COMPARISON OF THERMAL TESTS BEFORE AND AFTER THE FREE DROP TEST OF A RADIOACTIVE MATERIAL TRANSPORT PACKAGE

by

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Scientific paper
https://doi.org/10.2298/NTRP2303155M

The transport safety of radioactive material is of utmost significance, which is mainly based on the safety of packages. In accordance with the IAEA Regulations for the safe transport of radioactive material, radioactive material transport packages undergo rigorous testing under diverse transport conditions including free drop tests and thermal tests. The determination of the appropriate thickness for the insulation layer poses a challenge, as it necessitates the consideration of factors such as the dissipation of internal heat sources and protection against fire accidents. Finite element simulation is usually used for the design and testing of packages. The requirement of the cumulation effect for the drop test and thermal test makes it harder for the finite element method in testing. In this paper, a method for thickness changing of insulation layer thickness in finite element simulation was developed and verified. A radioactive material transport package is taken as an example for the cumulating effect of the drop test and the thermal test.

Key words: radioactive material transport, finite element simulation, thermal test

INTRODUCTION

All kinds of radioactive material (RM) are transported every day around the world [1] and the RM transport (RMT) safety is an important part of nuclear safety [2-4]. The RMT packages are the most important safety barriers for the transport of radioactive material. According to IAEA Transport Regulations (SSR-6) [5], RMT packages are subjected to tests under various normal transport conditions and accident transport conditions, such as free drop tests, and thermal tests. The thermal test is an important part of RMT package design. Insulation material is important in the thermal design of an RMT package, not only the properties of the material but also its thickness [6-9].

For an RMT package with an internal heat source, the thermal performance does not improve with thickness of the insulation layer. The thickness of the material needs to be such that the heat generated by the internal heat source can be dissipated. On the other hand, it is necessary to ensure that only limited external heat can be introduced to the internal in the thermal test. Therefore, the impact of the drop test on the thermal insulation performance is not necessarily solely favorable or unfavorable. Due to the complexity discussed above, finite element simulation is often used for the thermal design of packages [10-14].

For Type B packages, it is necessary to withstand the cumulative test of the drop test and the thermal test. The drop test may have an impact on the thermal performance of the RMT packages. However, few papers considered this effect, which means that few thermal designs consider drop tests for transport packages. Due to the complexity of the model building, the drop test and the thermal test are often considered independently in previous simulation studies.

In this paper, a method for simulating the thickness variation of the insulation layer by changing the material parameters is developed and verified by simulation. It is possible to simulate the thermal performance of the package with different insulation layer thicknesses without repeating building complex models. A typical RMT package was used as an example to illustrate the effect of the drop test on thermal performance.

METHODOLOGY

In the collision of RMT packages, in addition to possible damage to the package, damage to the sealed boundary, *etc*., the most influential factor on thermal

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performance should be the impact of the thickness change of the insulation layer. In simulation studies, it is a complicated matter to perform thermal analysis on the model after impact. This complexity is reflected in the fact that on one hand, the simulation of impact accidents generally requires the use of impact dynamics transient analysis, which is not easy to obtain the final plastic deformation after the package drops, on the other hand, the deformation of the package caused by the drop accident is often irregular. This would make the simulation much more difficult as the stability, contact analysis and other things are complex. In addition, the impact may break certain parts of the package, especially the outer parts, which creates additional problems.

A simplified and conservative method is to extract the thickness variation of the thermal insulation layer during the drop test. Based on the minimum thickness of the thermal insulation layer during the drop process, the finite element model is re-established for thermal test simulation analysis. However, the disadvantage of this method is that the workload of re-establishing the finite element model is large. Especially in optimization and comparative analysis, changing the geometric model always results in the entire process of the finite element analysis being repeated.

THEORETICAL ANALYSIS

If the change in geometrical thickness can be equivalent to changing the material parameters, the process will be very simple. Simply changing the material parameters can easily replace the re-establishment of geometric models, meshing, setting contacts, setting initial, and boundary conditions, and it can use the single-parameter optimization function of most software.

The main effect of thermal performance during the drop/thermal test is the thickness change of the heat-insulating material. The thickness variation of the heat-insulating material has two effects on heat transfer. First, assuming that the density of the insulation material does not change after the impact when the mass of the material decreases with thickness, the total heat capacity decreases and the absorbed heat decreases. Second, if the thermal conductivity of the material after the impact is constant, the heat flux of the insulation material changes with the thickness change.

The parameters affecting the previous two properties include: density, specific heat capacity, and thermal conductivity. According to the dimensional analysis, the specific heat capacity can be derived based on the density and thermal conductivity, so only the values of these two parameters need to be changed. When the thickness changes to N times, the mass is also changed to N times, and the density should be N times the original. The heat transferred per unit time becomes 1/N of the original, and the thermal conductivity is set to 1/N of the original. Summarized as follows

$$\rho \quad \mathrm{N}\rho_0 \tag{1}$$

$$\lambda \quad \frac{1}{\mathrm{N}}\lambda_0 \tag{2}$$

where ρ is the density, λ – the thermal conductivity, and subscript 0 represents the value before the thickness change N times.

Example design

As a verification of the aforementioned theory, a simulation scheme is designed. Assume a rod with a square-cross section of 10 mm × 10 mm, whose length $L_0 = 50$ mm. The material is a commonly used thermal insulation material called an aluminum silicate fiber blanket. Assuming that the compression factor is $\mathrm{N} = L_0/L = 2$ and 4, the length after compression is L = 25 mm and 12.5 mm. According to the formula in section Theoretical analysis, the material parameters are listed in tab. 1.

Table 1. Material parameters of aluminum silicate fiber

Parameter	No compression	N = 2	N = 4
Density, ρ [kgm^{-3}]	160	80	40
Thermal conductivity, λ [Wm^{-1}K^{-1}]	0.156	0.312	0.624
Specific heat capacity, c [Jkg^{-1}K^{-1}]	900	900	900

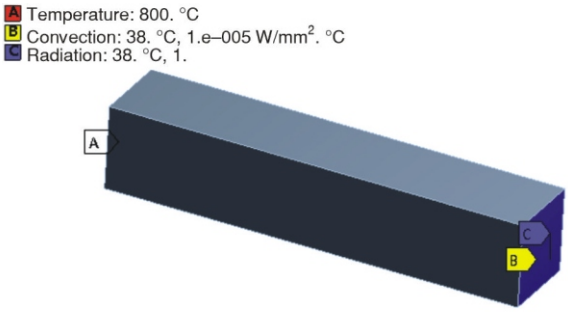
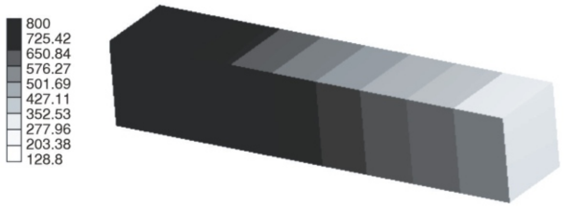


Figure 1. Model

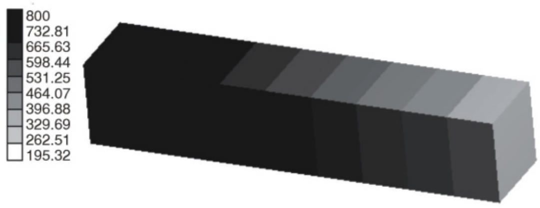
Apply the 800 °C temperature boundary condition at the left side of the rod, set the air convection heat transfer with a radiation boundary condition at the right side, and calculate the right end temperature at 1000 seconds by transient heat transfer. The calculation model is shown in fig. 1.

Comparison of test results

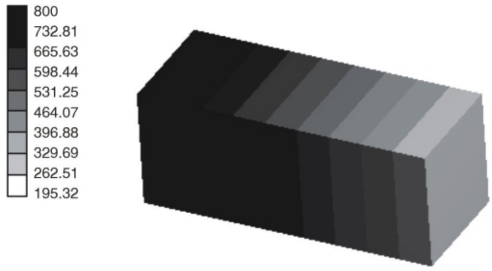
The temperature before compression, the temperature after compression of 50 mm length and the temperature under uncompressed parameters of 25 mm/12.5 mm length were calculated separately. The results are shown in fig. 2 and tab. 2.



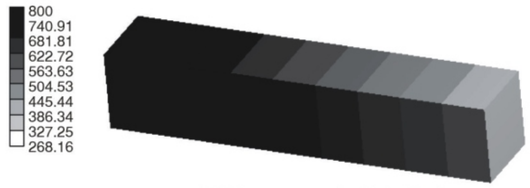
(a) 50 mm no compression



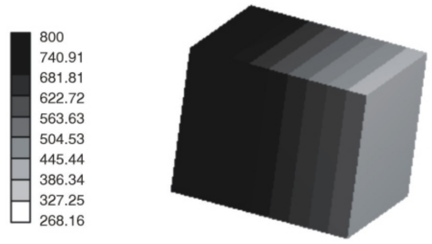
(b) 50 mm, compression factor N = 2



(c) 25 mm, no compression



(d) 50 mm, compression factor N = 4



(e) 12.5 mm, no compression

Figure 2. Simulation results

Table 2. Temperature of the right end

Condition	Temperature [°C]
50 mm, no compression	128.8
50 mm, compression factor N = 2	195.32
25 mm, no compression	195.32
50 mm, compression factor N = 4	268.16
12.5 mm, no compression	268.16

It can be seen from the previous simulation results that the calculated value of the right end temperature after compression of 50 mm by using the compressed parameter is higher than that of the uncompressed parameter, and the result is exactly the same as the length of 25 mm/12.5 mm which means that this method is reasonable.

CALCULATION AND RESULTS

For a typical radiation source transport package, drop and thermal test simulations were performed. The results of different drop attitudes were simulated, and the results with the greatest influence on the thermal insulation performance were selected and analyzed for thermal test simulation. The results were compared with the thermal test simulation for the package without the drop test.

Model

The structure of the package is shown in fig. 3. It mainly includes two parts: outer packaging and inner packaging. The outer packaging is made of aluminosilicate fiber coated with stainless steel, which is mainly used for impact resistance and heat insulation. The inner packaging is made of stainless steel and polyethylene, which is used for containment and shielding. Wood is between the inner and outer packaging as a shock-absorbing and insulating material. The thermal power of the contents of the package is 45 W, and the inner seal is the key location of the containment system. In this example, we need to pay attention to the temperature value to avoid rubber melting failure and ensure the sealing performance of the package.

According to the requirements of IAEA SSR 6, the Type B package shall be subjected to the superpo-

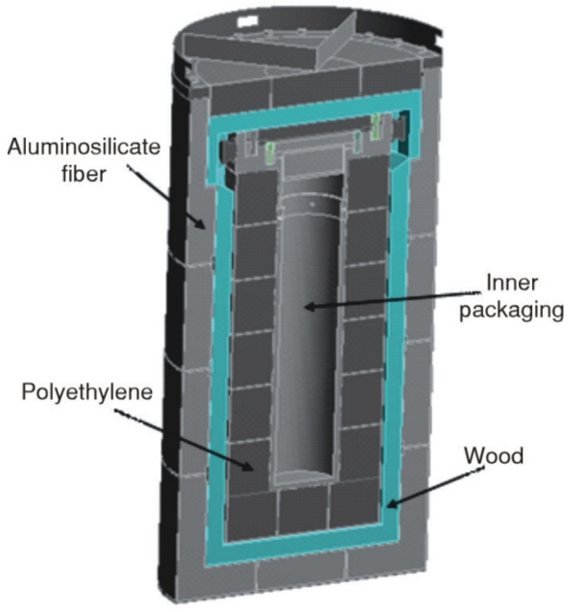


Figure 3. Package structure

sition test of the free drop Test I and the thermal test under accident conditions. In the drop Test I simulation, the package was free to drop from a height of 9 m onto the rigid target surface, taking into account the five attitudes of the bottom surface falling, the top surface falling, the side falling, the bottom corner falling and the top corner falling. The results of the drop simulation were analyzed to determine the thickness change of the insulation layer in different falling attitudes, and the maximum thickness variation of the insulation layer was extracted. The thickness change would be taken as an input condition for the thermal test next.

Drop test results

Figure 4 shows the deformation of the outer packaging when the compression is maximum under each drop attitude.

After analysis, it is considered that the top surface falling leads to the maximum compression of the heat insulation layer, and the minimum thickness after compression is 32 mm, which is used as the input condition for the package model of the after the drop thermal test simulation.

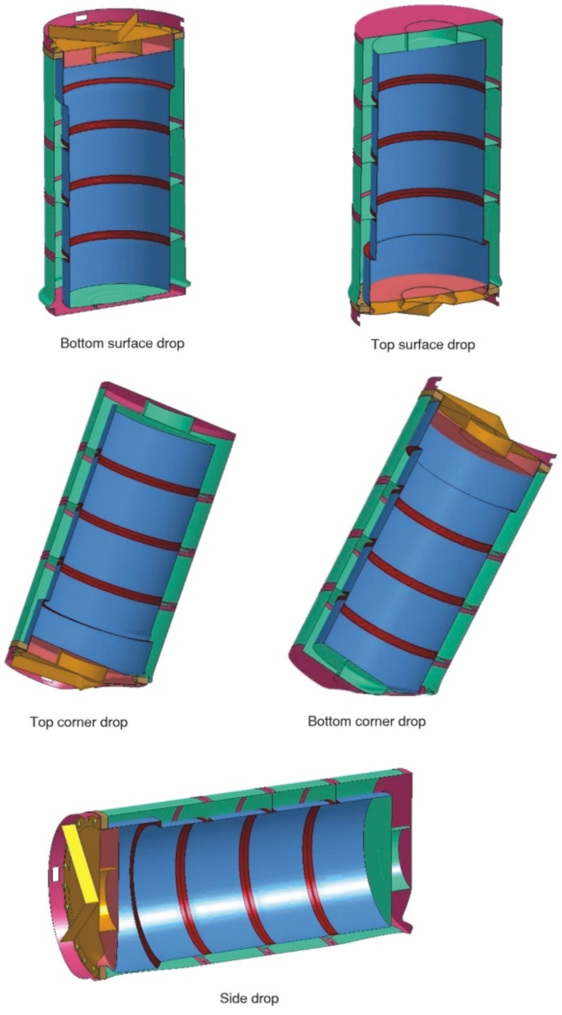

Bottom surface drop
Top surface drop
Top corner drop
Bottom corner drop
Side drop

Figure 4. Deformation for the drop test

Thermal test results

The original thickness of the heat insulating material in the top cover is $L_0 = 100$ mm, and the thickness after compression is $L = 30$ mm, taking $N = L_0/L$ 3.33. The main parameter values before and after compression are shown in tab. 3.

Table 3. Material parameters of aluminosilicate fiber

Parameter	Before compress	After compress
Density, ρ [kgm^{-3}]	160	48
Thermal conductivity, λ [Wm^{-1}K^{-1}]	0.156	0.519
Specific heat capacity, c [Jkg^{-1}K^{-1}]	900	900

According to the requirements of SSR 6, considering the internal thermal power of 45 W, the outer surface is applied with different insolation power conditions or flame temperature conditions and convective heat transfer coefficients for different surfaces according to the requirements and is calculated in three steps, as the insolation step, the burn step, and the cooling step. The results considering or not considering the compression of the thermal test were compared.

Step 1 – static thermal state under exposure conditions

The overall temperature distribution of the package and the temperature distribution at the seal of the inner package are shown in fig. 5.

It can be seen that under the insolation condition, the maximum temperature of the package without compression is about 84.4 °C, the temperature of the sealing ring is about 68.4 °C, the maximum temperature of the package after compression is about 83.6 °C, and of the sealing ring is about 56.1 °C. The temperature after compression is lower, because under this condition, the influence of the internal heat source on the temperature of the package, especially the temperature of the seal position, is dominant. When the thickness of the insulation layer of the package is reduced, the heat preservation capacity deteriorates, and the heat generated by the internal heat source is more easily exported, so the internal temperature is lower, which conforms to the physical principle, and also indicates that the impact of the collision on the temperature distribution of the package under insolation is obvious.

Step 2 – the transient thermal simulation

The transient thermal simulation is performed for the package at 800 ° C for 30 minutes burning and naturally cooled under insolation conditions

After 30 min heat, as shown in tab. 4, the temperature increase of the bottom of the out cover for the un-

Figure 5. Temperature results of the insolation condition

Table 4. Temperature for the bottom of the out cover

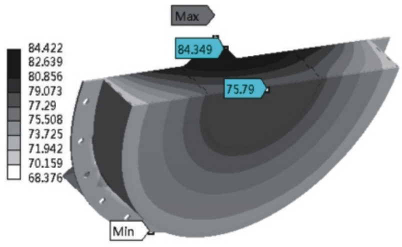
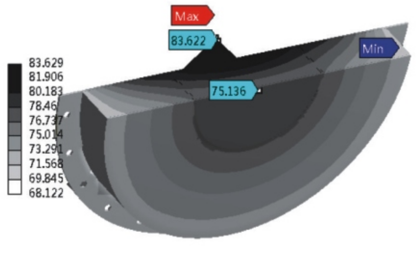
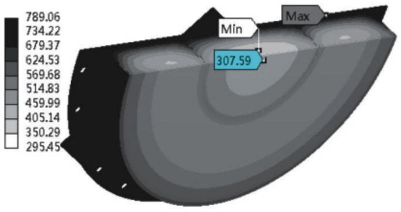
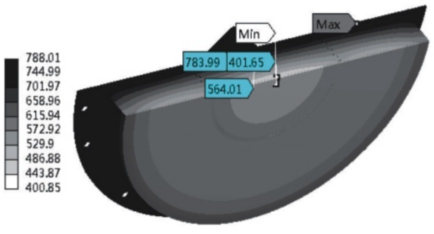
	No compression, [°C]	Compresion, [°C]
Before heating	 75.8 °C	 75.1 °C
After heating	 307.6 °C	 401.7 °C
Difference	231.8 °C	326.6 °C

Table 5. Temperature of the sealing ring

Temperature	No compression	Compression
Maximum temperature	76.2 °C	64.6 °C
Temperature change	7.8 °C	8.5 °C

compressed model and compressed model is 231.8 °C and 326.6 °C, respectively, which means the thermal insulation capacity has been weakened because of the compression during the drop test.

Check the maximum temperature of the inner packaging seal during this process. By simulation, for the package before and after the drop test, the sealing ring temperature reaches the highest temperature after 33478 seconds (9.30 hours) and 88383 seconds (24.55 hours), respectively, after the end of the fire. The maximum temperature of the non-dropped package seal is 76.2 °C, which is higher than 7.8 °C before burning, the maximum temperature of the seal after the drop test is about 64.6 °C, which is 8.5 °C higher than that before the fire, as shown in tab. 5.

CONCLUSIONS

In this paper, a method for simulating the thickness variation of the thermal insulation layer of RMT packages by changing the material parameters is developed. The theoretical analysis is verified by a simple example, and this method is applied to the drop test of a typical RMT package. The simulations of the thermal test before and after the drop test of the package were carried out. Quantitatively stated that for this package, the impact of the package will reduce the thermal insulation performance, which is beneficial to the derivation of internal heat, but is not conducive to thermal insulation during fire accidents.

This work illustrates:

The complexity of designing the insulation layer thickness of RMT packages. The internal heat dissipation and insulation functions need to be considered comprehensively, rather than the thicker, the better.

It shows that the cumulative impact of the drop test on the thermal test is significant and must be considered in the package test. According to the method in this article, the difficulty of designing the thickness of the thermal insulation layer using the FE method can be greatly simplified; it also provides a simple method for simulating the impact of the drop test on the thermal test.

It should be noted that in this method, the assumption that the density of the heat insulating material is constant before and after the impact and the thermodynamic parameters are not changed is not reasonable enough. In fact, the heat insulating material may be pressed during the impact process and also the density would be increasing, resulting in changes in its thermodynamic properties. Furthermore, different compression quantities at different locations lead to different material parameters. To further study the details of this problem, detailed experimental tests on the density and other thermodynamic parameters of insulation materials with different compression levels are required. In addition, the deformation of the metal casing wrapped around the insulation material also affects the heat transfer performance of the package. These issues are what we need to focus on in future research.

AUTHORS' CONTRIBUTIONS

The manuscript was written by D. Meng and S. Sun. The theoretical analysis was carried out by S. Sun and the finite element simulation was made by Q. Sun and Y. Zhang. All authors analyzed and discussed the results and reviewed the manuscript.

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Received on June 25, 2023
Accepted on December 4, 2023

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ПОРЕЂЕЊЕ ТЕРМИЧКИХ ТЕСТОВА ПРЕ И ПОСЛЕ ТЕСТА СЛОБОДНОГ ПАДА ПАКЕТА ЗА ТРАНСПОРТ РАДИОАКТИВНОГ МАТЕРИЈАЛА

Безбедност транспорта радиоактивног материјала је од највеће важности и заснива се углавном на безбедности пакета. У складу са правилником ИАЕА за безбедан транспорт радиоактивног материјала, пакети за транспорт радиоактивног материјала подлежу ригорозном тестирању у различитим условима транспорта, укључујући тестове слободног пада и термичке тестове. Одређивање одговарајуће дебљине изолационог слоја представља изазов, јер захтева разматрање фактора као што су дисипација унутрашњих извора топлоте и заштита од пожара. Симулација методом коначних елемената обично се користи за пројектовање и тестирање пакета. Кумулативни пад и термички тест отежавају примену методе у испитивању. У овом раду развијена је и верификована метода за промену дебљине изолационог слоја у симулацији методом коначних елемената. Пакет за транспорт радиоактивног материјала узет је као пример за ефекте кумулативног теста пада и термичког теста.

Кључне речи: транспорт радиоактивног материјала, симулација коначних елемената, термички тест