MODELLING THE THERMAL PERFORMANCE OF CORK AND WOOD IN THE THERMAL TEST

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ABSTRACT

Cork and wood are materials which are frequently used in the design of transport packages, both inside transport flasks and in impact limiters or heat shields which are placed on the flasks during transport. Cork and wood are used in transport packages because they readily compress, absorbing energy during an impact, and also have a low thermal conductivity, protecting the flask from the heat of a fire.

It is challenging to demonstrate, by testing alone, that a package meets all the thermal requirements of the IAEA Regulations. Nearly all thermal assessments therefore include some modelling. Cork and wood are natural materials and at high temperature their thermal behaviour is complex. A thermal assessment of heat transfer across a cork or wood heat shield, based just on reference values of density, specific heat and thermal conductivity may therefore be subject to considerable error.

This paper addresses the challenge of modelling heat transfer through cork and wood, in a demonstrably pessimistic way, such that the effects such as charring, evaporation and condensation of water and oils, shrinkage and burning can be shown to have been considered and included.

It is concluded that the modelling of heat transfer through cork and wood must be based on experimental data. Examples of thermal tests which include heat transfer through cork and wood are given and the calculation of the corresponding effective thermal conductivities described.

In some situations it is known that the wood inside a transport package or shock absorber may burn, releasing heat. Ways in which any heat generation from burning can be included in the thermal model are described.

INTRODUCTION

Wood and cork are materials which have been used in many designs of transport container for transporting radioactive material. They have been used in a wide range of designs from the large casks used to transport used fuel, down to the packages used to transport small sources. In some packages, wood and cork are used in the shock absorbers which are attached to the flask during transport. In other packages, they are incorporated inside the flask itself.

There are many reasons why wood and cork are commonly used. These include:

- Good impact absorbing properties
- Good thermal resistance against fire
- Relatively light weight
- Low cost

Although wood and cork are known to be good at protecting the contents of a transport flask from the heat of a fire, their behaviour when exposed to high temperatures is actually very complex. The phenomena which may occur include:

- The evaporation of moisture
- Carbonisation
- The release of waxes and oils

- Shrinking
- Burning

All these phenomena will affect the transfer of heat across the wood or cork.

WHY HEAT TRANSFER THROUGH WOOD NEEDS TO BE MODELLED

In the past, the thermal performance of a package design may have been demonstrated by testing alone. This would include a full-scale pool fire or furnace test upon a flask which had previously been subjected to a series of impact tests (as required by the IAEA Regulations [1]). Today, however, the thermal assessment required by many competent authorities is more rigorous and the following criticisms could be made of the practical approach to demonstrating the performance of a cask in the thermal test:

- Solar insolation is not included in the initial temperature distribution
- The initial temperature distribution does not correspond to an ambient temperature of 38°C
- The initial temperature distribution (probably) does not include the effect of heat generation by the radioactive material
- The ambient temperature during the cooling phase is not 38°C
- Solar insolation is not included during the cooling phase

Depending upon the conditions of the test, there may also be criticism of the flame coverage or that the flame temperature was not 800°C or higher for the full 30 minutes specified in the IAEA Regulations.

Today, therefore, some modelling of the thermal performance of a package design will usually be required, even if practical thermal tests have been performed. For those designs of flask incorporating wood or cork it will therefore be necessary to model heat transfer through these materials.

CHALLENGES TO MODELLING

Some of the processes which occur in wood and cork when heated to high temperature in a fire were listed in the introduction. However, it is not currently possible to reliably model any of these phenomena. Modelling heat transfer across wood and cork, when exposed to a fire, is therefore challenging and these materials cannot be treated simply as solids with values for density, specific heat and thermal conductivity which are available from published sources or the material suppliers. It is generally not valid to assume that thermal properties measured near room temperature can be used at temperatures up to 800°C. Nevertheless, as described in the previous section, it is important that heat transfer through wood and cork be included in thermal models of transport flasks.

An additional challenge to modelling heat transfer through wood and cork is that the modelling needs to be demonstrated as reasonably accurate, or pessimistic, to the satisfaction of the competent authority. Thus, even if models for the various phenomena were available, their accuracy would still need to be demonstrated.

RECOMMENDED APPROACH

The approach that is recommended is to model the cork or wood as a simple solid material with effective thermal properties (density, specific heat and thermal conductivity) which are demonstrated as pessimistic by comparison against practical tests. These tests need not be on a full-scale flask but instead could be designed to expose smaller samples of the cork or wood to conditions which would be experienced in the full-scale flask during the thermal test. Examples of such practical tests are given in the next section.

Many designs of flask will have pool fire or furnace tests performed upon full-scale, impact damaged prototypes. In principal such tests could be used to determine the effective thermal properties of any cork or wood in the flask, the assumed properties of the cork or wood being adjusted until reasonable agreement is obtained with the temperatures measured in the test. In practice, however, fire tests upon actual flasks are not intended as thermal property measurement tests and may be far from ideal due to:

- the complexity of the flask design
- the presence of several different heat paths through more than one material whose thermal properties are unknown
- the internal temperature measurement instrumentation inside the flask may be limited

In practice therefore, it is difficult to use the data from tests on actual flasks to determine the effective thermal properties of wood or cork. It should be recognised, however, that the ability to replicate the thermal performance of a flask in a pool fire or furnace tests is the best way to validate a thermal model but, ideally, the effective thermal properties of any wood or cork in the flask will have been determined in separate thermal tests prior to be applied to the model of the complete flask.

EXAMPLES OF LABORATORY SCALE TESTS

Example 1 – Simple Test Without Calorimeter

A series of tests on various materials which potentially could be used in transport flasks, including wood and cork, were performed at Harwell in around 1975 [2]. One of these tests is shown in Figure 1. The insulating material, or sandwiches of different insulating materials, were mounted at each end of a thick-walled cylinder, around 0.3m in diameter and 0.3m long, so that only the outer face of the insulating material was exposed. the test section was placed inside a furnace at 800°C for 30 minutes (the thermal accident conditions as specified in the IAEA Regulations [1]) followed by a period of cooling in the open air.

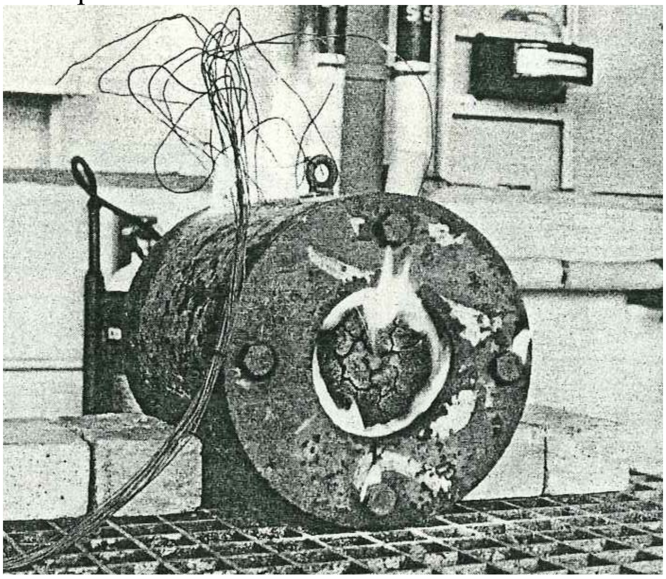
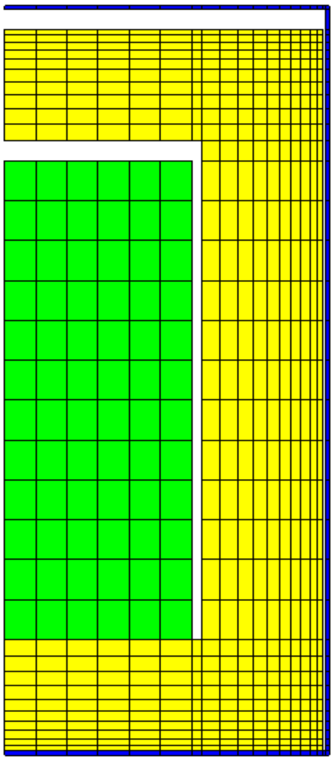


Figure 1. Test Section after Removal from Furnace

It should be noted that these tests were performed primarily to determine the behaviour of various insulating materials rather than as a measurement of heat transfer through the materials. Its shortcomings as a heat transfer test include the significant heating through the sides of the test section (i.e. 'edge effects') and the absence of any calorimeter to determine the heat flow.

Example 2 – Simple Test With Calorimeter

A second series of tests were conducted at Harwell in 1979 [3]. In these tests a steel cylinder (calorimeter), 244mm long and 175mm was surrounded by a 57mm thickness of the insulating material being tested and sealed inside a steel drum. The test section was again heated in a furnace at 800°C for 30 minutes. The test section is illustrated in Figure 2. This is a good heat transfer test as the heat transferred through the insulating material can be determined from the rate of heating of the calorimeter.



Key
Blue – stainless steel can
Yellow – wood or cork
Green – steel calorimeter

Figure 2. Design of a Simple test Section With Calorimeter

When a test such as this is performed, it should ideally be carried out using the same material as that proposed for the transport flask and the thickness of the insulating material around the calorimeter should be the same as the thickness of the material in the flask. Ideally the calorimeter should be designed to have a thermal capacity such that it heats up at approximately the same rate as the inner surface of the insulating material in the actual flask during the thermal test. Croft, for example, started a series of tests in September 2010, similar to the Harwell tests described above but updated to test a representative thickness of the particular cork that they use in their flasks, with a calorimeter designed specifically for the testing of that cork.

Example 3 – Test Of Wood Burning

A test was performed at Winfrith in 1990 [4] to test the performance of a shock absorber filled with balsa wood when exposed to the IAEA thermal test. The balsa wood is clad in stainless steel which should prevent the wood burning, as the supply of oxygen is limited. However, the impact tests, and the punch test in particular, can tear the steel cladding and this damage was simulated in the test.

Ideally, all heat transfer tests should be performed at full scale. However, cost considerations led this test to be performed at one third scale. Figure 3 shows the design of the test section. A slab of steel was placed inside the shock absorber to act as a calorimeter. Insulation was placed over the back of the calorimeter and the inside surface of the shock absorber (the faces which are normally adjacent to the transport flask).

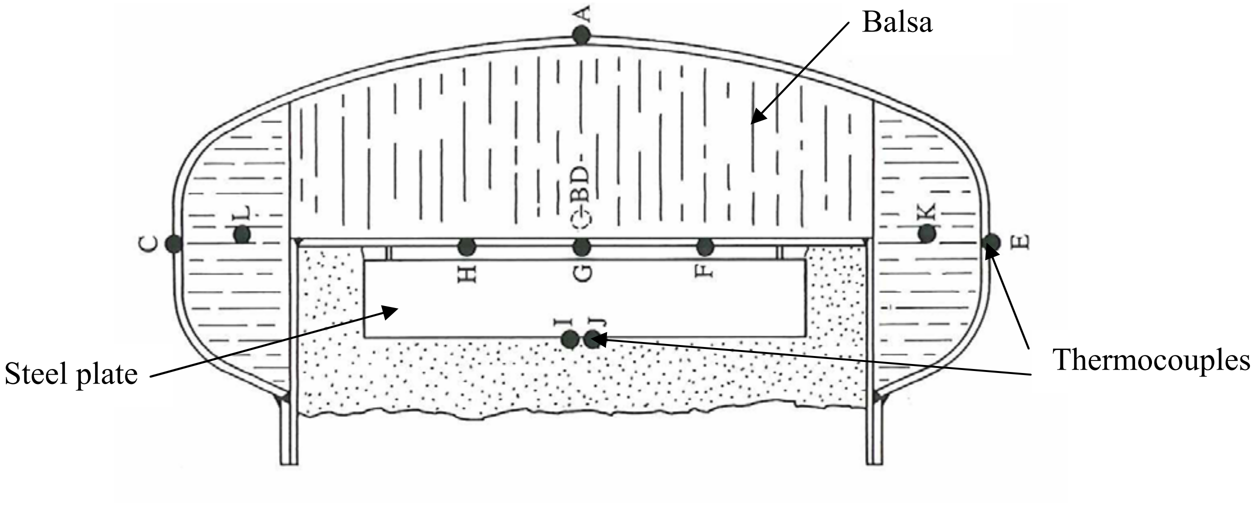


Figure 3. The Arrangement of the Balsa-filled Shock Absorber

The shock absorber was subjected to a 30 minute pool fire. The balsa was shown to act as an effective insulator, with little of the heat from the pool fire reaching the calorimeter. However, after the pool fire was extinguished the balsa continued to smoulder and slowly burn for a further ten hours. Figure 4 shows all the wood, now in the form of charcoal, that remained in the shock absorber when the burning had finally stopped. It can be seen that almost all the wood had been consumed. Although the heat from the slow burning of the wood is small compared to the heat from the pool fire, a thermal assessment of a transport flask containing wood should either include the heat generated by the burning of the wood or have a robust argument for why burning of the wood will not occur.

Figure 4. The Remnants of the Test Section after the Test

EXAMPLES OF MODELLING LABORATORY SCALE TESTS

Example 1 – Simple Test Without Calorimeter

The simple test without calorimeter, described previously, has been modelled using a simple 1-dimensional finite element model. It represented the cork, the cladding around it, and the insulation behind the cork. Figure 5 shows the temperatures measured in the test and the temperature predicted by the finite element model after adjustment of the cork thermal conductivity. In the model, the hot face of the steel cladding was fixed to the temperature measured in the test.

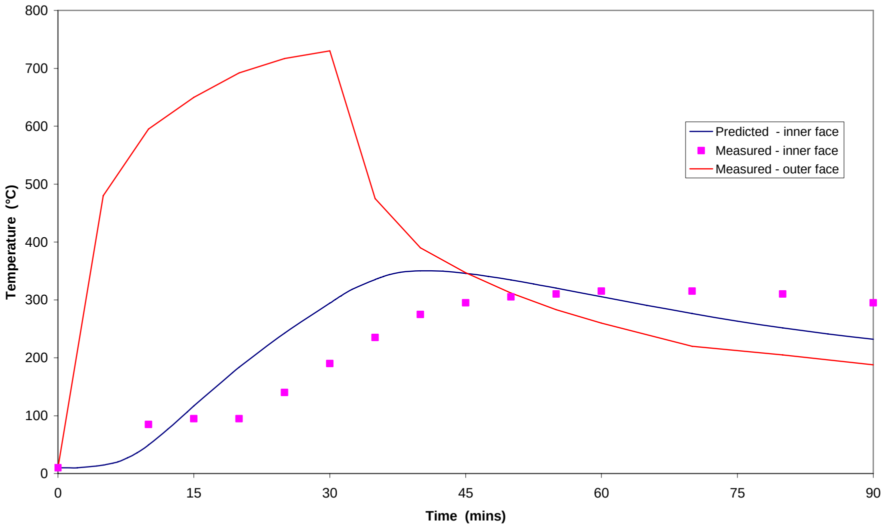


Figure 5. Measured and Predicted Temperature in the Test Without Calorimeter

It is interesting to note in this test that the measured temperature on the inner face of the cork rapidly rises to 100°C, where it remains constant for over 10 minutes. This is a clear indication of heat transfer by evaporation of moisture in the cork at the hot face and condensation at the cold face. This raises an issue of whether the effective thermal properties should be adjusted to match this observed rapid temperature rise. In practice, under the conditions of the thermal test as specified by the IAEA Regulations [1], an ambient temperature of 38°C plus the effect of solar insolation and any internal heat load will often raise the temperature of the flask contents to over 100°C before the start of the thermal test. No significant heat will therefore be transferred by evaporation and condensation of water vapour. To avoid arguments having to be made as to why the effects of condensation observed in a laboratory scale test should be ignored in the model, it is recommended that, before the start of the test, the temperature of the calorimeter at the centre of the test section (when present) be raised to the predicted temperature inside the actual flask under normal conditions of transport.

Example 2 – Simple Test With Calorimeter.

Figure 2 shows a axi-symmetric finite element model which has been used to model the simple test with a calorimeter conducted at Harwell described above. The model represents the cork, the steel drum and the steel calorimeter. Boundary conditions were applied to the exterior of the model representing heat transfer from the furnace.

The measured and predicted temperatures (after adjustment of the thermal conductivity) are shown in Figure 6. The measured temperature only starts to rise when the test section is removed from the furnace. It is suspected that the movement of the test section or disturbance of the instrumentation produces this observed sudden rise. It can be seen that the predicted heat transfer through the cork is pessimistic compared to be measured heat transfer.

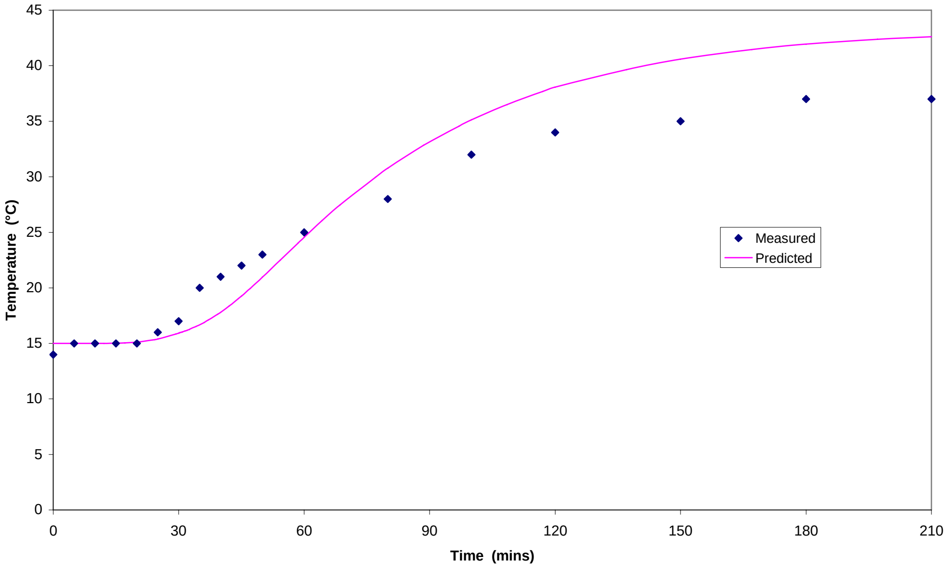


Figure 6. Measured and Predicted Temperatures in the Test With Calorimeter

<u>Example 3 – Test Of Wood Burning</u>

The measured temperature of the steel block inside the balsa-filled shock absorber is shown in Figure 7. During the pool fire there is only a modest rise in temperature, showing that the balsa provides effective insulation from the heat of the fire. After 2½ hours, however, the temperature of the block again begins to rise, reaching a peak 3½ hours after the pool fire has been extinguished. The measured temperature indicates a further, smaller, heat input to the steel block around 8 hours after the start of the test.

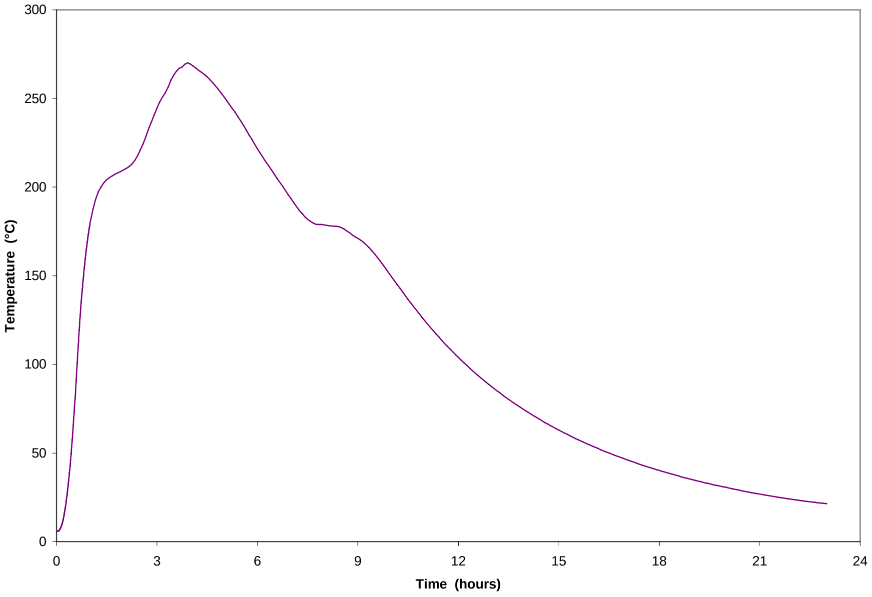


Figure 7. Measured Temperature of the Steel Block inside the Shock Absorber

Representing the heat from wood burning in an analytical model cannot be done by simply modifying the effective thermal properties of the wood. It is recommended that, from the result of the test, the heat flux to the calorimeter inside the test section be determined and a similar, or bounding, heat flux is applied to the surface of the flask inside the shock absorber to simulate the heat from the burning of the wood.

CONCLUSIONS

Heat transfer through cork and wood is complex because of the various physical and chemical processes which occur at high temperature. In the past, the modelling of such processes could be avoided by relying on practical testing of a transport flask in a pool fire or furnace. However, various aspects of the thermal test specified by the IAEA Regulations cannot be replicated by practical testing and so, today, some degree of thermal modelling will almost always be required.

When modelling heat transfer through wood and cork, it is generally not valid to assume that thermal properties measured at near room temperature can be applied at temperatures up to 800°C. It is therefore recommended that laboratory scale furnace tests be used to determine effective thermal properties for the wood or cork, and that these effective properties are then used in the thermal model of the transport flask.

Examples of such laboratory scale tests, and how they can be modelled to derive the effective thermal properties, have been presented.

REFERENCES

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