Pressure Build-Up During the Fire Test in Type B(U) Packages Containing Water - 13280

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ABSTRACT

The safety assessment of packages for the transport of radioactive materials with content containing liquids requires special consideration. The main focus is on water as supplementary liquid content in Type B(U) packages. A typical content of a Type B(U) package is ion exchange resin, waste of a nuclear power plant, which is not dried, normally only drained. Besides the saturated ion exchange resin, a small amount of free water can be included in these contents. Compared to the safety assessment of packages with dry content, attention must be paid to some more specific issues. An overview of these issues is provided. The physical and chemical compatibility of the content itself and the content compatibility with the packages materials must be demonstrated for the assessment. Regarding the mechanical resistance the package has to withstand the forces resulting from the freezing liquid. The most interesting point, however, is the pressure build-up inside the package due to vaporization. This could for example be caused by radiolysis of the liquid and must be taken into account for the storage period. If the package is stressed by the total inner pressure, this pressure leads to mechanical loads to the package body, the lid and the lid bolts. Thus, the pressure is the driving force on the gasket system regarding the activity release and a possible loss of tightness. The total pressure in any calculation is the sum of partial pressures of different gases which can be caused by different effects. The pressure build-up inside the package caused by the regulatory thermal test (30 min at 800°C), as part of the cumulative test scenario under accident conditions of transport is discussed primarily. To determine the pressure, the temperature distribution in the content must be calculated for the whole period from beginning of the thermal test until cooling-down. In this case, while calculating the temperature distribution, conduction and radiation as well as evaporation and condensation during the associated process of transport have to be considered. This paper discusses limiting amounts of water inside the cask which could lead to inacceptable pressure and takes into account saturated steam as well as overheated steam. However, the difficulties of assessing casks containing wet content will be discussed. From the authority assessment point of view, drying of the content could be an effective way to avoid the above described pressure build-up and the associated difficulties for the safety assessment.

INTRODUCTION

In Germany, BAM Federal Institute for Materials Research and Testing is the Competent Authority for the mechanical and thermal safety assessment of Type B(U) packages for the transport of radioactive material. In this kind of safety assessment the compliance of safety requirements is verified. The bases therefore are national and international regulations, which are based on IAEA SSR-6 [1]. Type B(U) packages are used to contain different types of high and intermediate radioactive material, e.g. spent nuclear fuel assemblies, core components, deconstruction residues and even contaminated cleaning material and other aids. Most of these contents are dry or dried. Potentially wet or liquid contents like evaporator bottom are often dried inside the package and could be treated like a dry content. Contaminated ion exchange resins are flushed into the package using water and afterwards the ion exchange resin is just drained, but not dried. BAM was involved in several approval procedures with ductile cast iron containers containing wet intermediate level waste. This paper refers to one aspect of the safety assessment: The thermal test as a part of the thermal safety assessment under accident conditions of transport, and the thereby resulting pressure build-up inside the package. Para 663 of IAEA SSR-6 [1] states that: “A package shall be so designed that if it were at the maximum normal operating pressure and it were subjected to the ... [tests under normal/accident conditions of transport], the levels of strains in the containment system would not attain values which would adversely affect the package in such a way that it would fail to meet the applicable requirements.” And Para 664 of SSR-6 [1] reads: “A package shall not have a maximum normal operating pressure in excess of a gauge pressure of 700 kPa.” These two paragraphs imply that under certain circumstances the thermal test starts with internal pressures of the packages up to 700 kPa. The total pressure, which is the sum of the internal pressure of the package in addition to the pressure resulting from the heat of the thermal test, has to be seen as the driving force from mechanical point of view. The mechanical resistance parameters of the package (body, lid, gasket), which are influenced by the heat and the previous mechanical tests, must be compared to the driving force. This paper shows the procedure of vaporization and discusses two approaches to determine the partial pressure of water steam build-up in the thermal test. Therefore, steam tables were put into graphs with relevant filling degrees to show the pressure build-up due to thermal load and water inside the package. Thermal states and the effects of vaporization and pressure build-up are shown.

TOTAL PRESSURE INSIDE A PACKAGE

The package is stressed by the total pressure inside the package. On the one hand, this pressure leads to mechanical loads to the packages body, the lid and the lid bolting. On the other hand, the pressure is the driving force on the gasket system regarding the activity release and a possible loss of tightness. The total pressure for any calculation is the sum of partial pressures of different gases like “air”, helium, water vapor or hydrogen.

The following effects could increase the total pressure:

- Initial fill up of the packages with an inert gas like helium during handling at normal temperature P0
- Increasing pressure P1 by warming up to 38 °C as stated in [1]
- Increasing pressure P2 by heating up caused by decay
- Pressure build-up P3 caused by radiolysis for the hole storage period
- Vaporization of water P4 driven by temperature at normal conditions of transport
- Vaporization of water P5 driven by temperature at accidental conditions of transport
- Pressure P6 resulting from combustion and pyrolysis

Under normal conditions of transport the total pressure results to

$$P_{tot,NCT} = P0 + P1 + P2 + P3 + P4 \leq 700\ \text{kPa} \qquad \text{(Eq. 1)}$$

Under accident conditions of transport the total pressure results to

$$P_{tot,ACT} = P0 + P1 + P2 + P3 + P5 + P6 \qquad \text{(Eq. 2)}$$

SPECIFIC ASPECTS OF SAFETY ASSESSMENTS CAUSED BY WET CONTENTS

Compared to dry contents, the use of wet contents leads to the need for attention to regulatory points of the regulation SSR-6 [1]. Para 614 [1] says, that “The materials of the packaging and any components or structures shall be physically and chemically compatible with each other and with the radioactive contents.” It should be noted, that wet/liquid does not necessarily mean that the fluid part is water. On the one hand it must be taken into account that different parts of the content could react chemically with each other up to exothermal reactions, or yet generate even more aggressive substances due to pyrolysis. On the other hand this paragraph means that corrosion of the packages and the gasket system must be prevented. When using huge amounts of fluids in the content (“liquid radioactive material”) Para 649 [1] must be followed. “The design of a package intended for liquid radioactive material shall make provision for ullage to accommodate variations in the temperature of the contents, dynamic effects and filling dynamics.” Regarding wet contents like ion exchange resin this paragraph is not crucial. An important point, however, is the pressure build-up inside the package due to vaporization. This could be caused by radiolysis of the liquid and must be taken into account for a possible storage period as well. Yet, the highest amount of loads to the package due to water steam will be generated by the thermal test under accident condition of transport.

MODEL CASK

The following described modeling, including the physical effects and boundary conditions refer to the generic cask shown in figure 1. The cask was modeled twice: The first modeled cask contains ion exchange resin in combination with water as fluid and will be discussed first. The second cask was modeled without content and will be discussed later in this paper. Additional effects or effects with other values (e.g. fluids freezing not at 0°C etc.) may occur with different wet contents with different fluids. The model cask was designed as a ductile cast iron cylinder with 2 m in height and an outer diameter of 1 m. The interior space is 1,5 m high and the inner diameter is 0,5 m. The interior space is filled with wet ion exchange resin up to a height of 1,10 m. Since the wet ion exchange resin is not specified properly its thermal properties are defined as a combination of the properties of water (60%) and air (40%). An air-filled cavity height of 0,40 m is considered above the content. The base and the lid-area of the cask are covered by encapsulated wooden impact limiter and the cask stands upright. As initial condition a temperature of 38 °C (cp. IAEA SSR-6 [1]) is assumed for the complete cask since the decay heat is usually very low.

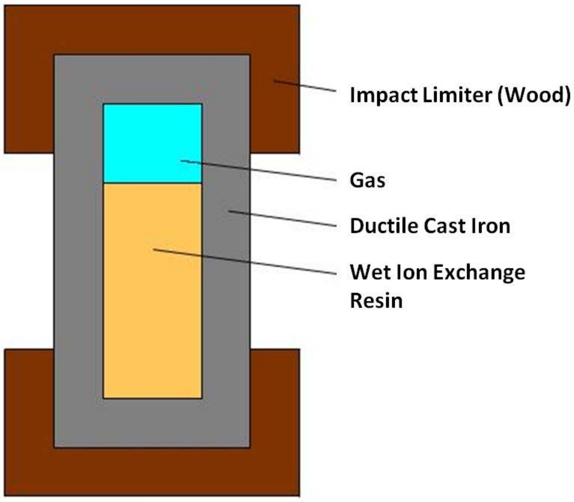


FIGURE 1 GENERIC MODEL OF A CASK USED TO CALCULATE TEMPERATURES

NUMERICAL MODEL

The numerical model of the above described cask was performed in the fluid-dynamic code ANSYS® CFX® [2] and consists in these first approaches out of 250000 elements. All materials of the cask and the wet ion exchange resin were modeled as solids, only the air-filled cavity was considered as a flow region including convection at its walls. In further levels the wet ion exchange resin will be considered as multiphase flow region, but for these first approaches solid modeling is sufficient. The thermal properties are assumed as the above described mixture of water and air. For all other materials their real conductivities, thermal capacities and densities were defined. The analysis was performed as a transient calculation with time steps of 15 sec during the fire period and 30 sec in the cooling down phase over a timeframe of 10 hours.

THERMAL TEST

According to Para 728 [1] the package, usually with its impact limiter, shall be in thermal equilibrium under conditions of an ambient temperature of 38 °C. The decay heat and also the solar insulation must be considered. Using this initial conditions the thermal test, which consists of a fire period and a cooling down phase, will be started. During the fully engulfing, 30 min. duration fire period, an average temperature of at least 800 °C should be applied to the package. In the following cooling down phase the ambient conditions should be the same as the initial conditions. The cooling down phase has to last until the temperatures decrease everywhere.

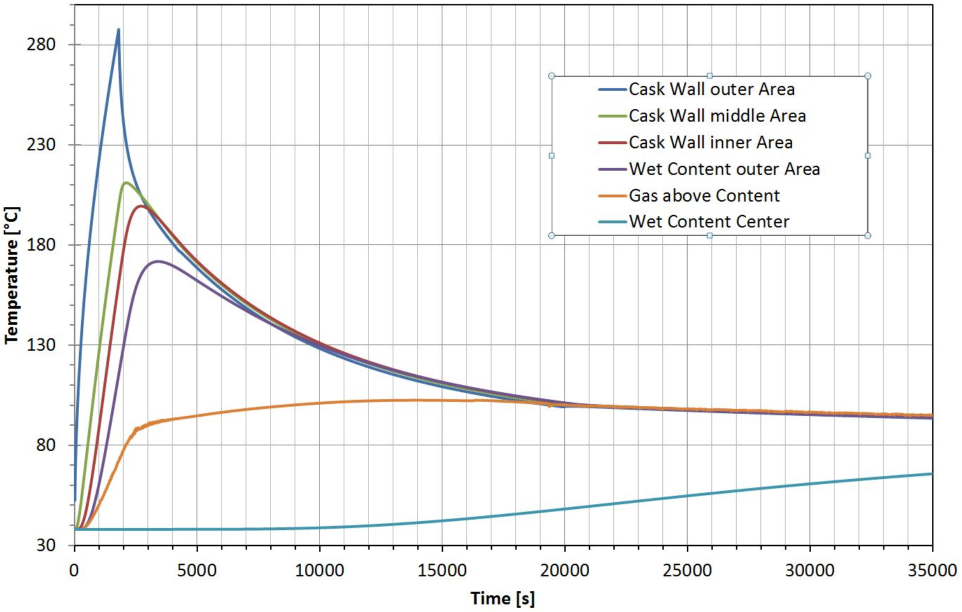


FIGURE 2 TEMPERATURES IN THE CASK MODELED WITH CONTENT DURING THE 1800 sec FIRE PERIOD AND THE FOLLOWING COOLING DOWN PHASE

HEAT TRANSPORT

Thermal energy is applied to the system as convection and radiation due to the fire. This energy will be transported throughout the materials (wood, cast iron and resin) as conduction only. Solely in the cavity above the content there could be radiation. In this cavity convection resulting from buoyancy at the inner cask wall is considered. This buoyancy induces an air flow which homogenizes the temperature in the cavity. However, the resulting heat transport is rather small compared to other transport effects. In a cask modeled without any content, higher temperatures of the inner wall surface will be reached. As shown in figure 2, the massive cask wall with its high mass, and hence a high thermal capacity lead to a relatively slow progress of temperature in terms of a thermal wave into the inner areas of the cask. For massive containers this means that the maximum of temperature and subsequently the maximum of pressure in the cask are obtained in the cooling phase after the fire period of 1800 sec.

EVAPORATION OF WATER

The vaporization of water is one process regarding the pressure build-up caused by the thermal test. Vaporization is the phase transition from a liquid phase to the gaseous phase. This is shown in the water steam diagram in figure 3 which is plotted over the temperature and the entropy. The diagram is constructed with values from [3]. The green lines showing isochors are plotted for different filling degrees of the cask. The blue graphs showing isobars of the water, steam or superheated steam. Under an isobaric energy supply at 1 bar, water begins to boil at a temperature of 99,6°C. The red boiling curve (X=0) is partly overlapped by isobars in the diagram, and meets the saturated liquid phase boundary (X=1) at a critical temperature of 374,12°C. Between these curves the wet steam region is located. At 99,6°C the 1 bar isobar crosses the red boiling curve. Water begins to evaporate at this point. Under continuing energy supply the temperature and the pressure stay the same with an increase of the volume until all liquid water is evaporated in an isobaric process. After reaching the saturated liquid phase boundary (X=1) the temperature continues to rise under continuing energy supply. The water steam is called overheated steam in this region and behaves like an ideal gas in figure 3.

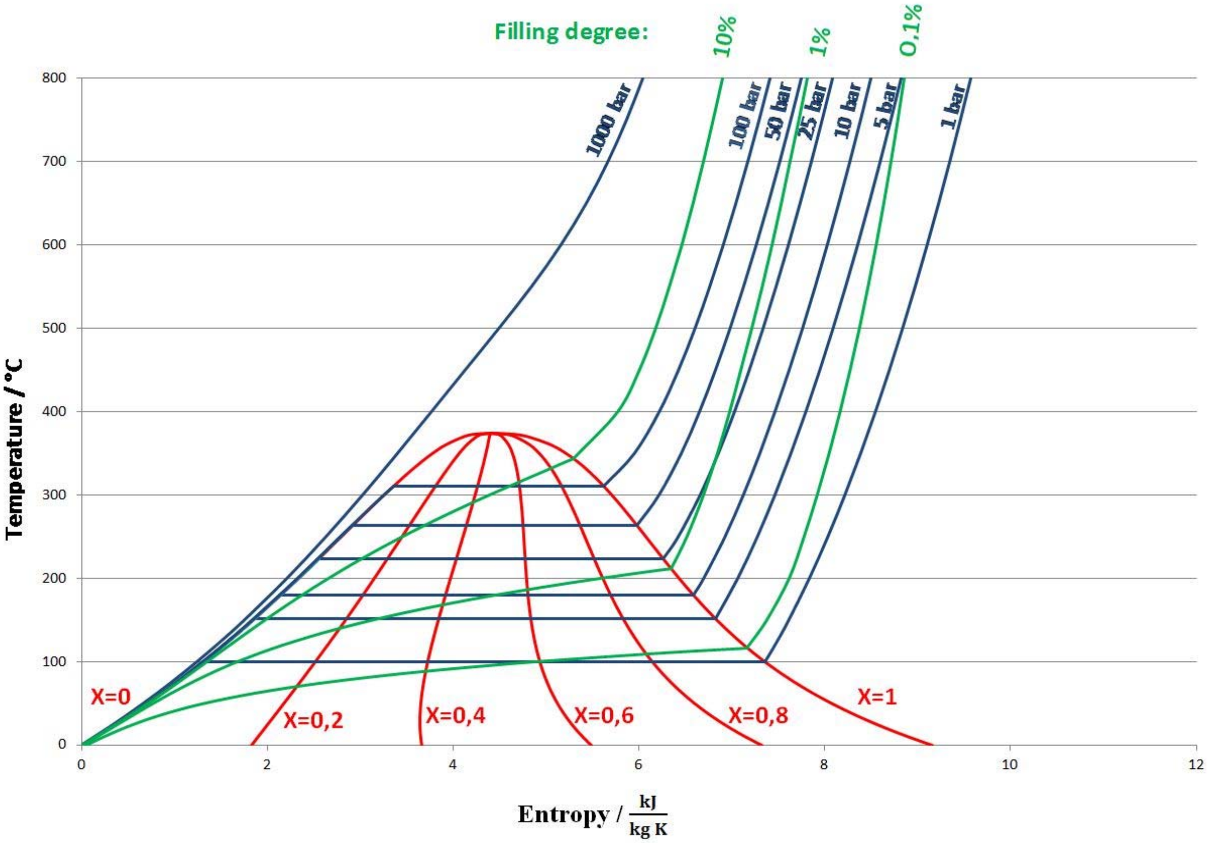


FIGURE 3 TEMPERATURE ENTROPY DIAGRAM SHOWING THE DEPENDENCY OF THE FILLING DEGREE THE POTENTIAL PRESSURE BUILD-UP AND THE TEMPERATURE

In a closed cask, the isochoric process is more interesting. In figure 3 these process is described in dependence of the filling degree of the cask. The filling degree is calculated as ratio between the volume of water in the cask and the sum of the volume of water and the free volume which is not taken by any other content. Under energy supply, the temperature and the partial pressure rise in the wet steam region as shown in figure 3. Even if all water in a cask is evaporated, the partial pressure will still rise with a continuing application of energy.

HEATING OF CONTAINERS WITH THICK WALLS

Contrary to common models of the process of vaporization in a closed system (autoclave e.g.) an uneven heating of the wet content occurs in packages with thick walls. As shown in figure 2, a thermal wave spreads out towards the centre of the container and its content during the fire test and even in the cooling down phase. As one consequence the maximum input of energy into the content happens after the fire period. Secondly the areas of the content close to the inner wall of the cask will be hotter than the inner areas. This means that in the outer and therefore hotter areas the vapor pressure will be exceeded earlier, and the free as well as the physically bound water starts to vaporize. Since the inner area of the content is cooler, the present steam condenses there. This results in a steam flow from the hotter areas into the cooler areas of the content. This steam flow transports mass in terms of water vapor stream, but also certain amounts of thermal energy. Thus, a lowering of temperature happens in the outer sections (as in the case of evaporative cooling) and inner sections will be heated up due to condensation. In total this process tends to balance the temperatures of the contents. Since the produced steam moves towards cooler areas and condenses, a lower pressure than expected is being build-up. This process of balancing the temperatures, and with this the reduction of the pressure build-up depends on many boundary conditions. The availability of free and physically bound water for vaporization depends on water permeability and bonding force of the content. The progression of a steam flow is strongly depending on the temperature distribution and the resistance to the flow. The more or less generic description of the content by the applicant (for such kind of transport approval procedures) due to insufficient availability of information does not allow inference of the above mentioned boundary conditions.

SIMPLIFIED TRANSFORMATION OF THE PHYSICAL EFFECTS FOR THE SAFETY ASSESSMENT

To determine the pressure, the temperature distribution in the content must be calculated for the whole period from the beginning of the thermal test until cooling-down. In this case, calculating the temperature distribution requires - besides conduction and heat radiation - consideration of evaporation and condensation including the associated processes of mass transport. If conservative temperatures of the content are considered, figure 3 could be used to determine the pressure in the cask. Using the dependencies between the filling degree and a conservative temperature, the effects of condensation and mass transport could be considered as included and the pressure in the cask can be determined as shown in figure 3. The difficulty is to determine a conservative temperature of the content which is not exactly specified.

The consideration of the heat transport into the content is another possibility if a finite element model is used which considers conduction and radiation only. The thermal energy evaluated in this way has to be related to the content. If it is assumed that the content is heated up uniformly, the average temperature of the content and the resulting pressure can be determined for any time step after the beginning of the thermal test. With the above described modeling (conduction only inside the cask) the temperature of the content right at the cask wall will be calculated noticeably too high. In reality, the boiling water remains at the temperature of 100 °C until the local water is vaporized entirely. Due to the modeling the temperatures at the interface of cask and content exceed 100 °C even if the corresponding boiling pressure is not reached. This leads to a lower thermal gradient and results in an underestimation of the thermal energy absorbed.

ANALYSIS OF THE MODEL TEST

The evolution of the temperature achieved from the numerical calculations was already shown in figure 2. The heat flux is analyzed by time in Figure 4 to consider the thermal energy transported into the content.

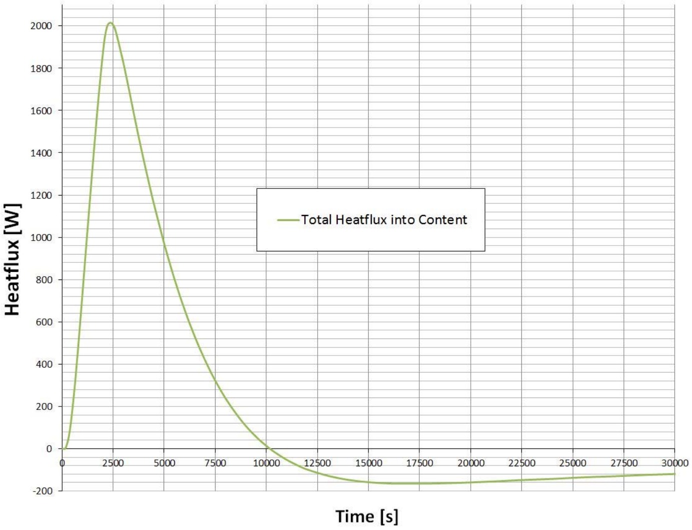


FIGURE 4 HEAT FLUX INTO CONTENT AS A FUNCTION OF TIME

The thermal energy transported into the content can be achieved by integration of the heat flux over time like shown in figure 5.

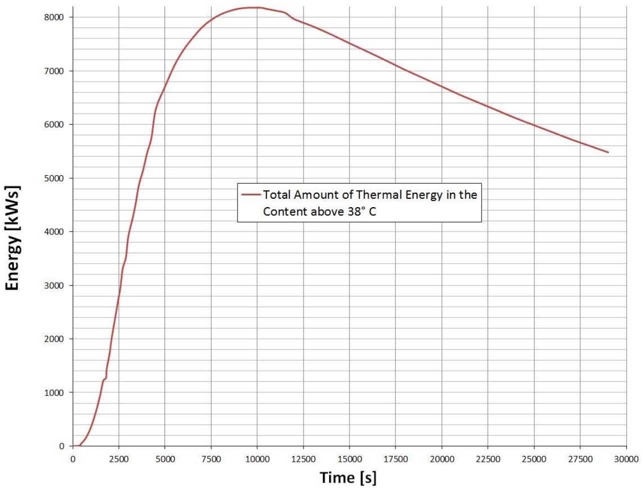


FIGURE 5 TOTAL AMOUNT OF THERMAL ENERGY IN THE CONTENT ABOVE 38 °C AS A FUNCTION OF TIME

The isotherms in the model cask at the point of the highest heat flux are shown in figure 6.

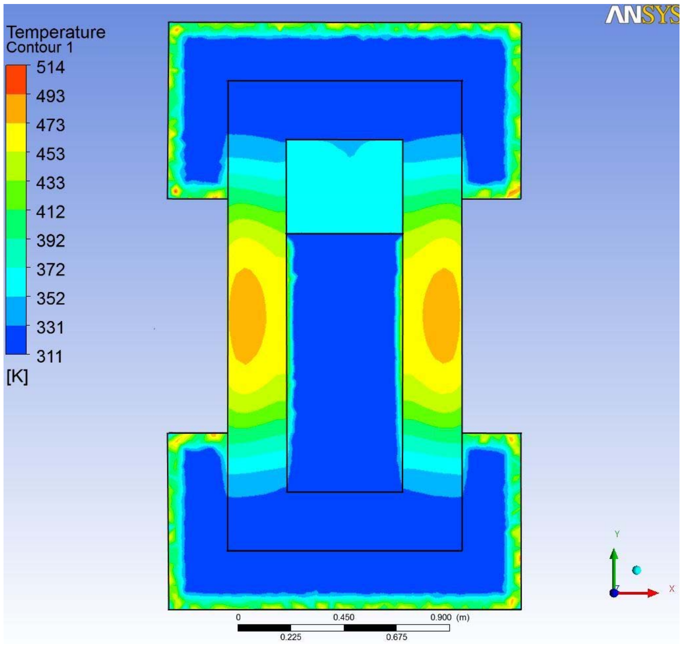


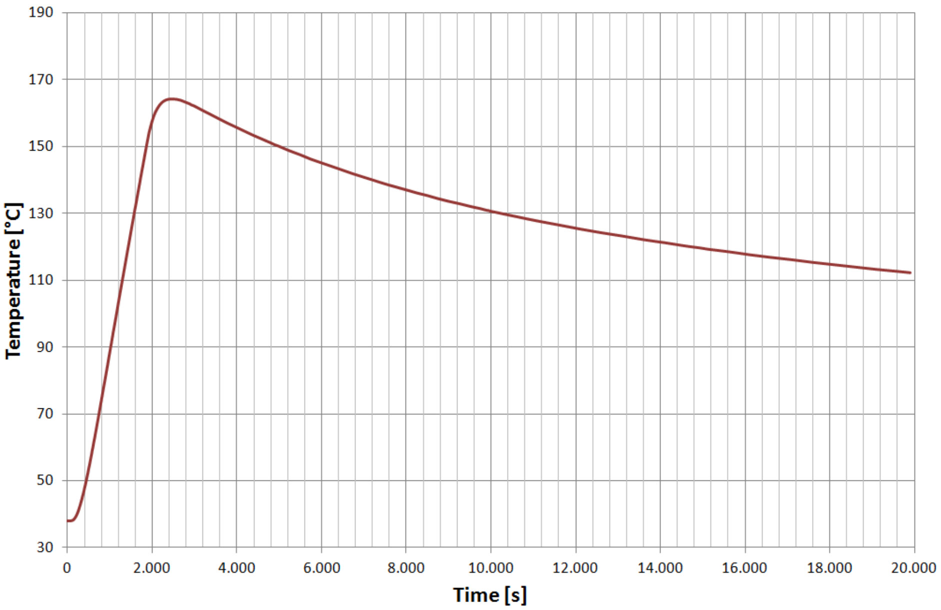
FIGURE 6 CROSS SECTION OF THE CASK MODEL WITH ISOTHERMALS AT THE TIME OF THE MAXIMUM HEAT FLUX INTO THE CONTENT

Since it is not possible to establish a proposition about the pressure based on the temperatures, additional consideration is given to energy. Concerning the simplified and noticeably not conservative assumptions a thermal energy of 8127 kJ was transported into the content at the point t = 10000 s (based on the initial temperature of 38 °C). Due to the insufficient specification of the content and the uncertainties in the numerical calculations a heating of the content in a layer of 5 mm at the cask wall will be examined with respect to the evaluation of a cask. This layer means a volume of 0,0043 m^3 which contains 2,6 liters of water. With the available energy the assumed amount of water will be vaporized to 4100 liters of steam. Since the inner volume of the cask (pores in the resin and the entire cavity) is 0,208 m^3, the water vapor partial pressure will be approximately 2 MPa in a first assumption. Actually partial pressures resulting from the emergence of gas out of radiolysis and additional effects are not taken into account so far. Even though the considered energy seemed to be rather small, a positive assessment is not possible for this simplified model. In the thermal assessment the description of the content is often enveloping, which means that the maximum masses and maximum radioactive activity of the content are given. This could lead up to a partly or even sparsely filled container at the end of the loading campaign. Assumed that such a container is filled with 5 liters of ion exchange resin only, a similar calculation as discussed before can be done: The small amount of water vaporizes completely, in this case into the larger space of 0,294 m^3 for gas. The resulting pressure will be approx. 1,5 MPa solely from the water vapor partial pressure. The heating of the package is determined by Para 728 "Thermal Test" [1] constraints. The heating of the content depends on more than just heat conduction and radiation, which in general are non-determinable. The determination of the temperature distribution inside the package for the calculation of the pressure build-up is not possible in the context of a safety assessment.

DETERMINATION OF PRESSURE BUILD-UP WITH RESPECT TO OVERHEATED STEAM

As it is often difficult to give an accurate specification of the content which is valid for all possible contents in the cask another conservative procedure will be discussed in the following to determine the partial pressure build-up due to water. This procedure takes into account limited amounts of water in the cask as well as a free volume which has to be guaranteed. A basic requirement is a negligible decay heat power of the content. With these values the description of the content can be limited to the essential parameters. To determine the partial pressure in the cask a FEM calculation will be used in connection with the diagram shown in figure 3. In the first step a thermal calculation of the cask without content has to be conducted to receive conservative temperatures. In most cases the highest average temperature reached during the process of the fire test and the cooling phase at the adiabatic wall in the cask can be taken as conservative temperature. As the amount of water is not exactly known in combination with the free volume in the cask, the boiling pressure of the corresponding temperature has to be considered. This takes into account the evaporation of all the water in the cask. But even in this case, a certain free volume has to be guaranteed; for the pressure to be determined at the saturated liquid phase boundary curve. If an accurate determined filling degree of the cask is given, it can be shown that the pressure stays below the corresponding boiling pressure corresponding to the determined temperature. With a filling degree of 0,1% of water it would not be possible to build-up a pressure higher than 0,5 MPa even at a temperature of 350°C as shown in figure 3. The cask shown in figure 1 was calculated again without any content, thus the inner wall has adiabatic boundary conditions. The average temperature of the inner wall during the fire test is shown in figure 7. The highest average temperature of the inner wall was reached after 2480 seconds and amounted to 164°C. When no decay heat power has to be considered in the cask, the maximum average temperature of the content will stay below this average temperature of the adiabatic inner wall of the cask. The calculated temperature of 164°C accounts for a partial pressure of 0,69MPa if in the approval procedure a certain volume is guaranteed but no filling degree is specified. If a filling degree of 0,1% can be guaranteed, a partial pressure of the overheated steam of almost 0,2MPa will be reached. Nevertheless, flow processes should be taken into account.

FIGURE 7 AVERAGE TEMPERATURES AT THE INNER WALL OF THE CASK WITHOUT CONTENT DURING THE 1800 sec FIRE PERIOD AND THE FOLLOWING COOLING DOWN PHASE



In summary, it can be shown by reference to the modeled cask with content, that a pressure of much more than 2 MPa can be achieved with simple and not even conservative assumptions. This model has shown the difficulties in modeling the content of the cask, and to find the correct interpretation of the calculated temperatures. Even modeling the evaporation and condensation would not solve the problem of developing a conservative model of the content. Comparing to the cask modeled without content, less attention has to be paid to define the content exactly. The water steam diagram (figure 3) displayed that the amount of water in the cask has to be specified in combination with the specification of the free volume to determine the pressure. This second model shows that the reduction of water in the cask reduces the partial pressure of water steam significantly. Nevertheless, gasification or even pyrolysis of the content is not considered in both shown procedures.

CONCLUSION

Computational Fluid Dynamics (CFD) analysis regarding mass and energy flow to determine a high quality temperature distribution are impossible without an exact specification of the content and other boundary conditions. As shown in this paper even small amounts of energy can lead to pressure inside the packages, which make it impossible to fulfill regulatory requirements for such kind of package designs and contents.

Doing these assessments by (computational) calculation only, three possible outcomes arise:

- The package design has very large safety margins, potentially because the package is totally covered by its impact limiter. Regarding the pressure build-up the package could fulfill the regulatory requirements.
- The package design could not fulfill the regulatory requirements, potentially because of an amount of energy which leads to total vaporization of all liquid inside the package.
- All assessments with results between those two extreme outcomes (fulfill/not fulfill) must be stated as unacceptable regarding the fulfillment of the regulatory requirements, since no trustworthy result regarding the pressure build-up inside the package could be produced.

To get realistic and trustworthy results in safety assessments, physical fire tests should be taken into consideration. Since in general physical fire tests could represent just a single state of content, the requested content for a package should be specified exactly. This helps to minimize the number of physical fire tests in a safety assessment. However, the difficulties of assessing casks containing wet content are shown. From the authority assessment point of view, drying of the content could be an effective way to avoid the above described pressure build-up and the associated difficulties for the safety assessment.

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