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Transport of Radioactive Material Code of Practice

Good Practice Guide to Thermal Analysis and Testing of Transport Packages

Produced by the Transport Container Standardisation Committee

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FOREWORD

Thermal performance is an important aspect of the design of any transport package and a key feature in regulatory testing and approval. This document provides guidance on the thermal testing and analysis of packages, to supplement and support the information provided in the IAEA Regulations and the accompanying advisory material. It is intended to assist packaging designers in selecting their approach to thermal testing, as well as experimentalists performing thermal tests, and analysts modelling the thermal performance of transport packages. It describes what is required from a thermal assessment and the issues which should be considered. It also provides guidance on which method (i.e. testing or analysis) might be most appropriate for different types of package.

Contents

1 Introduction

The temperature conditions experienced by a radioactive materials transport package are an important aspect of its safety. High temperatures could result in handling difficulties, as well as radiological safety issues caused by, for example, melting or softening of solid materials, degradation of seals or internal pressurisation. The control of temperature conditions is addressed in the IAEA Regulations for the Safe Transport of Radioactive Material (TS-R-1) [1], the prevention of damage caused by heat being one of the four principles of protection from the effects of radiation during transport. (The others are containment of the radioactive contents, control of external radiation levels and prevention of criticality).

The IAEA Regulations require that temperatures of the packaging and contents be considered under both normal and accident conditions of transport, according to the package type. For Type IP-3 and Type A packages, there are specific provisions relating to the temperatures of the packaging components (Para 637). For packages transported by air there are additional provisions relating to ambient conditions and to the temperature of the accessible package surface (Paras 617-619). For Types B(U), B(M) and C packages, and for some packages containing fissile material, there are more demanding requirements for normal conditions of transport (e.g. Paras 651, 652, 653, 664, 676). These include the package surface temperature and the effects of heat build-up on the package integrity and internal pressure. The package designer will need to demonstrate that, under normal conditions of transport, all the packaging materials (in particular the seals) are within their accepted temperature limits. The IAEA Regulations specify both the range of ambient temperatures and the heat flux from solar insolation that must be considered.

Additionally for Types B(U), B(M) and C packages etc., there are demanding thermal test requirements to verify the safety of the package contents under accident conditions of transport, comprising severe impact (or drop) tests followed by a fully engulfing fire (Paras 728, 736). The package designer needs to demonstrate that during and following these tests, the release of radioactive material remains within specified limits, the shielding provided by the package keeps the radiation flux outside it to within specified limits, and that criticality safety, where appropriate, is assured. The accident conditions specified for Type C packages are more severe than those for Types B(U) and B(M) containers. Type C packages also have to be able to withstand accidental burial (Para 668).

However, there is an exception for Type B(M) packages in Para 665 of the IAEA Regulations [1] in that alternative ambient temperature and solar insolation conditions may be assumed for packages to be transported solely within a specified country subject to the approval of the relevant Competent Authority. There is also an exception for packages containing fissile material in Para 676 of the IAEA Regulations [1] which states that packages shall be designed for an ambient temperature range of -40°C to +38°C unless the Competent Authority states otherwise in the certificate of approval for the package design.

The thermal assessment of a transport package is often inter-related with other aspects of the assessment:

- The temperatures experienced under both normal and accident conditions may cause thermal expansion leading to stresses and deformations in the package components.
- The temperatures experienced by the package under normal and accident conditions as appropriate will need to be taken into consideration when deriving the properties of materials during the structural, impact or shielding assessment.

- The damage caused to the container during the drop tests will need to be taken into consideration when assessing the temperatures experienced during a fire test.
- Any loss of material (e.g. due to burning or melting) which occurs during the fire test will need to be taken into consideration when assessing the shielding.

This Code of Practice is one of a series issued by TCSC. In using this guide, the reader is referred also to TCSC 1086 and TCSC 1087, which provide further guidance on drop testing of packages and on finite element analysis respectively.

2 Scope

This document provides guidance to designers on the thermal assessment of transport packages. It describes what is required from a thermal assessment and the issues which should be considered, and provides guidance on the choice of method (i.e. practical testing or analysis) for different types of package.

Testing for both normal and accident conditions of transport is covered, but because the thermal requirements on Type A packages are much less onerous than those on Types B(U), B(M) and C packages, the advice given in this guide is directed principally towards the thermal testing and analysis of these package types. Thus the term ‘transport package’ or just ‘package’ refers to Types B(U), B(M) and C packages or to appropriate package designs for fissile material or uranium hexafluoride.

The characteristics and applications of finite element analysis (FEA) and computational fluid dynamics (CFD) are considered, and advice on modelling and analysis, including the treatment of boundary conditions and uncertainties is included.

The range of provisions specified in the IAEA Regulations is not given in detail in this guide, and the reader is advised to consult the Regulations directly for the full and definitive requirements. The IAEA Regulations are updated from time to time and the appropriate edition should be consulted.

3 Testing or Analysis?

3.1 Regulatory Considerations

The IAEA Regulations [1] allow compliance, including thermal performance, to be demonstrated by either practical testing (exposure of the test package to a pool fire or heating under equivalent conditions in a furnace) or numerical modelling (Para. 701). Indeed, it is often not practical to perform some parts of the thermal assessment by practical testing and so some numerical modelling will be required. For example, when representing normal conditions of transport, it might not be practical to reproduce the ambient temperature of 38º C and solar insolation as specified in the IAEA Regulations, Paras. 654 and 655. Similarly, as solar insolation needs to be taken into consideration when specifying the temperature of the container at the start of the fire test, it might not be practicable to assess accident conditions solely by practical testing. Further to this, the IAEA Regulations specify that the package must be subjected to a specified series of drop tests prior to the fire test (Para 726). Currently these drop tests are always performed by practical testing. For packages which are relatively small in size or light in weight, the drop tests are usually performed on a full-scale package and may be followed by a practical pool fire or furnace test. For large, heavy packages (e.g. a used fuel package), scale models are usually used for the drop tests and these would not be suitable for a practical fire test, leaving calculation as the only realistic option. Numerical modelling is an invaluable tool for designers as it allows the thermal performance of a design, and design modifications, to be quickly and readily analysed without the need for practical testing. This modelling may be applied to both normal and accident conditions of transport.

It is possible for the thermal assessment of some packages to be performed by numerical analysis alone. For the majority of packages, however, the thermal assessment will include some practical tests. The decision on what practical tests should be performed will depend largely upon the design of the container. The Advisory Material [2] associated with the IAEA Regulations, provides extensive advice on the conduct of practical and analytical thermal testing.

3.2 Practical Considerations influencing Test Methodology

Under normal conditions of transport, the temperature of the package will be governed by the design of the package, the heat generated by its radioactive contents and the ambient temperature and any solar insolation. Heat transfer from the inside to the outside of the package is normally dominated by conduction. If this conduction is through a material with a well known thermal conductivity (e.g. stainless steel) and the geometry of the outer surface is one for which the natural convection heat transfer coefficient is well established (e.g. a flat vertical plate) then it should be possible to numerically model heat transfer across the package and heat loss from the outer surface with fair accuracy, depending on the quality of empirical correlations between calculated and actual convection effects. However, if the package design consists of different structures placed inside each other (e.g. an inner containment vessel inside an outer protective package) then there will be narrow air gaps and heat transfer between surfaces which may not be in good contact. These gaps will introduce uncertainty into the modelling of heat transfer across the package. Similarly, if the outer surface has a geometry for which there are no well-established correlations for heat transfer coefficient (e.g. a finned surface) then there will be uncertainty in the modelling of heat transfer on the outside of the package. If the temperature of the package is expected to be well below any temperature limits, then pessimistic assumptions on gap sizes and heat transfer coefficients can be used in the numerical model. If the safety margin is not large, however, a practical test of temperatures during normal transport will be required.

It should be noted that a practical test of temperatures during normal transport is not destructive. Therefore, if a full scale package is being built, either for testing under accident conditions or as a prototype, the additional expense involved in performing a thermal, normal transport test is probably quite modest. The performance of a test of temperatures under normal conditions of transport is recommended unless:

- The package design is such that heat transfer can be modelled with reasonable accuracy without any test data, or
- The safety margins are sufficiently large that pessimistic assumptions can be made to cover all uncertainties in the modelling, or
- Test data are already available from a very similar design of package.

A practical fire test is destructive in that, once exposed to a fire (or equivalent environment), the resulting thermal distortion, and any burning or melting, render the package unsuitable for any further purpose. A practical fire test can also only be performed at full scale since, from the equations describing heat conduction, scale model testing would only be applicable if the thermal properties of the materials from which the package is constructed could also be scaled (which is not feasible). It therefore follows that, if a practical fire test is to be performed on a complete package, a full-scale prototype of the package will need to be provided.

In order to numerically model the thermal test with acceptable accuracy, the behaviour of the materials from which the package is constructed, under the conditions experienced during the thermal test, must be known. For metals this is not a problem as long as they do not approach their melting point. However, package designers often use materials such as wood or foam to provide protection against the heat of a fire. These may be built into the packaging itself or incorporated in structures such as impact limiters which are attached to the package. The behaviour of these materials under fire conditions may be challenging to model. Wood, for example, will char, crack and shrink. It will also release steam and oils which may condense on colder surfaces. In the presence of sufficient air, wood may also burn, generating further heat. The heat generated by the burning of the wood will be much less than that of the pool fire (or equivalent thermal environment) but may continue for many hours. The package may be designed such that any combustible material is clad in steel, so that lack of access to air prevents combustion from occurring. However, the package designer will need to ensure that the drop tests to which the package is subjected prior to the fire test (particularly the punch test) cannot result in significant puncturing of this cladding. There are currently no established models for the behaviour of wood and similar materials that can be applied, with confidence, in a numerical model, without additional supporting experimental data.

If a package design contains a natural material with a complex behaviour, such as wood, but it is not feasible to perform a practical thermal test on the complete package (for example due to the cost of manufacturing a full-scale prototype package and impact testing it prior to the thermal test), then separate effects tests on samples of the materials, under the expected conditions, should be considered. Thus, if it is only the behaviour of the wood inside the impact limiter of a package which is uncertain, a thermal test on just the impact limiter should be considered. Or if foam or seals need to be shown to be capable of withstanding temperatures above their stated upper temperature limit for a few hours, a separate test could be performed just to demonstrate this. Again, such separate effects tests should ideally be performed at full scale. Thus, to demonstrate the heat transfer across a layer of cork under thermal test conditions, a sample of similar thickness should be tested under the conditions expected in the thermal test. When designing such separate effects tests, careful consideration should be given to how they will be analysed and how to appropriately represent any effects resulting from adjacent structures which would be present in a thermal test on a complete package (e.g. the presence of the package inside the impact limiters).

The objective of any separate effects tests on materials with complex behaviour, such as wood, would be to validate, or demonstrate as pessimistic, the way that the material is represented in the numerical model. It should be noted that standard tests (e.g. British Standard tests) may not always be appropriate for the intended purpose. For example, the measurement of thermal conductivity of an insulating material (such as wood) may specify that the sample should first be dried, whereas, in a package, the drying process (and condensation of the steam generated) is an integral part of its thermal behaviour.

4 Testing for Normal Conditions of Transport

4.1 Objective of Testing under Normal Conditions of Transport

The objective of a normal conditions of transport thermal test is to determine, for a known ambient temperature and internal heat load, the temperatures of the components of the packaging and contents. This enables the temperatures of the accessible surfaces to be determined and the performance of the package under the required mechanical test conditions to be evaluated (Paras 651 to 653 of the IAEA Regulations).

4.2 Set-up and Siting of Test Package

In a thermal test for normal conditions of transport, a full-scale package will usually be placed in a location where the ambient temperature can be controlled and electric heaters placed inside the package to simulate the heat generated by the radioactive material. The package will be left for sufficient time to reach steady conditions and its temperature measured. The electric heaters will not be able to reproduce exactly the heat distribution that would be created inside the package by the radioactive material. Nevertheless, the heaters should be arranged, as far as is reasonably possible, to reproduce the expected heat distribution. This may require the provision of some additional support or heat transfer structure (e.g. a copper or aluminium block with internal cavities for cartridge heaters to conduct the heat around the internal cavity of the package). Modification of some package components may also be required to enable the leads to the heaters and thermocouples to reach the inside of the package.

The package should be located in a room which is sufficiently large to have a minimal effect upon the convective natural heat loss from the outer surface of the package. Thus the amount of free space required around the package will depend upon the magnitude of the heat flux from the package. The room where the test is conducted should, as far as possible, maintain a constant temperature naturally and should be free of any draughts, forced air flows or sunshine. A room with thick walls and no windows, possibly underground, is likely to be suitable. It should be noted that, in general, the objective of the test is to provide data that can be used to validate the numerical model. Thus having a uniform temperature is more important than maintaining a specific temperature. For example, trying to create an ambient temperature of 38°C would probably require additional heaters which would create air currents (and possibly thermal stratification) which may affect the convective heat transfer from the package itself. If heaters (under thermostatic control) are provided in order to keep the ambient temperature constant, the target temperature should be as low as possible so that the heat required from the heaters is kept to a minimum. It should be noted that heat loss from the outside of the package will be by both natural convection and radiation. Heat loss by convection will be controlled by the ambient air temperature but heat loss by radiation will be controlled by the temperature of the walls and roof in the room. Ideally the walls and roof should all be at the same temperature as the ambient air. Measurement of the temperature of the walls would demonstrate whether they are at this temperature. Although heat loss by radiation from the surface of the package will, in principle, be affected by the emissivity of the walls and roof, as long as the room is considerably larger than the package (which it should be) and the walls and roof are not shiny, this should not be significant and no special treatment or measurement of emissivity should be required.

The package, in its support cradle or transport frame if used, should be stood on a layer of insulating material on the floor of the room. The insulation of the package from the floor both provides pessimism and simplifies the comparison of the test data with the numerical model, since there may be considerable uncertainty in the heat being transferred to the floor, especially if its temperature is not being measured.

Normal transport thermal tests should be performed with a heat load as near the design maximum as practicable to best differentiate the performance from thermal “noise” such as variations in ambient temperature. Tests may be performed for different orientations of the package as appropriate to transport practice.

4.3 Temperature Measurement

The package temperature is usually measured using thermocouples with an accuracy of ~1°C. In addition, a temperature probe can be used to measure the temperature of the accessible external surface. When mounting thermocouples, they should be placed, if at all possible, in good thermal contact with solid structures. Embedding the thermocouple junctions in holes drilled into structures is ideal. This avoids problems of not knowing what the measured temperature refers to (e.g. if just placed loose in an air gap) or any measurement errors due to heat conduction down the thermocouple tails. The temperatures should be recorded at regular intervals during the test. These transient data can then be used to demonstrate that steady conditions have been achieved or to compensate for any changes in ambient temperature during the test. The duration of the test will depend upon the design of the package and the internal heat load. Typically it may have to run for several days. Attention should also be paid to the measurement of the ambient temperature. Since what is required from the test is the temperature of the package above ambient, the ambient temperature should be measured with the same accuracy as the package temperatures. Ideally the ambient air temperature should be measured on each side of the package, at more than one height. Care should be taken for the thermocouples measuring the air temperature not to be affected by either radiation from the hot surface of the package or the hot convection currents adjacent to the package surface. Hence simple radiation shields might be placed around the thermocouples.

5 Testing for Accident Conditions of Transport

5.1 Objective of Testing under Accident Conditions of Transport

The fire test is performed in order to demonstrate that a package can withstand an accidental fire as required by the IAEA Regulations, which require the thermal test to provide a heat flux all around the package at least equivalent to an average temperature of 800°C with a flame emissivity coefficient of 0.9.

5.2 Factors Influencing the Test Method

A pool fire simulates most closely the thermal environment to which the package might be subjected, but pool fire tests produce large plumes of soot, unburnt hydrocarbons and carbon dioxide. Thus, on environmental grounds, furnace tests are preferred. Ovens or furnaces suitable for testing small packages are readily available although large furnace facilities are less easily procured.

One problem with the use of a furnace is that, at the end of the 30 minute (or 60 minute for Type C package) heating phase, the package has to be left to cool down in air at ambient temperature. This means that the package needs to be taken out of the furnace while still hot, and this may not be practical with some furnaces. Another problem, applying to both furnace and pool fire tests, is that the IAEA Regulations require the thermal test to be performed upon a package after first subjecting it to a series of drop tests. Following the drop tests, any protective shields on the package may be in a delicate state and liable to further damage during transport to the thermal testing facility. This requires that the minimum of transport be involved between the impact and thermal tests

5.3 Pool Fire Tests

For a pool fire test, the IAEA Advisory Material [2] advises that the pool should extend between 1 and 3 m beyond the edges of the package to help ensure a fully engulfing severe fire. In practice, however, there is no control over the resulting flame temperature or emissivity coefficient. This is generally recognised by the competent authority who has to attest whether the test meets the requirements of the regulations. The temperature of the flames should, however, be measured on each side of the package and the competent authority may only judge the test as starting once the flame temperature has reached 800°C. In a pool fire it can be challenging to ensure that the flames engulf the entire package. Any wind, in particular, will tend to distort the flame cover. The use of flame guides (thin vertical panels) below the package is recommended as these have negligible effect upon the flame temperature but prevent the flames from blowing under the package and leaving the upwind side with little, or no, flame cover.

A pool fire test will end when the fire goes out (rather than trying to remove the package from the fire). The fire can be carefully extinguished using foam once the specified heating time (30 minutes or 60 minutes for a Type C package) has been reached. The IAEA Regulations specify that the package should not be artificially cooled. Care must therefore be taken not to spray foam onto the package surface or to prevent any continued burning of the package itself. To avoid problems associated with extinguishing the fire, and to reduce the problem of dealing with unburnt fuel, it is preferable to let the fire burn itself out. However, sufficient fuel must have been loaded into the pool to ensure (with allowance for uncertainty) that the fire lasts for the required minimum time. The time for which the fire may burn before burning itself out may therefore be significantly longer than the fire duration specified in the IAEA Regulations.

The package should be oriented in the most pessimistic way during the fire test. For a package which is long relative to its width, orienting it horizontally is the only sensible option (although the package may be rotated). The location and nature of damage from the drop test also needs to be considered. It is recommended that the package be oriented so that any significant damage or loose panels are at the side during the fire, so as to maximize the heat input in this region, allow flames to enter any gaps and any loose material to fall out. The package designer would need to agree the most pessimistic orientation with the competent authority prior to the thermal (fire) test being conducted.

5.4 Furnace Tests

The temperature of a furnace is more controllable than that of a pool fire. In principle, therefore, a temperature close to (or ideally just in excess of) the 800°C specified in the IAEA Regulations should be achievable. The furnace may be pre-heated to the required temperature, but the act of opening the furnace for loading and the thermal mass of the package to be tested may reduce the temperature of the furnace considerably. The use of a relatively large and high power furnace, together with preheating to a higher temperature and ensuring a rapid loading procedure can minimize the cooling effect. The test is considered to start only when the required temperature has been reached or regained, although the competent authority may allow compensatory measures where appropriate. Ideally it is the temperature of the inner surface of the furnace walls that should be measured. If this is not possible and thermocouples are simply placed in the air inside the furnace, care should be taken that the measured temperature is not affected by the adjacent cold surface of the package itself (since heat transfer to the thermocouple will be dominated by radiation). Radiation shields between the thermocouple and the package could be used to prevent this from occurring.

5.5 Temperature Measurements

Ideally, in either a pool fire or a furnace test, the transient temperature at important locations (e.g. the lid seals) would be measured using thermocouples. However, because the thermal test is conducted after the package has first been subjected to a series of drop tests, in practice it is virtually impossible to attach any thermocouples to the internals of the package as these would get damaged by, or interfere with, the drop tests. Thus, thermocouples are only attached to locations which are readily accessible just prior to the thermal test, such as the exterior of the package and possibly through small gaps or holes (although their thermal contact with internal structures cannot then be assured). Temperature sensitive strips, which record through colour change the maximum temperature experienced (within a range of a few degrees), are well suited to measuring the maximum temperature reached inside the package. These strips can be attached to various solid structures when the package is assembled and can readily withstand the acceleration forces during the drop tests. However, if placed inside cavities containing wood or cork, oil and waxes given off by the heated wood can also discolour the strips. It is advised that any strips in such locations should be protected by covering with metal foil or similar material.

In a pool fire, and probably also in a furnace, the temperature measurements made by thermocouples can be affected by the heat from the flames. This has been clearly observed in type K thermocouples of 1mm diameter or less. Larger diameter thermocouples are less affected by the flames. If the thermocouple tails are long, false junctions are formed which add a variable component of the flame temperature to the temperature being measured at the thermocouple tip. This effect does not damage the thermocouple and the interference stops as soon as the fire is extinguished. If the thermal test is performed on a test section or component rather than a complete package (as discussed above) then, because the test section or component will not have to be subjected to actual drop tests, the use of thermocouples to measure internal temperatures can be more readily accomplished.

6 Thermal Analysis Techniques

6.1 General Considerations

Where temperatures are to be determined by calculation, straightforward situations may be assessed by basic calculation methods. However, for the complex thermal conditions obtaining in transport situations, particularly under fire accident conditions, computer-based techniques will be required. Both Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) codes can be used, in general, to solve thermal problems. Actually, the terms CFD and FEA are not mutually exclusive since some CFD codes use the finite element method. In general, however, most commercial CFD codes such as Fluent or CFX use a finite volume method and so are not classed as FEA codes.

6.2 FEA Codes

There are many FEA codes commercially available and the technique has been extensively developed over the years. Some codes (such as ABAQUS) focus on structural assessment but are also very capable of modelling heat transfer while others (such as TAU) are dedicated thermal modelling codes. Other codes, such as the widely used ANSYS code are very broad in scope and offer routines to deal with extensive ranges of structural and thermal analysis situations. FEA codes basically model thermal conduction through solid structures. Radiation heat transfer between structures or to ambient is modelled through appropriate boundary conditions. Convective heat transfer between structures or to ambient is also modelled through the application of appropriate boundary conditions. Most FEA codes require the user to input the appropriate convective heat transfer coefficient at each surface. The user may also have to input the appropriate radiation view factors but many FEA codes are able to calculate these automatically from the specified geometry. Further information on the use of FEA codes is given in TCSC 1087, see Introduction to this document.

6.3 CFD Codes

CFD codes, as their title suggests, model fluid flow and heat transfer. They model convective heat transfer at every element on the surface starting from the fundamental conservation equations governing fluid flow and therefore are intrinsically more accurate at calculating heat transfer into and out of a transport package. They also require far less input from the modeller as it is not necessary to calculate appropriate heat transfer coefficients for each surface or to adjust them to match actual performance during benchmarking or to document the process. They also automatically compensate for different package orientations and can readily include a fire updraught as mentioned in the Advisory Material [2]. CFD is especially suited to situations and geometries for which no established correlation for convection heat transfer coefficients are applicable. CFD codes can also model conduction through solids and thermal radiation between surfaces. When modelling radiation, CFD codes generally calculate the appropriate view factors automatically from the specified geometry.

6.4 CFD versus FEA

CFD codes are better suited than FEA codes for modelling convective heat transfer in complex or novel geometries. In the field of transport package heat transfer, a CFD code is more appropriate if a fluid medium (such as water) is used to transport heat around the interior of the package by natural convection (e.g. in some used fuel packages). CFD is also more appropriate for modelling heat transfer by convection and radiation from complex geometries on the exterior of a package (e.g. a finned surface covered by a shroud).

FEA codes are, theoretically, more accurate than CFD codes at modelling conduction heat transfer through solids. This is due to the ability of FEA codes to represent curved surfaces more accurately (as the elements used in FEA codes usually have mid-side nodes, enabling the side of a cell to be curved whereas CFD codes usually use only straight-sided cells). In practice however the difference in results from the two types of code is usually insignificant.

In general therefore, if both options are available, FEA codes may be used for the thermal assessment of simpler transport packages with adequate safety margins. Transport packages with more complex geometries and/or where margins are tighter are better modelled using a CFD code. Even if an FEA code is used to model the complete package, CFD may still be used to study particular aspects (such as heat transfer from a fin geometry on the outer surface).

Irrespective of whether a CFD or FEA code is used to perform the thermal analysis, the validation of the code needs to be demonstrated for the proposed application. Most FEA and CFD codes will be provided with validation cases. For CFD codes, however, these will probably focus more on modelling fluid flow than on conduction heat transfer. In 1986 a set of benchmark problems was established by NEACRP for demonstrating the ability of codes to accurately model transport package heat transfer problems [3]. These relatively simple benchmark problems would still be appropriate as a basis for demonstrating the validation, for performing package heat transfer modelling, of any FEA or CFD code for which insufficient validation is considered currently to exist.

7 Modelling – General Advice

7.1 Selection of Computer Code

Once the choice between Computational Fluid Dynamics and Finite Element Analysis has been made, there are additional factors to be considered in the choice of computer code. As well as the level of technical support available, the facility to import or export data and results to other codes that might be used for structural assessment of, for example, drop tests is important. Thus the selection of compatible codes would allow the predicted mechanical damage to be imported directly into the thermal model. Similarly the temperatures predicted in the thermal analysis of the package could to be used directly as input to an analysis of thermally induced stresses and distortions.

7.2 Considerations in the Application of Codes

The accuracy of any thermal calculation will depend not only upon the computer code used but also the experience of the user. All thermal calculations which are reported in the Design Safety Report should be performed by staff with appropriate training and experience of using the selected code to model thermal problems. The calculations will need to be performed in accordance with appropriate quality assurance procedures and verified by a suitably qualified person. Analysts should also follow any published best practice guides such as [4], [5] & [6]. Both the input decks and output from the code should be retained for at least as long as the package remains in use.

The design of the thermal model is discussed in the following Section. Section 8 discusses the selection of the material properties and boundary conditions which are applied to the model. More detailed advice on the modelling of normal conditions of transport and accident conditions is then given in Sections 10 and 11.

8 Modelling – Design of the Model

8.1 Simplification and Symmetry

Even with the processing power of modern computers, a calculation modelling the temperature of a transport package can take many hours to run because of the length and complexity of some thermal transient events. It is therefore worthwhile to simplify the model, if possible, in order to reduce the time required to perform the calculations. To this end, it may be possible to take advantage of design symmetry to model, say, a sector or quadrant of the design, or to consider a 2-dimensional model.

8.2 The Significance of Design Features

When designing a model and deciding the acceptable degree of simplification, it is important to assess the significance of the features of the design To make these decisions, the analyst needs to consider the important outputs from the model (e.g. the temperature at the lid seals) and the important heat transfer paths which will affect these outputs. Any feature which, from experience or simple calculations, is judged to have negligible effect on the temperatures of interest need not be represented in the model. Such features might include handles, tapped holes (for lifting attachments) and security features.

For items which may not be a significant heat transfer path but are important in their own right (e.g. vent valves) it may be more appropriate not to include them in the model of the overall package but, instead, to represent them in detail in a separate model. This would enable the item to be modelled in appropriate detail without adding significant complication to the overall model. If appropriate, the separate model could be used to derive effective thermal properties (e.g. conductivity) which could be used in the overall model to represent the separate item in a simple way.

8.3 Modelling Impact Damage

A further consideration when deciding whether a 2-dimensional model is appropriate is the detail of impact damage that needs to represented in the model (since the fire test is performed on a package which has already been subjected to a series of drop tests). Drop tests are frequently performed onto corners and even a ‘slap down’ impact on an axi-symmetric package will produce damage which is not axi-symmetric. However, if the impact damage is limited to structures with negligible thermal importance, or there is sufficient safety margin in the package design for the damage to be represented as occurring all around it, then it may reasonable to include the drop test damage in an axi-symmetric model.

When incorporating drop test damage into any model, the package is generally best modelled in the same orientation as was used for that drop test.

9 Material Properties and Boundary Conditions

9.1 The Effect of Temperature on Material Properties

In either a CFD or FEA thermal model, material properties will need to be supplied by the user for each of the materials. Reliable and citable sources should be used for these properties and the thermal conductivity and specific heat should ideally be specified as a function of temperature. Although the density of a solid will also change slightly with temperature as the material expands, in practice the mass of material in the package will remain constant. Appropriate values should be used for the density. If the design of the package includes a material for which no reliable data on material properties are available then it is recommended that the properties be measured. If there is significant uncertainty over the appropriate material properties then pessimistic assumptions should be made, as discussed in Section 12 below.

9.2 The Behaviour of Complex Materials

During the thermal (fire) test, some materials may be taken outside their normal range of operating temperatures (e.g. heating of foam to 800°C). Under these conditions, not only will material properties not generally be available but consideration will also have to be given to the behaviour of the material (e.g. charring). In particular this will apply to materials such as wood and cork which are commonly used in transport packages, or their shock absorbers, because of their ability to both provide insulation from a fire and absorb energy in drop tests. A further complication in the case of wood and cork is that they release steam and oils when they are heated which then condense on cool surfaces, introducing an additional heat transfer mechanism.

To ensure that the complex behaviour of materials such as foam, wood and cork at high temperature has been adequately captured in the thermal model, appropriate test data will be needed. As mentioned in Section 3, standard tests (e.g. British Standard) may not always be appropriate and tests should be conducted, as far as possible, to reproduce the conditions the material will experience inside the transport package when exposed to the thermal (fire) test. A separate effect test on a sample of material (of the correct thickness) has the advantage of being easier to analyse, since it will be designed to have just one dominating heat transfer path (through the material of interest). The results from a pool fire or furnace test on an actual prototype package, if performed, could alternatively be used to determine the effective thermal properties of any foam, wood or cork inside them. This has the advantage of reproducing most closely the correct thermal conditions but derivation of the thermal properties may be complicated by there being several important heat transfer paths and maybe more than one material whose properties are uncertain.

A further complication for wood is that, under some conditions, it will burn, potentially releasing heat for many hours after the pool fire has been extinguished or the package has been removed from the furnace. If the wood is clad in steel, this will prevent air from reaching the wood and prevent combustion from occurring, although the drop tests (particularly the punch test) prior to the thermal test may have damaged the cladding and exposed the wood. A practical test, on either an actual package or suitable test section, will therefore almost always be required to demonstrate that any wood near the surface of a package or shock absorber will not burn or, if it does burn, to determine the heat that is released. It should be noted that some woods, such as cork, char when heated but generally produce insufficient heat to sustain burning when removed from the external source of heat.

9.3 The Application of Boundary Conditions

Appropriate boundary conditions need to be applied to the external surfaces of the model. These are discussed in Sections 10 and 11 below.

Many designs of transport package involve different components nested one inside another. Clearances will be included so that the package can be assembled. These clearances will result in narrow air gaps existing between structures which can present significant thermal resistances. If an air gap is narrow, convective heat transfer will be negligible and the heat transfer will be dominated by thermal radiation and conduction. Radiation heat transfer will be independent of the assumed gap width, conduction heat transfer, however, is inversely proportional to the gap width. Some gaps may have a precisely engineered width. Most, however, will be uncertain to some extent. Depending on the orientation, the width of the gap between two structures may also vary with position (e.g. small at the bottom where the objects are in contact and larger at the top). The analyst will need to consider what range of gap width is possible and whether the assumption of a large or small gap will be pessimistic. Sensitivity calculations on the assumed gap width may be appropriate. If a normal transport heating test or accident thermal test has been performed on a prototype package, the assumed gap widths can be adjusted, within reason, to give the best agreement between the measured and predicted temperatures.

10 Analysis – Normal Conditions of Transport

10.1 Validation of Models

Prior to using a FEA or CFD model to predict the temperature of a package under normal conditions of transport, the model should first be validated against any normal operation thermal tests which have been performed (as described in section 4). Parameters which are uncertain such as gap widths, the thermal conductivity of natural materials (such as cork) and the contact resistance between touching components can be varied in order to improve the agreement between measured and predicted temperatures but such parameters should not be extended beyond what might reasonably be expected to occur. The boundary conditions applied to the exterior of the model should reflect the measured ambient temperature in the test.

10.2 Adjustment of Model to the Test Conditions

The model should then be modified to reflect the conditions specified in the IAEA Regulations [1]. The boundary conditions applied to the exterior of the model should reflect the requirements of the IAEA Regulations [1]. Thus the ambient temperature should normally be 38°C unless otherwise agreed, e.g. for a Type B(M) package. It may be assumed that the package, or its support frame, is sitting on a perfectly insulating flat surface with an appropriate emissivity, e.g. for concrete. However, as the floor is also exposed to insolation, this may result in an abnormal floor temperature which could affect local air temperature. The analyst should check the floor temperature is reasonable. At least two calculations will be required, one representing steady conditions with no solar insolation, the other with solar insolation. The first of these is a steady-state calculation while the second may require a transient calculation. If the package is massive and has a very large thermal capacity, it can be argued that diurnal changes in temperature will be relatively small and that the heat flux from solar insolation, although considered active for only 12 hours each day (according to the IAEA Regulations), can be averaged over 24 hours, or even modelled as continuous. This would enable a steady state calculation to again be performed (the latter case being clearly conservative having the added advantage of not requiring any justification).

The heat generated by the radioactive material inside the package will need to be represented in the model. This may be done by explicitly representing the radioactive material with a volumetric heat generation rate. Alternatively the heat may simply be input as a heat flux on the inner surface of the package. The analyst will need to ensure that the distribution of this heat flux corresponds to what would be expected under the transport conditions being considered. For example, if heat transfer between the radioactive material and the package inner surface is dominated by natural convection, the heat flux to the region of the package surface below the bottom of the radioactive material will be much less than that to the package surface above it.

10.3 Modeling Solar Insolation

If a calculation including the effect of solar insolation is being performed, the solar heat flux should be imposed for 12 hours of each day as shown in Table 13 of the Regulations as follows:

- Flat surfaces transported horizontally – downward facing (0 W/m^2)
- Flat surfaces transported horizontally – upward facing (800 W/m^2)
- Surfaces transported vertically (200 W/m^2)
- Other downward facing (not horizontal) surfaces (200 W/m^2)

- All other surfaces (400 W/m^2)

Some degree of judgement and common sense needs to be applied when deciding the solar insolation flux to apply to different surfaces. It is recommended that a ‘broad brush’ approach be used so that different fluxes are not applied to each side of small features (such as handles or lugs) but instead a uniform flux is applied to all surfaces on one side. Similarly, a degree of compromise should be allowed when judging which category a particular surface fits into, for example, when considering whether a downward facing surface is a ‘flat surface transported horizontally’ or ‘other downward facing surface’. If the surface is largely flat, or generally flat, then it can be considered to be a ‘flat surface transported horizontally’. If in doubt, consider whether the surface in question can reasonably expect to have the sun shining onto it. Thus, if a package has a hollow base, none of the surfaces inside the hollow will ever, in practice, receive heat from the sun, whatever their shape and orientation. The IAEA Regulations (Table 13) state that, for the last three cases listed above, ‘a sine function may alternatively be used’. The advisory material [2] explains that this sine function is a function of time rather than orientation of the surface. Interestingly, this option of use of a sine function does not apply to upward facing horizontal surfaces. For simplicity it is recommended that this option of a sine function is not used.

The application of solar insolation can be problematic for complex geometries such as a finned surface. It would obviously be unreasonable to fully apply the insolation flux to both sides of the fins plus the base of the fin cavity. The solar insolation data given in the IAEA Regulations are intended to simulate the heat flux onto the outer envelope of the package. For a complex surface geometry (such as a finned surface) one method of representing this is by adjusting the temperature at which the surface of the package is exchanging heat by radiation. For example, for a black body, a radiation heat flux of 800 W/m^2 can be represented by changing the surface temperature to T_{eff}, given by the equation:

$$800 = \sigma \left((T_{eff} + 273.15)^4 - (38 + 273.15)^4 \right)$$

where σ is Stefan’s constant and T_{eff} is in °C.

It should be noted that the IAEA Regulations specify the solar insolation heat fluxes incident upon the surface of the package. The heat flux which is absorbed by the surface is this heat flux multiplied by the absorptivity of the surface. The absorptivity of a surface is equal to its emissivity for a given wavelength of radiation, although for many materials the emissivity is a function of wavelength. Thus the absorptivity at the short wavelengths typical of solar insolation will not necessarily be the same as the emissivity at the longer wavelengths typical of heat loss from the package surface, and which will have been specified to model radiation heat loss. Reliable data on absorptivity at short wavelengths may not be available for many materials and pessimistic assumptions may have to be made by the analyst or appropriate measurements made.

10.4 Notes on Interpretation of Calculations

When interpreting the results of a transient calculation representing a package under normal conditions of transport, subject to solar insolation for 12 hours each day, it should be noted that while the maximum temperatures on the outside of the package will be achieved at the end of each 12 hour period of insolation, there will be a delay while heat is conducted to the inside of the package and hence the maximum temperature at inner locations will occur some time after the end of each 12 hour period of insolation. The temperature at positions of interest (e.g. seals) therefore needs to be monitored as a function of time throughout the calculation so that the maximum temperature can be properly determined. Even for a package with a relatively small thermal capacity, the transient calculation will need to model a period of several days so that it can be demonstrated that the temperatures have settled down to a regular oscillating pattern.

11 Analysis – Fire Accident Conditions

11.1 Validation of Model for Fire Accident Conditions

The objective of a fire accident calculation is to demonstrate that the design of transport package can safely withstand being subjected to the thermal test specified in the IAEA Regulations [1]. This thermal test has to be performed on a package which has already been subjected to the drop tests specified in the Regulations.

The CFD or FEA model used to model the fire accident is usually very similar to that used to model normal conditions of transport. Some modification of the model will probably be required, however, to represent the damage caused to the package by the impact tests, and to include the thermal conditions at the start of the fire as required by the regulations. If a practical fire test has been performed on the package, this should first be modelled in order to validate the further model which will include variations to allow for the regulatory requirements. When modelling a practical test that has been performed, the boundary conditions and length of test should be based upon the measured conditions in the fire or furnace. The question of whether the model should be best estimate or pessimistic is discussed in Section 12. If necessary, parameters such as the conductivity of natural materials (such as cork) or the size of gaps (following being subjected to the drop tests) can be adjusted to ensure that the model is not over-optimistic compared to the measured test data.

As discussed in Section 9, some materials used in transport packages are combustible and may continue to burn, generating heat, long after the 30 minute (60 minute for Type C package) heating phase of the thermal test has finished. If such burning is possible, particularly in a drop-test damaged package, then the analyst will need either to demonstrate why continued burning will not occur or make allowance for it in the thermal model.

11.2 Establishing Boundary Conditions

The IAEA Regulations require that the starting point for the thermal test is the temperature profile under normal conditions of transport (Para 728). The effect of solar insolation needs to be included so the temperature profile at the end of the 12 hour ‘day’ should be used. It is worthy of note that Paragraph 665 of the current Regulations, which give the requirements for a Type B(M) package, do not include Paragraph 728 (the specification of the thermal test) in the list of Paragraphs for which revised conditions may be specified by the competent authority. This could be interpreted to mean that, for a Type B(M) package, even if an ambient lower than 38°C is used to assess normal conditions of transport, the conditions at the start of the thermal test should still correspond to the 38°C ambient temperature. An ambient of 38°C would also have to be assumed during the cooling phase of the thermal test.

The boundary conditions applied to the outside of the package during the heating phase of the thermal test should comply with the IAEA Regulations and simulate the package being engulfed in a pool fire. The Regulations do not specify a value of convective heat transfer coefficient which should be used. The Advisory material [2] however, specifies that the value used should be justified and suggests the value used should be around 10 $W/m^2/K$ (corresponding to 5-10m/s typical air velocities in a fire). Heat transfer to the package from the fire is generally dominated by radiation. The analyst can therefore generally afford to be pessimistic with the value of assumed convection coefficient and a value of 15 $W/m^2/K$ is frequently used. Alternatively the CFD analyst may set a forced updraught which generates similar values and which takes better account of the flow patterns around the transport package.

When modelling the fire accident, the heat generated by the radioactive material should be applied to the inside of the model in the same way as when modelling normal conditions of transport. It should be noted, however, that the package contents may contribute some thermal capacity to the package which will help to reduce the temperature rise during the fire. To cover times when less material is being transported, it may be advisable to not include an explicit representation of the package contents but just to include the heat that it generates as a boundary condition.

11.3 Absorption of Heat by the Package

The IAEA Regulations [1] specify the flame temperature, the emissivity of the flames and the absorptivity of the package surface which should be assumed if no other value can be justified. In practice it would be hard to justify the emissivity of a surface when the surface may be oxidized by the high temperatures or blackened by soot from the fire. It is therefore recommended that the value of 0.8 specified in the Regulation is used. The emissivity of 0.9 specified for the flames introduces some degree of uncertainty when included in a thermal model. The view factors at any surface must sum to unity. Therefore one approach is to assume that the 'missing 0.1' corresponds to the surface seeing the ambient environment (38°) beyond the flames. The resulting radiation flux will be the same as that from a black body at 772.3°C. The surface of an object in the fire will therefore probably never reach a temperature of 800°C. An alternative approach is to consider the emissivity of 0.9 representing the emissivity of a furnace wall. The 'missing 0.1' then corresponds to the radiation reflected by the wall and the resulting radiation flux will depend upon the geometry of the furnace and the view factor of the package from the furnace wall. The easiest way to avoid having to justify the way in which the emissivity of the flames have been modelled is to pessimistically model the flame emissivity as being unity (i.e. the flames are a black body).

If the package is finned the Advisory Material [2], allows the emission of radiation from the flames within the fin cavities to be ignored and modelled as from a surface outside the fins. The modelling of the radiation heat transfer inside the fin cavities should include the effects of reflection of radiation and radiation from the hot fin tips to the cooler base of the fin cavity. Similarly a feature sticking out from the body of a package (e.g. a trunnion) will be able to see the surface of the package in addition to the flames of the fire. A radiation boundary condition that takes this into effect would therefore be justified.

11.4 The Cooling Phase

According to the IAEA Regulations [1], the boundary conditions on the exterior of the package during the cooling phase of the thermal test should be the same as those applied when modelling normal conditions of transport. With regard to solar insolation, if the temperature profile at the start of the fire corresponded to the end of the 12 hour 'day' during which solar insolation was incident upon the package, then logically the first 11½ hours of the cool-down period will occur during the 'night'. However, the analyst would need to demonstrate that this was a more pessimistic assumption than starting the fire at the beginning, or part way through, the 'day' and the package receiving solar insolation at the start of the cooling period. Rather than perform several fire test transient calculations, with the fire starting at different assumed times, a simpler and clearly pessimistic approach is to assume that the fire starts at the end of the 12 hour insolation period and that a further 12 hour insolation period starts at the beginning of the cool-down phase. Alternatively, if safety margins are not critical, it is much simpler and quicker to model the insolation as continuous, i.e. solve it as if the sun were shining 24 hours per day, which avoids all argument.

If the boundary conditions during the cool-down phase of the thermal test were identical to those during normal transport, the emissivity of the surface of the package would correspond to that of the paint or metal of the outer surface, which may be significantly different from the value of 0.8 assumed during the heating phase of the fire. If the normal emissivity of the surface is greater than 0.8, it is unreasonable to assume that the emissivity of the surface suddenly increases at the end of the fire. However, if the normal emissivity of the surface is less than 0.8, it is reasonable to assume that the emissivity of the surface remains at 0.8 during the cool-down phase of the fire transient.

12 Best Estimate or Pessimistic?

The objective of performing a CFD or FEA thermal analysis is to demonstrate that the package design satisfies the requirements of the IAEA Regulations [1]. There are no confidence limits specified in the Regulations, hence the designer must demonstrate that the safety performance of the package meets or exceeds the regulatory requirements.

There are a number of parameters that will influence the thermal performance including:

- The material properties
- The size of air gaps
- The emissivity of surfaces
- The time of the start of the fire test relative to the solar insolation period
- The behaviour of materials that might char, shrink or burn during the fire test
- The contact resistance between components.
- The mesh design/sophistication
- The turbulence model.

While it would be possible to use the best estimate for each of these parameters, it would then be necessary to perform sensitivity calculations to determine the significance of the uncertainty in each parameter upon the predicted temperature at the locations of interest, and to use reasoned argument to justify the combined effect of the uncertainties. An easier approach is to select reasonably pessimistic values for each of the assumed parameters so that sensitivity calculations are not then required.

When validating a thermal model against data from thermal tests, parameters should be adjusted, within the bounds of what is reasonable, so that the model is always pessimistic (or only underestimates the peak temperature at important locations by an insignificantly small amount). It should be noted that it is usually the peak temperature at location of interest (e.g. the seals) which is of importance. Hence, when validating a thermal model against results from a fire or furnace test, the model needs to be demonstrated as pessimistic when predicting the peak temperature and there is less need for accuracy or pessimism in the predictions of the temperature at all times during the transient.

For some parameters it may not be self evident whether a high or low value will be pessimistic. For example, if cork is used as insulation in a package design, a high value of thermal conductivity will increase the heat entering the package during a fire test but a low value of thermal conductivity will increase the temperature of the package under normal conditions of transport and during the cooling phase of the fire test. Overall, therefore, it is not self evident whether a low or high value will be pessimistic. One approach to resolving this problem is to perform a number of fire test calculations with different assumed values of thermal conductivity. Alternatively, the self evident pessimistic value could be used in each phase of the calculation. Thus a pessimistically low value of conductivity would be used to calculate the temperature distribution under normal transport conditions, a pessimistically high value would be used during the heating phase of the fire test and a pessimistically low value again used during the cooling phase of the thermal test.

When deciding the value of any parameter to be assumed in a thermal model, it should be remembered that the analyst will need to justify the value assumed to the competent authority. Any values of parameters which are even moderately optimistic will be difficult to justify. The use of reasonably pessimistic assumptions is therefore recommended.

13 References

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