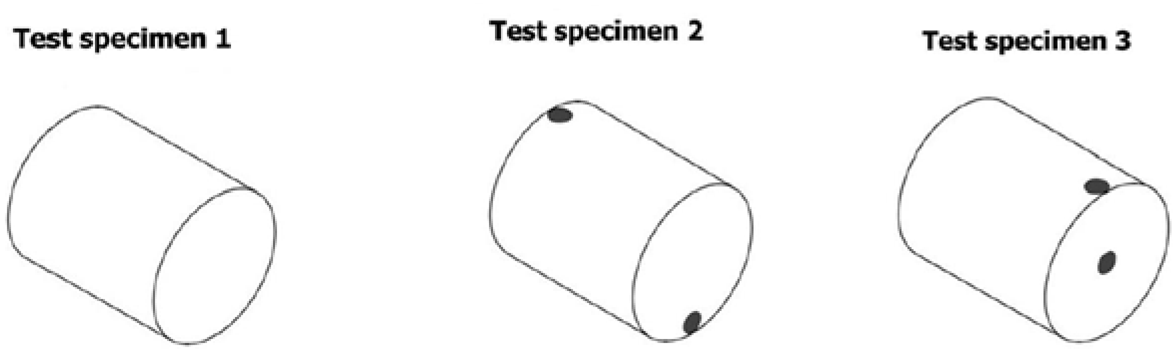

Fig. 2: Specimens with no pre-damage (left) and two kinds of pre-damage

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. Furthermore, several wood layers were equipped with thermocouples at different locations to measure the temperature development during the fire test. Even though thermal tests are not scalable due to different non scalable effects like heat transfer mechanisms depending on dimensionless parameters and pressure loss coefficients from the inlet to the embers and the embers to the outlet, these small scale test have been performed to examine the process of combustion.

ASSESSMENT OF COMBUSTION AND SMOULDERING

Different processes leading to energy release as smouldering and flaming can occur in wood filled impact limiters during the fire test. Smouldering fire distinguishes from flaming by the fact that less specific energy is released during burning. Smouldering moves slower and the composition of exhaust gases differs from flaming conditions with sufficient oxygen supply. The oxidation reaction and heat release during flaming occur directly at the surface, whereas during flaming gases ascend from the surface and burn in the gas phase [13]. A requirement for the smouldering fire is that the fuel converts into a high-carbon rich material. T.J. Ohlemiller describes the heat release is proportional to the oxygen supply [14]. The more oxygen is available, the higher the temperature in the oxidation zone gets, the faster the adjacent fuel gets heated and the bigger the smouldering velocity is.

If the available oxygen is insufficient, not all the fuel is released, with the smouldering front propagating and unburned wood staying behind. The oxygen supply is a determining influence factor in the process of smouldering. This could also be observed after the fire test with test specimen 1 (figure 3). It was discovered that a 30 mm to 60 mm thick area in the outer edges was charred which can be seen on the left side of figure 3.

Fig. 3: Test specimen 1 and test specimen 3 after opening

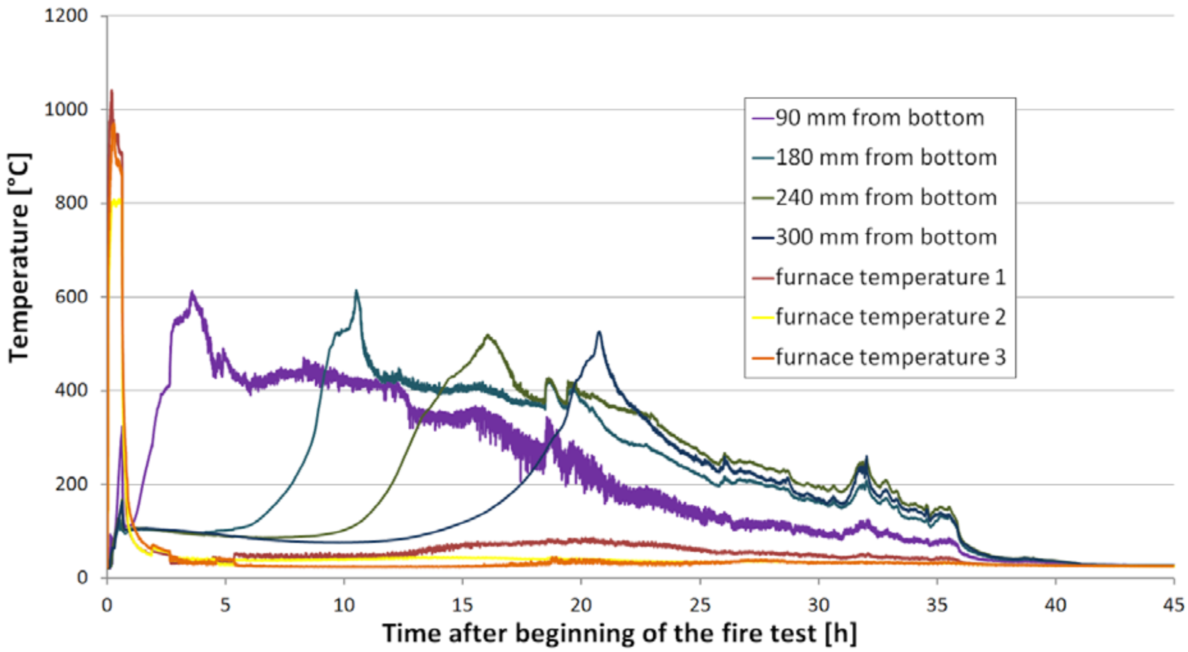

Fig. 4: Temperature development in different wood layers of test specimen 3 during and after fire test 1

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 oxygen supply was too little for a continuing flaming or smouldering process. On the right side of figure 3, test specimen 3 and the rest of its almost completely charred wood after the fire test is shown.

For test specimen 3, different thermocouples were evaluated, showing a heat wave in the test specimen and the environmental temperature in the furnace during the thermal test (figure 4). The distance of some thermocouples from the lid is indicated in figure 4. The curves show a proceeding process of energy set free beginning at the bottom of the test specimen where the initial damage is located. The temperature curves in figure 4 show clearly 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. Furthermore, the direction of the burning process might be a reason for different periods of heat release. Smouldering distinguishes by the direction of the burning process - forward and backward smouldering. The burning direction is one of the characteristics of smouldering. Concerning wood it was already intensely studied by Ohlemiller [14]. If oxygen approaches the reaction zone against the direction of smouldering propagation, the process is named backward smouldering. If the oxygen flow is in the same direction as the propagation of smouldering, the process is named forward smouldering. In the forward smouldering process oxygen flows through the reacted material and gets heated before entering the reaction zone. Afterwards the exhaust gases flow through the unburned fuel, which gets consequently preheated. A characterisation of forward- and backward smouldering was realized in [15]. Experimentally it was proven, that forward smouldering on similar conditions moves 90 percent slower compared to backward smouldering. The determination of a maximum and a minimum speed of smouldering might be an important procedure for the assessment of the maximum energy transported into the closure system. This process has a lot of different influencing parameters which are partly shown here.

The availability of oxygen in the embers depends among others on the location, number and geometry of pre-damage. Pressure losses as a result of the oxygen flow through formed supply ducts as well reduces the amount of provided oxygen. The performed tests with different pre-damage could show different overall periods of energy release. The heat generation in the test specimen 3 dropped sharply after about 36 hours (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 leading to different pressure loss coefficients for the airflow and different modes of smouldering as described above.

Heat losses also represent an important parameter. If the heat losses to the surrounding environment are bigger than the heat flux from the flame, the fire will extinguish. When the smouldering area gets insolated by the charring of adjacent layers, the heat losses are reduced [15]. The faster the generated heat is transferred, the better the smouldering fire can propagate. On the right side of figure 3, 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 of the impact limiter may be a parameter influencing this phenomenon as a part of the overall heat generated in the impact limiter leaves it via its surface. 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 of the smouldering process, when sufficient oxygen can be supplied. This might lead to a thermal insolation layer existing during the whole fire test period under the outer surface of the impact limiter. Such an additional outer insolation layer on the embers, which might result from the IAEA-fire, reduces heat losses to the environment and increases the stability of smouldering. Bigger humidity of wood will contribute to increasing heat losses and might change energy transportation in the impact limiter during the fire phase.

In summary smouldering and burning processes in wood filled impact limiters have to be regarded as a complex process. Many influencing factors and different behaviour of forward- and backward smouldering were shown in the literature, [15], [14], [13] amongst others. Further influencing factors on the smouldering process might be the direction of grain or the condition of wood after the impact.
Regarding the safety assessment, the overall thermal energy released from the combustion of wood in an impact limiter is an important value and has to be considered in relation with time and the location. The amount of thermal energy and the period 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 peak 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.
Further aspects concerning the assessment of wood filled impact limiters during the fire test have been described in [12]. For example, a pressure build up in the small-scale tests due to pyrolysis gas and water vapor generated during the thermal test was observed in [12] and exceeds the assessment of the process of combustion.

FURTHER TESTS PLANNED – SECOND TEST PHASE

Regarding the size of the described test specimens, 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 behavior 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]. However, the tests could show heat transfer mechanisms and smouldering processes, which should be assessed in non-scaled safety analyses. The regulations state 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. 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. As shown above, it is of importance, to analyze the process of smouldering for unscaled impact limiter and get more knowledge about the relevant energy release of an impact limiter into a closure system. The scope of the second test phase is to develop and expand methods for the assessment of the behavior of wood filled impact limiters. A fire test corresponding to [1] with a representative impact limiter design is going to be performed. The design of the experimental setup is shown in figure 5 and figure 6. Nevertheless, as it could be shown that complex processes of burning and smouldering lead to the energy release and that one test can show just one possible result of energy release, which will not represent the covering case.

Test specimen

The test specimen for the second test phase has a circular design as shown in figure 5. It has a diameter of about 2.3 m and is 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] as described above. The chosen pre-damage is representative for typical damage of impact limiters after mechanical tests. 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 represent tearing of welding seams. The outer metal shell of the impact limiter will be pre-damaged at different locations as shown in figure 5.

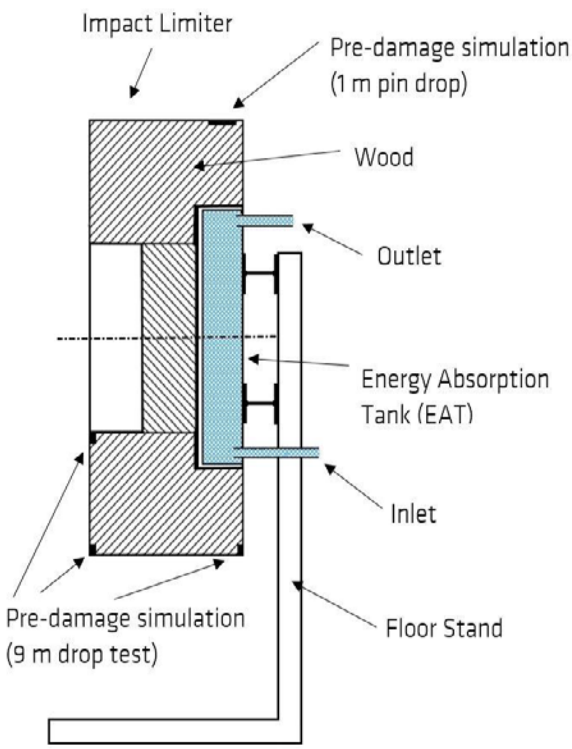

Fig. 5: Experimental setup with impact limiter

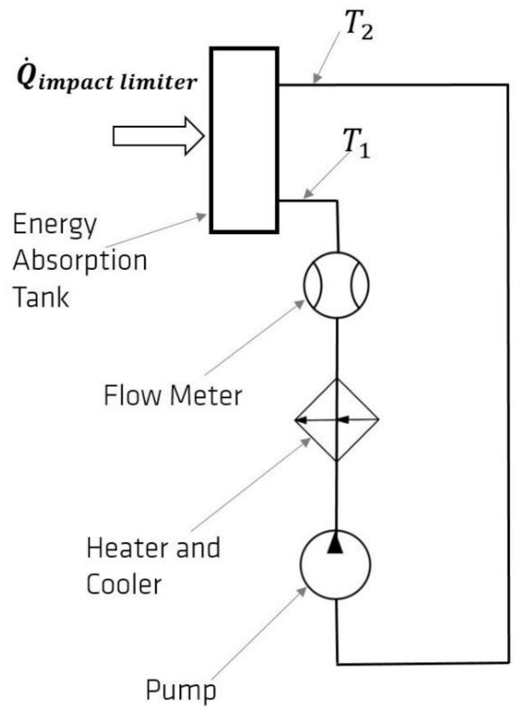

Fig. 6: Schematic layout of the experimental setup

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 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 and chosen such to represent the temperature level of a transport package. 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 to prevent boiling in the EAT. The heating system will ensure the inlet temperature not to fall under a certain level. The experimental setup is shown in figure 6 schematically.

For the initial phase, a 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. Therefore, 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 vaporization 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 small scale tests conducted by BAM [12] and the tests conducted by IRSN [3] show that wood encapsulated in metal sheets may generate additional thermal energy by smouldering and burning during the IAEA thermal test. Challenges of the assessment based on the IAEA regulatory test requirements [1] for packages for the transport of radioactive material have been shown. Increased temperatures may lead to an elevated activity release. It is shown that the most damaging position of the mechanical tests, with regard to the thermal test depend on many variables concerning the smouldering and burning process of impact limiters. Due to the special designs and dimensions of the impact limiters, in connection with a wide range of possible pre-damage scenarios and the complexity of the smouldering and burning process, further investigations have to be performed for a realistic safety assessment. The arrangement of one possible combustion process in a large-scale impact limiter will be examined by BAM in a fire test.

The major outcomes concerning the safety assessment of packages for radioactive material with wood filled impact limiter with respect to combustion of wood presented in this paper are:

1. Different locations and size of pre-damage of impact limiters have a significant impact on the combustion and smouldering process of the wood in the IAEA thermal test.

2. A wide range of pre-damage of the outer shell of impact limiters after the 9 m drop test and the pin drop test is possible. Damage of the outer shell can be different in quantity, geometry, size and location and has to be chosen with respect to the most damaging combustion process in the thermal test.

3. Different parameters could be located in the tests and the literature, which have to be assessed in the safety analyses of packages for the transport of radioactive material. The determination of the additional amount of energy in dependence of the time and location 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 for instance. Several parameters influencing the characteristic of smouldering and burning as the oxygen supply, which involves the geometry and the arrangement of mechanical pre-damage, have to be taken into account.

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