TCSC 1042 **December 2002**

Transport of Radioactive Material Code of Practice

Design of Transport Packaging for Radioactive Material

This code of practice has been declared obsolescent as the TCSC has considered that it is not financially viable to maintain this guidance document. However, it is recognised that the Code of Practice does contain useful guidance that could serve as introductory training material to personnel who are new to the field of transport packaging design. Date of issue December 2011.

Produced by the Transport Container Standardisation Committee

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FOREWORD

The safe transport of radioactive material is governed by various national and international regulations that are based on the International Atomic Energy Agency (IAEA) Regulations for the Safe Transport of Radioactive Material 1996 Edition (Revised) No. TS-R-1 (ST-1, Revised).

The design of packagings for safe transport of radioactive materials can be a complex process that requires many different skills. The regulations that form the ground rules for design require expert interpretation because the implications of this regulatory interpretation can have far reaching consequences on the subsequent design processes.

The purpose of this Code of Practice is to bring together the regulatory framework and provide designers in-depth guidance on the regulatory requirements. The IAEA publish advisory material, TS-G-1.1 (ST-2), which contains some advice on aspects of packaging design. The intent of this code is not to replicate that material, but to take a view of the process and offer guidance on related aspects that are important to good design practice. It covers all aspects of package design from initial specification, shielding, criticality, containment, thermal, impact and quality through to final design approval.

1 THE DESIGN PROCESS

1.1 SCOPE

This Code of Practice gives an overview on the complex process of designing packagings for radioactive material that requires many different skills. The regulations that form the ground rules for design require expert interpretation because the implications of this regulatory interpretation can have far reaching consequences on the subsequent design processes.

The remainder of this section gives an introduction to the design process, lists the regulatory constraints from TS-R-1 and cross references supporting documents. Sections 2 to 9 provide guidance and information on the most important parts of the design process. Each part can be used as a stand-alone document, and may be used for design that is not directly related to packagings.

1.2 INTRODUCTION

Package design tends to follow a fairly well-defined path. The term “design” includes all of the activities from specification of the material to be transported, through to achieving a design that has been formally demonstrated to satisfy the legal requirements of the nation(s) where it is to be operated. In practice there is inevitably a lot of inter-connection between all of these activities which will not necessarily be sequential and most, if not all, will be repeated and refined as work proceeds elsewhere. For example, the design of a package’s lifting points may need to be revised when the weight increases as a consequence of more detailed shielding calculations.

There are four key stages that are illustrated in Figure 1.

Specification - of the material to be transported, the package type and the package design requirements.

Deliverable: A clear statement of the duties the packaging will be required to carry out.

Design - of the appropriate packaging to meet the specification requirements.

Deliverable: Manufacturing drawings with supporting calculations and documentation.

Testing – of specimens, models and prototypes, as necessary, to prove the performance of the design.

Deliverable: A report of the tests that have been carried out to validate the design.

Design approval.

Deliverable: Documentary evidence that the design has been assessed and shown to satisfy the relevant transport regulations.

The design process is presented here as a series of constraints that must be satisfied before the design can be approved. These constraints are, essentially, paragraphs in TS-R-1. To assist the designer in meeting these constraints there is available a number of guides, codes of practice and standards. The following sub-sections list the constraints affecting each stage, and recommends appropriate aids to assist the designer in meeting these constraints.

The entire design process, from specification to approval, must be carried out under a strict system of quality assurance. Additionally, the designer must work with other areas, e.g. package users and shippers to ensure that dose uptake during the life of the packaging is minimised. The organisation’s Radiation Protection Programme [301] may be addressed in standard company procedures, by HAZOP or design review, or be developed specifically for the packaging. The designer must also recognise the need for ultimate disposal and make allowances for this as necessary. These are, in effect, constraints that apply to all activities.

Activity	**Constraints** TS-R-1 para	**Support**
All activities	301 310	TCSC 1042 section 7

1.3 SPECIFICATION OF RADIOACTIVE MATERIAL AND ACTIVITY

This is the activity that initiates the design of the package, and specifies the requirements that the design must comply with. The information supplied to the designer would normally include:

(a) the nature of the materials to be transported

(b) the maximum activities

(c) ambient temperature conditions

(d) transport mode

(e) design life

(f) materials to be used, or any material restrictions

(g) where the packaging is to be used.

(h) any specific handling and/or operating requirements.

Items (a) and (b) will generally determine the package Type, i.e. whether it is Type B, Type A, IP or Excepted. This immediately sets targets for whether accident or normal conditions of transport will need to be designed for. For Type B packages item (c) will have a direct bearing on whether the package needs to be a Type B(U) or Type B(M) design and some bearing on the choice of materials, identified in (f).

Item (d) can impose size and weight limitations and result in constraints on the position, form and shape of lifting and tie-down features.

Item (e) can have a significant affect on the overall design of the package. For example a non returnable, or short-life, package may not need to take on board the effects of longer term wear and tear, or corrosion, allowing the use of less exotic and cheaper materials.

Items (g) and (h) will affect the more detailed aspects of the design. For instance, if a package is to be loaded and unloaded using a posting port into a cell it may need to be operated horizontally and have an integral gamma-gate. If it is loaded and unloaded inside the cell, it may be operated vertically and have a simple bolted lid, but must be suitable for remote handling. Failure to correctly specify (d) is not likely to affect the design to the extent that it cannot be certified as a packaging, but could severely impair its operability, or significantly add to the cost of certification.

1.4 DESIGN

Activity	**Constraint** TS-R-1 para	**Support**
Definition of package Type	401 408 - 419	
Mechanical strength	612 614 622 623 624 625 626 627 628 646 648 649 657 661 668 669 670	TCSC 1042 part 6 TCSC 1042 part 8
Shielding	530 531 532 572 645 656	TCSC 1042 part 2 TCSC 1042 part 8
Thermal design	615 617 618 637 651 652 653 654 655 658 660 661 662 664 668	TCSC 1042 part 5
Containment	619 639 640 641 642 643 644 645 659	TCSC 1042 part 4

Activity	Constraint TS-R-1 para	Support
	660 670	
Lifting and handling	606 607 608	TCSC 1079
Tie-downs	636	TCSC 1006
Criticality	528 569 671 – 682	TCSC 1042 part 3
Miscellaneous issues	609 610 611 613 616 634 635 647 663	TCSC 1042 part 9
Preparation of manufacturing drawings		TCSC(99)P121

1.5 TESTING

Included within this activity is manufacture of test specimens, models and prototype packaging (or packagings). Evidence will be required to demonstrate that the test set-up accurately represents the conditions and loadings experienced in transport, and uses accurate representations of the packaging(s), or component parts, that will eventually be used to transport the radioactive contents. If the test components and test conditions deviate from what is expected to be encountered in practice then a justification for their use will need to be provided.

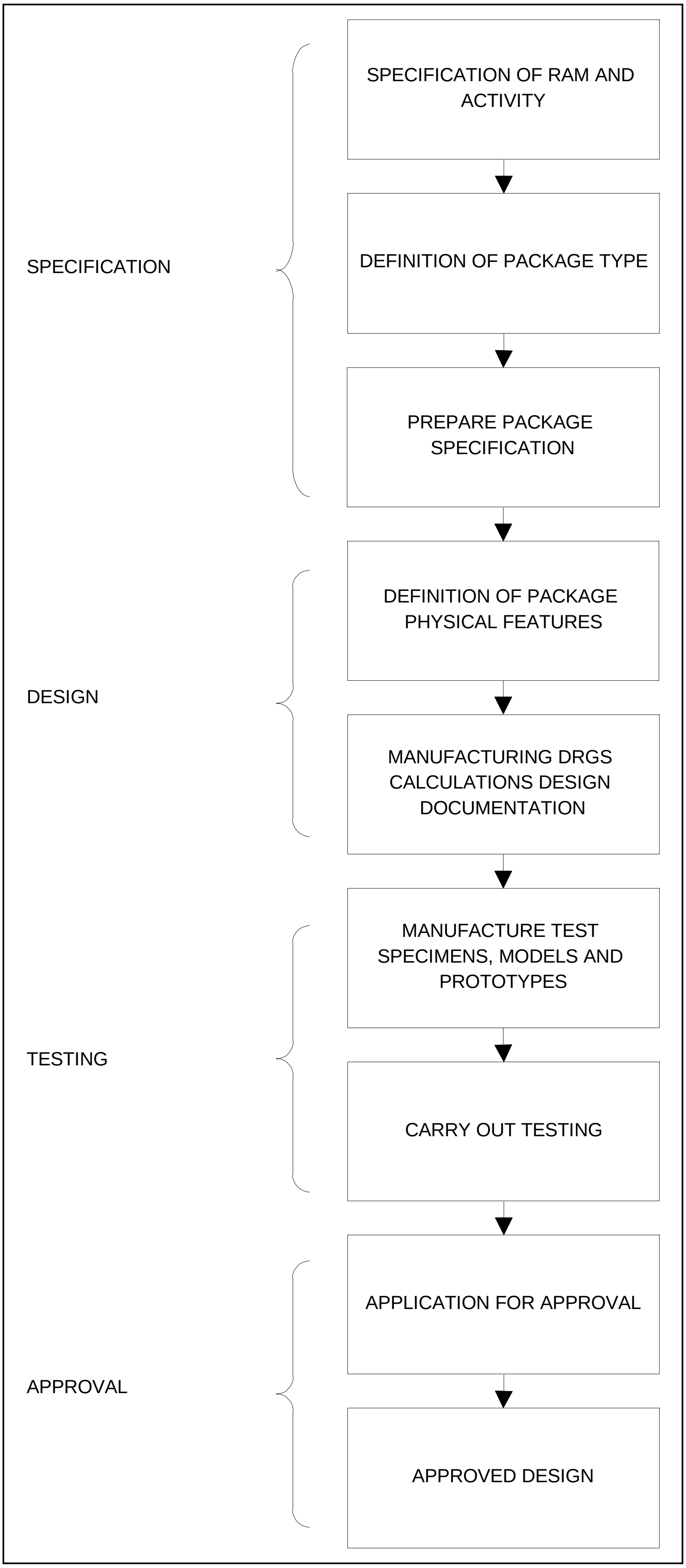
Activity	Constraint TS-R-1 para	Support
Prepare test rig, test specimen, or prototype drawings as necessary.		
Prepare manufacturing specifications		TCSC(99)P121
Demonstrate that the prototype accurately reflects the design.		TCSC 1086
Prepare test specification	713 – 717	TCSC 1086
Agree test programme with independent assessor		TCSC 1086
Control during manufacture	638	AESS 6067 AECP 1053
Implement testing and review test results	718 – 737	TCSC 1086 TS-G-1-1 Section VII

1.6 DESIGN APPROVAL

It must be appreciated that this is a process, not an event. Approval will need to be gained at all stages, as the design progresses from concept, through the production of supporting calculations etc, to final design drawings.

Activity	**Constraint** TS-R-1 para	**Support**
Preparation of DSR	801 – 818	TCSC 1078 Competent Authority Applicants' Guide

Figure 1 Flowsheet for package design and approval process



2 SHIELDING

2.1 REGULATORY REQUIREMENTS

Since 1961, the International Atomic Energy Agency (IAEA) has provided the national and international regulatory basis for RAM transport. Safety Standards Series No. TS-R-1 (ST-1, revised) (Ref. 1) published by the IAEA provides the regulatory guideline for the safe transport of radioactive material. The objective of the regulations is to protect the public, transport workers, property, and the environment from the effects of radiation during transport.

In TS-R-1 there are four primary types of package defined (in increasing order of potential hazard);

Excepted package

Industrial package

Type 'A' package

Type 'B' package

Note: TS-R-1 introduced restrictions [416] on the transport by air of large quantities of radioactive material. In conjunctions with these restrictions, the Type ‘C’ package was introduced to enable large quantities of radioactive material to continue being transported by air. However, the design constraints on Type C packages are so restrictive as to make the use of air transport uneconomic for most applications. Consequently, this code of practice will not cover in detail the design of Type C packages until there is greater interest expressed by users.

The regulations specify what packaging is appropriate to the type and quantity of the radioactive material. Safety measures are built in to the design of the package and take account of possible accident conditions during transport to ensure that radiation exposures are as low as reasonably practicable (ALARP). The requirements for radioactive materials and for packagings and packages are provided in Section VI of TS-R-1.

The limits for the transport index and radiation level for packages and overpacks can be found in Section V, [530] to [532] of TS-R-1. The regulations require that at the surfaces of the packages and overpacks, specific radiation levels shall not be exceeded. Even though a package is permitted to have an external radiation level up to 10 mSv/h the requirement for a maximum dose limit of 2 mSv/h on the surface of the conveyance or of 0.1 mSv/h at any point 2 m from the surface of the conveyance may be more limiting in certain instances. In the case of a large radiation source such as a Type 'B' flask transporting irradiated fuel elements from a nuclear power station, the 2 m dose rate target is normally the more onerous condition to satisfy. In many instances the operators of nuclear facilities will have their own limits, which are likely to lead to much more restrictive package dose rates.

The requirements for Radiological Protection are outlined in Section III , [301] to [307] of TS-R-1. The underlying principle in radiation protection is that the radiation exposures from the handling, storage and transport of radioactive material shall be kept as low as reasonably practicable; economic and social factors being taken into account.

The radiation exposure of transport workers and of the general public is subject to the requirements specified in (Ref. 2) Safety Series No.9, Section V gives the administrative requirements applicable to transport workers.

The international agreement on radiological protection is largely due to the recommendations of the International Commission on Radiological Protection (ICRP).

The ICRP provides guidance on the fundamental principles on which appropriate radiological protection can be based.

The current dose limits incorporated in both UK and European Community legislation are still based on the 1977 recommendations of ICRP Publication No. 26 (Ref. 2) and the data for the calculations of the dose being based on ICRP Publication No. 21 (Ref. 4). ICRP Publication No. 60, published in 1990 (Ref. 5), presents the latest recommendations regarding the concepts associated with determination of dose by radiation.

The 1990 recommendations on radiation protection principles issued by ICRP introduce lower dose limits for radiation workers and for members of the public. In addition they recognise that persons can be exposed to radiation from more than one source and prescribe that dose constraints be applied to each practice involving radioactive material. The National Radiological Protection Board (NRPB) is required by ministerial direction to provide advice on the relevance of the recommendations of the ICRP to the U.K. The response of the Board to the ICRP recommendations is provided in Ref. 6.

ICRP Publication No. 60 has led to proposals for the revision of the IAEA's basic safety standards and of the Euratom Basic Safety Standards Directive, a revised draft of which is currently being negotiated. When agreed, the Euratom Basic Safety Standards will be adopted in the UK and all Member States of the European Union.

Within the UK regulations are in force for all modes of transport. Some of these are made enforceable by various statutory instruments, e.g. the carriage of radioactive materials by road is governed by the Radioactive Substances (Carriage by Road) (Great Britain) Regulations. These regulations do not relieve persons from obligations under other acts which may apply, e.g.

- The Health & Safety at Work etc. Act 1974
- The Ionising Radiations Regulations, 1999
- The Nuclear Installations Act, 1969
- The Radioactive Substances Act, 1993
- Radioactive Material (Road Transport) Regulations, 2002
- Radioactive Material (Road Transport) Act, 1991

2.2 TYPES OF RADIATION

There are five main types of radiation encountered in the nuclear industry:

Alpha particles are positively charged particles and are very easily absorbed. They are easily stopped by paper or skin and so they never present a shielding problem. Alpha radiation is not normally regarded as an external radiation hazard as it cannot penetrate the outer layers of the skin.

Beta radiation consists of high speed electrons which originate in the nucleus. Beta particles can be stopped by thin layers of water, glass or metal. One important problem encountered when shielding beta radiation is the production of secondary X-rays, or 'Bremsstrahlung' which is formed when the beta particle is slowed down by the positive charge on the target atom nucleus. The intensity of the 'Bremsstrahlung' radiation is highly dependent on the energy of the incident beta particles and atomic number of the target material. Bremsstrahlung is usually only a concern when the shielding is thin (i.e. less than the beta particle range) or the betas are of high energy.

γ and X-radiation are electromagnetic in nature similar to light and radio waves but with shorter wavelengths. They can be very penetrating and are attenuated exponentially when they pass through any material.

Neutrons carry no charge and can penetrate many materials with ease. Neutron shielding is complicated by the very wide range of energies encountered and the variation in material cross-sections with energy. The most useful reactions to employ in neutron shielding are called 'non-radiative capture' reactions which only result in an alpha or low energy beta particle being emitted.

2.3 BASIS FOR SHIELDING

2.3.1 Overview

There are four basic methods of protection against external radiation: distance, shielding, time and minimising the strength of the source for the task in hand. A combination of these methods will give protection necessary to ensure that the doses are kept *as low as reasonably practicable,* economic and social factors being taken into account within the relevant dose limits.

The shielding design is driven by safety and economic considerations, normally within a certain boundary restriction for size and weight. Factors to consider are:

- the choice of the shielding material
- the effect on other aspects of the design, such as heat transfer and the structural integrity of the package under both normal and accident transport scenarios
- ease of maintenance
- ease of decontamination

Often the shielding analyst is involved in an iterative process to optimise shielding design.

The type, thickness and arrangement of shielding required depend on the type of radiation, the activity of the source and the dose rates acceptable outside the package or overpack. For both γ and neutron shielding it is essential to avoid "shine paths". To avoid streaming problems it is essential to keep the width of straight gaps to a minimum. Multiple steps are necessary and should be equi-spaced or, better still, 60° V-shaped joints should be used, see Figure 1. Useful information can be found in AIL Report 363 (Ref. 7).

2.3.2 Gamma ray attenuation

There are a number of processes that attenuate γ radiation, the three main ones are:

Photo-electric effect: A γ photon gives all of its energy to an atom, causing the ejection of an electron from its orbit. The effective cross-section of this event is approximately proportional to Z^5. This is the dominant process for low energy photons.

Pair production: The γ photon loses energy through the creation of a positron-electron pair. This does not occur for photons with an energy less than 1.02 MeV, and its effectiveness increases at higher energy. The cross-section is proportional to Z^2.

Crompton effect: The γ photon interacts with an atomic electron, giving up part of its energy, then continuing with a lower energy and in a different direction. Cross-section is proportional to Z.

It is apparent from the above that the higher the material density, the more effective the shielding against γ radiation.

2.3.3 Neutron attenuation

The energy of a neutron is proportional to the square of its speed. Neutron shielding is a process of slowing them sufficiently that they can be captured. The three main process are:

Inelastic scattering: A neutron with an energy greater than 1 MeV strikes a nucleus and raises it to an excited state. As it returns to the ground state it emits γ radiation, so hence the neutron has lost energy. Steel and concrete are useful for this; lead is less so.

Elastic scattering: The neutron strikes an atom and shares energy, this is analogous to a snooker ball striking another. It follows that this process is most effective when the particles are of a similar mass, i.e. the decelerating atom is hydrogen. The effectiveness of this process diminishes above neutron energies of 2 MeV.

Capture: Certain materials have an affinity for neutrons that have already been slowed by elastic and/or inelastic scattering, or had a low energy to start with. (There are no suitable capture reactions for fast neutrons.) Unfortunately, the most common neutron capture reactions lead to the emission of penetrating γ radiation (secondary γ) with energies up to 7 MeV. For example:

Iron(^{58}Fe) + Neutron (n) $\rightarrow$ Iron (^{59}Fe) + γ

The most commonly used neutron absorbers are cadmium, boron and lithium. Cadmium does not emit capture γ, but is used much less these days because it is toxic and there are health and safety issues.

Cadmium (^{113}Cd) + Neutron (n) $\rightarrow$ ^{114}Cd (stable)

Boron is commonly alloyed in steel plate, or with aluminium (Boral). It does have the disadvantage that as the neutron is captured a γ photon is emitted and this will require shielding.

Lithium does not emit a capture γ, but is less amenable to alloying. It is usually mixed with material such as polythene in the form of a fine powder.

For effective neutron shielding designs there must be both moderation and absorption. There are no cases where there is a 'pure' neutron source; there will always be simultaneous neutron and γ emissions, and so the shielding must be adequate for both. This can either be achieved by use of a single material which is relatively effective for shielding both sources (e.g. concrete) or a combination of a predominantly γ shield with a predominantly neutron shield (e.g. lead/polythene). For some sources (e.g. the α, n reaction in beryllium) the neutron component is the most significant.

2.4 SHIELDING MATERIALS

2.4.1 General remarks

The choice of shielding materials should also take into account the criticality, heat transfer and structural requirements for the package under normal and accident transport scenarios.

2.4.2 Beta

For soft beta emitters the normal construction of the packaging should provide sufficient shielding.

For hard beta emitters it is preferable to use a light shielding material such as polystyrene or polyethylene, adjacent to the source, which is thick enough to stop the primary beta radiation and minimise the production of secondary γ radiation. Additional γ shielding can then be added if necessary.

2.4.3 Gamma radiation

Materials commonly used for shielding are:

(a) Lead which is relatively cheap, easily fabricated and suitable for quantity production techniques. It is advisable to use 4% antimony lead which improves the flowing properties and mechanical strength, though it depresses the melting point; see BS 3909; for testing shielding integrity see AESS 6067 and AECP 1056. It should be noted that the addition of antimony also reduces the lead density from 11,340 kg/m^3 to 11,030 kg/m^3. Small lead pots may be used bare but larger pots should be clad in steel. Due to its low melting point, thermal protection will be required for lead in Type B packaging. For satisfactory heat transfer it is necessary to ensure good adhesion between the lead and the steel. Further information on lead for shielding can be obtained from 'The Lead Development Association'.

(b) Mild steel or stainless steel, both of which have good mechanical strength and a high melting point. Protection from corrosion is required for mild steel, and since steel is less dense than lead, thicker sections are needed for effective shielding and this results in a larger and generally heavier packaging.

(c) Depleted uranium metal, which is expensive, but can be economical since it will make a small, compact and comparatively light packaging due to its effective γ attenuation. It has a high melting point but can be pyrophoric if prepared from powder. It must be clad to prevent oxidation, and at temperatures lower than the regulatory 800°C thermal test it can form a eutectic with steel. Furthermore, depleted uranium is subjected to safeguard controls and the subsequent restrictions during the packaging life should be taken into account at the design stage. Account should be taken of radiation emitted by the uranium itself.

(d) "Heavy Alloy" is mostly tungsten based. Various densities can be obtained. Since it can only be produced by powder metallurgy techniques its use is generally limited to small packagings. The material is expensive and can be difficult to machine.

(e) Ductile cast iron has the advantage of being cast in a single manufacturing process. Surface quality, decontaminability and corrosion resistance are provided by galvanically applied nickel plating. Since ductile cast iron is less dense than steel, thicker sections are needed for equivalent shielding. However, it is difficult to non-destructively test and to guarantee the material impact resistance. Consequently it is rarely used for transport packages.

(f) Concrete may be used where shielding requirements are relatively light, and its performance as a shielding agent can be enhanced by the addition of aggregates such as barytes. Concrete is particularly useful in radioactive waste packages, in that it provides a means of immobilising the waste and any loose activity and thus forms a self-shielded package. Additional layers of concrete with no waste in them may form an outer layer of extra shielding. This may be achieved by grouting waste into a pre-formed outer package or around waste contained in a steel basket. It is particularly suited to large production runs.

External steel cladding may be necessary to protect the concrete from wear or damage during normal handling or transport, while for Type 'B' packagings thermal protection may be necessary to prevent degradation and steam generation.

Typical material prices are given below.

Material	Density – kg/m^3	Cost - £/kg (note 1)	Cost - relative to mild steel
Concrete	2200 to 2400	0.1	0.18
Mild steel plate	7850	0.55	1
Stainless steel plate, grade 304S11	7900	1.2	2.2
Carbon steel forging, ASTM A-350 LF5	7850	10 – 16 (Note 3)	18 – 29
Stainless steel forging, 304S11	7900	13 to 22 (Note 3)	23 – 40
Lead plus 4% antimony	11030	2	3.6
Lead	11,340	2	3.6
Tungsten/nickel alloy		45	82
Depleted uranium	18,700	(note 2)	(note 2)

Note 1: Costs as of January 2000

Note 2: Depleted uranium is a difficult material to source and work with. A price is not quoted since it can vary considerably; it is unlikely to be less than £15/kg.

Note 3: Forgings are priced as rough machined. The price can vary widely, depending on the required shape.

2.4.4 Neutron

Materials having a high hydrogen content are effective moderators. Examples of materials in current use include polyethylene, water extended polyester resin (WEP), timber, bonded granulated cork and silicone rubber based compounds. All of these materials require external cladding, e.g. either to provide mechanical strength or fire protection. The designer should consider the effects of γ radiation on this sort of shielding material. The physical properties may be degraded, so that the package resistance to impact and/or thermal loads is reduced. Also, radiolysis may lead to hydrogen being evolved, in which case the designer must ensure that the lower explosive limit is not exceeded. (In the case of hydrogen in air this is 4%.)

Polyethylene can be easily cut into required shapes and is often used with steel to form a combined γ/neutron shield. A suitable neutron absorber (e.g. boron) may be incorporated in the formulation.

WEP is intrinsically fire resistant and has the advantage of being a good thermal insulator. A suitable neutron absorber (e.g. boron) may be incorporated in the formulation.

Timber, especially hardwood, has good mechanical and thermal properties.

Silicone rubber based compounds, because of their good fluidity prior to the curing process, can be readily used to fill cavities within the packaging. It has excellent heat and fire resistance and its mechanical properties are stable over a wide range of temperature. Boron is often included in such compounds for capturing thermal neutrons and reducing capture γ radiation.

Metal plates with a boron content (Ref. 32) are suitable as absorbers when used in conjunction with a moderator. Two such materials are currently in use in irradiated fuel transport applications, namely, boronated stainless steel plate and Boral, an aluminium clad sandwich containing an aluminium/boron carbide matrix. The principal use of these materials is to control criticality rather than for shielding.

2.5 BASIC DESIGN METHODOLOGY

2.5.1 Definitions

Photon A quantum of electromagnetic radiation with energy *hv*, where *h* is Planck's Constant and *v* is frequency.

Specific gamma-ray constant (Γ) The exposure rate from a given source at a given distance.

Transmission factor The fractional reduction in beam intensity on passing through a shield.

Build-up Factor (*B*) A multiplication factor applied to transmission parameters for γ radiation calculated from measurements on thin shields and narrow beams to give predictable results applicable to thick shields and broad beams. It allows for Crompton scattering back into the beam of photons scattered out at lesser depths. The value depends on photon energy, shielding material and shielding thickness.

Mass absorption coefficient For a uniform shield of thickness *x* and a narrow beam of radiation, the fraction of the beam remaining unabsorbed is $e^{-\mu m.x}$. The mass absorption coefficient is μ_m.

Linear absorption coefficient For a uniform shield of thickness *x* and a narrow beam of radiation, the fraction of the beam remaining unabsorbed is $e^{-\mu a.x}$. The linear absorption coefficient is μ_a. (The LAC = MAC × material density.)

Attenuation coefficient Similar to the LAC and MAC, but includes the energy emitted as secondary radiation, and therefore gives a higher result for the emitted radiation.

Half-thickness The thickness of a material that, when placed in the path of a beam, reduces the measured dose rate by one half.

2.5.2 Units

Roentgen (R) A unit of exposure to radiation based on the capacity to cause ionisation. It is equal to 2.58×10^{-4} Coulomb/kg in air.

Gray (Gy) The SI unit of absorbed radiation dose, 1 Joule/kg. (Replaces the rad.)

Sievert (Sv) The SI unit of radiation dose equivalent – the product of absorbed dose in Gy and the Quality Factor. (Replaces the rem.)

Bequerel (Bq) The SI unit of activity, equivalent to one disintegration/s. (Replaces the Curie (Ci).)

Generally an exposure of 1 R will result in an absorbed dose in tissue of about 0.01 Gy (1 rad).

Conversions between SI and obsolete units are given below. To convert between Gy and rad, use the same factors as for Sv and rem.

Conversion	Action
Radiation dose: old units to SI	
rem to Sv	÷100
rem to mSv	× 10
mrem to μSv	× 10
μrem to μSv	÷ 100
Radiation dose: SI to old units	
Sv to rem	× 100

mSv to rem	÷ 10
μSv to mrem	÷10
Activity: old units to SI	
Ci to Bq	$\times 3.7 \times 10^{10}$
Activity: SI to old units	
Bq to Ci	$\times 2.7 \times 10^{-11}$

2.5.3 Analytical Methods - γ shielding

Details of analytical techniques for calculating unshielded and shielded dose rates for a variety of source configurations can be found in many text books (see for example, Refs. 8, 9 and 10). However, the calculations are often restricted to well defined sources and geometry.

From BS 4094, for an unshielded point source, the exposure rate is:

$$= \frac{\Gamma Q}{d^2} \quad \text{R/h}$$

where Γ is ……, Q is the activity in Curies, and d is the distance from the source in metres.

For a shielded point source the exposure rate is:

$$= \frac{\Gamma Q\, T}{d^2} \quad \text{R/h}$$

T is the transmission factor, where:

$$T = B\, e^{-\mu t}$$

where B is the build-up factor, μ is the linear absorption coefficient, and t is the shielding thickness.

Calculations using a point source will always be safe since they will give the maximum shielding thickness. However, the dose rate will fall more slowly than $1/d^2$ when moving away from a physically large distributed source, so a degree of care should be taken when making dose comparisons near extended sources.

It is almost inevitable that a computer model will be used at some stage to verify that the proposed shielding design is adequate. Since modelling is usually a relatively expensive process, made more so if the design has to be modified and the modelling repeated, it is sensible to aim for a design that is close to that required before modelling begins. There are some basic techniques that allow the designer to assess the design and improve it prior to modelling, and these are described below. These are not intended to replace rigorous shielding assessment, but are a simple and inexpensive way of introducing getting the design on the right track and reducing the possibility that is may contain major flaws.

Use past experience: A quick review of previous successful designs will provide a starting point. Typical shielding thickness are:

- small irradiated steel specimens: 50 mm lead
- intermediate level waste: 150 mm lead
- irradiated fuel, having cooled for a significant period: 250 mm lead

Use of beam-lines to locate shielding weakness: It is often found, particularly on more complicated designs, that shielding weaknesses are introduced that are not immediately obvious. A quick way to locate these areas is to take an assembly drawing of the packaging, draw beam-lines from the source to the exterior, and summate the total thickness of shielding that each line passes through. These lines need to come from all parts of the source, not just the centre. Attention should be paid to the areas where sub-assemblies join, and the effect of having the γ-gate open must be checked. It is also prudent to carry out the same process on a different view – it is easy, when examining a two-dimensional drawing, to miss a weakness that may be more apparent from another direction.

Use of density to check shielding uniformity: It is a reasonable approximation to assume that shielding effectiveness is proportional to density, and this can be used to quickly check for shielding uniformity.

> Example: Assume that a packaging body is to be fabricated from steel and lead filled. The steel shell is 10 mm thick inside and outside, and the lead is 100 mm thick. The packaging's γ-gate is to be solid steel, but the thickness needs to be determined. The density of steel is 7850 kg/m^3, the density of lead is 11,340 kg/m^3. The thickness of the γ-gate is:

$$= 10 + 100 \times \frac{11,340}{7850} + 10 = 165 \text{ mm}$$

This technique is particularly useful when drawing beam-diagrams (above) and the packaging is made from more than one material, e.g. steel and lead. In this case, each beam-line should be recorded on a table with the material thicknesses converted to a common basis and the total recorded. A typical weakness is around the flange of a lead-filled body, where it is bolted to a door assembly.

Half thickness: This is the thickness of a material that, when placed in the path of a beam, reduces the measured dose rate by one half. This is useful for quickly estimating the effect of varying the thickness of a shield. Again, it is an approximate tool since it takes no account of photon energy or changes in distance from the source to the outer surface of the shield. The following values are derived from ^{60}Co, and are commonly used:

Material	**Half thickness - mm**
Lead	12 mm
Steel	20 mm
Concrete	70 mm

The most common shielding materials are steel and lead: they are reasonably effective against γ radiation, cheap, and easy to manufacture. In some situations, where a packaging has a shielding weakness that cannot be easily designed out, the designer may be forced to use more expensive material (say, tungsten). In other situations the cheapest appropriate material will be specified.

The use of dense material is generally an advantage in improving the handling of smaller packagings, particularly those that are expected to be lifted manually. However, denser materials usually cost more and the designer will need to justify this.

2.5.4 Analytical Methods - neutron shielding

Neutron shielding calculations are not easy, and Monte Carlo calculations are invariably required.

2.6 CALCULATION BY MODELLING

2.6.1 Source Characterisation

Prediction of the radioactive source characteristics is an essential prerequisite for the analyst to evaluate the shielding performance of the package. In the case of simple sources the source nuclides and strengths are usually known and can be used directly in the shielding calculations. However, in cases such as irradiated nuclear fuel from commercial thermal reactors, computer codes are required to model the complex reactions in the fuel. Typically the codes provide the analyst with the inventory for the fission products, activation products and actinides. The principal computer codes used to calculate source strengths are briefly described below.

FISPIN computer code (Ref. 12) is originally an UKAEA program to determine fission product, activation and actinide inventory resulting from a known irradiation of a material. All validation work has been carried out for 'normal' fuel irradiations and enrichments. Extrapolation to higher enrichments and irradiations is carried out with increasing uncertainty about the validity of the results. A comprehensive validation report for FISPIN was produced in support of the Sizewell 'B' PWR design (Ref. 13).

ORIGEN (Ref. 14) is a point depletion code developed at Oak Ridge National Laboratory. The ORIGEN computer code uses a different method of solution than FISPIN and has large independently derived data libraries. KORIGEN is a revised version of ORIGEN, developed by staff at the Karlsruhe Nuclear Research Centre. It is used by various organisations as a primary method of calculation in the Federal Republic of Germany.

Other codes include APOLLO (France) and FAKIR (developed by Nuclear Transport Limited).

2.6.2 Shielding Computer Methods

The calculational methods available for shield design assessments in the U.K. employ both rigorous Monte-Carlo methods and more approximate techniques based on the kernel method. The methods were evolved to provide efficient solutions having regard to the limitations of the existing computer software and performance of the computer hardware. However, many of the constraints no longer apply with the advent of affordable and powerful workstations. With Monte-Carlo the analyst now has a method of solving most shielding problems.

Furthermore, the method is rigorous and, within constraints imposed by material tolerances and subjective modelling approximations, its accuracy is limited only by the knowledge of the basic cross-section data.

The computer codes highlighted below are readily available to the shielding community in the UK together with some popular alternatives.

<u>Monte-Carlo Method</u>

In Monte-Carlo calculations the required response is estimated by generating a number of typical particle tracks. At each stage the position of the next collision, the type of interaction which then occurs, and the energy and direction of the resulting particles are all sampled from known physical laws by choosing random numbers. In this way a particle in the calculation follows the same procedure as it would experience in reality. By recording properties of the tracks which reach the regions of interest for a given number of samples started it is possible to estimate a response such as dose-rate. Monte-Carlo has the advantage of being applicable to general geometries and to be able to use nuclear data which is effectively specified at point energies. Monte-Carlo suffers from the statistical uncertainties on its results, and the need to apply methods of accelerating the calculation which require skill.

The MCBEND Code (Ref. 15) is firmly established as the preferred Monte-Carlo method of calculation in the U.K. for most shielding studies. MCBEND is an AEA Technology ANSWERS Software Service computer code capable of solving a wide range of problems and offering a large number of options. MCBEND may be used for neutron, γ -ray, electron/positron and coupled calculations in detailed models which can represent all the essential shielding features. The code uses nuclear data from the DICE-GAMBLE libraries which are effectively point energy cross-sections. The calculation can be accelerated by superimposing a separate orthogonal mesh over the geometry of the material regions and specifying importances as a function of energy for each of the mesh intervals.

Other Monte-Carlo codes developed outside the U.K. include MCNP (Ref.16), TRIPOLI (Ref. 17) and MORSE (Ref. 18) .

Deterministic Transport Codes

Equations can be derived to describe the average behaviour of the particle population throughout the shielding system. A completely general equation would have, as its dependent variable, the number of particles as a function of position, velocity and time. In its complete form the resulting equation (the Boltzmann transport equation) cannot be solved analytically for practical problems. Methods have been developed for discretising the independent variables of space, velocity and time to give systems of equations which can be solved by numerical methods. Deterministic methods include techniques such as Discrete Ordinates, Spherical Harmonics and Diffusion Theory which make various simplifying assumptions. The equations generated may be solved by finite-difference or finite-element methods, often in geometries reduced to one or two dimensions.

The Oak Ridge National Laboratories one and two-dimensional discrete ordinates transport codes **ANISN** (Ref. 19) and **DOT** (Ref. 20) are widely used, particularly for validation studies. ANISN remains popular for selected applications, such as transport flasks, where the one-dimensional modelling does not introduce significant approximations. The codes offer the ability to consider very complicated nuclear interactions such as those occurring in multi-layered shields, neutron calculations, γ-ray calculations and secondary γ calculations. The calculations are performed using multi-group nuclear data libraries.

In the U.K. two transport codes, **MARC/PN** (Ref. 21) and **FELTRAN** (Ref. 22), have been under development for many years. Both are now developed to a position where they can handle deep penetration problems and include many input/output features required by the user. It remains only to establish fully the validation base before the codes can be used in design applications.

MARC/PN was originally written to solve the multi-group transport equation using the diffusion approximation. Subsequent development included the facility for a spherical harmonics expansion of the flux and anisotropic scatter. The methods of solution are based upon either finite difference or finite element techniques.

FELTRAN solves the Boltzman transport equation by the method of finite elements using variational techniques. The latest version of the code operates in two spatial dimensions and models the material geometry using rectangular and arbitrary triangular finite elements. Cross-section data is supplied in the multi-group ANISN format which enables neutron, γ-ray and coupled calculations to be performed.

Point Kernel Method

The Point Kernel method was the first shield design method and remains a well respected technique for γ-ray studies. The method is based on the calculation of the uncollidated flux which can always be achieved by determining the thickness of materials penetrated along the direct path from the source point to the dose point. The contributions of scattered γ-rays are then determined by applying build-up factors which give the ratio of the total dose rate to that from the uncollided component. For distributed sources the kernels are integrated over the energy spectrum and spatial variation of the γ-ray emitters in order to obtain the total dose rate.

RANKERN (Ref. 23) is an AEA Technology ANSWERS Software Service computer code developed to satisfy the requirement for a rapid method for the design and assessment of γ-ray shielding. The code solves the point kernel equations by a stochastic integration method and uses the material, geometry, source and tracking modules of MCBEND. The code uses combinatorial geometry techniques to enable complicated three-dimensional geometry systems to be described with minimum effort.

MICROSHIELD (Ref. 24) is a popular and highly versatile point kernel direct γ shielding and exposure rate analysis software developed by Grove Engineering, Inc., U.S.A. The key to the usefulness of a tool such as MicroShield is the fast turnround time using personal computers.

An alternative popular point kernel code to RANKERN and MICROSHIELD is QAD (Ref. 25). QAD performs the integration over the source volume by sub-dividing it into specified number of regions, each of which is replaced by a point source at its centre.

Diffusion Method

The earliest U.K. shield design method was based on the removal-diffusion method of Spinney et al (Ref. 10). Most diffusion calculations are now carried out using the adjusted diffusion coefficient (ADC) method (Ref. 26) in one or other of its form. The diffusion codes in general use for shield assessment are the three-dimensional finite difference code SNAPSH (Ref. 27) and the finite element code FENDER (Ref. 28).

Diffusion methods would not generally be used for package shielding assessment. If used at all, they would only be used for initial scoping calculations.

Comparison of Shielding Codes

Over the period 1985-1992 the Reactor Physics Committee of the Nuclear Energy Agency (NEACRP) organised an exercise in which participants from twelve countries applied a variety of computer codes to shielding calculations for a series of benchmark problems. Twenty codes were applied in the calculations for the NEACRP organised intercomparison of codes. The codes fell into the three categories of Monte-Carlo, Discrete Ordinates and Point Kernel. The blind international intercomparisons have revealed a wide range in the predictions of dose rates for a set of typical problems and shown that the codes must be used by experienced shielding analysts. The details and the conclusions drawn from the intercomparison of the shielding codes can be found in Ref. 29.

ANSWERS Software Services

The ANSWERS Service (Ref. 30) provides users with access to an established set of computer programs for radiation calculations. The shielding codes are fully tested and validated against experimental and other reference data. The codes are quality assured and comply with the ISO 9001 software quality standard. The ANSWERS Software Service provides a high level of user support by way of customised training, user group seminars, comprehensive documentation and a "hot-line" support service during normal office hours.

The ANSWERS Radiation Physics and Shielding Manual (Ref. 28) is highly recommended for information and guidance over the full range of radiation transport and shielding applications. As well as containing basic information, the manual refers to other appropriate documents such as applications guides which will describe the data and methods used in calculations, detail the validation base for use of the codes in particular applications, and give examples of code input data.

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3 CRITICALITY

3.1 BACKGROUND

Atoms of certain isotopes of some elements can be induced to split, or fission, by being struck by a neutron. These isotopes are called fissile isotopes and when they fission they produce two or three new neutrons that can go on to cause further fissions. In some configurations, a self-sustaining neutron chain reaction can occur and the system is said to be critical. Nuclear Criticality Safety is the discipline that ensures that fissile material cannot become critical outside of a nuclear reactor.

In the United Kingdom, transport packages that contain fissile material must be assessed against the requirements of the ‘Regulations for the Safe Transport of Radioactive Material’ (Ref. 1) to ensure that the contents will remain sufficiently subcritical under the normal and accident conditions specified by the Regulations. Such safety assessments must be submitted to the UK Competent Authority, the Department for Transport (DfT), as part of the overall transport safety case. DfT will review the submission, including the criticality safety assessment and, if satisfied, give approval for the package to be transported.

The following Sections have been prepared to assist the designer in understanding the basic criticality safety requirements in transport package design. However, due to the highly specialised nature of criticality safety assessment, it cannot be recommended strongly enough that advice is sought from a criticality safety specialist at an early stage in the design of any package that may be used to transport fissile material.

3.2 DEFINITIONS

The following definitions are provided to aid understanding and are relevant to criticality safety issues relating to the transport *of* packages containing fissile material. Included with the definitions are additional notes of clarification if these are considered appropriate. Only those definitions considered to be important to criticality safety issues are included.

Confinement system is that part of the package deemed necessary to maintain the fissile material in the configuration that was assumed in the criticality safety assessment for an individual package. Typically, the confinement system could be:

- A complete transport package
- An inner receptacle, with defined dimensions, carrying contents in a transport package
- An inner structure, of the transport package, maintaining the dimensions of an assembly of fissile parts

It should be noted that the containment system consists of packaging components only, whereas the confinement system consists *of* packaging components and the package contents. Although the confinement system may have the same physical boundary as the containment system, the two might be seen differently since the confinement system maintains criticality control whereas the containment system prevents leakage of radioactive material.

Consignment means any package or packages, or load of radioactive material, presented by a consignor for transport.

Containment system means the assembly of components of the packaging specified by the designer as intended to retain the radioactive material during transport.

Criticality Safety Index (CSI) assigned to a package, overpack or freight packaging containing fissile material means a number which is used to provide control over the accumulation of such items containing fissile material.

It is obtained by dividing the number 50 by the smaller of the two values of "N" (the allowable number) derived in Paragraphs 681 and 682 of the Regulations (Ref. 1) (i.e. CSI=50/N). The value of the CSI may be zero, provided that an unlimited number *of* packages is subcritical (i.e. "N" is effectively equal to infinity in both cases).

The Criticality Safety Index for each consignment must be determined as the sum of the indices of all the packages contained in that consignment. In the 1996 Regulations, the CSI has replaced the Transport Index (TI) for the criticality safety control of packages containing fissile material. The use of the Transport Index has been retained but effectively relates to radioactive consignments that do not carry fissile material.

Fissile material means U-233, U-235, Pu-239, Pu-241, or any combination of these radionuclides. The following are excepted from this definition by the Regulations (Ref. 1):

(a) Natural uranium or depleted uranium which is unirradiated, and

(b) Natural uranium or depleted uranium which has been irradiated in thermal reactors only.

Special Arrangement means those provisions, approved by the Competent Authority under which consignments, which do not satisfy all the applicable requirements of the Transport Regulations, may be transported.

Natural uranium means chemically separated uranium containing the naturally occurring distribution of uranium isotopes (approximately 99.28% U-238 and 0.72% U-235 by mass).

Depleted uranium means uranium containing a lesser mass percentage of U-235 than in natural uranium.

Enriched uranium means uranium containing a greater mass percentage of U-235 than 0.72%. In all cases, a very small mass percentage of U-234 is present.

3.3 FACTORS AFFECTING CRITICALITY SAFETY

3.3.1 System Reactivity

The reactivity of a system containing fissile material is dependent upon the behaviour of neutrons and the overall neutron population present in the system. The neutrons present in fissile material effectively have four fates. All of these four possible outcomes can be influenced to provide criticality control:

1. they are absorbed by fissile material, causing further fission;

2. they are absorbed by fissile material, without causing further fission;

3. they are absorbed by other materials without causing further fission;

4. they escape from the system by leakage without causing further fission.

The overall reactivity of a system, which includes a package or an array of packages, is expressed by the term K_{eff}, the effective multiplication factor, whereby:

$$K_{eff} = \frac{\text{rate of neutron production}}{\text{rate of loss of neutrons by absorption + leakage}}$$

A system is just critical when the rate of production exactly balances the rate of loss, either by escape or by capture, and $K_{eff} = 1$.

Hence, the factors that affect the criticality safety of a package or array of packages are those that affect the production and loss of neutrons. These can be listed as:

- Type *of* fissile material (e.g. uranium or plutonium system, including isotopic composition).
- Mass of fissile material.
- Density of fissile material.
- Geometry of fissile material.
- Concentration of fissile material.
- Moderation of neutrons.
- Neutron absorption.
- Neutron Reflection
- Neutron interaction between packages.

The proportion of neutrons leaking from a system containing fissile material is affected by the geometric configuration both of the individual packages themselves and also the spacing between packages in arrays of packages. Neutrons leaving one package (by the leakage process) could enter adjacent packages and induce further fissions. This process is known as neutron interaction and raises the reactivity of a system overall.

Some of the more important factors that influence neutron behaviour are described below.

3.3.2 Moderation of Neutrons

Moderators are materials which possess the ability to reduce the energy (and speed) of fast neutrons down to thermal levels, so far as possible, without capturing them. Neutrons at background energy levels are known as thermal neutrons. The most effective moderators are light elements, principally hydrogen, carbon and beryllium, and their compounds. These have the ability to efficiently slow down neutrons to energies that have an increased probability of causing further fissions. The addition of such moderating material can significantly increase the reactivity of a system and reduce the mass of fissile material required to form a critical assembly.

In many situations, water is the most commonly encountered moderator and potential changes in system K_{eff} can occur both by water in-leakage and loss from a system. Such situations might be encountered during an accident situation and the availability of water in an accident during transport on the open roads makes water in-leakage or loss an important aspect.

- Other examples of common moderating materials are; woods, rubbers, waxes, foams, water extended polyester resin (WEP) oils, fuels, and polyethylene.

The above are frequently encountered as part of packaging materials or in transport operations. Particular care must be taken not to incorrectly estimate the hydrogen content of these materials and their subsequent moderating ability. This aspect is of particular importance in packages that are usually transported dry, and allow a degree of neutron interaction between packages as a result of their design. In the case of organic materials, such as polyethylene, care must also be taken to correctly assess their moderating ability because they can be more effective moderators than water.

Two aspects that may require particular attention are those of "partial" and "differential" flooding. In the case of the former, a normal or accident condition may result in low-density water being present within (such as steam) or outside (such as snow or fog) a package. The subtle conditions of moderation that may prevail could mean that the reduced equivalent hydrogen concentration results in enhanced reactivity for the package or array of packages. It is impossible to be more prescriptive since the neutron behaviour of each system must be considered to be unique and assessed on a case-by-case basis.

In the case of "differential" flooding, water may leak from one part of the package yet remain in others. This may result in the efficient moderation of the fissile material content of a package but also the removal of interstitial water, which may be contributing to the neutron absorption process between discrete regions of fissile material. This happens most importantly within individual packages. Care must therefore be taken in the design of the package to ensure that water in-leakage or loss takes place in a balanced and even manner, preventing the potential formation of localised accumulations of water. This could be achieved, for instance, by the use of drainage holes in lodgements that hold fuel elements in transport flasks. This would prevent the formation of well-moderated fuel elements in the lodgements that did not have water between them. The presence of this interstitial water would have provided some degree of neutron absorption.

The transport of powders needs careful consideration because, by their nature, they can never be completely dry of moisture. Depending upon the moisture content, the amounts of hydrogen present as a result could be important from a moderation viewpoint and cannot be discounted. The potential moderating effect of even modest amounts of packaging materials, such as polyethylene wrapping, must also not be underestimated.

3.3.3 Neutron Absorption

Neutron absorbing materials (neutron poisons) can be deliberately introduced into a package design to reduce the reactivity of the package. Clearly, if such materials are used, the continued presence and effectiveness of the neutron absorbers, throughout the lifetime of the package, must be ensured and must be readily demonstrable. This latter point is important when assessing the criticality safety of the confinement system for single packages in isolation, which rely on neutron absorbing materials as a form of criticality control. A programme of inspection and Quality Assurance may be necessary as part of the design application to address this issue.

Examples of various neutron absorbing materials which can and have been used in the design of transport packages are as follows:

(a) Boronated material (material containing boron) has been used in a number of ways in *package* designs. Although most efficient as an absorber of thermal neutrons, boron has some effectiveness over a range of neutron energies. For example:

- Boral sheet - which is a boron carbide/aluminium alloy sandwiched in aluminium. This has been commonly used in the design of fuel element frames and Multi-Element Bottles (MEBs) in irradiated fuel transport flasks.

- Boronated steel - this is similar to Boral described above and is used in similar applications, although, in this case, the boron is part of the steel matrix. Unlike Boral, boronated steels can be machined and applied in a number of shapes other than flat sheets, e.g. tubes.

- Flexible boronated material — which has the ability to be easily moulded into convenient shapes to fit *package* applications but is clearly less robust and resistant to attack or damage.

(b) Cadmium is a more efficient neutron absorber than boron for neutrons of thermal energies, although its efficiency diminishes rapidly as neutron energy increases. Cadmium is generally not used in new package designs due to its undesirability from other aspects of safety, e.g. toxicity. It may also be unsuitable in some applications because of its low melting point.

(c) Rare earths such as samarium, gadolinium and hafnium have been used but generally only for very specific applications, as compared with boron, say, which is a good all-purpose neutron absorber. These materials are also very expensive.

Although maybe not designated as formal neutron absorbers in the sense described above, the packaging and structural materials may have some inherent neutron absorption properties. An example of this might be the internal structure of an irradiated fuel transport flask. However, it must be borne in mind that such material may also act as a neutron reflecting material (see below), so there may be some "trade-off" between one effect and the other.

To enhance the effectiveness of certain neutron absorbers, a neutron moderating material may be incorporated as part of the design to ensure sufficient neutron thermalisation and hence efficient neutron absorption. This might be achieved by the use of cellulose based materials (e.g. wood) or organic materials (e.g. waxes). It may also be possible to combine moderators and neutron absorbers, as in the case of the flexible boronated material mentioned above, which has the boron neutron absorber present in a rubber matrix material.

Flux traps incorporate a region of moderator between two regions of neutron absorbing materials. This increases the probability of neutron absorption by ensuring that some thermalisation of the neutrons has occurred before the neutron enters the absorbing region. The careful engineering of flux traps between adjacent fissile locations may give rise to significant reactivity benefit for identical spatial separations of the fissile material, and for identical inventories of neutron absorbing material. Care must however be taken in the subsequent assessment of accident conditions, whereby severe impact damage may give rise to compression of the flux traps and hence the loss of some of the reactivity benefit they provide.

Also mentioned above is the issue regarding the continued presence and effectiveness of the neutron absorbing material. This is particularly important when considering the effects of the package impact and fire tests required by (Ref. 1) as part of the transport package approval process. The potential effect that such tests may have on neutron absorbing materials must be addressed as part of the criticality safety assessment, including the displacement, loss or deformation of such materials. The same may also be true of structural materials that have neutron absorbing properties.

During the production of the criticality safety assessment, it is important to consider all tolerances that might apply to the manufacture of any neutron absorbing materials. This may include:

- Tolerances associated with the neutron absorber content (e.g. boron) in the material overall

- Tolerances associated with the dimensions of the absorber material as manufactured

- Tolerances associated with the density of the absorber material, either during manufacture or as a result of some modification that reduces the effective density

All of the above tolerances can combine to reduce the effective poison concentration of the neutron absorbing material overall and must be carefully taken into account. An example could be the introduction of holes in the neutron absorbing material, which aids the circulation of water or air for cooling purposes. This not only has the effect of reducing the effective density of neutron absorbing material but also introducing paths which might result in neutron streaming between discrete fissile material units within the same package. How such a design is treated depends upon the package design itself, the size of holes and the number of holes that are present in the absorbing material.

3.3.4 Neutron Reflection

When a package containing fissile material is surrounded by air, neutrons reaching the surface of the package can easily escape from the system and are lost by the leakage process. If the same package is surrounded by water (or some other reflecting material), the neutrons that would otherwise escape the system may be reflected back into the package, hence resulting in less neutron leakage from the system. As well as reducing leakage, some of the reflected neutrons may cause further fission in the fissile material of the package.

The Regulations require that the individual package in isolation and arrays *of* packages are reflected on all sides by 20 cm full density water. However, it is required that if reflectors more efficient than water may be encountered in practice, the most pessimistic case should be considered. This requires some judgement as to what conditions may reasonably be encountered during transport, particularly during an accident condition. Examples of more efficient reflectors than water that might require consideration are concrete, rock and massive graphite. The exact elemental composition of concrete and rock can be difficult to both obtain and justify but, when encountered purely as a reflecting material, this is less problematic to the criticality assessor. Pessimistic representations of concrete should be considered.

Clearly for heavily shielded packages, such as irradiated fuel transport flasks where an infinite array (in all directions) may be acceptable from a criticality safety viewpoint, the latter requirement is not generally relevant.

3.3.5 Neutron Interaction Between Packages

When more than one package is present in a consignment or array of packages, any neutrons leaving one package may enter another *package* in the consignment, thus reducing the overall loss of neutrons from the system. This process has the potential to increase the overall reactivity of the system, in this case an array *of* packages. This process, as already mentioned above, is known as neutron interaction and one which should either be prevented or reduced from the viewpoint of criticality safety, possibly resulting in the benefit of increased package payload.

Neutron interaction can be prevented or reduced in a number of ways, with examples as follows:

- Increase the amount of shielding material external to the package itself. An example of this is a heavily shielded irradiated fuel transport flask that is essentially isolated due to the thickness of the shielding.

- Use of neutron absorbing materials. In contrast to the use of neutron absorbing materials within a package design (such as the frames used in irradiated fuel flasks, and MEBs), absorbers can be used externally to the package fissile material contents to reduce interaction between packages. This approach is usually of more use for lightly constructed packages where the potential for neutron interaction is enhanced. An example of modern practice is the use of expanded foam impregnated with boron.

- Increasing the spacing between packages. As the space between packages increases the probability of a neutron escaping from the system without causing further fission also increases. This could be achieved by designing a package with engineered external features that guarantee a spacing between packages irrespective of array layout, e.g. a cage, spacing lugs. It is important, however, that the performance of such engineered features is assessed for all conditions of transport, including accident conditions. If the spacing is also associated with the presence of water, thicknesses of around 30cm full density water can reduce interaction between packages to insignificant levels. In fact any thickness of water greater than approximately 5cm will give progressively greater benefit in reducing the interaction and hence reactivity of an array of packages.

- Limiting the numbers of packages in an array, or the package fissile material contents. For packages which exhibit a tendency for neutron interaction, limiting the allowable number of packages in a consignment or the fissile material contents reduces the reactivity of the system and increases the overall degree of criticality safety. From a viewpoint of consignment efficiency this must be seen as the least desirable option for reducing interaction, although in some circumstances it may be the only option.

- Limiting the shape of an array of packages. For a given number of packages within a consignment, it may be possible to engineer a feature that prevents the optimum closely packed arrangement of packages. For instance, an arrangement which is flat and where the package height is limited is more beneficial from a criticality safety viewpoint than a compact arrangement. In general, any increase in surface area to volume for packages, or arrays of packages, has the effect of reducing the reactivity of the system since the potential for neutron leakage is increased. Once again, any feature that is incorporated must be an engineered feature and must still be in place after postulated accident scenarios, if any credit is to be taken for it in the criticality safety assessment.

3.4 PACKAGES CONTAINING FISSILE MATERIAL

The criticality safety assessment for a given package is performed for a specific set or range of parameters. Normally these parameters are indicated in the transport certificate of approval. This is due to the fact that different parameter values could adversely affect the neutronic behaviour of the system and thus invalidate the CSI for the transport package. As such any package containing fissile material, other than "excepted packages", must not contain:

(a) A mass of fissile material different to that authorised.

(b) Any fissile material different to that authorised.

(c) Contents in a form or physical or chemical state different to that authorised.

It is, therefore, important to list all those parameters upon which the criticality safety of a package may be based and those that should not be subject to change without further assessment. Examples may include:

- A statement of any fixed neutron poisons which may be present.
- Other non-fissile material included in the contents. Examples of this would be inner receptacles and packing materials.
- A statement of the form in which the fissile material must be transported. For example, it might say that the fissile material should be transported as a complete fuel assembly, or it might say that it should be transported in such a way that the formation of a heterogeneous arrangement would be prevented.

3.4.1 Fissile Excepted Packages

Some packages containing fissile material are excepted from the relevant sections of the Regulations (Ref. 1) and the Guide to Applicants (Ref. 2) which cover packages containing fissile material. The exceptions from the requirements of the Regulations essentially and broadly relate to:

(a) The fissile mass being less than a given fissile material mass limit for the package and for the overall consignment. The mass limit depends upon a number of factors, including:

- The isotope in question, i.e. U-235 or other fissile material.
- The average hydrogen density of the substances with which the fissile material is mixed. The average density of these substances relative to water should be given.
- A limit on the fissile material content of each package or the fissile material per unit volume or in a given volume of hydrogenous material.
- Neither beryllium nor deuterium must be present in quantities exceeding 0.1% of the fissile material mass. This restriction is imposed because the three exceptions immediately above are based upon the assumption of hydrogenous moderation and reflection.

The restriction of an allowed fissile material mass per consignment allows for the mixing of fissile material types [1, Para 672].

(b) Essentially homogeneous uranium systems with a maximum uranium enrichment of 1% U-235 by mass, which, if present in metallic, oxide or carbon forms, cannot form a lattice arrangement.

The homogeneity requirement is intended to preclude latticing of slightly enriched uranium in a moderating medium. Concentrations can also vary throughout the material, although variations in concentration of the order of 5% should not compromise criticality safety.

(c) Liquid solutions of uranyl nitrate with a maximum uranium enrichment of *2%* U-235 by mass and with a minimum nitrogen to uranium (N/U) atomic ratio of 2. Packages containing not more than a total of 1kg Pu, of which not more than 20% by mass can be Pu-239, Pu-241 or any combination of these radionuclides.

It is important to note that only one type of exception is allowed per consignment.

3.5 CRITICALITY SAFETY ASSESSMENT

The package designer can make use of criticality data handbooks, sources of other criticality data and hand methods of criticality assessment, examples of which are contained in References 4 to 7 inclusive and can often be used as part of the initial design process. However, as package designs become more complex, use is commonly made of neutronics computer codes that are capable of dealing with complex package designs and payloads. It is, however, prudent to involve a criticality safety specialist in any early discussions and throughout the development stages of a package design.

Whilst not mandatory, it is preferred by the Regulator that the criticality assessment is submitted in a format laid down in Part III of the Guide to Applications [Appendix A]. The guide is in the form of questions that enable the regulator to assess each aspect of the design information required for fissile material. The applicant is required to address each aspect of the guide in turn, either providing a specific response or stating "not applicable" where relevant. The benefit of the guide is that by following the format of the Guide to Applications, the relevant issues of the Transport Regulations will have been addressed.

The criticality safety assessment is required to consider the contingencies set out in Paragraph 671 of the Regulations (Ref. 1). These contingencies represent possible changes in the package or environment that could occur during transport under normal or accident conditions and that could affect the overall reactivity of the package or consignment. It must be confirmed in the criticality safety assessment that such changes do not reduce the margin of subcriticality to an unacceptable level.

The contingencies listed in Paragraph 671 are discussed in the following Sections.

3.5.1 Water Leaking Into or Out of Packages

The effect of water leaking into or out of a package can have many different effects on criticality safety depending upon the fissile material type and package design in question. When water is acting as a reflector of neutrons, it should be borne in mind that its effectiveness is reduced when located outside the confinement system and less still outside the package as a whole. The criticality safety assessment also needs to carefully consider changes in the package geometry and conditions that may cause water to behave more as a moderator than as a reflector, or vice versa. All forms or water including ice, snow, spray and firefighting foam, for example, need to be addressed.

3.5.2 The Loss of Efficiency of Built-in Neutron Absorbers or Moderators

Any change that can affect the potential efficiency of built in absorbers or moderators, either by total or partial loss, needs to be considered. This may not only be due to erosion or corrosion but also due to the effects of severe impacts causing deformation or redistribution of absorbers present in the package as presented for transport. For example, a neutron absorber may become dislodged and drop outside the fuel region or become so distorted that it cannot perform as efficiently. The effects of a severe fire on the absorber must also be considered.

Built-in moderators can be viewed in a similar way to neutron absorbers in the context of this contingency. If they are built-in, they will have invariably been used to perform some neutron attenuating function, either solely or in conjunction with a neutron absorber. Also, there is a strong probability that they will consist of an organic or cellulose based material (e.g. wax or wood), which could be particularly affected by a severe fire, resulting in partial or even total loss.

3.5.3 Rearrangement of the Contents

This contingency and the next below can cover many possibilities but are essentially contingencies arising from dimensional changes or movement of the contents during transport. When considering rearrangement <u>within</u> the package, the effects on both the fissile material itself and any related aspects which guarantee subcriticality need to be addressed. For instance:

- For the transport of oxide fuel pins, an accident condition could lead to fuel break-up occurring where fuel particles are released from a damaged fuel pin. It is normally assumed that a damaged pin loses all of its fuel and that this fuel finds its way into the worst possible part of the package in the worst credible orientation and concentration. It is necessary to assume that all the fuel could leak out of a damaged or cracked pin due to the cracking and break-up of UO_2 fuel pellets under irradiation. Clearly, an important part of the fuel break-up analysis is estimating the maximum mass of fuel that can escape from the fuel assemblies. This estimate must take into account the effect of irradiation on the physical properties of the fuel assemblies.

- There is a secondary effect of considering fuel break-up. LWR fuel assemblies are generally slightly undermoderated, so a small increase in the number of missing pins can lead to an increase in reactivity. If the fuel particles leak from a pin then this results in an effective increase in the number of missing pins and hence an increase in reactivity. This effect has not always been considered explicitly in the past when it has been judged that the treatment of the released fuel was sufficiently conservative. The assumption that all the fuel leaks out of a cracked pin probably is very conservative. This effect may need to be considered in more detail in some cases.

- If subcriticality within a *package* is maintained by geometrical restrictions, an accident condition might result in the deformation or movement of internals, which play an important role in maintaining subcriticality.

Any fissile material lost from the array of packages must also be demonstrated to be a subcritical quantity.

3.5.4 Reduction of the Spaces Within or Between Packages

This has partially been addressed above. However, the assessment needs to be extended to cover what the effects might be if the spacing between packages in an array is reduced, resulting in the potential for increased neutron interaction. If engineered features are used to guarantee package spacing, it is important that adequate spacing remains following accident conditions, otherwise a reduction in spacing will need to be addressed. An example of spacing that is provided in the package as presented for transport but is unlikely to remain following an accident is that provided by shock absorbers in heavily shielded irradiated fuel transport flasks. It might be concluded that taking credit for shock absorbers at all is unwise in view of their vulnerability. If packages are assessed in infinite arrays, then this effect must be covered.

3.5.5 Packages Becoming Immersed in Water or Buried in Snow

Immersion in water may affect water in-leakage as considered above. Packages being immersed in water or buried in snow (equivalent to reduced density water) may have an effect of producing enhanced neutron interaction for certain package designs and particularly those that allow neutron interaction due to lack of significant shielding. Any effects are likely to be negligible for heavily shielded packages. Where the flask is water filled for transport, water in-leakage is unlikely to cause an increase in reactivity unless soluble poisons are involved.

3.5.6 Temperature Changes

The effects of temperature changes on the stability of the fissile material form or on the neutron interaction properties need to be examined. Temperature changes may also influence the package integrity, such as that predicted by the fire tests.

The contingencies listed above are intended to be those typically relevant to criticality safety assessments. This does not preclude the requirement to consider additional contingencies that may be dependent upon a particular package design or any special conditions anticipated in transport and handling. Similarly, there may be a need to consider a number of contingencies simultaneously following the outcome of package design tests.

When undertaking the criticality safety assessment, where the chemical or physical form, isotopic composition, mass or concentration, moderation ratio or density, or geometric configuration is not known, the assessment of the individual package in isolation and arrays of packages must be performed assuming that each parameter that is not known has a value which gives the maximum neutron multiplication factor. In practice this requirement may be met by covering the effect of these uncertainties by a suitable allowance in the criticality acceptance criterion. It is also important to determine the combination of parameters that produce the maximum neutron multiplication.

In addition to be above, the package must be designed for an ambient temperature range of -40°C to +38°C unless the Competent Authority specifies otherwise.

3.6 ASSESSMENT OF AN INDIVIDUAL PACKAGE IN ISOLATION

For an individual package in isolation, it must be assumed that water can leak into or out of all void spaces of the package, including those within the containment system. This is regardless of the test results, unless the package design incorporates special features to prevent such leakage of water into or out of certain void spaces, including all of the following:

- Multiple high standard water barriers, each of which would remain watertight if the package were subject to the tests prescribed in the Regulations [1, Para 682b]. These

effectively relate to those tests for demonstrating the ability to withstand the normal conditions of transport followed by the more limiting of a number of tests relating to the ability to withstand accident conditions of transport.
and

- A high degree of quality control in the manufacture, maintenance and repair of packagings,
  and

Tests to demonstrate the closure of each package before each shipment.

To be considered "watertight" for the purposes of preventing in-leakage or out-leakage of water in relation to criticality safety issues, the effects of both the normal and accident condition tests need to be considered. Definitive leakage criteria for watertightness need to be set out in the criticality safety assessment report for each package and accepted by the regulator.

Notwithstanding the above, there is a set of special requirements for packages containing uranium hexafluoride only. The neutron multiplication for packages containing uranium hexafluoride is very sensitive to the amount of hydrogen present. As a result, careful consideration needs to be given to restrict the possibility of water leaking into the package.

3.7 TRANSPORT OF PACKAGES BY AIR

Special attention needs to be given to packages transported by air. A special set of test conditions are prescribed in Paragraph 734 of the Regulations which are more stringent than those for other package types, particularly in the areas of thermal and impact testing.

The requirements for packages transported by air only apply to the criticality safety assessment of an individual package in isolation. Paragraph 680(a) requires a single package, with no water in-leakage, to be subcritical following the Type C test requirements and is provided to preclude a rapid approach to criticality that may arise from potential geometrical changes in a single package; thus water in-leakage is not considered.

Depending on the intended use of the transport package, there may be a requirement to address additional local design criteria beyond the IAEA Transport Regulations. For example, the transport of plutonium by air in the United States is subject to the conditions of the US Nuclear Regulatory Commission (US NRC), notably NUREG-0360 which specifies additional package qualification tests (Ref. 8).

3.8 ASSESSMENT OF ARRAYS OF PACKAGES

The criticality safety assessment needs to consider arrays of packages both under normal and accident conditions of transport, from which an allowable number "N" shall be derived for use in the Criticality Safety Index. "N" is derived for both conditions of transport as follows:

Under normal conditions of transport, the allowable number "N" is derived such that five times "N" is subcritical for the conditions that provide the maximum neutron multiplication with:

(a) Void between the packages, and the array of packages reflected on all sides by at least 20 cm full density water, **and**

(b) The state of the packages in their assessed or demonstrated condition having been subjected to the tests described in Paragraphs 719-724 of the Regulations (i.e. those relating to normal conditions of transport).

It is important that the array arrangement considered must be such that the maximum neutron multiplication occurs and might require, for example, compact cubic arrays or close hexagonal packing unless there is some feature that allows a less restrictive arrangement to be considered.

Under accident conditions of transport, the allowable number "N" is derived such that two times "N" is subcritical for the conditions that provide the maximum neutron multiplication with:

(a) Hydrogenous moderation between packages, and the package arrangement reflected on all sides by at least 20 cm full density water, and

(b) The required most limiting tests to represent accident conditions, and

(c) Where any part of the fissile material escapes from the containment system following the above tests, it must be assumed that fissile material escapes from each *package* in the array and all of the fissile material is arranged in the configuration and moderation that results in the maximum neutron multiplication with close reflection by at least 20 cm of full density water.

Even though there may be only one such package in existence, the determination of "N" for use in the Criticality Safety Index must still recognise the need to demonstrate subcriticality for 5N packages as presented for transport and 2N packages under accident conditions of transport.

3.9 IRRADIATION HISTORY

The Regulations (Ref. 1) do allow for the irradiation history of irradiated fuel, prior to shipment, to be taken into account when evaluating the subcriticality of a package or consignment of packages [1, Para 674]. Care must be taken to ensure that any allowances which result in a decrease in system reactivity of the package or packages which are attributed to irradiation are both demonstrable and auditable. This requires that a measurement be made after irradiation but prior to shipment that confirms the conservatism of any isotopic composition used in the criticality safety assessment of the package.

The type of measurement required will depend on what proportion of the actual irradiation is being accounted for and how much the safely subcritical limit would be exceeded if irradiation were not taken into account.

Alternatively, an isotopic composition that provides the maximum neutron multiplication during the irradiation history can be used.

Care must also be taken to accurately assess reactor fuel designs that incorporate fixed neutron burnable poisons as part of the fuel design. Such fuels can experience an increase in reactivity for short-term irradiations where the reactivity gain due to the depletion of the fixed neutron poisons is greater than the reactivity loss due to the change in fuel composition.

"Burnup credit" is the term used for the method which takes account of the loss of fissile material content (depletion) and/or the presence of neutron absorbing fission product poisons in the overall calculation of system reactivity. It should be noted that the word depletion is used to cover depletion of U-235 and the production of other fissile actinides. It is sometimes also known as “actinide only” credit. It is a marked deviation from the traditionally used "fresh fuel" approach that makes use of the fact that the maximum neutron multiplication generally occurs in the unirradiated state. However, the acceptability of burnup credit is undergoing constant reappraisal and is, at the time of writing, comparatively new with respect to submissions for Competent Authority Approval. It is thus advisable that advice be sought from a criticality specialist as to the applicability of techniques used to account for a decrease in reactivity. Indeed, there are international collaborative exercises that address the issue as a whole.

Notwithstanding the above comments, submissions considering the “actinide only” component of the burnup credit technique are perhaps easier to make and defend at this point in time. Even so, there are a large number of factors that need to be considered or may be of some relevance to the criticality safety case being made. These include:

- The fuel element type, e.g. PWR or BWR, enriched uranium or mixed oxide (MOX).
- The initial isotopic abundance.
- The specific power, power profile and reactor operating history.
- The presence of burnable poisons and/or control rods.
- The cooling time after discharge.
- The axial isotopic distribution of irradiated fuel.
- The techniques used to predict the depletion of the fissile isotopes.

The above list is illustrative but demonstrates that many factors can be of relevance. If the fission product poisoning component is added, additional factors include:

- The techniques used to predict the quantity of fission products present.
- An assessment of those fission products which are long lived, of neutronic significance and chemically stable in the environment likely to be encountered.
- The accuracy of fission product cross sections in nuclear data libraries

It is clear that the issue of burnup credit is both complex but also one which will become more important as the fissile isotope enrichment of reactor fuels is increased for the purposes of economy and reactor efficiency in years to come.

3.10 CRITICALITY CODES AND VALIDATION

Unless a package design and fissile material payload are of the nature that can make use of simple criticality handbooks or hand methods of calculation, there will be a requirement to make use of a neutronics criticality computer code. Whilst there are no prescriptive requirements regarding the use of neutronics codes, they must be justified as being fit for purpose and evidence must be provided on the validity of their use for the package being assessed.

Economic factors are now driving any package design to maximise payloads and hence reduce transport costs. This approach maximises the permitted quantity of fissile material per package and the allowable number of packages per consignment, inevitably requiring a high standard of criticality assessment and the frequent use of neutronics codes.

The performance of neutronics codes and their associated nuclear data libraries should ideally be evaluated against critical experiments using similar:

- Fissile material isotopes.
- Fissile material enrichments.
- Moderating materials and degree of moderation.
- Reflecting materials and degree of reflection.
- Neutron energy distributions.
- Degrees of neutron leakage.
- Amounts and type of neutron poisoning materials.

It may not always be practicable to do this and hence it is often necessary to choose a range of experiments that may, when considered overall, encompass the key features of the package design and ensure that the code is validated for the specific package modelled. It should be noted that most experiments quoted in literature are critical experiments so the calculated K_{eff} for systems of low reactivity may be considered to be less well validated than that for systems of higher reactivity.

In the majority of cases, a computer code will have an associated validation database which covers a wide range of critical experiments. If a particular application is not covered by such a database, effort may be required to identify a suitable critical experiment that will need to be considered explicitly. If no suitable critical experiment exists or the pedigree of such an experiment is in doubt, consideration must be given to applying a bias to any results obtained using the code. Any bias used must be justified. The latter point is one that particularly affects the application of burnup credit when considering the presence of fission products. There is little data in published literature that considers the presence of fission products, so the accurate assessment of the nuclear data of certain fission product poisons is less than straightforward. Again, suitably justified biases may need to be applied to account for the potential uncertainty in the accuracy of fission product nuclear data.

In calculating the neutron multiplication of a system, due consideration must be given to other associated errors and uncertainties, including:

- The standard deviation associated with the calculation of K_{eff} by statistical codes (if appropriate) and the number of standard deviations used (if appropriate), commonly 2 or 3.
- An allowance for any non-conservative modelling approximations used. This is rarely applied given the modelling flexibility available with a number of computer codes.
- An allowance to account for more reactive systems than those assessed explicitly. This is used less frequently nowadays given that the submission should consider the full range of conditions that might be experienced by the package and its contents.

- An allowance to account for uncertainties in the chosen nuclear data library used, which can be broken down into at least two components. For example, one component to reflect the level of agreement between experiment and calculation and one component which recognises that there is a less than ideal match of application and experiment and reflects the interpolation/extrapolation performed.

- An allowance that is unique to the uncertainties of allowing the burnup credit techniques, if used.

In addition to those errors and uncertainties indicated above which may be of relevance, an adequate margin of safety must also be justified and applied. This is the margin of subcriticality, in addition to any errors and uncertainties, which must be applied to a critical system. The margin of subcriticality used in the criticality safety assessment is dependent upon the particular system in question and as such is a matter of judgement. However, plutonium and highly enriched uranium systems exhibit a different rate of change of K_{eff} with fissile material quantity compared with low enriched uranium systems, say, and so the application of a fixed value of the margin of subcriticality is not appropriate.

Typical practice for transport packages is to apply a margin of subcriticality of 0.05, although a value lower than 0.05 may be appropriate in some cases. Any value of margin requires justification based on available validation and demonstrated understanding of the system in question to potential changes. Finally, a paucity of critical experimental data or the need to extend beyond the range of applicability may indicate the need to increase the margin of subcriticality beyond that typically applied.

3.11 FURTHER INFORMATION

Due to the complex nature of criticality safety assessment and the multiplicity of requirements and important factors, it is not possible to provide complete and fully comprehensive advice into all aspects which have or may have an effect on acceptable fissile material package designs. However, it is hoped that the information provided in this document provides an insight into the aspects of major importance that require consideration. It is essential, as highlighted throughout this document, that the package designer and criticality safety specialist demonstrate close liaison at all stages. This is to ensure that the final design is likely to meet all requirements of the Regulations and address the issues raised in the guide to applications for Competent Authority Approval. Additionally, whenever a change is proposed to the package design or contents, the criticality safety specialist should be made aware to ensure that the criticality safety assessment is not inadvertently undermined.

Further information regarding advisory material that may be consulted to support a submission for Competent Authority Approval can be found in (Ref. 3). Particularly important is Appendix VII, which provides a much fuller picture of the requirements for the production of criticality safety assessments.

REFERENCES – SECTION 3

1. Regulations for the Safe Transport of Radioactive Material, 1996 Edition (Revised), Regulations, No. TS-R-1 (ST-1, Revised), IAEA Vienna.

2. DETR/RMTD/0003 “Guide to an Application for UK Competent Authority Approval of Radioactive Material in Transport (IAEA 1996 Regulations)”, Department of the Environment, Transport and the Regions, Radioactive Materials Transport Division, January 2001.

3. Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material, Safety Guide No. TS-G-1.1 (ST-2), IAEA Vienna.

4. AHSB(S) “Handbook of Criticality Data, Volume 1”, 1st Revision, 1965 and 1967.

5. ARH-600 “Criticality Handbook”, Atlantic Richfield Hanford Company, 1968 et seq. LA-10860-MS “Critical Dimensions of Systems Containing U-235, PU-239 and U-233”, 1986 Revision.

6. LA-12808 “Nuclear Criticality Safety Guide”, September 1996.

7. NUREG-0360 “Qualification Criteria to Certify a Package for Air Transport of Plutonium”, January 1978.

4 CONTAINMENT

4.1 GENERAL REMARKS

4.1.1 Radioactive material transport packages must satisfy the regulatory requirements for the transport of nuclear materials specified in the International Atomic Energy Agency (IAEA) Safety Standards Series TS-R-1 (Ref. 1). This is referred to here as TS-R-1 and relevant paragraphs are given in square brackets thus [ ]. The classification of the package will depend on the quantity and nature of radioactivity to be contained. Packages classified as Type B, fissile or Special Form require approval by the UK Competent Authority (CA). Other classifications of package do not require CA approval before use but must comply with the relevant regulations. Additional advisory and explanatory information is provided in IAEA Safety Guide No. TS-G-1.1 (ST-2) (Ref. 2).

4.1.2 TS-R-1 [213] states that the "Containment System shall mean the assembly of components of the packaging specified by the designer as intended to retain the radioactive material during transport."

In practice this means the sealing system that prevents the release of the radioactive liquid, gas or solid particles. The package classification determines the performance of the sealing system under normal conditions of transport and accident conditions of transport.

4.1.3 Special form radioactive material is either an indispersible solid or a sealed capsule containing radioactive material. If it is a capsule, it can only be opened by destroying it. Consequently containment is addressed at the manufacturing stage, and is considered to be outside the scope of this document.

4.2 CONTAINMENT SYSTEM REQUIREMENTS

4.2.1 The following is a summary of the main package containment requirements. Designers must examine TS-R-1 to ensure that all aspects are properly addressed in the design.

4.2.2 All packages

[613] Packaging materials must be compatible with each other and the radioactive contents. Radiation damage must be addressed.

[618] The containment of packages transported by air must remain effective in the ambient temperature range -40° to +55°C.

[619] Packages containing radioactive material transported by air shall have a containment system able to withstand without leakage a reduction in ambient pressure to 5 KPa.

4.2.3 IP-2

[622] When subjected to the tests specified in [722] and [723] there is no loss or dispersal of the contents. (The "no loss or dispersal" also applies for other qualification routes.)

4.2.4 IP-3 and Type A

[637] The package design must take in account an operating ambient temperature range of -40°C to +70°C for the components of the packaging.

[639] The containment system shall be secured such that it cannot be opened unintentionally or by internal pressurisation.

[640] Special form radioactive material may be considered as part of the containment system.

[641] If the containment system forms a separate unit in the package its closure system must be independent of any other part of the packaging.

[642] The containment system design must take into account physical and chemical changes which are consequences of the radiation emitted by the contents.

[643] The containment system must retain the radioactive contents under a reduction of ambient pressure to 60 kPa.

[645] Radiation shielding that encloses all or part of the containment system must be designed to prevent unintentional release of the containment.

[646] When subjected to the tests in [719] to [724] (representing normal conditions of transport) there will be no loss or dispersal of the radioactive contents.

[648] A Type A package containing liquids must exhibit no loss or dispersal of contents when subjected to the tests specified in [725]. In addition, absorbent material must be provided to absorb twice the volume of liquid carried, or the containment system must comprise inner and outer components so that the liquid is retained if the inner component should leak. This does not apply to Type B packages designed for liquid carrying active liquid of less than one A_2 activity.

[649] A package that is designed to carry gas shall prevent loss or dispersal of the radioactive contents when the package is subjected to the tests specified in [725].

4.2.5 Type B(U)

[651] Temperature rise caused by both internal and external effects will not adversely affect the containment if the package is left unattended for one week.

[656] If the package is subjected to the tests in [719] to [724] (representing normal conditions of transport) the leak rate will not exceed 10^{-6} A_2/hour. If subjected to the tests in [726], [727], [728] and [729] (representing accident conditions of transport) the leak rate will not exceed A_2 in one week.

[657] The containment system of a package containing irradiated nuclear fuel with an activity greater than 37 PBq will not rupture when subjected to the enhanced water immersion test in [730].

[658] Compliance with the permitted activity release rates shall not depend on filtration nor mechanical cooling.

[659] No pressure relief system may be fitted that would release radioactive material under the conditions of the tests in [719]-[724] and [726]-[729].

[660] The package containment system must meet the limits on leakage when it is subjected to the tests in [719]-[724] and [726]-[729] at maximum normal operating pressure.

4.2.6 Type B(M)

[666] Intermittent venting during transport is permitted provided the relevant competent authority agrees.

4.3 PACKAGING SEALING

4.3.1 The design of a package sealing system will be influenced by:

a) Type of package.
b) Standard of containment required.
c) Chemical nature of the contents.
d) Temperatures reached in the seal region during normal transport and accident conditions.
e) How often the package is used.
f) How long the package will remain sealed.
g) Radiation dose uptake.

These factors influence the seal configuration and the seal materials.

4.3.3 Examples of typical sealing systems:

a) Elastomeric O-rings are generally preferred to flat gaskets. These seals can usually be used a number of times before replacement but are susceptible to damage when used on cylindrical surfaces as a piston seal, or during rough handling. Relatively low compression forces are required to provide the seal.

b) Flat gaskets made from fibre or synthetic materials may be used provided the material is resistant to the contents of the package. Except for rubber these should only be used once.

c) Metallic O-rings can be supplied in the form of hollow gas-filled toroidal O-rings (e.g. Wills ring). These perform satisfactorily over a wide temperature range and do not deteriorate over long periods, making them suitable for transport/storage applications. However they do have limitations on reuse and should not be applied to systems where this is the normal requirement. This type requires a high level of cleanliness to work properly, and high compression forces to form the seal.

d) Metallic gaskets may be used for higher temperature applications (above 300°C). Flat gaskets are most commonly used, made from metals such as copper, nickel or silver. The gasket should be annealed before use and only used once. They are generally restricted to diameters less than 250 mm, since larger sizes become very expensive. The bolt load required for a successful seal is high, leading to a heavy flange design.

e) Corrugated metal filled rings are suitable for high temperatures but require high closure bolt loads to achieve an adequate seal and withstand the type B tests. These have limitations on reuse and in most cases can only be relied upon once.

f) Small packages use a range of sealing methods, typically: heat-sealed vials, screw-cap packagings, metal faces mechanically roll bonded (“fruit cans"). These are frequently one-trip packagings that are destroyed by opening.

4.4 ELASTOMERIC O-RINGS

4.4.1 Elastomeric O-rings are probably the most common form of package seal because they are simple, reliable and can be remade and then tested to provide a numerical value of leak rate. They are also readily available from a number of suppliers. The most commonly used materials are discussed below.

Note: The UK Competent Authority has produced an "Applicants' Guide" (Ref 3) to selecting elastomeric sealing materials. All designers specifying a sealing system should be conversant with the Competent Authority guide as it relates specifically to RAM packaging (unlike seal manufacturer's data which is aimed at the volume user such as automotive).

a) Silicone rubber (MVQ) is a material with a wide temperature range and can operate effectively from around –50°C up to 230°C (or even 300°C for short periods) with good resistance to chemical attack. The disadvantages are that, compared to other sealing materials, it is susceptible to tearing, and has a high permeability. Where large lengths of silicone O-ring are used the high permeability can appear as a leak when tested.

b) Chloroprene rubber (CR) is a well established seal material with good chemical resistance and is relatively inexpensive. (The Du Pont trade name is Neoprene.) Its temperature resistance is limited compared with other elastomeric materials, -40°C to +100°C.

c) Fluorocarbon rubber (FPM) is a material widely used for O-ring seals being relatively inexpensive and having a high resistance to chemical attack. (The Du Pont trade name is Viton.) It is strong and resistant to tearing and O-rings can be readily made from cord. Viton compounds can stand temperatures up to 200°C for long periods and temperatures up to 250°C for short periods (i.e. 3 to 4 hours) without degradation. Users should be aware that these materials can decompose at high temperatures and release hydrogen fluoride, requiring provision of protectictive clothing and suitable ventilation. Performance at low temperature is poor and it is not really suitable below -20°C, though some special formulations may improve on this.

d) Ethylene-propylene rubber (EPDM) has a high resistance to chemical attack and low permeability. The advantage with the material is it can be used down to approximately -50°C whilst its upper temperature limit is 150°C (170°C for short periods, i.e. 10 hours).

e) Acryl-nitrile butadiene rubber (NBR) has good mechanical properties and wear resistance, but suffers from a restricted temperature range of -20°C to 100°C. (The Bayer trade name is Pebunan, and it is commonly referred to as nitrile rubber.)

4.4.2 It is very common for O-rings to be used in concentric pairs. The inner O-ring provides containment; the outer O-ring is used to provide an interspace volume so that the leak rate of the sealing system can be measured. Pressurising the interspace and then measuring the pressure change allows the Standardised

Leakage Rate (SLR) to be calculated. (Note that the SLR will also include any leakage through the outer seal and test equipment.) The theory and basic technique are described in AECP 1068 (Ref. 4). Proprietary equipment is available that calculates the SLR and provides a verified print-out of the results. Figure 4.1 provides basic design data for a typical double O-ring seal between two bolted faces. Note that the land between the O-ring grooves is slightly undercut to allow free movement of the pressurising air. It is good practice to machine the O-ring grooves in the cheapest or most easily handled component, so that damage can be easily repaired or the component replaced. These standard O-rings grooves should be used wherever possible on the grounds of cost and simplicity. However, in some cases (notably remote operations under water, or the underside of a lid) it is necessary to ensure that the O-rings remain trapped within their grooves and this is usually achieved by shaping the groove sidewalls. Refer to Figures 4.2 and 4.3 for further details.

4.4.3 The volume between the concentric O-rings used for leak testing (and this includes the drilling leading to the instrument) should be kept to a minimum. This enables the reading to be made quickly, which reduces the effect of temperature change and improves accuracy. Occasionally the packaging design is such that the drilling leading to the O-ring interspace may be quite long. Drilling a 2 mm diameter hole is more difficult as the depth increases; the drill tip wanders and breakage becomes more likely. In this case it is recommended that the hole is drilled to a suitable practical diameter and the volume reduced by fitting a slotted rod, which can be left permanently in the hole. See Figure 4.4. (Note that the pressure connection will be larger than the usual G1/8 size.) Regardless of size, when the test point is not in use it is good practice to blank it off with a conventional plug fitting.

4.4.4 Standard O-ring sizes should be specified to reduce costs and the need to carry stocks of specials. Where this is not practicable, O-rings can be made to size from O-ring cord and the ends bonded using, typically, cyanoacrylate adhesive. Care must be taken to ensure that the adhesive and the material are compatible and suitable for the package thermal limits. Silicone rubber for instance is almost impossible to join in this way. The user must also be aware that this type of joint will not tolerate temperatures much in excess of 80°C and that a cyanoacrylate adhesive bond can be affected by moisture. There is a degree of controversy over whether the O-ring cord ends should be cut square (to make a simple butt joint) or at an angle (a scarf joint). The idea of the scarf joint is to increase the bonded area and so improve the strength of the bond. However, some degree of misalignment is almost inevitable so generally speaking the simple butt joint is preferable. Care must be taken to cut the O-ring cord to the correct length. If the assembled O-ring needs to be stretched more than 6% to fit in the groove the consequent reduction in diameter can affect the compression ratio (see 4.4.7 below).

4.4.5 Joint performance can be improved by bonding and then vulcanising. Manufacturers can make non-standard O-rings in very small batches using soft metal moulds. Designers must consider whether the additional cost and stock problems are justified.

4.4.6 O-ring performance is improved by lightly coating with proprietary grease, such as Apiezon or O-lube, prior to use. Note, however, that if a seal is subjected to a large temperature increase (i.e. the fire test for accident conditions of transport) this grease will evaporate and the package will need to maintain its integrity with dry seals. Therefore seals on a Type B package, which must be leak tested prior to each journey to demonstrate Regulatory compliance, should be tested dry. Other seals may be lubricated. The most likely causes of a high leak rate are dirt in the grooves, or dirty or damaged O-rings. If checking these points still fails to achieve the desired leak rate then the grooves and sealing face should be carefully examined for radial scratches.

4.4.7 The O-ring compression ratio is calculated from:

$$\frac{(\text{uncompressed O-ring diameter - groove depth}) \times 100}{\text{uncompressed O-ring diameter}}$$

This is typically 17% to 22%, depending on how the tolerances stack up. The coefficient of thermal expansion of elastomers is typically ten times that of steel, so a designer may need to consider the effect that differential expansion may have. Coefficients of thermal linear expansion are given below for a range of common materials:

Elastomer	**/°C**
Acryl-nitrile butadiene rubber (NBR)	112×10^{-6}
Chloroprene rubber (CR)	137×10^{-6}
Fluorocarbon rubber (FPM)	162×10^{-6}
Ethylene-propylene rubber (EPDM)	160×10^{-6}
Silicone rubber (MVQ)	200×10^{-6}
Metal	
Aluminium alloy	23×10^{-6}
Carbon steel	11×10^{-6}
Stainless steel	17×10^{-6}

4.4.8 Compression set is the term used to describe the permanent deformation in O-ring cross section that can result from aging or being subjected to too high a temperature. It can also occur as a temporary effect at low temperatures when the material loses its elasticity. Once compression set appears, the material is offering a reduced force against the sealing faces and the sealing effectiveness is reduced. Hence care must be taken to ensure that the material is suitable for the expected operating temperature range, and installed O-rings must be examined at suitable intervals and replaced when necessary.

4.4.9 Compression set and brittleness are also the consequence of radiation damage. As a rough guide, the properties of most rubbers will not be significantly affected up to an absorbed dose of 10^4 Gy. The properties will certainly be affected at a dose of 10^5 Gy. The best material in this respect is Silicone (Ref 3).

4.4.10 Tritium permeates through O-ring seals and, given sufficient time, will permeate through steel too. Ref 5 provides experimental data on permeation through EPDM O-rings.

4.5 ACTIVITY RELEASE CRITERIA

4.5.1 No specific leakage criterion is given for Excepted, Industrial and Type A packages. However leak tightness is required in practice to ensure that under normal transport conditions the radioactive contents cannot escape.

4.5.2 Given the range of sealing methods adopted for Industrial and Type A packages, and the lack of a specified leak rate, a pragmatic approach must be adopted depending upon the form of the contents. Additionally, Quality Assurance procedures in the design, manufacture, operation and maintenance of the packaging components should ensure that the basic concept of "no leakage of contents" is realised in practice. A leak rate of 10^{-4} Pa $m^3 s^{-1}$ SLR (10^{-3} bar cm^3 s SLR) is frequently considered to be acceptable for a single seal. Other methods may not allow the leak rate to be measured directly but only by inference from the sensitivity of the test. See the table in 4.7.1. Provided that a reasoned justification can be put forward, other indicative methods may be used during package drop testing. For instance, a liquid may be dosed with fluorescein to provide visual indication of no leakage. Similarly a package intended to transport, say, contaminated rubble may use a colour contrasted fine powder indicator such as flour or carbon black. These methods are only applicable to full size packages i.e. not to scale models.

4.5.3 The regulations require Type B packages to be designed to restrict loss of radioactive contents to an acceptably low level. This is specified as a permitted release of radioactivity expressed as a fraction of A_2 per unit time for normal and accident conditions of transport. These criteria have the advantage of expressing the desired containment performance in terms of the parameter of primary interest; the potential hazard of the particular radionuclides in the package.

4.5.4 Type 'B' designs must meet the relevant requirements as given below [656 (a) and 656 (b)].

Conditions	Type B
After test for Normal Conditions [719-724]	$A_2 \times 10^{-6}$/hour
After tests for Accident Conditions [726-729]	A_2 in one week for all radionuclides except ^{85}Kr which can be $A_2 \times 10$ in one week

Note A_2 values in TBq for radionuclides are given in Table I of TS-R-1.

4.6 CALCULATIONAL METHOD TO DEMONSTRATE CONTAINMENT STANDARDS

4.6.1 To demonstrate a package containment system complies with the requirements of TS-R-1, the radioactive specification of the contents must be known. Where the contents cannot be precisely defined it is usual to apply a pessimistic activity and provide evidence to that effect. The essential problem thereafter is to relate that activity release rate to a measurable leak rate. TCSC 1068 provides guidance on how this can be achieved.

4.6.2 Where the radioactive contents of a package are particulates, i.e. in powder form, the above method of assessment cannot be applied directly. However, if the containment system can be shown to have a SLR not greater than 10^{-6} Pa $m^3 s^{-1}$ (10^{-5} bar cm^3 s^{-1}) then it is generally accepted that no particulate matter can be released (Ref 6). However, a greater SLR may be acceptable where it can be shown that the minimum particle size is larger than a single capillary that corresponds to the measured leak rate.

4.6.3 If the radioactive contents are liquid, the weight specific A_2 value must be determined from a knowledge of the radionuclides involved. Having determined the weight specific A_2 concentration of the liquid, the allowable volumetric leak rate can be calculated for both normal transport and accident conditions. The appropriate limit must be applied and related to the liquid conditions at normal and accident conditions. For example, if the temperature in the region of the seal was 100°C during a fire accident, then the liquid density at 100°C should be applied when calculating the allowable volumetric leak rate during accident conditions. It is usual to assume that the leak path geometry is unchanged during the fire accident unless the temperature exceeds the limits for the sealing materials.

4.6.4 When gaseous leakage is being assessed the maximum allowable volumetric flow rate may be calculated by taking the volume specific A_2 value and dividing this by the package containment requirements. The maximum allowable volumetric leak rate may then be multiplied by the gas pressure at the relevant condition to provide the measured leak rate.

4.7 LEAK TEST METHODS

4.7.1 A single standard test procedure is not feasible so a range of test procedures are used. These are described in Refs. 4, 7 and 8. From the test procedures given in these references, thirteen methods are recommended as practical for specific package types. These are briefly described below in increasing order of sensitivity.

TEST TYPE	**TEST SENSITIVITY** Pa $m^3 s^{-1}$ SLR (bar cm^3 s^{-1} SLR)	**DESCRIPTION**
1 HOT WATER BUBBLE	10^{-4} (10^{-3})	Qualitative test for small items without pressure tap connections. Package submerged in hot water - leak indicated by stream of bubbles.
2 SOAP BUBBLE	10^{-4} (10^{-3})	Qualitative test for packages with pressure tap connections. Package pressurised with gas and surface coated with soap film, leak indicated by bubbles on surface.
3 PRESSURISED CAVITY BUBBLE	10^{-4} (10^{-3})	Qualitative test for packages with pressure tap connections or where internal pressure may be generated by vaporisation of carbon dioxide. Package immersed in liquid, i.e. water or alcohol where leak is indicated by stream of bubbles.
4 GAS PRESSURE RISE	10^{-5} (10^{-4})	Quantitative tests for packages with pressure tap connection to interspace between parallel seals. The interspace is evacuated to pressure of about 0.1 bar and then pressure rise from this indicates leakage. Method often used on irradiated fuel transport flasks where contents are at sub-atmospheric pressure.

TEST TYPE	**TEST SENSITIVITY** Pa m^3s^{-1} SLR (bar cm^3 s^{-1} SLR)	DESCRIPTION
5 VACUUM BUBBLE	10^{-6} (10^{-5})	Qualitative test suitable for welded capsules and small resealable items. The test item is submerged in a liquid within a sealed packaging, a vacuum is produced above the liquid, a leak being indicated by a stream of bubbles.
6 GAS PRESSURE DROP	10^{-7} (10^{-6})	Quantitative test for packages with an interspace between parallel seals. The interspace is pressurised with gas and the fall in pressure measured over a period of time. A method widely used on Type 'B' packages for the transportation of irradiated fuel.
7 SNIFFER-GAS MASS SPECTROMETER	10^{-7} – 10^{-9} (10^{-6} – 10^{-8})	Qualitative test, best for large items. The item must be pressurised with helium, a 1 bar gauge. Leakage is detected by moving a probe, connected to a mass spectrometer, across the areas under test.
8 SPRAY-GAS MASS SPECTROMETER	10^{-7} - 10^{-9} (10^{-6} – 10^{-8})	Qualitative test for vessels or packages that can be evacuated and where the outside is easily accessible with supply of test gas. The method is to evacuate the test item connected to a mass spectrometer. The test gas is sprayed over the surface.
9 LIQUID NITROGEN	10^{-7} - 10^{-9} (10^{-6} – 10^{-8})	Qualitative test suitable for small sealed capsules that can withstand being immersed into liquid nitrogen. The test item is submerged into liquid nitrogen and then submerged into warm methanol. A leak is indicated by a stream of bubbles.
10 EVACUATED ENVELOPE MASS SPECTROMETER	10^{-9} (10^{-8})	Qualitative test for small items which have a replaceable seal. The method involves pressurising the test item with a test gas and subsequently placing it in a vacuum chamber connected to a mass spectrometer.
11 GAS FILLED ENVELOPE MASS SPECTROMETER	10^{-9} (10^{-8})	Qualitative test for large test items which have a replaceable seal. The test item is surrounded by an envelope containing the test gas. The test item is then evacuated through a mass spectrometer.

TEST TYPE	**TEST SENSITIVITY** Pa m^3s^{-1} SLR (bar cm^3 s^{-1} SLR)	DESCRIPTION
12 BACK PRESSURISATION GAS MASS SPECTROMETER	$10^{-7} – 10^{-11}$ ($10^{-6} – 10^{-10}$)	Quantitative test suitable for welded capsules on any size that will fit into the pressurising chamber. The item is pressurised in an envelope containing helium gas, then placed in an evacuation chamber connected to a mass spectrometer.
13 HYGROSCOPIC CRYSTALS	10^{-5} g/s of water in-leakage	Specialist method where contents of packaging are dry. Crystals are placed into packaging, the packaging is sealed and then submerged in water. The mass of water in-leakage is determined by weighing the crystals before and after the test.

4.7.2 Most of the tests described above are qualitative, giving an indication of a leak, but not its magnitude. Tests which are quantitative can be used to measure the size of a leak (SLR) but the accuracy of these tests may be affected by changes in the ambient temperature and temperature changes in the item being tested. The Gas Pressure Rise (Test 4 above) and Gas Pressure Drop (Test 6 above) methods are frequently applied to Type B packages as they give a quantitative measurement of leakage. However, heat generated within the package by the radioactive contents may adversely affect the accuracy of the measurement; this particularly applies to the Gas Pressure Drop method.

4.7.3 This problem may be overcome either by waiting for thermal equilibrium or by introducing a system of temperature change compensation. Where speed of operation is essential a system of temperature change compensation is recommended because, with larger package types, reaching thermal equilibrium may take up to two days. Temperature change compensation may be accomplished by introducing a device on to the package which will experience similar temperature changes to those seen by the seal under test. This device may be a pocket to hold a thermometer, placed that the changes in temperature measured reflect those in the seal area. Data generated by this device may then be used to compensate directly or indirectly the measurements given by the test method. It is good practice to shield or otherwise insulate the test equipment from draughts.

REFERENCES – SECTION 4

1. Regulations for the Safe Transport of Radioactive Material, 1996 Edition (Revised), IAEA Safety Standards Series No. TS-R-1 (ST-1, Revised) IAEA Vienna 2000.

2. Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material Safety Guide No. TS-G-1.1 (ST-2), IAEA Vienna 2002.

3. UK Competent Authority, Radioactive Materials Transport Division, An Applicants Guide to the suitability of elastomeric seal materials for use in radioactive material transport packages, DTLR/RMTD/0004 February 2002.

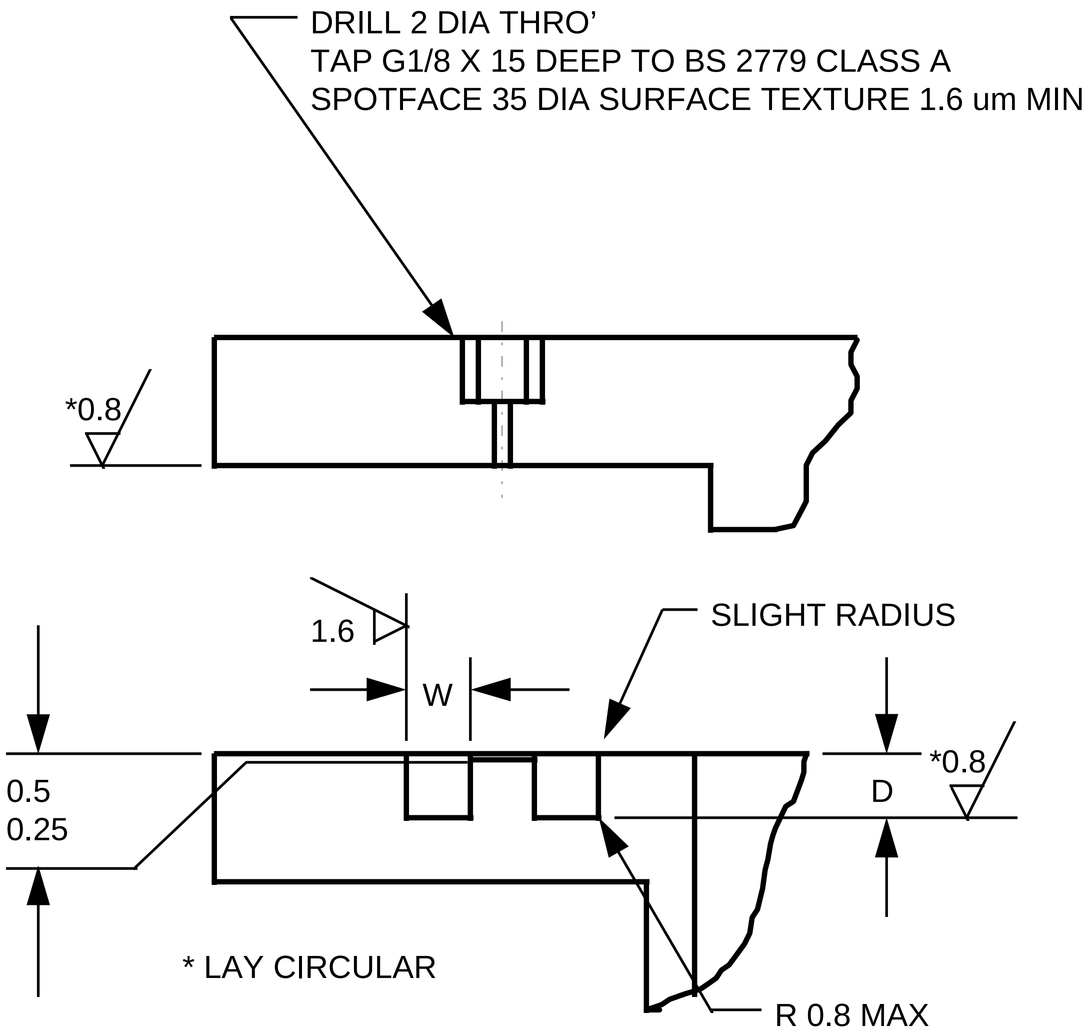
4. Leakage Tests on Packages for the Transport of Radioactive Material, AECP 1068, February 1992.

5. Tritium, deuterium and helium permeation through EPDM O-rings, SAND91-8591, Sandia National Laboratory.

6. Leak Testing to Demonstrate Retention of Particulates - TRDC(89) P108, AEA Technology, Winfrith.

7. ANSI N14.5 American National Standard for Leakage Tests on Radioactive Packages for Shipment of Radioactive Material.

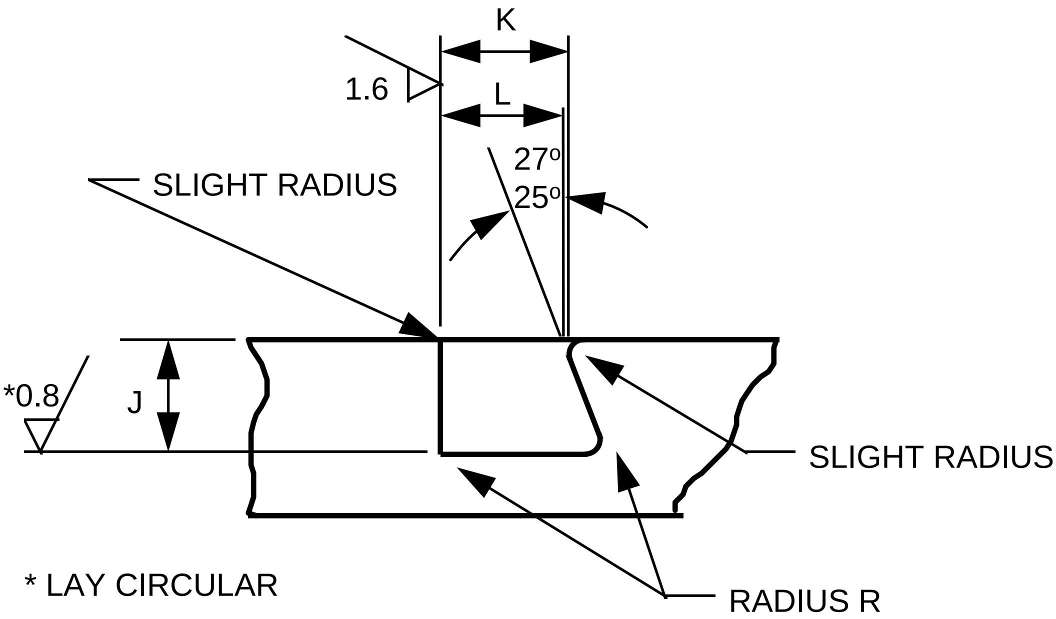
8. ISO Standard 12807 Leakage Testing on Packages for the Safe Transport of Radioactive Material.



O-RING DIA	D		W	
	MAX	MIN	MAX	MIN
4.1 5.7 8.4	3.38 4.46 6.60	3.16 4.07 6.00	5.00 7.3 10.4	4.7 7.0 10.1

Figure 4.1 Design data for standard O-ring grooves, showing a typical arrangement for the interspace leak test point.

Note: The groove dimensions must take account of the fill ratio for the design temperature range, see Ref 3.

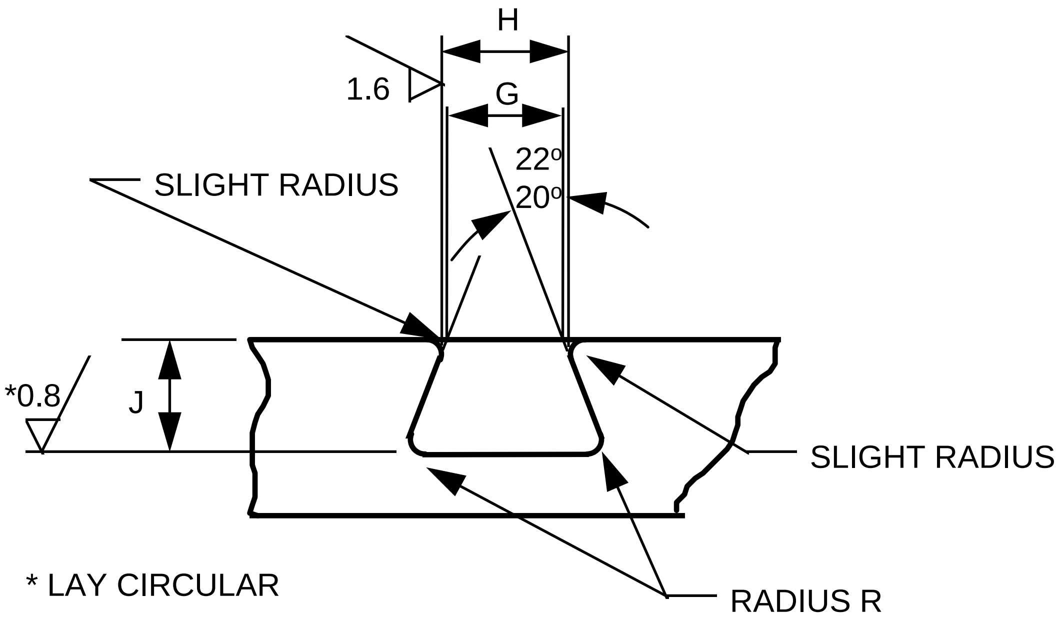


O-RING DIA	K		L		J		R
	MAX	MIN	MAX	MIN	MAX	MIN	MAX
4.1 5.7 8.4	3.96 5.56 8.23	3.82 5.43 7.89	3.82 5.43 7.89	3.68 5.30 7.55	3.4 4.8 7.0	3.2 4.3 6.4	0.5 0.8 0.8

Note: This design is recommended for annular grooves.

Figure 4.2 Design data for half-dovetail O-ring grooves

Note: The groove dimensions must take account of the fill ratio for the design temperature range, see Ref 3.

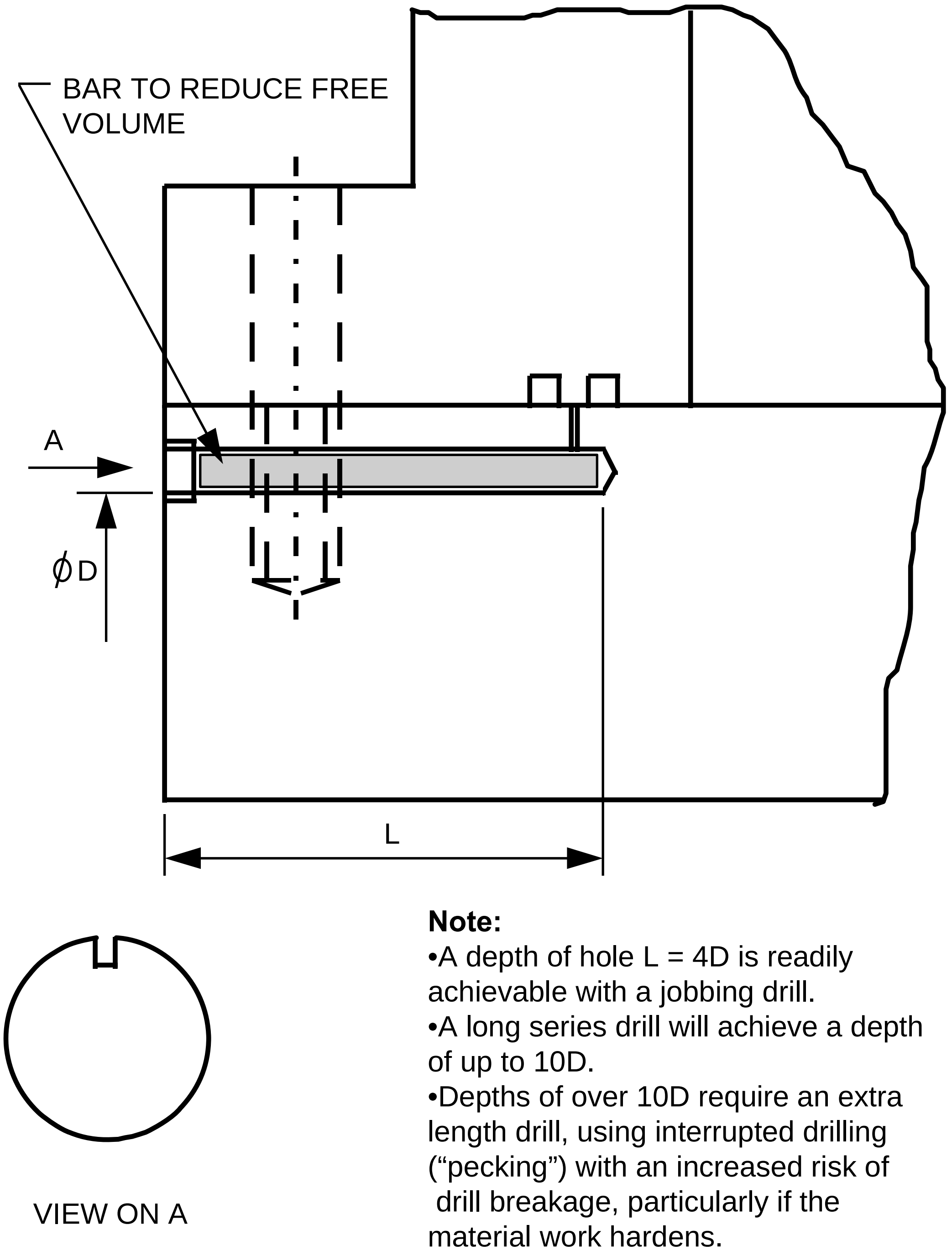


O-RING DIA	H		G		J		R
	MAX	MIN	MAX	MIN	MAX	MIN	MAX
4.1 5.7 8.4	3.62 5.18 7.50	3.28 4.80 6.77	3.96 5.56 8.23	3.62 5.18 7.50	3.4 4.8 7.0	3.2 4.3 6.4	0.5 0.8 0.8

Note: This design is recommended for non-annular grooves

Note: The groove dimensions must take account of the fill ratio for the design temperature range, see Ref 3.

Figure 4.3 Design data for dovetail O-ring grooves



Note:
- A depth of hole L = 4D is readily achievable with a jobbing drill.
- A long series drill will achieve a depth of up to 10D.
- Depths of over 10D require an extra length drill, using interrupted drilling ("pecking") with an increased risk of drill breakage, particularly if the material work hardens.

Figure 4.4 Suggested method for use with deep-drilled leak test points

5 DESIGN FOR THERMAL PERFORMANCE

5.1 REGULATORY REQUIREMENTS

5.1.1 Before any packaging for transporting nuclear materials is given a licence for its use a safety submission has to be approved by the designated competent authority. This safety submission must demonstrate that the package satisfies all the regulations for the transport of nuclear materials as specified in IAEA Safety Standards Series No TS-R-1 (Ref. 1). Additional advisory information is provided in IAEA Safety Guide No. TS-G-1.1 (ST-2) (Ref. 2). In the planning of the assessment of the thermal performance of any new packaging, it is also useful to study the UK Competent Authority Applicant's Guide (Ref. 3), since this details the information and calculations that should be provided.

5.1.2 For Type A packages there are no requirements with regard to thermal performance other than that it should be able to withstand ambient temperatures ranging from -40°C to +70°C [637]. There is no requirement for a Type A package to withstand fire.

5.1.3 For Type B packages there are regulations governing performance both during normal transport and during a fire. Under normal transport there are regulations controlling the effect of the package temperature upon its shielding materials [651], the maximum accessible outer surface temperature [652] and [662], and the maximum internal pressure (which is partly controlled by temperature) [661]. Type B packages must be able to withstand a fire test [728] without loss of containment of the contents or major loss of shielding. There is no requirement under the IAEA regulations for the temperature of the contents not to exceed their own temperature limitations, either during normal or accident conditions, but this could be expected to be a requirement of the operator. The designer must consider the effects of temperature if the contents or the receptacle can be damaged by the combination of an ambient temperature of 38°C and maximum insolation, [651(a)].

5.1.4 A further class of packages, designated Type C, has been introduced [417]. Although the requirements for this class of package are more stringent than those for Type B packages, the issues to be addressed are similar.

5.1.5 The IAEA regulations are very prescriptive, e.g. a surface temperature of 85.5°C is unacceptable while 84.5°C is satisfactory. However, the designer usually endeavours to make a package as safe as is reasonably practicable and build in a realistic safety margin wherever possible. The protection provided against one hazard, however, often affects the margin of safety relating to another. For example, added protection against fire will increase normal operating temperatures and may reduce the impact resistance of the package. In such situations it is left to the designer to reach a reasonable compromise.

5.1.6 In optimising the design of a packaging the designer should also consider the effect of accidents less severe, but more probable, than those specified under the IAEA regulations. For example, the use of fusible links to cut off the flow of heat into a package may appear a suitable way of minimising package temperatures during a 30 minute fire. However it may be that under normal operation the loss of such links leads to overheating and damage of the contents. If even a very short fire can cause the links to fail then the use of such links may not be the optimum design solution.

5.2 PACKAGE TYPES

5.2.1 As far as thermal analysis is concerned there are two types of Type B package. The first transports highly active materials, such as irradiated fuel, which may generate a significant amount of heat. The second transports materials of much lower activity, such as industrial sources or waste, which generates very little heat.

5.2.2 The thermal performance of these two types of packaging is generally very different. The packaging for highly active materials will need to provide efficient heat paths so that the heat from the contents can be dissipated from the package surface without the contents reaching an unacceptable temperature. Liquid cooling, or materials such as copper or aluminium which have high conductivity, is often employed. The outer surface of many such packagings often has fins to enhance the heat transfer to the air.

5.2.3 The provision of efficient heat paths might be expected to create a problem for such packages during the fire test. Some flask designs do include thermal resistances, thermal diodes or fusible links near the surface in order to reduce the flow of heat into the package during a fire test. However, because packages holding highly active materials must necessarily possess substantial shielding against radiation and this shielding is normally massive, such packages often have a very high thermal capacity and this is very effective in limiting the temperature rise during a fire test. A 100 tonne steel flask, for example, will only experience a modest rise in temperature after being exposed to a pool fire for 30 minutes.

5.2.4 Packagings designed for transporting materials of low activity will possess negligible shielding and hence have a relatively low thermal capacity. In this case protection against the fire test is provided by insulating materials all around the package. This insulation may produce an increase in the temperature of the contents under normal transport but, if the heat generated is small, the temperature rise will be only modest.

5.3 OVERVIEW OF THERMAL ASSESSMENT

5.3.1 During normal transport there are usually a number of separate steps in the transfer of the heat generated by the contents from the contents themselves to the external air. In the analysis of the temperature distribution each of these stages is usually taken in turn. Such stages may include:

- Heat transfer from contents to surrounding box by radiation and natural convection.
- Heat transfer across the wall of the box by conduction.
- Heat transfer across a narrow gap by radiation and conduction.
- Heat transfer to the outer surface by conduction.
- Heat loss from the outer surface by radiation and natural convection.

5.3.2 Since the rate of heat output from the contents is known, and constant, the temperature difference required to produce this heat flux across each of these stages may, for some geometries, be calculated in turn and simply added to obtain the steady state temperature distribution.

5.3.3 For designs of packaging which cannot be broken down into a series of separate and sequential heat transfer processes, finite element or finite difference computer codes are normally used to model heat transfer. Such a code may use a two or three dimensional model to represent the package, as appropriate, and can potentially model heat transfer in extremely complex geometries possessing multiple, competing, heat transfer paths.

5.3.4 Modelling the fire, or thermal test necessarily involves a transient calculation. While analytical solutions do exist for some simple geometries, the non-linearity of the boundary conditions and material properties in practice almost always preclude the use of 'hand' calculations for determining transient temperatures. Finite element or finite difference computer codes are therefore almost always used for modelling heat transfer inside packages during the fire test.

5.3.5 In some situations, when the geometry is extremely complex or the heat transfer mechanisms uncertain, it may be cost effective to determine the temperature distribution during normal transport by conducting a practical test rather than by analysis. This may be necessary, for example, in support of the package's safety submission when 'engineering judgement', which is perfectly acceptable during the design phase, cannot be rigorously proven without significant additional analysis. Practical tests are usually performed on a full size prototype packaging with electric heaters simulating the heat which would be generated by the package contents.

5.3.6 Practical pool fire or furnace tests may also be the preferred method of performing the thermal test upon the package. If a packaging is partly constructed from materials which may either melt, char or burn during a fire test then these may present significant difficulties to a theoretical analysis. Conducting a practical test avoids any uncertainty associated with the behaviour of such materials and may therefore be the preferable alternative for demonstrating compliance with the regulations. It is necessary to carry out any practical fire tests at full scale and, unless a full scale flask has already been produced (e.g. for drop testing) then the cost of supplying the package may render a practical test unattractive. In such situations tests upon individual components or materials may be necessary to provide data for input into an analytical assessment.

5.4 BASIC EQUATIONS OF HEAT TRANSFER

5.4.1 This section provides a reminder of the basic equations of heat transfer by conduction, convection and radiation. It is not intended to be thorough or detailed and for more detailed study one should refer to one of the many excellent text books on the topic e.g. McAdams (Ref. 4) or Holman (Ref. 5). Even the basic equations shown, however, may be adequate to provide a guidance, for design purposes, of the thermal performance of a package. Only steady state heat transfer is addressed.

5.4.2 **Conduction**

The temperature difference across a plate of material due to heat being conducted through it is given by Fourier's law:

$$\Delta t = \frac{qd}{k} \qquad \text{Eqn 1}$$

where Δt is the temperature difference across the plate, K
q is the heat flux through the plate per unit area, W/m^2
d is the thickness of the plate, m
k is the material thermal conductivity, W/mK

This equation is only correct for a flat plate of uniform thickness, with a uniform temperature on each side, and for a material with a constant thermal conductivity. In practice, however, it can be applied to curved surfaces and materials with varying conductivity without introducing serious errors.

5.4.3 **Convection**

Convection is a much more complex process than conduction since it involves the movement of fluids. There are two categories of convection: forced convection in which the flow of fluid is driven by some external mechanism, and natural convection in which the flow of fluid is driven by buoyancy as it gains or loses heat. In transport packages the use of an external power source to drive pumps is not permitted and therefore generally only natural convection is relevant.

Heat transfer from a surface to a fluid by natural convection is a function not only of the fluid properties and the temperatures of surface and fluid but also the local and global geometry of the system, the surface orientation and the heat transfer to the fluid from other locations on the surface. If the system being studied involves not just heat transfer to a fluid (as may occur on the outside of a package) but a fluid transferring heat between surfaces (as inside a wet flask), then the problem becomes even more complex. When the fluid involved is a liquid, however, natural convection is generally very efficient and it may be possible to assume that the liquid has a uniform temperature.

By analogy with the conduction equation, the convective heat flux is expressed in terms of a heat transfer coefficient *h* which is defined by the equation:

$$q = h\Delta t \qquad \text{Eqn 2}$$

where *q* is the heat flux, W
h is the heat transfer coefficient, W/K
t is temperature, K

The convection coefficient is often expressed in dimensionless form as the Nusselt number defined as

$$Nu = \frac{hL}{k} \qquad \text{Eqn 3}$$

where *L* is a characteristic length of the surface, m
k is the thermal conductivity of the fluid, W/mK

Correlations for the Nusselt number are available for many different geometries. These correlations are usually derived from experiment and are usually expressed in terms of two other dimensionless numbers, the Grashof number:

$$Gr = \frac{L^3 \rho_2 g \beta \Delta t}{\mu^2} \qquad \text{Eqn 4}$$

and the Prandtl number:

$$Pr = \frac{C_p \mu}{k} \qquad \text{Eqn 5}$$

where ρ is the fluid density, kg/m^3
g is the acceleration due to gravity, m/s^2
β is the volumetric coefficient of expansion, K^{-1}
Δt is the temperature difference between surface/bulk fluid, K
μ is the dynamic viscosity of the fluid, Ns/m^2
C_p is the specific heat of the fluid at constant pressure, J/kgK

For example the Nusselt number for natural convection to a fluid from a vertical surface has been fitted to the correlations:

Case 1: laminar flow, $10^4 < Gr.Pr < 10^9$

$$Nu = 0.59\,(Gr\,Pr)^{0.25} \qquad \text{Eqn 6}$$

Case 2: turbulent flow, $10^9 < Gr.Pr < 10^{13}$

$$Nu = 0.13\,(Gr\,Pr)^{0.33} \qquad \text{Eqn 7}$$

For some geometries the definition of the characteristic length is open to interpretation. From equations 3, 4 and 7 above it can be seen that, for turbulent natural convection, the variable L conveniently cancels out.

Simplified versions of the dimensionless correlations can also be found in reference books. For example, equation 7 can be approximated, for air at atmospheric pressure and ordinary temperatures, to the dimensional equation:

$$h = 1.3\,\Delta t^{\,0.33} \qquad \text{Eqn 8}$$

From this equation the temperature difference between surface and fluid can then easily be determined as:

$$\Delta t = \frac{q}{h} = \frac{q^{0.75}}{1.3} \qquad \text{Eqn 9}$$

where q is the heat flux from the surface per unit area, W/m^2

Because natural convection is produced by the buoyancy driven movement of fluids it is more efficient for vertical faces than for upward facing faces. For downward facing surfaces it can be very inefficient. On average, the natural convection coefficient from cylindrical surfaces is only slightly lower than that for vertical surfaces. Further details on convective heat transfer can be found in text books such as McAdams (Ref. 5), Holman (Ref. 6) or Platten & Legros (Ref. 7).

5.4.4 **Radiation**

In transport packages only radiation heat transfer between surfaces is generally of interest. The emission and absorption of radiation by gases can therefore be ignored.

The heat radiated from a surface is given by:

$$Q_{rad} = \sigma\,\xi_{rad}\,t^4 \qquad \text{Eqn 10}$$

where Q_{rad} is the heat radiated from the surface per unit area, W/m^2

σ is Stefan's constant
ξ_{rad} is the emissivity of the surface
t is the absolute temperature of the surface, K

Values for emissivity range from 0.95 for a matt black surface to 0.2 for a highly polished one. In practice, such a shiny surface becomes tarnished rapidly and a more realistic value is 0.4. Emissivity is usually taken to be independent of temperature - the so called 'grey surface' assumption. This is usually acceptable since emissivity is strongly affected by surface conditions (e.g. oxidation) and in practice there is usually enough uncertainty over what value to assume without bothering with its temperature dependence.

The radiation absorbed by a surface is also controlled by its emissivity:

$$Q_{abs} = \xi_{abs}\, Q_{in} \qquad \text{Eqn 11}$$

where Q_{abs} is the heat flux absorbed, W/m^2
ξ_{abs} is the emissivity of the absorbing surface
Q_{in} is the incident radiant heat flux at the surface, W/m^2

The absorbing surface is, in turn, radiating back to the emitting surface. The direct radiant exchange between two surfaces can therefore be calculated as:

$$Q_{rad} = \sigma\ \xi_{rad}\ \xi_{abs}\ F\ (t_{rad}^4 - t_{abs}^4) \qquad \text{Eqn 12}$$

where F is the view factor from absorbing surface to emitting surface

Any radiation which is not absorbed by a surface is reflected and no account of this reflected radiation is taken in equation 12. If the emissivities of the two surfaces are high then this may not be significant. For surfaces with modest or low emissivities it can, however, be a significant effect, increasing the overall rate of exchange and enabling radiation to 'bounce' round corners etc. The only geometry for which a simple exact expression is available is the case of effectively infinite parallel plates (e.g. radiation across a narrow gap). In this case the radiant heat transfer is given by:

$$Q = \sigma \frac{\zeta_{rad}\ \zeta_{abs}}{(\zeta_{rad} + \zeta_{abs}) - (\zeta_{rad}\ \zeta_{abs})} \left(t_{rad}^{\ 4} - t_{abs}^{\ 4}\right) \qquad \text{Eqn 13}$$

where Q is the heat flux per unit area, W/m^2

Further information about the calculation of radiant heat transfer, view factors for different geometries etc can be found in texts such as McAdams (Ref. 3), Holman (Ref. 5) or Siegel & Howel (Ref. 7).

A popular misconception about thermal radiation is that it is only significant at high temperatures. It is true that the fourth power term makes it very efficient at high temperatures but it can also be significant at modest temperatures. Consider, for example, a vertical surface which is just 1°C hotter than the ambient air temperature of 38°C. From equation 6 the convective heat flux to the air will only be 1.3 W/m^2. The heat flux from thermal radiation, however, will be (for an emissivity of 0.9) 6 W/m^2, and is therefore dominant.

5.5 COMPUTER CODES

5.5.1 As mentioned in Section 5.3, the use of computer codes is recommended over simple 'hand calculation' methods for both transient calculations and for the analysis of packagings with complex geometries. The most common codes that are used for this purpose are general purpose finite element or finite difference codes. There are many such codes which, although often primarily designed for structural analysis, have a thermal analysis capability. Such codes include TAU, ANSYS, PAFEC and ABAQUS. Advertisements for these and similar codes can be found in many technical journals (e.g. Ref. 8). Most codes now have user-friendly graphical interfaces for pre- and post-processing

5.5.2 In both finite element and finite difference codes a model of the package geometry is built up from individual elements. Elements for building both 2- and 3-dimensional models are usually provided.

5.5.3 These codes basically perform static or transient analysis of conduction in solids. Fluid motion is not usually represented, convection heat transfer being modelled simply through a user specified boundary condition on the surfaces. Radiation heat transfer is an area where some finite element and finite difference codes fall short however. Radiation elements that produce heat transfer between surfaces are often provided but it is important that the code will calculate automatically all the necessary view factors. Even though it is fairly straightforward to implement, representation of reflected radiation is unfortunately often not included.

5.5.4 General purpose finite element and finite difference codes as described above can be used to model almost any situation. In some instances, however, they are extremely inefficient and a simple, special purpose computer code is far easier to use. For example RIGG (Ref. 9) is a relatively small code for calculating the temperature distribution in an array of dry fuel pins. Because the heat transfer is dominantly by radiation a general purpose code is very inefficient at solving this same problem.

5.6 THE MODELLING OF FLUIDS

5.6.1 Natural convection can be a very significant heat transfer mechanism in transport packages. Liquids, in particular, can be very efficient at transferring heat. For some geometries, however, such as downward flow of heat, natural convection is very inefficient.

5.6.2 As described in Section 5.5, natural convection is generally modelled via the application of heat transfer coefficients to surfaces. These coefficients are obtained from correlations for the geometry of interest. Although correlations exist for an extensive range of geometries and materials, designers of transport packagings still frequently manage to produce geometries for which no valid correlation exists. In this situation it is often necessary to make experimental measurements, on the full scale packaging, a component, or a scale model, in order to produce a valid correlation. An alternative to experimental testing is numerical modelling using a Computational Fluid Dynamics (CFD) code. CFD codes model the flow of fluids in any geometry of interest and include heat transfer and natural circulation. Both steady state and transient solutions may be produced. Most CFD codes can also model conduction heat transfer in solids. It would therefore be possible, in principle, to perform the complete thermal analysis of a package using a CFD code. Such codes usually require far more computing power and time than finite element codes and are therefore seldom used for performing the entire thermal analysis.

5.6.3 In modelling fluids it is necessary to remember that, in an accident, the package may end up in any orientation. Consideration therefore needs to be given to the buoyancy driven flow paths in orientations other than that for normal transport. Consideration also needs to be given to the flow paths that may be produced during a fire test, when the direction of the flow of heat is reversed from that during normal transport. If a 'dead leg' can be generated, where minimal fluid flow occurs, then the fluid may become very hot. When the surface of a liquid becomes hot then evaporation and condensation may become a significant heat transfer mechanism and should be considered. Hot liquids can also generate high vapour pressures which may pressurise the packaging.

5.7 FINNED SURFACES

5.7.1 Fins are frequently placed on the outside of flasks containing irradiated fuel in order to dissipate their high heat load more efficiently and therefore have a lower temperature during normal transport. Various different designs of fin have been applied to packagings but their design is often dictated more by their resistance to handling and impact and ease of decontamination rather than optimisation for heat transfer. Some designs of flask have thousands of individual fins whereas others have fewer, but larger, fins. When a flask has many fins this restricts the air flow and therefore reduces their efficiency. It should not therefore automatically be assumed that a surface with more fins can dissipate heat more efficiently than one with fewer fins.

5.7.2 An interesting feature of fins is that they can cause a reduction, rather than increase, in the heat flux into a flask surface during a fire test. This is due to heat transfer being dominated by radiation. The tips of the fins heat up quickly so that the fire 'sees' a hot surface rather than the cold surface of the flask.

5.7.3 Fins are often not included explicitly on any finite element or finite difference model of a flask because their scale is so much smaller than that of the overall flask that to represent each one in sufficient resolution would require an extremely large and fine model. Instead a separate, simple, model of one or two fins can be used to determine the effective heat flux to the surface of the package as a function of surface temperature or time. This heat flux can then be applied to the plane surface of a model of the whole flask as a boundary condition.

5.7.4 When fins are close together they restrict the flow of air and therefore reduce the efficiency of natural convection. It is therefore important that the convection coefficient applied in the simple fin model is appropriate to the geometry being considered. Many correlations are available for the effective convection coefficient for different fin geometries. However, if a novel design of fin is used for which there is no data, experimental tests may be necessary to determine the appropriate convection coefficient.

5.8 GAPS

5.8.1 Heat transfer across narrow gaps occurs by conduction and radiation. For a gap of a known size these processes are well understood and, assuming the emissivities of the surfaces are known, can be modelled accurately. Significant uncertainty can arise, however, if the gap size is unknown. Surfaces in contact, for example, may, or may not, effectively have a gap between them. The effect of handling and impact tests can also change gap sizes.

5.8.2 In any analysis it is therefore always prudent to make pessimistic assumptions about gap sizes. Whether a large or small gap is the most pessimistic case may not always be evident. Calculations testing both assumptions may therefore be necessary. Thermal expansion during the fire test can also cause gaps to be formed, grow or shrink and these effects may also have to be considered.

5.9 INSOLATION

5.9.1 The IAEA Regulations [651] require the effect of insolation to be included in the assessment of the temperatures inside a package during normal transport. The incident radiant heat flux for surfaces of different orientation are specified which must be applied for 12 hours each day. This creates a complication because a transient boundary condition is being imposed upon what had previously been a steady state analysis.

5.9.2 Large heavy packagings, with their very great thermal capacity, will respond only very slowly to the effect of insolation. It can therefore be argued that the variation from night to day in the package temperature is negligible. The incident heat flux from the solar radiation which is received during the day can therefore be spread over 24 hours and a steady state analysis performed.

5.9.3 For small packages with insulation around them it cannot be argued that the surface remains at a constant temperature. The contents, however, because they are insulated from the surface, may take many days to come into equilibrium with changes in the external ambient conditions. A transient calculation to model the temperature distribution under normal transport conditions would therefore need to represent many diurnal cycles. A simpler approach is to either pessimistically represent insolation as being present continuously, or calculate the steady state temperature distribution both with and without insolation and then assume that the actual temperature distribution is the average of these two situations.

5.10 REVIEW OF MATERIALS

5.10.1 The various materials used in the construction of nuclear transport packages generally serve a number of different functions such as structural strength, shielding, criticality control or impact protection. Materials are seldom selected for their thermal performance alone and the material selected is generally a compromise between all the different functions it has to perform. Many of the materials commonly used in packagings are described below.

5.10.2 **Structural materials**

Steel is the structural material most commonly used for constructing packagings. Low carbon/low alloy steel is more common because of its low cost and ease of forming, casting and welding. Stainless steel is more resistant to corrosion and is often used for surfaces which may need to be scrubbed clean for decontamination purposes. Mild steel has a reasonably high thermal conductivity and a high specific heat capacity. Stainless steel has a similar specific heat capacity to mild steel but has a much lower thermal conductivity. This low thermal conductivity may prove advantageous in restricting heat flow into a package during a fire test.

5.10.3 **High conductivity materials**

Sometimes materials are provided solely to produce an efficient heat transfer path. The materials normally selected for this role are copper and aluminium because they both have a high thermal conductivity. Of the two, copper has the higher conductivity but it should be noted, where weight is a controlling factor, that the conductivity of aluminium is greater per unit mass. Liquids such as water can also provide very efficient heat transfer paths. However, because of other problems associated with liquids, such as potential loss of coolant and boiling, flask designers generally tend to avoid their use if possible.

5.10.4 **Insulating materials**

There is a wide range of different types of insulating material which are marketed commercially for various applications and many are potentially suitable for use in packagings. Insulating materials such as glass or ceramic fibre are very effective and have a very low density but they have effectively no structural strength. Cork, board and other woods are poorer insulators but are much stronger, particularly under compression and are therefore often used in packagings. A simple air gap, without any filling material, also provides a very effective barrier to heat transfer. Its effectiveness is improved if the surfaces are highly polished, though this may be difficult to maintain in practice.

5.10.5 **Impact absorbing**

Some materials are provided to give both impact and thermal protection. For example the impact limiters on flasks for transporting irradiated fuel have this dual function. Balsa wood is often used for this purpose because of its efficiency at absorbing impact energy. Cork is also effective as both an insulator and impact absorber. Sometimes metal honeycomb material is used to provide impact protection. This will give a much more efficient heat transfer path than wood but consideration should be given to aluminium having a relatively low melting point and therefore possibly melting in a fire test.

5.10.6 **New materials**

New materials are continually being developed which, potentially, could be used in packagings. Because they are new, however, extensive testing may be required to demonstrate their thermal and impact performance and durability under the operational conditions to which the packaging will be exposed over its life. One material which is finding many varied applications is glass reinforced plastic (GRP). GRP is a light structural material which is now being considered for packagings. It does, however, normally give off a flammable vapour when heated. Another type of material gaining in popularity is the intumescent coating. This swells up when heated to provide an insulating layer. It is not a new idea, but many new types and formulations have been produced in recent years. These have many potential applications in protecting packages from the effect of fire but, if space permits, a fixed layer of insulating material may still be considered preferable. Users are warned that they may have difficulty demonstrating that the coating remains in place after the impact testing, particularly when the requirement to demonstrate consistency down to -40°C is considered. It must also be noted that improving the insulation during the fire may give rise to problems afterwards if the contents emit a significant heat output.

5.11 MATERIAL PROPERTIES

5.11.1 Uncertainty in material properties is often the single largest source of error in a thermal analysis. This is because notionally similar materials from different suppliers often have slightly different compositions, or the material for which data is readily available is slightly different to that being used. Material properties can also vary with time and local conditions e.g. the properties of wood are dependant upon its moisture content, which can both increase and decrease under different conditions. The conductivity of wood is also a function of the grain direction. The emissivity of a surface is very dependant upon its degree of oxidation and can give rise to a large uncertainty. For most materials the thermal properties are also a function of temperature but it is often difficult to find information on this temperature dependence.

5.11.2 Copper is a good example of how material properties can be different to those expected. Copper plates are quite frequently used in packagings to provide heat conduction paths. The thermal conductivity of pure copper is quoted at 397 W/mK. Pure copper is very expensive, however, and the material normally used contains a few impurities. 'Copper' with under 1% of impurities can have an actual thermal conductivity as low as 200 W/mK, half that of the pure material.

5.11.3 The main properties of interest in a thermal analysis are the thermal conductivity, density and specific heat. Typical values for some materials often used in packagings are given in Table 1. The values quoted are for illustrative purposes only and should not be used in other than preliminary design calculations.

5.11.4 There are many references from which material properties can be obtained. Some suggested sources are given (Ref. 10, 11 and 12). Many properties have been compiled into a computer database, which is a very convenient source (Ref. 13). For proprietary materials the most useful and reliable source of data is often the manufacturers data sheet and this is to be recommended wherever possible. In cases where no values for the necessary material properties can be found, or where an unacceptable uncertainty exists in the correct value, it may be necessary to have the properties measured, on a specimen of the material, over the range of temperatures of interest.

5.12 CONSIDERATION OF TESTING METHODS

5.12.1 The IAEA regulations allow the thermal performance of a Type B package during a fire test to be demonstrated by a real pool fire test, an equivalent furnace test, or by calculation. The regulations specify an average flame temperature of at least 800°C and sufficiently quiescent ambient conditions to provide an average emissivity coefficient of at least 0.9. The advisory material, Safety Guide No. TS-G-1.1 (ST-2), gives valuable advice in paragraph 728, including [728.11] which states that, “The Regulations specify certain fire parameters which are essential input data for the calculation method but are generally uncontrollable parameters in practical tests. Standardisation of the practical test is therefore achieved by defining the fuel and test geometry for a pool fire and requiring other practical methods to provide the same or greater heat input”. While available evidence (Ref. 14) indicates that the prescribed temperature of 800°C, combined with an emissivity of 0.9, does not accurately reflect the maximum flame temperature which may be observed locally in practical pool fire tests, it does produce a reasonable estimate of the heat input into a relatively cold surface. If the temperature of the package, or of surface details, approach 800°C within the 30 minutes duration of the fire, it may be prudent to consider that flame temperatures can reach 1100°C locally in real fires.

5.12.2 In the design of a packaging no consideration should be given to which type of test will be performed upon it. All the methods of testing are intended to be equally severe and a package should potentially satisfy being tested by any of them. For small packages the most cost-effective testing method is usually a furnace test.

Furnace tests generally cost less than pool fire tests, since they consume far less fuel, produce less pollution, and are more controllable. For large heavy flasks analysis is often the preferred method since this avoids the construction of a full scale prototype flask (the drop tests usually being carried out on a scale model flask). Practical pool fire testing is often the best option for packages which do not fit into either of the previous two categories. Pool fire testing is also the preferred testing method if a clear demonstration of the package's safety needs to be provided to the customer or public since it exposes the package, in a very dramatic way, to the actual hazard the thermal test is intended to protect against

5.12.3 Another important consideration in the choice of test method is the requirement by the IAEA Regulations that all the tests are carried out consecutively on the same package. Thus the package which is subjected to the fire test must first have been subjected to various other tests including the 9 m drop test and the 1 m punch test. If the performance in a fire test is being demonstrated by calculation it is therefore necessary to include the effect of any impact damage. For large heavy flasks the impact damage may be negligible and so can be ignored. For packagings which are not as strong, however, the impact tests may produce damage and distortion which makes an accurate theoretical analysis of its performance in a fire test very complex. In such cases a practical test in a furnace or pool fire may be more cost effective.

5.12.4 Transport flasks frequently contain combustible materials, such as wood, to provide impact and thermal protection, as described above. Some of these materials, such as cork, will char and become partly consumed but will not burn freely. Others have the potential to burn freely and so are normally encased in a cladding of steel or similar material. If this cladding is intact then the material can be assumed not to burn in a fire test. If, however, the cladding is ruptured in the preceding drop or punch test then the degree to which it will burn during the fire test becomes an important issue. If the analysis is being performed by calculation then pessimistic assumptions may have to be made. The only sure way of removing the uncertainty in the degree and rate of burning is to perform a practical test. It should be noted that burning may continue for long after the 30 minutes for which the package is exposed to a pool fire or furnace. In a test on a balsa-filled shock absorber (Ref. 15) very little of the exposed balsa was consumed during the 30 minute fire. In the following 24 hours, however, almost all the balsa slowly burnt away. It should also be noted that materials such as wood, even though clad in steel, will give off flammable vapours upon being heated in a fire test. Holes, possibly with fusible plugs, therefore need to be provided to prevent the cladding becoming pressurised. Care should be taken to ensure that these flammable vapours do not collect and form an explosive mixture inside the package or cause problems by burning with any available air.

Table 1 Typical material properties

Material	**Density – kg/m^3**	**Conductivity – W/mK**	**Specific heat – kJ/kgK**
Aluminium	2710	204	0.896
Aluminium alloy	2800	135	0.917
Copper	8950	385	0.383
Steel, mild	7850	54	0.465
Steel, stainless	7900	16	0.502
Balsa	130	0.05	2.301
Cork (expanded)	100	0.036	1.9
Cork (resin-bonded)	255	0.055	2.0
Pine	700	1.4	2.6
Calcium silicate	200	0.06	1.0
Ceramic fibre	300	0.06	1.0
Mineral wool	200	0.04	0.7

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6 DESIGN FOR MECHANICAL STRENGTH AND IMPACT RESISTANCE

6.1 GENERAL

6.1.1 This section deals with aspects of packaging design which must be considered to ensure that the package is mechanically strong enough to withstand testing, normal conditions of use and accident conditions. The most onerous situation that needs to be considered is usually the consequence of the 9 m free drop test and the punch test. Consequently the emphasis is on impact resistance.

6.1.2 Other criteria will have to be taken into account in the design, such as fire protection and radiation shielding. Occasionally, a compromise may have to be made in the choice of materials to give adequate all-round performance; but, more often than not, materials can be found which will satisfy the various criteria together (e.g. cork is a good thermal insulator and a good shock absorber; lead shielding provides impact energy absorption too). The limiting constraints on mechanical strength of packages are usually governed by cost or by operational considerations (size/weight limits, handling considerations, operator dose etc).

6.1.3 The designer should choose the most appropriate method for assessing the mechanical strength or impact resistance of a particular package. Methods include engineering experience and judgement, prototype testing, scale-model testing, hand calculations and computer analyses. The latter range from simple PC programs to advanced finite element codes which require considerable expertise to use reliably. Computer codes must be validated for the purpose they are being used for.

6.1.4 The best guide for designers is experience of previous package performance. Most organisations in the nuclear industry will have considerable in-house experience and access to results of drop testing, computer simulations and material property measurements. In addition there is extensive published literature on the impact performance of a wide variety of packaging types, covering experimental testing and computer analyses (e.g. Ref. 1).

6.1.5 It must be appreciated that calculation and numerical modelling are appropriate for packaging design, and for demonstrating the worst-case orientation for drop test. However, the Competent Authority will only accept physical testing as proof of the design unless the package in question is demonstrably similar to an existing design that has been tested.

6.2 DESIGN REQUIREMENTS

6.2.1 The requirements of the IAEA regulations which relate to mechanical integrity are summarised in Table 6.1. The main aims in design are to prevent loss of containment and to maintain sufficient shielding. In the case of fissile material, the arrangement of contents and package components must also be kept sufficiently sub-critical.

6.2.2 Selection of material types and thicknesses must take into account the range of environmental temperatures and pressures which might be encountered when in use. Since some package contents will generate heat, the component temperatures may be significantly higher than ambient. For Type B packages, this should be taken into account [651].

6.3 LIFTING ATTACHMENTS

6.3.1 TCSC 1079 provides extensive design information on packaging lifting points, some of the key requirements are summarised below.

6.3.2 The packaging must be designed so that the package can be easily handled and lifted. This requires provision of (a) a means of manual handling for packages weighing between 10 kg and 50 kg gross, or (b) a means of mechanical handling for packages over 50 kg gross.

6.3.3 When used in the intended manner, the lifting attachments must not fail and there must be no unsafe stresses on any other part of the package. The assessment shall take account of appropriate safety factors to cover snatch loading; the snatch factor is 100% unless there are valid reasons for using a lower value. Fatigue failure due to cyclic loading should be taken into account in the design.

6.3.4 If failure of the lifting attachments were to occur (e.g. because of snagging during a lifting operation), package containment and shielding must not be impaired. The lifting attachment should therefore be the weak link in cases of severe overload.

6.3.5 Any other features on the packaging which could be used for lifting must be designed for lifting as above, or be rendered incapable of use during transit (e.g. by being completely covered or removed).

6.4 TIE-DOWN SYSTEMS

6.4.1 Tie-down systems are fully covered in TCSC 1006. Briefly, the requirements are (a) under normal conditions of transport the package must remain secured to the transport vehicle at all times; (b) under accident conditions the package may break away from the vehicle but no features of the tie-down system should impair the containment or shielding.

6.4.2 Under normal conditions of transport, the forces experienced in tie-down members, attachment points and anchor points are governed by inertial forces on the package resulting from accelerations (longitudinal, lateral or vertical). Fatigue failure from cyclic loading should also be considered. This arises from vibration and the natural frequency of the vehicle suspension.

6.4.3 Under accident conditions, tie-downs are not required to remain intact. For Type B packages, attachment points such as trunnions should be designed such that, for the 9 m drop test with the centre of gravity of the package directly over the attachment point, damage to the package will not violate the requirements for containment and shielding. This also applies to lifting attachments or any other protruding features on the outer surface of the package.

6.5 PACKAGE TYPES AND OPTIONS FOR IMPACT PROTECTION

6.5.1 The smallest packagings, such as those for carrying radioactive sources, will be lightweight and simple to fabricate. Impact protection can be provided by wood, cork or expanded polystyrene. If the source is in a steel or lead pot for shielding, this may be enough in itself.

6.5.2 Drums are commonly used for low-level radioactive waste. There is a large body of data on drum impacts with a variety of wasteforms. If using hand calculations, it is generally sufficient to neglect the drum material and to just consider the impact resistance of the wasteform alone. (This of course assumes that the waste is solid and not loose in the drum.) Practical testing has shown that mild steel 200 litre drums filled with material such as rubble and dropped from 1.2 m must have a wall thickness of at least 1 mm to prevent puncturing. It is not usual for this type of packaging to be fitted with impact limiters; the impact energy is dissipated by deforming the drum and, in some cases, the wasteform.

6.5.3 Type B packagings comprising lead-shielded flasks (typically used for irradiated material or fuel sections) are usually transported within an outer box that provides impact resistance as well as thermal shielding. The box design is sufficiently rigid to prevent gross distortion on impact, and provide protection against the punch. This sort of arrangement is also to be found with packages where the contents are α-contaminated material. In this case the inner packaging does not provide γ shielding, only containment. The outer box however carries out an identical function.

6.5.4 Irradiated reactor fuel and high level γ-waste needs a lot of radiation shielding, and so the package is inevitably heavy and there is a large amount of energy to absorb in a drop test. This type of flask is often made from solid steel and impact protection is given by two impact limiters – typically wood or some crushable material in a steel shell. If fitted, metal cooling fins along the body can also help to absorb impact energy.

6.5.5 Steel-clad reinforced concrete boxes have been assessed for long-term storage of immobilised waste. Concrete absorbs energy by crushing and is very strong in compression. In an impact however, it is not possible to avoid tensile or shear stresses in some parts of the box and cracking is likely in severe impacts. Damage is mitigated by the rebars (particularly if pre-stressed) and by the cladding. This is achieved in various ways: by distributing the load, containing the concrete, and by absorbing energy through deformation. Any corner or edge features further reduce impact damage to the concrete by sacrificially deforming.

6.6 IMPACT ON TO A FLAT SURFACE

6.6.1 The kinetic energy of a package of mass *m* kg dropped through height *h* metres is given by

$$E = m\,\mathrm{g}\,h$$

where g is the acceleration due to gravity, 9.81 m/s^2. Here *h* is the distance from the lowest point on the package to the target surface. If the orientation is such that the centre of gravity (c.o.g.) is directly over the contact point all of the kinetic energy will be dissipated in this initial impact.

6.6.2 For sufficiently small *h*, the stresses produced in the package will be purely elastic and will be reused as the package rebounds. As *h* increases, the yield stress or compressive strength of a part of the package will be reached and energy will be absorbed irreversibly by the processes of plastic deformation, compaction and, possibly, fracture. For substantial drops, such as from 9 m, the energy absorbed elastically is negligible in comparison with *E*.

6.6.3 Impact forces experienced by the package are determined by the drop orientation, package geometry and dynamic flow stresses of the yielding components. For thick-walled flasks or impact limiters, deformation will normally occur locally, i.e. at or near the point of contact with the target surface (assumed to be unyielding). For packages which are relatively strong in the contact region, deformation may occur throughout the package. Either way, the extent of deformation will depend on the amount of energy which has to be absorbed.

Formulae for the various impact orientations and shape of package are given in Appendix A.

6.7 IMPACT ON A PUNCH

6.7.1 For Type B packages with a thin skin attached to a strong crash frame, the most critical test will often be the drop from 1 m on to a punch. The punch is a 150 mm diameter solid steel cylinder with a flat end. The response of the panel depends on the method of support as well as on panel thickness and strength; it may deform or puncture. Usually the goal is to limit the former and prevent the latter.

6.7.2 Experimental data exists for puncture of various types of panel, under both static loading and impact loading conditions. Formulae for the puncture force and puncture energy of metal panels are given in Appendix B.

6.8 CLOSURE BOLTS

6.8.1 The most common method of achieving closure is to clamp the seal faces of the lid (or flange, cover plate or other containment closure) using a number of bolts or studs. This is often the most critical component of the package as bolt failure may mean partial or total loss of contents. Bolts can fail by tensile loading, shear loading, bending or by severe damage to bolt heads. Bolted joints can fail by thread stripping, but should be designed so that they fail preferentially by some other mode. Refer to TCSC 1079 for relevant design data.

6.8.2 During impact the lid will always be subject to inertial loading as a result of deceleration of the lid mass and any contents mass that may be free to move.

6.8.3 If the lid is also subject to direct impact loading, damage will normally be worst when the loading is along an edge or corner. Possible response modes are (a) sideways slip, in cases where there is no spigot or other such restraint, causing shear loading in all bolts; (b) sliding or jacking of the spigot, resulting in bolt bending, or shear or tensile loading, according to the location of the bolts; (c) rotation of the lid by inertial forces, causing tensile loading in bolts on the side farthest from the impact zone; (d) convex flexure of the lid by inertial forces, resulting in bending and prying loads on the bolts.

6.8.4 If the lid is protected from direct loading (for instance, by being recessed into the packaging body), inertial forces from deceleration of the lid can still be significant. Also, if the package is dropped with its lid uppermost, elastic shock waves from the base can travel up the sides of the package and produce unloading stresses in the lid bolts.

6.8.5 In addition to impact loads, there may be a force due to internal pressure.

6.8.6 Closure bolts should always be tightened to ensure adequate compression of the seal/gasket and prevent fatigue damage from cyclic loading during transport movements. The pre-load should be such that the bolt axial stress is 60-80% of the material 0.2% proof stress. The bolts should be tightened using a torque wrench and the threads should be well lubricated. When the outward force applied to the lid exceeds the total pre-load, then the containment seal is lost, even if only temporarily. The applied force required to achieve tensile failure of the bolts is independent of pre-load.

6.8.7 Having estimated the total load F_b that the bolts may be subjected to, the minimum bolted area A_b is given by

$$A_b = \frac{F_b}{\sigma_y}$$

where σ_y is the 0.2% proof stress of the bolt material. Guidance on the number and size of bolts around the flange to achieve this area is given in pressure vessel standards (e.g. BS 5500). A large number of small bolts is generally preferable to a few large bolts from a structural point of view, but this may be compromised for operational reasons.

6.8.7 Yield and tensile strength data and section areas are given in the appropriate standards. For high strength carbon steel bolts, failure is most likely to occur in the threaded regions of the bolt shanks. The length of unengaged thread should be kept to a minimum.

6.9 RECOMMENDED PRACTICES FOR LID CLOSURES

6.9.1 Wherever possible protect the lid and seal regions by means of shock absorbers / impact limiters (see Section 6.10). Use a recessed lid design, with a sufficiently thick surrounding rim. Consider using a dual closure, e.g. separate shielding and sealing functions. Use a deep lid spigot (shear lip), but maintain a sufficient thickness for the flange. The spigot should be tapered for ease of fitting, but with limited clearance when bedded down.

6.9.2 Alternatives to threaded fasteners exist and may be suitable for certain applications. These include: sliding bolts, twist-locks, pawl latches, toggle latches, clamping rings, bayonet fittings, shear pins and wedges. When used, these are almost invariably limited to small packages.

6.10 SHOCK ABSORBERS AND IMPACT LIMITERS

6.10.1 The term "shock absorber" refers to a design feature intended to reduce the effect of vibration or sudden accelerations, jolts etc. and can include springs and hydraulic dampers as well as packaging materials. "Impact limiters" are structures that absorb impact energy by compaction. Often the two functions can be combined and the terms are used interchangeably. For the larger packages, the main concern is to protect against impact, so the term "impact limiter" is preferable.

6.10.2 Some common types of impact limiter are: expanded polystyrene/ polyurethane; rubber buffers; cork-filled panels; wood-filled shell; aluminium honeycomb; solid aluminium; gusseted and finned structures; tubular members.

6.10.3 The important parameters in choosing a design of impact limiter are (a) the maximum force which can be allowed to be transmitted to the closure region or contents, and (b) the amount of energy which has to be absorbed. These depend on the contact area, depth, compressive strength and lock-up strain (that is, the degree of compression before the material locks up and the compressive load rises sharply).

6.10.4 The methodology described in Appendix A can be used to estimate the size and shape of impact limiters required for a particular package. Compressive strength data should take account of the anisotropic nature of many crushable materials.

6.10.5 Wood is one of the best energy absorbing materials when compressed along the grain direction. It should be confined in a steel shell with blocks arranged so that the grain is in the direction of potential impact forces. Wood has the additional advantage of being a good thermal insulator and hence can protect seals from heat damage in a fire test (provided the shell is not pierced, allowing the wood to burn). Balsa, redwood and pine are commonly used; the latter two have higher compressive strength than balsa and so are generally only suitable for strong, heavy flasks. Balsa has the advantage of being light weight.

6.10.6 Aluminium honeycomb is a cheap alternative and crushing strengths lower than those for wood can readily be obtained. Honeycombs will not, however, provide thermal insulation, and have very little resistance to lateral compression. Gusseted and finned structures and tubular members, made from steel or ductile alloys, can give very good impact protection when designed correctly.

6.10.7 The method of attachment of external impact limiters should be given careful consideration, so that they will not fail before the impact load has been absorbed.

6.11 LEAD SHIELDING

6.11.1 Impact forces imposed on a flask, even when fitted with shock absorbers, are sufficient to cause lead to flow (slump) in the direction of impact. Even when lead is enclosed in a steel jacket, sufficient pressure can be exerted by the lead to cause the jacket to bulge at the impact end, producing a gap in the lead shielding at the other end. The thickness of the steel jacket must therefore be sufficient to prevent this happening.

6.11.2 Being relatively soft, lead is good at absorbing impact energy and can mitigate loadings transmitted to the more vulnerable parts of the package. The methodology described in Appendix A may be used to estimate peak loads and the extent of deformation (and hence reduction in shielding). However, lead offers little resistance to puncture and so the outer jacket should provide the necessary protection (see Section 6.7).

6.11.3 Consideration should also be given to static loads imposed (a) during pouring of the lead, (b) from shrinkage on cooling, and (c) by expansion when in a fire.

6.12 WELDED JOINTS

6.12.1 Welds are often particularly vulnerable to impact damage for a variety of reasons. Many are located in regions of large deformation. They do not possess the ductility of the base metal, and they are almost always stressed to a significant degree as a result of the welding process. Also many welds contain flaws that reduce their ability to deform without rupture.

6.12.2 Where possible, welded seams should be located away from corners or edges which could be liable to gross deformation. This may be done by using formed or dished plates rather than flat ones. Where this is not practical, the welded joint should be made significantly stronger than the structural (base) metal, so that any deformation takes place in the base metal rather than in the weld. Recommendations on welding practice are given in Ref. 4.

6.13 MATERIAL PROPERTIES (MECHANICAL STRENGTH)

6.13.1 Material property data used for assessing the mechanical strength of a package should be taken for the worst environmental conditions. Metals generally become weaker at higher temperatures, so the yield and tensile strength data at highest design temperatures should be taken. The failure strain, however, decreases at lower temperatures and, at sufficiently low temperatures, the phenomenon of ductile/brittle transition occurs.

6.13.2 Ductile tearing of sheet metal can occur under severe tensile or shear straining. For conditions of uniaxial tension, standard tensile strength data can be used. For more complex states of stress, the von-Mises equivalent stress should be compared with the yield stress; in such cases, the failure strain will be significantly lower than the value derived from uniaxial elongation.

6.13.3 Brittle fracture can occur for most metals under conditions of low temperature, high strain rate, large dimensions, or some combination of these. To avoid this possibility, careful consideration should be given as to the choice of carbon steel, stainless steel or ductile cast iron in the package structure, especially if the package is to be designed for use at -40^{o}C. Austenitic stainless steel and aluminium and its alloys have a very low transition temperature and, if they are used, brittle fracture may be discounted entirely. In the case of carbon steels, provided the section is less than about 6 mm failure will occur by plastic collapse rather than fracture and low temperature brittle fracture becomes increasingly unlikely the thinner the material.

6.13.4 The yield stress of many materials is known to depend on strain rate. At impact velocities achieved in drop tests or ground transport collisions, the strain rate sensitivity of steel is only slight, and static values may be used. For lead, however, the dynamic flow stress may be a factor of 1.5 to 3 higher than the static value, depending on the chemical composition. (Antimony is usually added to lead to strengthen it and improving its casting properties.)

6.13.5 Wood shows a dynamic increase in compressive strength of around 30% at the velocity achieved in a 9 m drop test. The compressive strength is also known to increase at lower temperatures and at lower moisture content.

6.14 FULL SIZE AND SCALE MODEL TESTING

6.14.1 The impact orientation in a drop test must be chosen to give maximum damage. This will usually be an orientation with the c.of.g. over the contact point so that no energy remains as rotational kinetic energy. The precise choice of orientation and attitude will depend on the vulnerable features of the flask e.g. considering protuberances, seal areas and thinner parts of the structure. Usually, drops on to a lid corner are the worst. If, however, the corners are designed to absorb impact energy without damaging the lid, drops on to an edge could be more damaging because of higher loads transmitted to the lid closure.

6.14.2 Scale model testing may be used for a preliminary assessment of a package or of part of a package. If scale models are used instead of full size prototypes for licensing purposes, this must be rigorously justified and, in any case, models less than quarter scale must not be used.

6.14.3 Ideally, and often in practice, deformation will be in proportion to the scale size (i.e. strains and stresses remain the same) for drops from the same height. However scaling will not hold if any of the following are significant: strain rate sensitivity of the package materials; ductile tearing; brittle fracture (transition temperature is scale dependent); pressure loading by liquid contents.

6.14.4 In addition to the above, there are practical problems in scaling features such as bolts (standard threads do not scale), material thicknesses (standard sizes), welds, surface roughness and construction tolerances.

6.15 METHODS FOR IMPACT ANALYSIS

6.15.1 Impact analysis is used to provide the designer with assurance that the package will successfully resist the drop tests. Numerical modelling and lengthy hand calculations are both costly and at the start of the design process a cost-benefit analysis should be carried out to determine the scope of any analysis. The cost of building a prototype for testing will, in most cases, be sufficiently large to justify at least some hand-calculations. Some packagings however may be sufficiently inexpensive to make it cheaper to drop test it and stand the risk of failure because the cost of doing it again is low.

6.15.2 For simple geometries with local deformation of a flowing or crushable component, such as a lead-shielded flask or an impact limiter, a **quasi-static method** may be employed to determine the extent of deformation and peak impact loading (see Appendix A). The method is approximate and should be applied only for orientations with the c.of.g. over the impact point.

6.15.3 Another method which can sometimes be useful is the **dynamic lumped parameter method**. Here, the various components of the package are represented by lumped masses connected by "springs", as in Figure 6.1, and the equations of motion are solved subject to appropriate boundary conditions.

In its simplest form, the system may be represented in one dimension. For elastic springs the equations can be solved analytically, but for realistic non-linear springs and where compression and relaxation are described by separate load/displacement functions, an iterative or time-stepping solution is required. A simple computer program or spreadsheet would be sufficient for this.

6.15.4 When extended to two or three dimensions, a more sophisticated program is required, and proprietary software is available. This allows impact orientations other than c.of.g. over impact point to be analysed. Details of the above methods are given in Ref. 2.

6.15.5 For certain structures deforming in a predictable way, **plastic hinge theory** may be applied. An example application is a drum with rolling rings being impacted on its end. In this method, plastic deformation is assumed to be highly localised at pre-determined locations ("hinges"), and the work required to rotate the hinges is calculated. The flow is usually assumed to be perfectly plastic (i.e. no strain hardening), so the method has limited accuracy (Ref. 3).

6.15.6 The use of computer programs has already been mentioned. Some personal computer applications are available specifically for flask analysis, e.g. the SCANS software from Lawrence Livermore National Laboratory (LLNL) in the USA, which uses a combination of dynamic lumped parameter and simplified finite element methods.

6.15.7 There are an increasing number of sophisticated finite element codes available which are able to deal with impact conditions and non-linear deformations. When used to simulate complex structures such as transport packagings, these codes will normally require a powerful workstation or mainframe to run on. Codes with an explicit time integration scheme are usually best for short duration events such as impact.

6.15.8 A mesh generator and a means of defining sliding interfaces, pressure loading, rigid walls etc are required, as is a post-processor for displaying and analysing the results of a simulation. Where possible, codes should be used which have been extensively validated against experimental results. An example of a code suitable for impact applications is LS-DYNA from LLNL, together with its pre and post-processors INGRID and TAURUS.

6.15.9 Careful thought should go into the specification of the finite element mesh. Some packages may be modelled in two dimensions, e.g. those with axial symmetry, but this can give unrealistic results if the package response is particularly sensitive to impact angle (as in a flat faced impact). The degree of mesh refinement should reflect the expected level of deformation, and so will often vary across the model. Example of finite element simulations of packaging impacts may be found in Ref. 1.

6.15.10 Shell elements may be used for thin shell-like parts of the structure, such as metal panels, provided the ratio of element width to thickness is sufficiently large (e.g. 5:1 or more). There are many different formulations of shell elements, and specialist advice should be sought regarding the optimum choice, especially for conditions where elements experience in-plane compression.

6.15.11 The code chosen should offer the required range of material modelling types. It is recommended that only material models which have been validated against test data should be used for package assessments. Metals can be represented with an elastic-plastic model, and it is best to choose one which can describe non-linear hardening and strain-rate dependence.

6.15.12 The compaction behaviour of concrete and foams can be represented with a crushable material model. Concrete cracking and reinforced concrete, however, requires purposely written material routines. Wood can be modelled using orthotropic crushable models such as those intended for metallic honeycombs (Ref. 5).

6.15.13 The importance of having correct, reliable material data can not be over-emphasised. It is imperative that engineering stress/strain data are transformed into true stress and true strain data before inputting to the code.

6.15.14 Reliance on the material data specified by the standards is usually only sufficient for an approximate or bounding analysis. For metals, uniaxial tensile test data from material specimens should be used; an accurate simulation can only be achieved by using data derived from measurements of the complete stress/strain curve.

Fig. 6.1 Component Arrangement for Dynamic Lumped Parameter Analysis

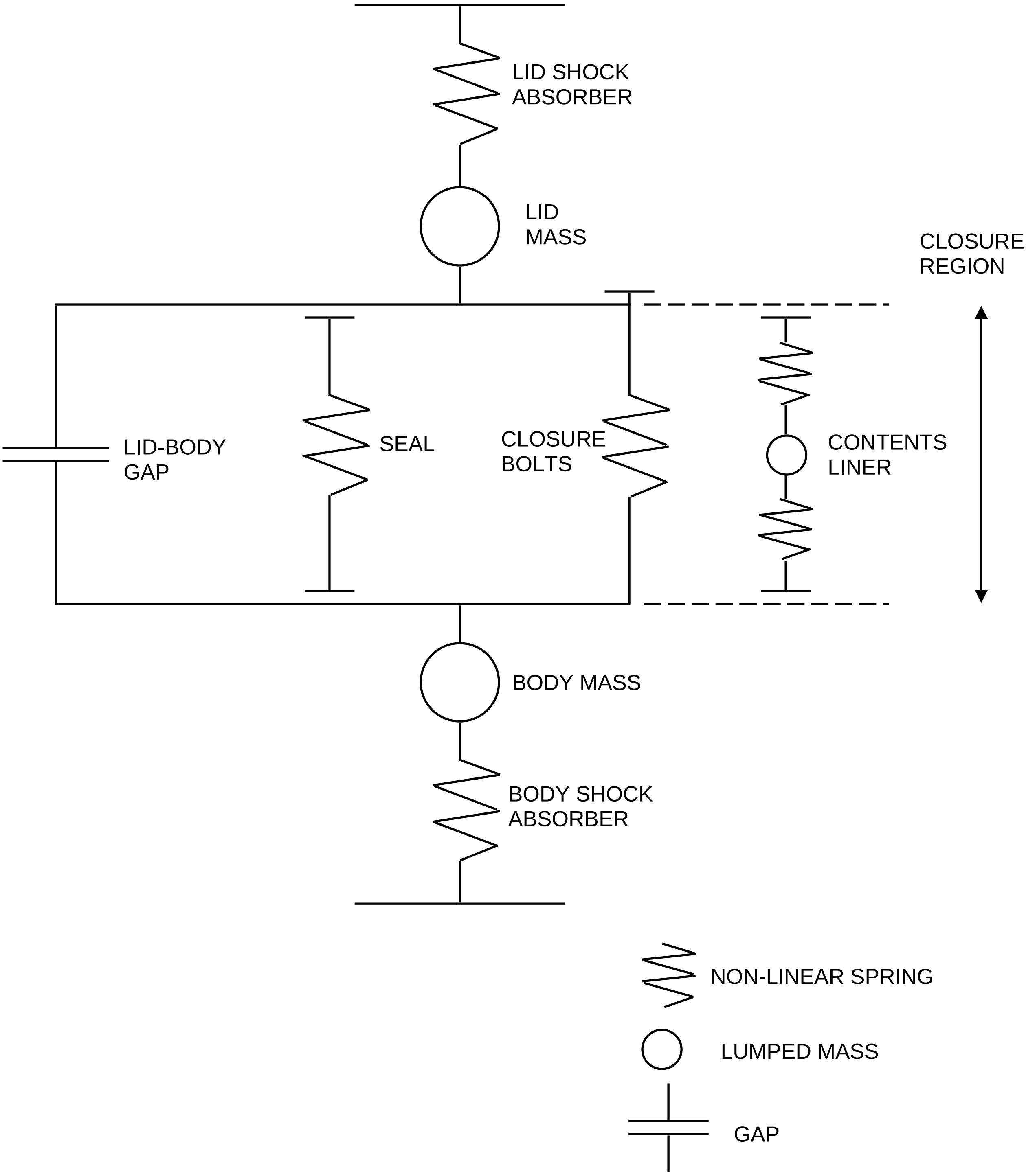

Table 6.1 Requirements for mechanical integrity

Package	Conditions	Requirements
All	Normal operations • handling, lifting, securing	Lifting and tie-down points shall not fail [607,608].
All	Normal transport conditions • accelerations, vibrations	No loose nuts/bolts on closure joints [612].
IP-2 IP-3, Type A	Normal transport tests • drop from 0.3 - 1.2 m [722] • stacking test [723]	No loss/dispersal of contents; increase in surface radiation ≤ 20% [622]. Sub-critical [679].
IP-3, Type A	Normal transport test • penetration by bar (1 m) [724]	No loss/dispersal of contents; increase in surface radiation ≤ 20% [646]. Sub-critical [679].
Type A, liquids & gases	Penetration test (1.7 m), Drop test from 9 m [725].	No loss/dispersal of contents; increase in surface radiation ≤ 20% [646].
Type A - liquids	Spillage from primary containment	Provide either (a) liquid absorbers able to absorb twice the volume of liquid, or (b) a double containment system [648,649].
Type B	Normal transport tests • drop from 0.3 - 1.2 m [722] • stacking test [723] • penetration by bar (1 m) [724]	Loss of contents ≤ 10^{-6} A_2/hour [656]. Sub-critical [671].
Type B	Accident transport tests • drop from 9 m [727] • drop from 1 m on punch [727] • fire and water immersion[728,729]	Loss of contents ≤ 1 A_2/week (≤ 10 A_2/week for ^{85}Kr) [656]. Radiation ≤ 10 mSv/h at 1 m from surface [656]. Sub-critical [671].
IP-3, Type A, Type B	Low ambient temperature (-40^{o}C) [637,664, A-528]	No damage from contraction of components, freezing of liquids (expansion), changes in material strength (e.g. ductile to brittle).
IP-3, Type A, Type B	High temperature Component: 70^{o}C [637]; Ambient (Type B): 38^{o}C [653,664], air transport packages: 55^{o}C [618]	No damage from expansion or melting of components, vapour pressure of liquids, decrease in material strength TS-G-1.1 para 628.
IP-3, Type A, Type B	pressure reduction to 60 kPa [643]	No loss of contents.
Air transport packages for liquids	Pressure reduction to 5 kPa [619]	No leakage.
Special forms	Drop from 9 m [705] Percussion test [706] Bending test [707]	Specimen shall not break or shatter [603].

REFERENCES – SECTION 6

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4 *Cask Designers Guide - A Guide for the Design, Fabrication and Operation of Shipping Casks for Nuclear Applications* Shappert L P, ORNL-NSIC-68, 1970. (To be reissued soon as the "Packaging Handbook".)

5 *Computer modelling of wood-filled impact limiters* Butler N, Nucl. Engn. Des., Vol. 150, pp 417-424, 1994.

APPENDIX A, SECTION 6 - CALCULATION OF CRUSH VOLUMES: QUASI-STATIC METHOD

This method can be applied to a package where most of the available kinetic energy, E, is able to be absorbed by local compaction near the impact zone, and where the affected component has a well defined compressive strength σ_f. It is usual to make the approximation that the contact area at a given instant during impact is the same as the area of intersection of the target plane with the undeformed structure, in the same position relative to the remote parts of the package. Thus the target plane may be said to sweep out a volume V of intersection with the package, given by

$$V = \frac{E}{\sigma_t}$$

For a crushable structure, such as an impact limiter, σ_f can be taken as the compressive strength of the infill material (i.e. neglect the resistance of the shell) at the relevant loading rate. For plastic deformation of metals the volume of metal is conserved, resulting in local bulging and widening of the contact area. Nevertheless, if the approximation stated above is made, reasonable predictions can be obtained. In this case it is generally adequate to take σ_f as the average of the yield stress and the tensile strength, again at the relevant strain rate. An exception is for situations where the deformed material is laterally confined by undeformed material (such as lateral impact of a cylinder), where σ_f can be up to twice the normal value.

Having determined V in this way, the maximum contact area A_m is determined by the geometry of the package. The "knockback", i.e. the depth of compression normal to the target plane, can also be derived. The method is illustrated below for cylindrical geometries impacting at various orientations. The peak loading F_m is then given by

$$F_m = \sigma_f A_m$$

The package peak deceleration is then found by dividing both sides of the equation by the package mass, m

$$d = \frac{\sigma_f A_m}{m}$$

Example - Impact of a solid cylinder

In the following it is assumed that the knockback volume V, radius R, and length L of the cylinder are all known.

Axial impact (Fig. 6.A1)

The contact area A_m is independent of knockback volume,

$$A_m \approx \pi R^2$$

and the knockback distance k is simply

$$k = \frac{V}{A_m}$$

Lateral impact (Fig. 6.A2)

The equation

$$\theta - \sin\theta\cos = \frac{V}{R^2 L}$$

is to be solved for θ, either iteratively or graphically. The contact area A_m and knockback distance k are given by

$A_m = 2\ R\ L\ \sin\theta$

$k = R\ (1 - \cos\theta)$

Oblique impact (Fig. 6.A3)

For impact on an edge with the cylinder axis at an angle ϕ to the vertical, the equation

$$\sin\theta - \theta\cos\theta - \frac{\sin^3\theta}{3} = \frac{V}{R^3\tan\theta}$$

is to be solved for θ, either iteratively or graphically. The meaning of θ is the same as in Fig. 6.A2 (taking this as an end view along the cylinder axis), but now θ could be more than 90° for small angle ϕ. The contact area A_m and knockback distance k are given by

$$A_m = R^2\frac{(\theta - \sin\theta\cos\theta)}{\cos\phi}$$

$k = R\ \sin\phi\ (1 - \cos\theta)$

Example - Impact of a cuboid

Corner impact (Fig. 6.A4)

The knockback is

$$k = \left[\frac{3V\sin\theta\tan\theta}{1+\tan^2\theta}\right]^{0.33}$$

$$A_m = k^2\frac{(1+\tan^2\theta)}{\sin\theta\tan\theta}$$

Edge impact (Fig. 6.A5)

$$k = \left[\frac{2V \tan\theta}{L\left(1 + \tan^2\theta\right)} \right]^{0.5}$$

where *L* is the length of the impacted edge.

$$A_m = \frac{Lk\left(1 + \tan^2\theta\right)}{\tan\theta}$$

Fig. 6.A1 Axial impact of a solid cylinder

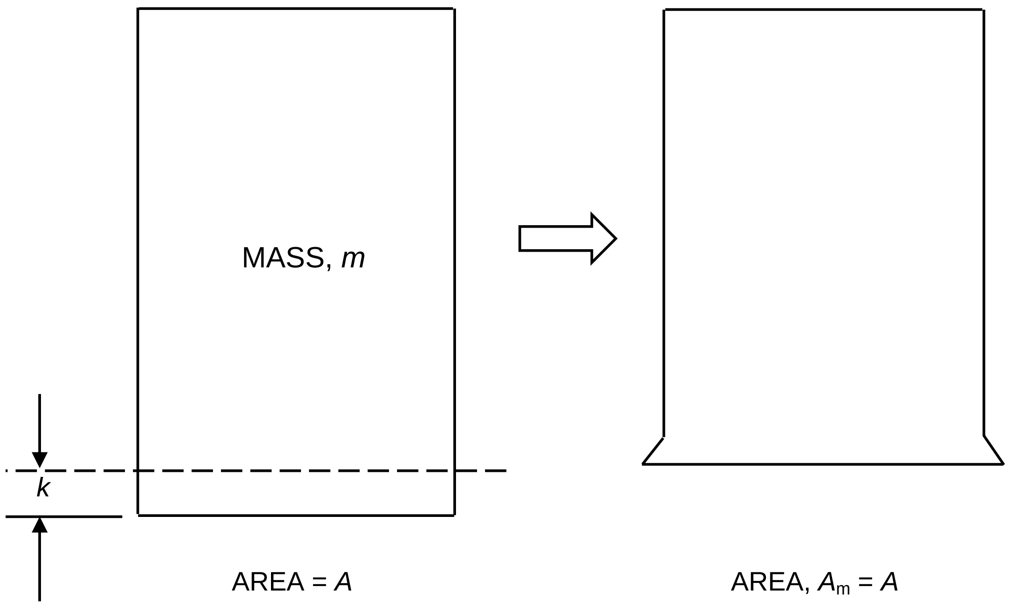


Fig. 6.A2 Side impact of a solid cylinder

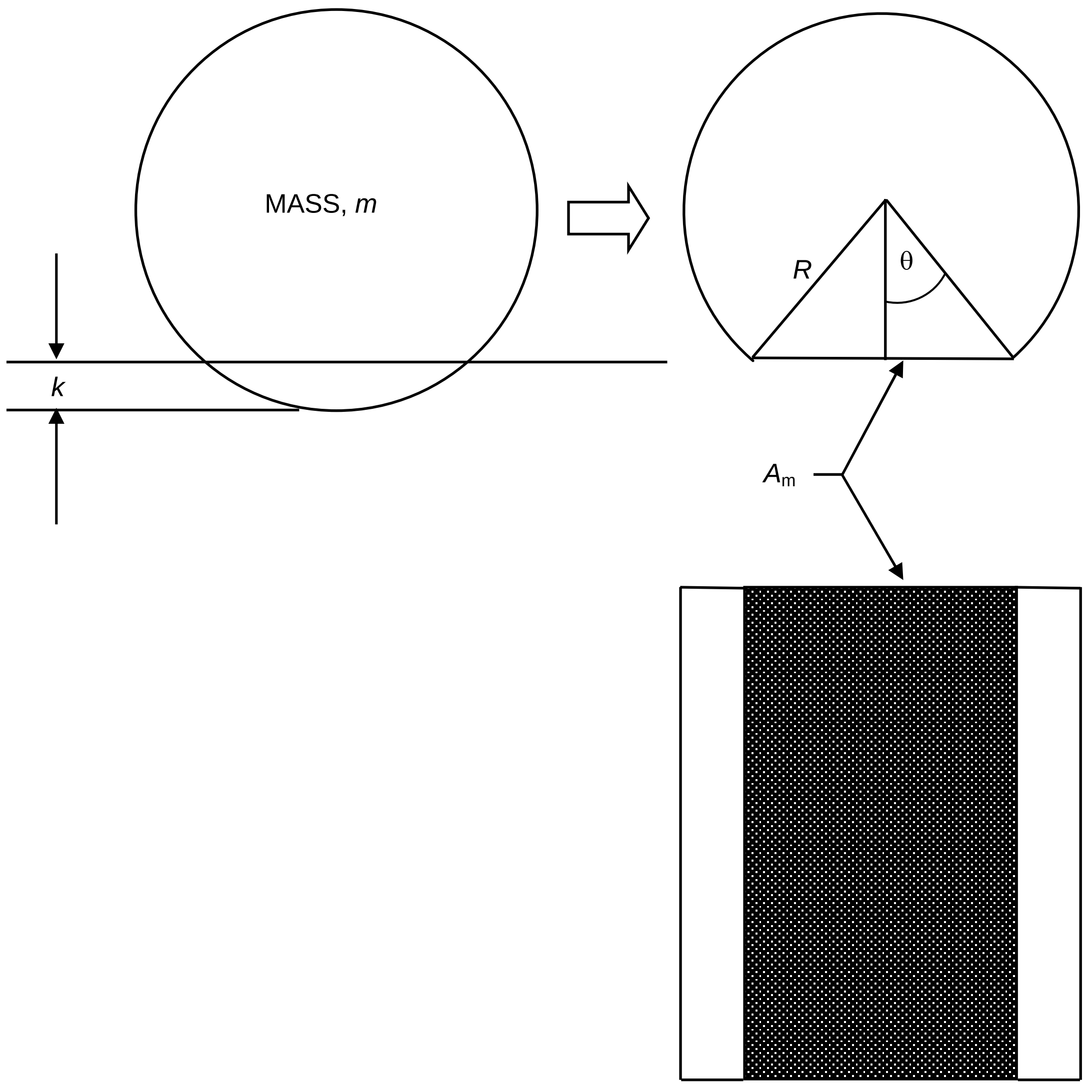


Fig. 6.A3 Edge impact of a solid cylinder

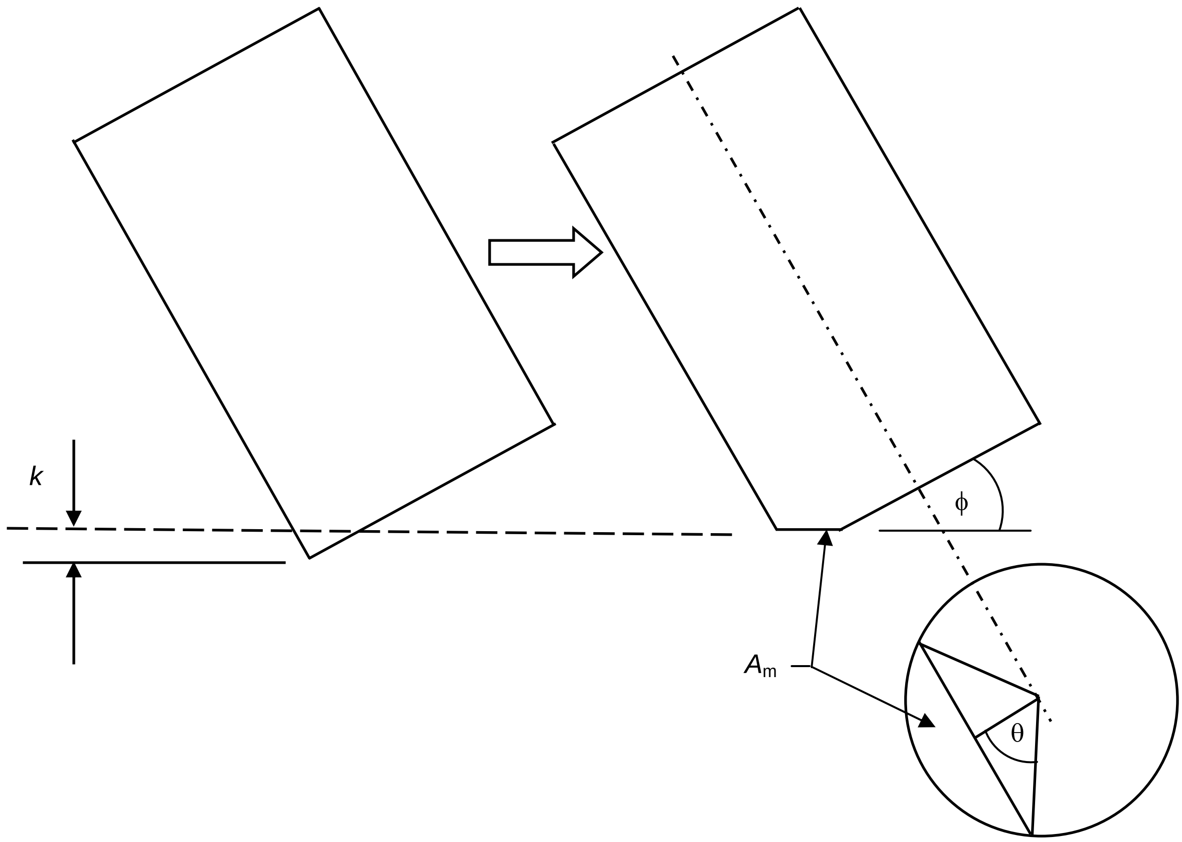


Fig. 6.A4 Corner impact of a cuboid

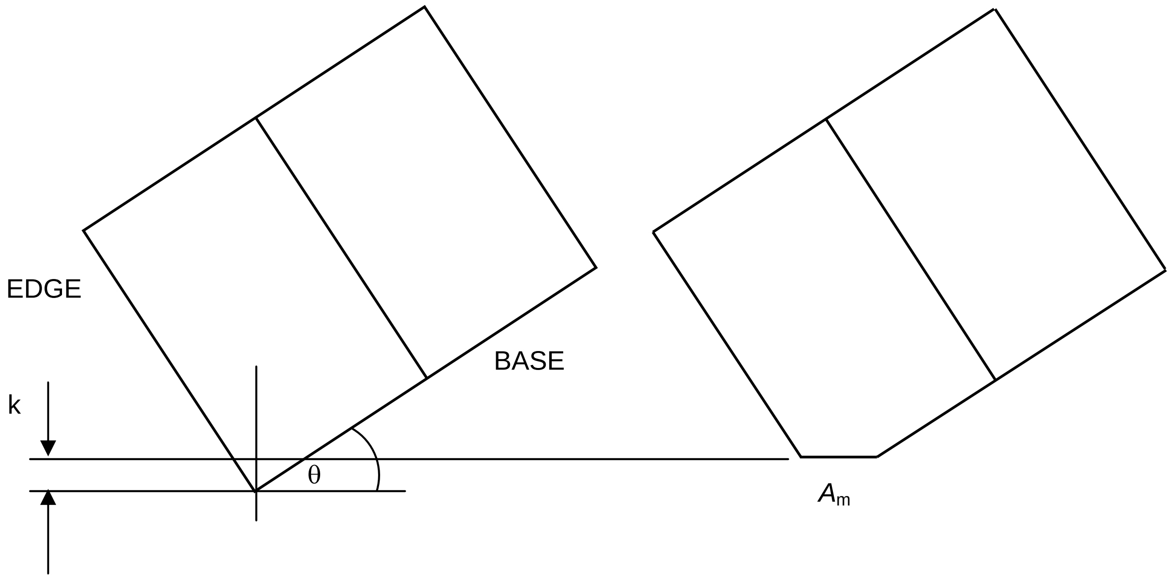
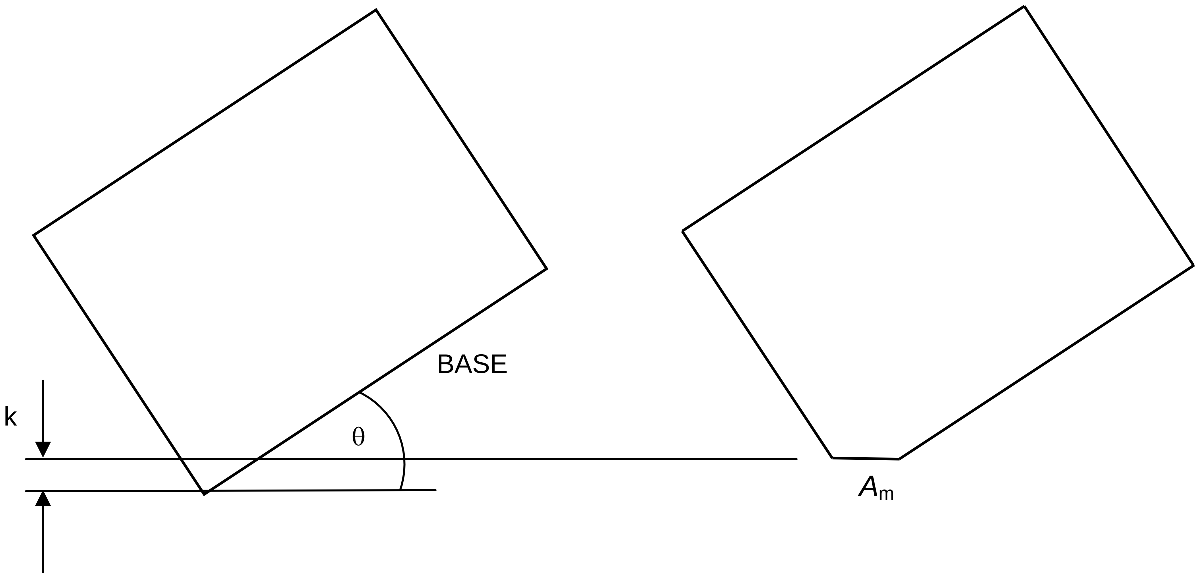


Fig. 6.A5 Edge impact of a cuboid



APPENDIX B, SECTION 6 - PUNCTURE OF METAL PANELS BY IMPACT ON A PUNCH

For metal panels of thickness t, the force required to puncture (ie shear) a hole of diameter d by a solid cylindrical punch is given by the theoretical formula

$$F_p = 0.6\, \pi\, d\, t\, \sigma_u$$

where σ_u is the ultimate tensile strength of the metal. The puncture energy E_p is given by the equation

$$\frac{E_p}{\sigma_u d^3} = \frac{ct^n}{d}$$

where c and n are dimensionless constants. For perfectly supported panels (i.e. no indentation), $c \approx 1$ and $n = 2$. For mild or stainless steel panels backed by lead, empirical data give $c \approx 2.2$ and $n \approx 1.4$ (Ref. 6.4). For clamped unbacked steel plates, test data indicate $c \approx 1.5$ and $n = 1.5$, though these tests were at higher velocities than achieved in drop tests.

7 APPLICATION OF QUALITY ASSURANCE

7.1 INTRODUCTION

7.1.1 This section aims to provide general guidance on the application of Quality Assurance to the transport of Radioactive Material (RAM) with particular emphasis on designer/applicant activities and responsibilities. Designers and Applicants must however recognise that their responsibilities extend to the complete life cycle of the package, and their actions should ensure that the designs and actual packages produced are able to meet all relevant requirements during the period of approval (or successive periods of approval).

7.1.2 Quality programmes must be established for **all** aspects of RAM transport, and should cover the design, manufacture, testing, documentation, use, maintenance and inspection of **all** packages as well as transport and in-transit storage operations. Where Competent Authority approval for design or shipment is required, such approval shall take into account and be contingent upon the adequacy of the quality assurance programme.

7.1.3 The purpose of this section is not to repeat the requirements of the various quality system standards available for use. An appropriate standard that is acceptable to the relevant Competent Authority should be used to develop and implement the required quality programme. In the UK standards such as BS EN ISO 9001 (Refs 1, 2 and 3), IAEA 50-C-/SG-Q (Ref 4) or other similar documents like Appendix IV of IAEA Safety Series No 37 (Ref 5) or Appendix IV of IAEA Safety Series TS-G-1.1 (Ref. 6) and Safety Series No 113 (Ref 7) are acceptable to the UK Competent Authority.

7.1.4 The nature and form of the quality programme will depend on the size and complexity of the organisation involved in the transport operations. An important principle to maintain during the development of any quality programme is that it should be “as straightforward as possible, and only as complex as necessary”.

7.2 DEFINITIONS

Quality Assurance: A systematic programme of processes and systems applied by any organisation or body involved in the transport of radioactive material which is aimed at providing adequate confidence that the standard of safety prescribed in the Regulations (Ref 8) is achieved in practice.

Quality Assurance Programme: The overall programme established by an organisation to implement stated requirements. The programme generally defines responsibilities and authorities, policies and requirements and provides for the performance and assessment of work.

Design: The description of special form radioactive material, package or packaging which enables such an item to be fully identified. The description may include specifications, engineering drawings, reports demonstrating compliance with regulatory requirements and other relevant documentation.

Quality Plan: Document setting out the specific quality practices, resources and sequence of activities relevant to a particular product, project or contract that are not covered by the quality programme.

7.3 PHASES OF TRANSPORT

7.3.1 While one organisation can be totally involved and responsible for all phases of transport in respect of a particular package or series of package transport operations, usually there is more than one organisation involved. Therefore the different phases of transport must be recognised and addressed in whatever quality programme(s) apply. The different phases of transport can therefore involve the following:

- Package designers and testers
- Package manufacturers
- Consignors
- Users
- Carriers

Support services (can be linked in with designers in for example the case of criticality, stress analysis, or risk assessment specialists, or linked with consignors and users in the example of maintenance specialists).

7.4 QUALITY PROGRAMMES

7.4.1 The quality programme must be in a documented form, and should aim to be as straightforward as possible, with the minimum of complexity. For transport purposes, it can range from a dedicated single document to a company-wide documented quality system covering all activities undertaken by that Company. Irrespective of its form, the quality programme must provide for the appropriate responsibilities, authority and controls to be identified, specified, verified and recorded.

7.4.2 For specific projects or sub-projects such as the design, prototype testing, or manufacture of a package, a sub-project quality plan may be developed which can be more specific and detailed than the overall quality programme, as well as addressing any “grey or overlapping” areas of responsibility or activity.

7.4.3 The size of the organisation and the degree of its involvement in transport will heavily influence the development of the quality programme. Quality requirements are independent of the size of the Company, but a small company may be able to meet the quality requirements with a much simpler organisation and with less administration than a larger company.

7.5 MINIMUM REQUIREMENTS

7.5.1 Irrespective of the size of the organisation or the scale of its activities, there are certain requirements that must be addressed in all quality programmes. The table below gives guidance on the applicability of the various elements to the different types of organisations and their quality programmes. Where an organisation is involved in more than one activity, e.g. design and manufacture, or is both a user and carrier, the quality programme should reflect that multiple involvement and address the appropriate elements. **See Table 1.**

QA Programme Element	Designers	Manufacturers	Consignor/ Users	Carriers
Management Responsibility	x	x	x	x
Contract Review	x	x	x	x
Design Control	x			
Document and Data Control	x	x	x	x
Purchasing	x	x	x	
Control of Customer Supplied Product		x	x	x
Product Identification and Traceability	*	x	x	
Process Control	*	x	x	x
Inspection and Testing	*	x	x	x
Control of Inspection, Measuring and Test Equipment	*	x	x	x
Inspection and Test Status	*	x	x	x
Control of Non conforming Product	*	x	x	x
Corrective and Preventative Action	x	x	x	x
Handling, Storage, Packaging, Preservation and Delivery		x	x	x
Control of Quality Records	x	x	x	x
Internal Quality Audits	x	x	x	x
Training	x	x	x	x
Servicing			x	x
Statistical Techniques	x	x	x	

TABLE 1 - Applicable elements of a quality programme

*See Section 7.5.2 below.

7.5.2 Care should be exercised in the interpretation and understanding of these elements. Reference should be made to the appropriate quality standard to ensure that all the requirements of these elements are clearly understood and included in the organisation's quality programme. For example, a designer who solely engages in pure design work, with no control or direction over supporting test work could have a programme which addresses the elements shown above, however if a designer is actively managing any design support work such as conceptual or regulatory proof testing, the elements marked * should also be considered in the quality programme.

7.6 QUALITY ASSURANCE CONSIDERATIONS FOR THE DESIGNER

7.6.1 The designer must be able to assure the manufacturer, user and the certifying body as appropriate, that all necessary steps and design processes have been addressed during all phases of design; this can often be achieved by the provision of a Design Quality Plan (DQP).

7.6.2 There are a number of different aspects of design control, all of which require consideration and action during the design process; these can be identified in the DQP under the following headings.

Design and Development Planning. Each new package design should have appropriate design and development plans established. This planning activity should clearly define the project in terms of agreed specifications of what is to be designed (and subsequently made as a package), who is to carry out the design work and who is to be responsible for that work, who is to be consulted during the design phase, what external requirements and regulations have to be taken into account, what hold points should be included in the overall design process, and how the design is to be accepted and by whom.

Organisational and Technical Interfaces. The designer's quality programme should provide for the necessary organisational and technical interfaces (internal and external) to be identified and established, so that the design process information can be controlled, transmitted and reviewed, thus enabling the final design to be accepted.

Design Input. All design input requirements shall be established and documented. Such input should identify the applicable statutory, regulatory and safety requirements, the acceptance criteria for the design, the quantities and characteristics of the materials to be transported, as well as the choice of package material, possible methods of test and manufacture, operational and handling considerations, and servicing and maintenance needs. (This listing is not intended to be exhaustive and other pertinent design inputs should be added as they become apparent to the particular designer.) Any incomplete, ambiguous or conflicting requirements should be identified and resolved with those responsible, before final agreement of the design inputs.

Design Output. Design output documents should clearly specify the design intent and requirements, and should be capable of verification and validation against the agreed design input requirements. Design output should meet the design input requirements, specify or refer directly to acceptance criteria, and identify those features of the design which are crucial to the continued safety and functioning of the package (e.g. operational, handling, servicing and maintenance requirements).

Design Review. Design reviews should be carried out at appropriate stages to monitor the progress of the design in meeting the specifications requirements. Design reviews should be formal and documented activities, involving representatives of all functions or groups affecting the quality of design. Design reviews should systematically and critically review the design to identify and anticipate problem areas and inadequacies, and initiate corrective actions to ensure that the final design result meets the specification. Where a design has been in existence for a long time, it may be necessary to conduct periodic design reviews to take account of evolving or changing requirements (regulatory or otherwise).

Design Verification. In order to clearly demonstrate that design objectives are being achieved, or are soundly based, design verification activities should be carried out that are consistent with the complexity or novelty of the proposed design. Such verification activities can include design review, alternative calculations and analyses, tests and demonstrations using models or prototypes, appropriate comparison of the new design with a similar proven design, or independent verification of design results by peer review or other bodies.

Design Validation and Acceptance. The final design result, following the design review and verification phase, should be subject to a documented validation and acceptance process. Validation and acceptance mechanisms can include:

(a) independent assessment of design specifications and drawings including any approved modifications, for compliance with all identified requirements,
(b) prototype or early production item inspection and performance testing,
(c) confirmation of validation of computer systems and software used.

Whilst final design validation and acceptance occurs at the end of the design process, it may be important to gather supporting evidence of validation during earlier phases of the design process, e.g. validation of computer codes and input before commencing calculation or analysis. The final validation and acceptance of the design should be undertaken by suitably qualified personnel at the appropriate level of management.

Design Change. The designer's quality programme must also provide for adequate control when design change becomes necessary. Control of design output must be maintained, both during and after the change period. Adequate procedures must be in placed to:

(a) ensure that design change is **really** necessary and that all interested bodies including users of the packages, have input to the design change process
(b) control the approval and timing of modifications and other changes
(c) ensure the removal of obsolete drawings and specifications
(d) prevent the continued manufacture or use of obsolete equipment
(e) carry out further design review, certification or validation work when the magnitude, complexity, or safety importance of the change warrants such action.

7.7 QUALITY ASSURANCE CONSIDERATIONS FOR THE APPLICANT

7.7.1 Quality programmes are necessary for **all** packages used in the transport of RAM, not just those subject to Competent Authority Approval. The application of a "Graded Approach" to quality is covered later in this chapter, and the facility for tailoring the quality arrangements to the type of package and attendant approval should not be overlooked.

7.7.2 When formal application for approval by a Competent Authority is necessary, the applicant is required to specify what quality provisions are to apply. This means that the applicant will be expected to quote the quality programme(s) for those aspects of the design, manufacture, testing, documentation, use, maintenance and inspection of packages, transport, and storage in transit for which they are responsible. They will also have to demonstrate the adequacy and effectiveness of their programme upon demand.

7.7.3 The self certifying organisation can also expect to be asked to demonstrate that appropriate quality programme will be applied during the life cycle of the package.

7.7.4 It is often the case that the applicant has not carried out all the preparatory design work, but has engaged design specialists to assist in the preparation of certain elements of the work. Similarly the applicant may engage one or more manufacturers to make the packages, and different organisations to maintain and service the packages. In such circumstances however, the applicant will still be responsible for the quality programme of that delegated work, and should be able to demonstrate adequate control of the work.

7.7.5 For those activities over which they have no direct control or responsibility, the applicant will be expected to prescribe other specific or general quality programmes, or more general quality arrangements, that are acceptable to the Competent Authority concerned. This situation may arise where there are multiple independent manufacturers and users of packages, and may be satisfied by appropriate reference to compliance with an acceptable national or international quality standard.

7.7.6 When preparing the application for approval, the Applicant should ensure that they have prepared the application document in accordance with the relevant document control procedures, and that all information contained within is traceable and verifiable.

[NB The UK Competent Authority has prepared and issued a “Guide to Applications for Competent Authority Approval” which is freely available to potential applicants.]

7.7.7 Packages which do not require Competent Authority approval can be self-certified and should be treated in a similar manner, using a graded QA approach commensurate with the type of package, its radioactive material, and the expected life of the package(s).

7.8 THE GRADED APPROACH TO QUALITY ASSURANCE

7.8.1 When appropriate, the structure and content of the quality programme can make due allowance for a “Graded Approach” in the application of quality to both packages and contents. The intention is to ensure that such measures are sufficiently stringent to give adequate control, without being excessively severe. Any system used for grading packages or components of packages should be based on the safety significance of those items directly, or on their significance in the final package in transport. A graded approach example is given below, which is essentially similar to the one shown in Ref. 6.

Grade 1 items are those essential to safety, and should be those directly affecting package leak-tightness or shielding, or for packages of fissile material, those directly affecting geometry and thus criticality control.

Grade 2 items are those with a significant impact on safety, such as structures, components or systems whose failure could indirectly affect safety in combination with a secondary event or failure.

Grade 3 items are those with minor or no impact on safety, such as those affecting structures, components or systems whose malfunction would not affect the packaging effectiveness and so would be unlikely to affect safety.

7.9 GRADING CRITERIA

7.9.1 When considering the use of a graded approach and the different grades indicated, careful consideration should always be given to the effect on shielding, containment, criticality and heat dissipation, as well as the determination of actual contents and the hazards posed by the radioactive contents.

The following examples of detailed requirements illustrate the application of a graded approach to quality.

7.9.2 For Grade 1 Items/Systems:

(a) The design should be based on applicable industrial standards or codes, and design verification should be accomplished by design review, prototype testing or by the use of calculations or computer codes.
(b) The procurement documentation for materials or services should specify that only approved suppliers are used.
(c) The manufacturing planning should specify traceability of raw materials and the use of certified processes and process operators, e.g. welders.
(d) Test and inspection work should require the use of qualified test methods and qualified inspectors to verify conformance to specified standards and codes.
(e) Audits should be carried out only by qualified and nominated personnel.
(f) Acceptance after manufacture and authorisation of use of such items should be made only by the consignor or a nominated representative of the consignor.

7.9.3 For Grade 2 Items/Systems

(a) The design should be based on applicable industrial standards and codes; design verification may be through the use of calculations to computer codes.
(b) Specified processes need to be carried out by certified personnel.
(c) Components and materials should be supplied with a certificate of conformity.
(d) Tests and inspections should require the use of inspectors qualified to verify conformance to appropriate standards, codes or industrial specifications.
(f) The lead auditors need to be properly qualified and nominated personnel.

7.9.4 For Grade 3 Items/Systems

(a) In general, the design needs to follow accepted engineering or industrial practice in which items would be standard (“off the shelf” or proprietary). All items would be subject to inspection to confirm acceptability for use.

7.10 RELATIONSHIP OF GRADING TO PACKAGE TYPE

7.10.1 The following guidance applicable to each category of package listed should be regarded as indicative and is not intended to rigorously cover all situations. However, it gives a general indication of the level of quality assurance to be aimed at. Obviously, higher grades than those suggested may be used, and should be considered especially for those packages designed for radioactive materials having other significant dangerous properties (subsidiary hazards), such as uranium hexafluoride.

(a) **Excepted packages and industrial package type 1 (IP-1)**
In determining the radioactive contents and package radiation levels, the instrumentation and processes used should be subject to quality at Grade 1 level. In all other aspects, such as design, manufacture, etc., Grade 3 should be applied.

(b) **Non-fissile Type A packages and industrial package Types 2 & 3**
Matters affecting shielding integrity and containment should be subjected to quality at Grade 1 level. All other matters should be subjected to Grade 2, except where there is minimal effect on safety, in which case Grade 3 can apply.

(c) **Special form radioactive material**
In all matters affecting compliance with the special form radioactive material requirements, quality at Grade 1 is appropriate.

(d) **Fissile packages (other than Type B packages)**
In the case of criticality assessment and other factors affecting the assumptions in the criticality assessment, quality at Grade 1 is appropriate. All other aspects should be subjected to Grade 2 except where there is minimal affect on safety, in which case Grade 3 is appropriate.

(e) **Type B packages (non-fissile and fissile)**
In all aspects contributing to the integrity of shielding and containment together with criticality safety (where applicable), quality at Grade 1 is appropriate. All other aspects should be subjected to Grade 2 except where there is minimal effect on safety, in which case Grade 3 is appropriate**.**

(f) **Shipment and special arrangements**
Quality should be applied to shipments and special arrangements according to the individual features of each case.

REFERENCES – SECTION 7

1. BS EN ISO 9001: 1994 Quality systems - Specification for design, development, production, installation and servicing. Note: the 1994 standards (Refs 1 and 2) have been replaced by Ref. 3 and will be withdrawn at the end of 2003.

2. BS EN ISO 9002: 1994 Quality systems - Specification for production, installation and servicing.

3. BS EN ISO 9001:2000 Quality management systems – Requirements.

4. IAEA Code on the Safety of Nuclear Power Plants: Quality Assurance, Safety Series No 50-C-/SG-Q.

5. IAEA Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material (1985 Edition), Third Edition (as amended 1990), Safety Series No 37.

6. IAEA Safety Standards Series No TS-G-1.1(ST-2) Advisory Material for the IAEA Regulations for the Safe Transport of Radioactive Material.

7. IAEA Quality Assurance for the Safe Transport of Radioactive Material, Safety Series No 113.

8. IAEA Safety Standards Series, Regulations for the Safe Transport of Radioactive Material 1996 Edition (Revised) No TS-R-1 (ST-1 Revised).

8 DESIGN OF LIGHTWEIGHT PACKAGINGS

8.1 GENERAL INFORMATION

8.1.1 The IAEA regulations define a set of design and performance requirements that packages must comply with in order to meet the requirements of Type A packaging. These requirements can be satisfied by a wide range of packaging designs dependant on the item needing to be packaged and the careful choice of the outer packaging needed to protect it. Such designs could range from simple corrugated cases containing glass vials to plastic drain pipes containing static eliminator bars to `engineered' steel packagings weighing many tons. All can satisfactorily meet the requirements of the regulations if the design is carefully considered.

8.1.2 This section will deal with the lightweight designs, often referred to as the `expendable packaging designs', although in many cases they can readily be used as returnable packagings but often with a limited life expectancy. It does not include packages for fissile products greater than the exception levels for which expert advice should be sought.

8.1.3 There are lesser requirements under the regulations for excepted packages and these are identified in Appendix A. Section 8.2 discusses design and, while intended mainly for Type A packagings, may be pertinent for certain features of excepted designs.

8.1.4 In most cases the packaging will be a combination (composite) structure comprising a range of materials. However, the design will usually incorporate the following elements:

Primary containment
The first layer of packaging in direct contact with the radioactive product.

Intermediate packaging
The next layer of packaging comprising the shielding (if required), absorbers (if a liquid product) and cushioning materials to protect vulnerable packaging elements.

Outer packaging
The outermost layers comprising additional cushioning where required and the outermost layer of packaging used to `contain' the lower levels of packaging, and onto whose surface the appropriate labels and markings are sited.

8.2 CONTAINMENT

8.2.1 Refer to Section 4 for a detailed review of containment issues covering all packagings. This section looks at those aspects that are especially relevant to small packages.

8.2.2 The containment system shall retain its radioactive contents against a reduction of ambient pressure to 60 kPa without leaking. For all packages transported by air there is a higher standard; the containment system shall be able to withstand without leakage a reduction in ambient pressure to 5 kPa. Unlike Type B packagings where the degree of permissible `leakage' is defined, the regulations for Type A packagings define the containment requirement as maintaining a seal without leakage.

8.2.3 In reality there is no such thing as a perfect seal when one considers such mechanisms as diffusion, permeation etc, so the containment system has to contain the product within measurable limits when subjected to the above pressure differentials.

8.2.4 For containment systems that are closed at atmospheric pressure a practical test that demonstrates an adequate level of containment for Type A packages is bubble leakage testing. With a minimum test sensitivity of 10^{-4} Pu $m^3 s^{-1}$ (10^{-3} bar $cm^3 s^{-1}$) testing can be carried out in less than 10 minutes. A secondary benefit of bubble leakage testing is that the ability of the containment system to withstand a pressure reduction may also be demonstrated.

8.2.5 Where small quantities of liquid are involved, a practical leakage test has been determined that after two hours subjection to the required pressure differential there shall be no more than 3 mg weight loss from a radioactive liquid product weighing 5 g. If the solution under investigation is dyed with 0.1% methylene blue or fluorescein, and the packaging seal area immersed in water of no greater than 250 ml, then under normal lighting this level of product loss can be determined visually.

8.2.6 The regulations also state that the packaging shall withstand a temperature range of -40°C to +70°C [528]. The containment system should be capable of withstanding this temperature range prior to the leakage test and still maintain a seal. To achieve this the packaging should have sufficient ullage to allow for any expansion of the liquid contents without generating excessive internal pressure.

8.3 CONTAINMENT MATERIAL AND SEALING SYSTEMS

8.3.1 Glass packagings are commonly used because of the inert nature of the material. The low solubility of most products in glass, and the low levels of materials extractable from the glass, means that it is an ideal material for containing most sensitive products. A variety of sealing methods can be employed dependent on the design of glass packaging and usage required.

a) **Flame sealed glass ampoules** are thin walled glass packagings that can be flame sealed to provide a hermetic seal which then requires the packaging to be broken to gain access to the contents. For some applications this is acceptable and provides a securely sealed packaging that is appropriate for products that may be extremely sensitive to contact with other materials and/or permeating gases. Flame sealed packagings are usually thin walled so they are invariably fragile and need appropriate cushioning.

b) **Crimp sealed packagings** seal a vial using a rubber seal (bung) held in compression on the sealing surface of the packaging by a crimped aluminium overseal. The crimping achieves a consistent result with relatively simple equipment. Crimp sealed packagings can vary from those made from relatively thin walled glass tubing to blow moulded packagings with relatively thick glass walls, and the strength will vary accordingly.

c) **Screw sealed packagings** rely on the closing torque of a threaded closure to generate compression of a resilient liner (gasket) or other sealing feature within it. Of the three closing methods mentioned here, screw closures probably represent the most widely used, because of the convenience and ability to re-close them. However, they are the most prone to variations in sealing performance since this is dependent on the frictional properties at the closure/packaging interfaces, the design and material choice of the closure/ packaging system and the torque application method. Nevertheless, careful consideration and control of all these features can produce a consistent and acceptable performance.

8.3.2 The majority of plastic packagings are closed using a screw threaded cap although packagings are available with all the same closing systems as glass packagings. The main criteria involved in selecting the appropriate plastic packaging for a particular application are usually those associated with the choice of packaging material. This will have to satisfy such general requirements as transparency, chemical compatibility with the product [613], susceptibility of the product to permeation of external gases etc. In order to satisfy the IAEA regulations, the choice of packaging in addition will normally need to consider such issues as:

a) **Strength.** In order to meet the drop and penetration test requirements then impact resistance packagings are preferred such as orientated polyethylene terephthalate (PET), polyvinyl chloride (PVC), polypropylene (PP), high and low density polyethylene (HDPE and LDPE) packagings. Fragile materials such as polystyrene etc should be avoided. For Type A packages para 637 specifies a temperature range from $-40^{o}C$ to $+70^{o}C$.

b) **The sealing performance** of plastic bottles is very dependent on the manufacturing process used. As a general guideline, packagings made by injection blow moulding or one of its variants will tend to give a better sealing performance than extrusion blow moulding because of the better quality of the sealing surface and threadform of the former. However, inadequacies in the quality of the sealing surface can be overcome by the choice of a suitable cap liner system (including heat sealed liners) or using closures that seal within the bore of the packaging.

c) **Permeation.** Plastics materials can give quite high levels of permeation of product through the walls of the packaging (or closure) unless careful consideration is given to the choice of the material, process, coatings etc. Generally permeation decreases as:
- the wall thickness increases
- the orientation of the polymer increases
- the solubility of the product in the plastic decreases.

8.3.3 There are a wide range of materials and constructions that could be considered for containment systems all of which, with suitably designed outer packaging, can meet the requirements of the regulations. These include:

- Heat sealed pouches made from plastic laminates.
- Extruded aluminium screw thread packagings.
- Machined metal packagings.
- Seamed tinplate/aluminium cans.

8.4 SHIELDING

8.4.1 The type of shielding for a particular nuclide or mixture of nuclides will depend upon that nuclide(s), the activity present and the design of the package. Normally the shielding will be one of the first elements of the design to be determined as this is invariably fundamental to the design and will be a major factor in determining the overall design. Refer to Section 2 for general information on shielding.

8.4.2 It should be remembered that a reduction in the dose rate at the package surface can be achieved both by surrounding the nuclide with a material that will absorb the radiation being emitted and/or by increasing the distance between the nuclide and the package surface. For most of the common nuclides that are gamma emitters, the shielding achieved by different materials can be calculated. In Appendix B, a way of estimating the amount of lead shielding required for a range of nuclides is described in order to achieve the required surface dose rate on the package and Transport Index (TI). (The limit for Type A packages is a maximum surface dose rate of 2 mSv/h and a TI of 10. The data in Appendix B assumes a safety margin of 20% and therefore values are calculated on the basis that 1.6 mSv/h is the target surface dose rate.)

8.4.3 For many nuclides at low activity then no specific shielding will be needed and Appendix B gives the dose rate with no shielding. Some commonly encountered nuclides are low energy beta emitters and may consequently require no shielding even at high activities (up to 500 GBq) are ^{14}C, ^{3}H and ^{35}S.

8.4.4 Lead is commonly used for shielding and can be readily formed by machining, extrusion, casting, or a combination of these. Since lead is relatively soft and deforms readily, it is common practice to alloy it with up to 4% antimony to improve its durability.

8.4.5 In some countries lead is classified as a poisonous material and will need to be segregated when it comes to disposal. Similarly, if the lead packaging needs to be handled, there is often a requirement to paint the external surface.

8.4.6 Other common materials than can also be considered for gamma shielding within lightweight packages are steel (where shielding requirements are modest) and tungsten (which is denser, and therefore more effective than lead). However, price and weight will usually determine the optimum material. For beta emitters materials such as thermoplastics or glass may be sufficient. For instance, a 6 mm thickness of Perspex will absorb all beta particles with energies up to 1 MeV, and 25 mm will absorb all energies up to 4 MeV.

8.5 ABSORBERS

8.5.1 For liquid products, the IAEA Regulations [648] require either sufficient absorber to be present within the package to absorb twice the volume of the product or a double containment system. The Regulations [648(b)(i)] specify the positioning of the absorber to be such that the liquid product will contact it in the event of leakage. Under ideal circumstances the absorber should totally enclose the primary packaging of liquid, though for some designs this is impractical. In this case the absorber should be placed in such a position that the liquid could not escape from the package without contacting the absorber. For instance, with a design incorporating a slip-lidded tinplate can, the absorber should be placed at the open end(s) of the can prior to closing. Any absorber must also comply with para 613 on compatibility e.g. most cellulose based absorbers are not compatible with acidic solutions.

8.5.2 The list of materials that can be used as absorbers is significant and all have their particular applications. The following list is not exhaustive but is intended as a guide to the types of materials that could be considered.

a) The most commonly used absorbers are paper tissue based, usually multiple ply depending on the application and availability. They are capable of absorbing a wide range of liquids, although they are not suitable for strong alkali solutions. Tissue absorbers can be readily punched/cut into a range of shapes suitable for the particular application. A typical value for the absorption of water in paper tissue would be approximately 100 g/m^2 for each tissue ply. Compressed paper absorbers are also available that expand when exposed to liquids.

b) The fibreboard used for forming cartons and cases will itself display absorption properties and can be considered as the absorption system within certain designs. Generally the absorption properties of fibreboard are similar to paper tissue, although the rate at which it absorbs liquid is much slower.

c) Sawdust is probably one of the oldest absorbers in common use, though its absorption properties are difficult to characterise because of the variable nature of the product. Because it is generally a dusty/dirty material its usage is usually limited to shipping large volumes of liquid in industrial packagings where cleanliness is not an issue.

d) Thermoplastic foams with open cell structures generally make quite good absorbers. Because of the nature of the product then liquid can readily be absorbed into these open cells, but can equally be squeezed out when the foam is compressed which may be a disadvantage in some designs. The advantage of thermoplastic foams is that they can readily be formed into complex shapes should the design require it by wire cutting or other such process, or by moulding to the required shape. The degree of absorption will be dependent on the number and size of open cells, however, chemical compatibility should be carefully considered with these materials. The most commonly available foams are the polyurethane foams and these will suit most applications, however, most of the commonly used thermoplastic materials are available in foam form.

e) Vermiculite is a commonly used mineral absorber. It suffers from the disadvantage of other free flowing materials of being dusty and only appropriate for certain types of designs. It has the advantage of being inexpensive, readily available and chemically compatible with a wide range of materials.

f) Gel forming materials are increasingly being used because of their exceptional ability to absorb liquids. The materials are usually supplied as powders held within a cellulose matrix. These powders are capable of swelling to many times their original size upon exposure to liquids, however, care should be taken with their use. In order to comply with the regulations the absorber must be capable of absorbing twice the volume of liquid, however, a gel can only absorb this volume if it has the space to expand and the design should allow for this. Some gel forming materials also tend to show a reversible reaction with time as the gel breaks down and releases the absorbed liquid. Another significant failing is that the ability to form a gel is very dependent on the chemical nature of the liquid so their compatibility needs to be determined.

8.6 SECONDARY CONTAINMENT

8.6.1 Secondary containment can be used [648(b)(ii)] instead of absorbers to contain the product in the event of leakage. This would normally be achieved by incorporating within the design another containment system (packaging) outside the primary packaging. The guidelines given earlier for containment are appropriate also for secondary containment.

8.6.2 One commonly used design for secondary containment is to incorporate a sealing system within the lead or other shielding material such that upon closing the shield, the sealing material is compressed thereby providing a seal. Ideally the secondary containment system should be within the shielding system, however, this is impractical in some designs and is not a requirement of the regulations. Care should be taken to ensure that liquid leakage past the shield does not lead to more than a 20% increase in the reduction level at any external surface [646(b)].

8.7 OUTER PACKAGING

8.7.1 A wide range of materials can be used as the outer packaging and will generally need to satisfy the following requirements:

a) to contain the inner components and in some instances to provide the means of mechanically holding them together;

b) to provide protection for the inner components against the drop, penetration test and stacking test requirements of the regulations;

c) to provide a suitable surface for labelling and/or marking as required by the regulations.

8.7.2 The types of materials that could be considered for the outer packaging are as follows:

a) Solid fibreboard and corrugated fibreboard are widely used for outer packaging for Type A packages for weights up to 50 kg. A degree of water resistance will be needed to retain sufficient strength after the water spray test. This can be achieved by using either plastic laminated fibreboard or boards coated with a suitable resin or varnish. Plain brown Kraft boards will resist the water spray to a greater extent than bleached Kraft boards of an equivalent construction, and both will be suitable for some packaging designs generally at the lower weights. Generally stitching (stapling) will result in a stronger package than gluing, although the latter can be considered for the lightweight packages. For simple packaging designs where a degree of cushioning internally is provided, single wall corrugated board of construction 200 g/m^2 Kraft laminated to 125 g/m^2 fluting laminated to 200 g/m^2 Kraft, is capable of meeting the requirements of the regulations for package weights up to 8 kg. For higher weight packages then both the grammage of the board material can be increased and the number of `walls' of corrugated material, ie double wall or triple wall boards are available. The advantage of using solid or corrugated fibreboards, or for that matter any similar flexible materials as outer packaging, is that in combination with an inner cushioning material they deform and absorb the energy dissipated as a result of the impact in the drop test. Rigid materials do not tend to have the ability to deform and absorb this energy.

b) Wood can be used as outer packaging, although as mentioned earlier it is inherently rigid and care needs to be taken in the design to ensure it will meet the requirements of the drop tests without excessive deformation.

c) Many plastics can be considered as outer packaging materials. However, high material cost and origination costs often preclude their usage for non-reusable lightweight package designs. The range of materials that can be considered is large, the most commonly considered ones include:

- HDPE (high density polyethylene)
- ABS (acrylonitrile butadiene styrene)
- PVC (polyvinyl chloride)

These would normally be converted into suitably shaped articles by injection, blow or rotational moulding. Plastic films can also be used in the form of shrinkwrap to contain the inner packaging components and could be considered for certain lightweight non-reusable applications.

Extruded plastic materials that simulate corrugated fibreboard are readily available under a variety of trade names and these can be used as direct alternatives to fibreboard but with improved strength characteristics that, by careful design, may be used to offset the higher cost of the material.

d) Metals form an important class of materials for outer packaging as they often combine all the required properties of such materials. They have the inherent strength and ability to deform under load to provide an ideal solution to many applications. Preformed metal packagings are readily available in the form of drums, cans, chests etc which can be either tailored to fit or designed for the purpose depending on the application. The metals most commonly used are either mild steel, stainless steel or aluminium and one of these three will usually suit most requirements.

8.8 PACKAGING STRUCTURES

8.8.1 The packaging design for the shipment of radioactive material will depend primarily on the following factors:

- The weight and volume of the product.
- The shielding required.
- Whether the product is a solid liquid or gas.
- Whether the pack is classified as excepted or Type A.
  The functional requirements of the package.

8.8.2 The functional requirements of the package design will include such issues as the filling line or source loading requirement, the end-user (customer) requirements and any issues such as aesthetics. It is not proposed to deal with such specific issues here other than to make the following points:

a) The radiation dose experienced by a user of a packaging design will be dependent on the radiation being emitted from the package and the time of exposure to the radiation. The ability to be able to access the product quickly and easily or be able to use remote or shielded devices should be borne in mind when designing the packaging.

b) Smooth surfaces are easier to swab test for contamination and decontaminate than irregular or absorbant surfaces.

8.8.3 For solid products requiring no shielding then simple packaging designs can be used if the primary packaging is robust and will resist the drop test and penetration test requirements.

8.8.4 At the other end of the scale, liquid or gaseous products in fragile packagings requiring significant shielding will often require quite complex designs in order to meet the design and performance requirements of the regulations and also the commercial demands placed upon it.

8.8.5 The following points/comments may be used as guidance in selecting the materials of construction of a design.

a) The cushioning properties of polyethylene foams are similar to EPS.

b) The resistance to the penetration bar in the penetration test is greater for polyethylene foams than EPS.

c) A simple construction such as a fragile inner packaging, EPS and a corrugated fibreboard case is unlikely to pass the penetration test. A barrier such as a tinplate can, use of a polyethylene foam etc will usually be necessary.

d) The resistance to the drop test of corrugated fibreboard or metal outer packagings are usually better than rigid wood or plastic packagings, ie materials that deform readily tend not to fail catastrophically under drop test conditions.

8.9 SPECIALIST PACKAGE DESIGNS

8.9.1 The package structures dealt with so far have assumed a hypothetical product contained within a primary packaging, shipped under ambient conditions. In reality many products will not fit this idealised condition and will either be awkward shapes or require the temperature conditions to be controlled within the package. This section will attempt to provide guidelines as to how these requirements can be satisfied whilst still meeting the requirements of the regulations.

8.9.2 In most cases controlled temperature conditions will mean maintaining the temperatures of the product at normal refrigeration temperatures, ie 0-4°C, or a lower temperature such as -80°C (solid carbon dioxide).

8.9.3 The temperature range 0-4°C is normally achieved by using water, frozen in a convenient form, within an insulated packaging. The packaging for the water can range from plastic screw sealed packagings, to the freezer packs sold for picnic boxes, to commercially available water filled plastic foams within heat sealed plastic bags. The latter usually consist of either an open cell thermoset foam such as a phenolic foam, or an open cell polyurethane foam. The latter water filled plastic foams are convenient for designing packages as their uniform shape lend themselves to efficiently fitting the square section cavities available within commercially available EPS icepacks. It is usually a relatively easy operation to fit the appropriate number of these packs within an EPS icepack and then hold the product to be shipped centrally within the cavity using a convenient gap filling material, eg EPS, polyethylene foam, bubblewrap etc.

8.9.4 A temperature of -80°C is around the sublimation temperature of solid carbon dioxide and this provides a readily available material to achieve the low temperatures necessary for the shipment of chemically unstable radioactive products. A commonly used design consists of an EPS icepack, referred to previously, within a corrugated case. The cavity of the icepack would then be filled after placing the product within the cavity. A typical icepack for small radioactive products lasting approximately 96 hours would incorporate a cuboidal cavity for the product and solid carbon dioxide of dimensions 210 mm × 210 mm × 210 mm with an EPS wall thickness of approximately 70 mm.

8.9.5 Whilst it is difficult to anticipate the shape, size or weight of a product that may need to be shipped, the following list of packages may assist in identifying a suitable solution.

a) Aluminium chests or cases, steel drums etc with suitable fittings/absorbers inside to locate the product provide a convenient and relatively inexpensive packaging method for solids and liquids.

b) ABS pipes with suitable end caps (available as high pressure water pipe), with suitable outer packaging, eg EPS and a corrugated case, can be used for small, long, fragile primary packagings. Alternatively for large, long items such as static eliminator rods, then the larger diameter high pressure water pressure piping can be used which is capable of withstanding the penetration bar without further outer packaging.

c) ABS or other impact resistant polymers and laminates, in the form of cases or other boxes with fixings, can provide a suitable protection for the contents.

d) For many applications a simple corrugated case (or corrugated plastic, eg Corex) with foam polyethylene fittings will provide sufficient protection to pass the requirements of the regulations. The advantage of such materials is that the small numbers can readily be produced at a low cost (no tooling charges) by companies who specialise in this type of product.

8.10 TESTING TYPE A PACKAGING

8.10.1 Water Spray Test

Water Spray Test [721] The water spray test may conveniently be carried out using mains pressure water through a hose nozzle. By regulating the spray and placing a measuring cylinder in the test area the correct flow rate can be achieved. It may be advisable to record the amount of water sprayed onto the specimen photographically. If a video camera is used, then the time and date feature can be used to demonstrate the duration of the test if the start and finish of the test is recorded. The water spray test should be carried out in an area where the water can drain freely; the regulations do not require the package to sit in accumulated water.

8.10.2 Free Drop Test

Free Drop Test [722] The regulations require that packages are tested in their most vulnerable orientation ([722], [724] and [725]) in respect of their containment systems and safety features. For many package designs this may be difficult to identify, in which case the package should be tested in each major orientation dependent on the design of the package. In this way the assessor can be confident that the most vulnerable orientation must have been encountered during testing. If this method of assessment is used then one specimen may be used for each orientation tested. In these circumstances it is considered acceptable to record the moment of impact using high speed photography or video to demonstrate the impact orientation.

8.10.3 Stacking Test

Stacking Test [723] This is readily achieved by placing a stout board over the top surface of the package and loading with appropriate weights, or a packaging filled with water. Care should be taken to ensure that, if the stack should collapse, it would do so in a safe manner, bearing in mind that many materials will creep with time when under load and not necessarily show immediate signs of failure.

8.10.4 Penetration Test

Penetration Test [724] As with drop testing, for many designs it is easier to test all the major orientations rather than make an assessment of the most vulnerable. In practice, assuming the inner packaging is centrally positioned, for most cuboid packages this will entail aiming the penetration bar at the centre panel of each face. Otherwise the bar should be aimed at the inner packaging or packagings when testing each face of the package. For packages such as drums, cases etc., where there may be a clamping band or clasp, then at least one of the tests should include aiming the penetration bar at this feature with the aim of destroying its effectiveness, or at any other vulnerable features such as bolts, flanges, drain valves etc.

APPENDIX A, SECTION 8 - TYPE A AND EXCEPTED PACKAGING REQUIREMENTS OF THE IAEA 1996 REGULATIONS

A brief summary of the packaging design requirements of the regulations are outlined below. There are many ways that each of these can be satisfied by a particular design, however, here we have attempted to indicate the more common packaging designs that meet these requirements.

Sections Pertinent to Excepted Packaging Design

[516] **Surface radiation level less than 5 μSv/h**

The activity limits for an excepted package are defined in Table III, however, in addition all excepted packages shall have a radiation level at any point on the external surface not exceeding 5 μSv/h [516].

Many commonly shipped nuclides at low activities will satisfy this requirement with minimal shielding such as ^{14}C, ^{3}H, ^{35}S etc. However, optimum use of shielding to reduce the radiation and distance between the source and package surface to reduce the dose rate may bring it down to the excepted limits.

One significant advantage of designing an excepted package rather than a Type A package is that the performance requirements are significantly less. There are no drop tests or penetration tests defined within the regulations for excepted packages so the degree of protection needed for the inner primary packaging is reduced, particularly in the case of liquids or gases. For liquids there is also no requirement to include an absorber or provide secondary containment (see [648] below). There is also no requirement to label the outside of the package but the ADR regulations require the package to be marked with the appropriate number, see Table VIII.

[517] **Radioactive material forming part of an instrument or other manufactured article**

If the radioactive material forms part of an instrument or other manufactured item then in order to satisfy the conditions of an excepted package there must, in addition, be not greater than 0.1 mSv/h radiation level at any point 10 cm from the surface of that instrument. The instrument or article must bear the marking `radioactive'.

[518(a)] **Retention of package contents**

The regulations require that the package retains its contents under routine transport. To demonstrate compliance with this then tests may be performed such as drop tests and transit tests representing normal conditions likely to be encountered in practice, in order to show the package remains intact and the contents retained within the package. The ability of the package to continue its journey after such testing is normally considered a reasonable acceptance criterion for judging the acceptability of the design.

Corrugated cases with minimal cushioning around internal primary packagings is normally adequate to meet this requirement, however, for large glass packagings significant cushioning may be necessary.

[518(b)] **'Radioactive' marking within the package**

The requirement is for the marking `Radioactive' to be present on an internal surface in such a manner as to be visible on opening the package.

The positioning of this mark could be on the underside of the flaps on a corrugated case or on the surface of the intermediate packaging revealed when the outer packaging is opened. Printing of the packaging surface is considered acceptable.

[519] **Sheathed Uranium or Thorium**

A manufactured article where the only radioactive material is Uranium or Thorium must have the outer surface of these materials sheathed either in an inactive metal or other substantial material. Such substantial materials may be considered to be ones that will retain the potentially dispersible oxidation products of Uranium and Thorium and will continue to do so after a degree of mechanical abuse. Suitable materials could well be epoxy resins and other encapsulating plastic resins or engineering thermoplastics such as nylon that are designed to completely encapsulate the item.

Sections Pertinent to Type A Designs

[536] **Package weight marking**

If the gross package weight exceeds 50 kg then the maximum permissible gross weight must be legibly and durably marked on the outside of the packaging. For corrugated cases then the weight should be printed on the case surface rather than labelled. For steel packagings then either a durable label should be fixed, eg riveted, on the surface or the steel surface printed and protected, ideally avoiding common contact areas of the packaging.

[537(b)] **Type A marking**

All packages needing to comply with the regulations shall be marked `Type A' on the outside surface. The same comments apply as per Package Weight Markings above.

[606] **Package handling and tie-down facilities**

This is a general requirement that the package shall be designed so that it can be easily and safely handled and transported. It should also be capable of being properly secured during transport.

For corrugated case type packaging then the design should be such that it can be picked up and handled readily. The Manual Handling Operating Regulations 1992 Guidance Notes provide some information on the size and weight of packages that can be safely handled under different conditions. Whilst these do give some guidance their main theme for safe handling is to hold the package close to the body to minimise the strain due to the load. With radioactive packages this is not advised and the package should be designed, where possible, to be as far away from the body as practical. For large packages where there is significant radiation dose on the surface then every attempt should be made to ensure that handlers do not hold the package close to their bodies. Appropriate warnings should be displayed together with handling advice if possible. The provision of handles to allow two people to carry the package should also be considered.

Corrugated cases can be readily secured during transport using nets, cages or other such devices. For steel packagings, eg drums, chests etc, then an appropriate handle design can allow them to be also used for tie down.

[607] **Strength of lifting points**

Applicable mainly to heavier packaging designs, however, such features as hand holds in corrugated cases should be carefully considered before including in designs as they could significantly affect the ability of the package to meet the other requirements of the regulations if they failed in practice.

[608] **Strength of other external features**

Again more applicable to heavier packaging designs covered by other sections.

[609] **Ease of decontamination and surface protruding features**

Packages should have smooth external features such that they can readily be decontaminated. Corrugated cases and drums fit into this category. The handles on drums can be considered to be protruding features, however, their presence is necessary in order to comply with the handling requirements of the regulations. In their design, however, consideration should be given to their ease of decontamination.

[610] **Retention of water**

Packages should be designed to shed water. Taped corrugated cases have been demonstrated to not do so. Drums, cans and similar packagings may well retain some water in the area of the lid, however, they should be designed so that the water cannot enter the packaging. Such retained water will readily evaporate given the right conditions.

[611] **Added features**

Any features added to the package at the time of transport and not part of the package shall not reduce its safety. This is not usually applicable to lightweight packaging, however, if for example a secondary package is attached to the approved package, its mass will increase and the combination may not then pass the performance tests.

[612] **Vibration effects**

The package shall be designed to withstand the vibration, acceleration etc effects occurring during normal transport without affecting the closing devices or integrity of the package.

Packages may be tested using, for instance, a transit test which simulates the likely worst case scenario that the package will encounter in practice. If a route is chosen that involves many van changes then the severe conditions often experienced during handling can be reproduced.

The higher frequency vibrations often involved with air transport may be simulated using vibration test equipment available at many commercial test laboratories. An alternative is simply to ship out test packages on air routes which simulate the conditions the design is likely to be subjected to, repeating such shipments; possibly on the same package, until confidence is achieved in its performance.

Taped corrugated cases constructed of fibreboard of suitable grammage and thickness can withstand quite severe transit conditions as long as the board quality is appropriate for the mass of the contents.

Drums and cans etc are usually robust enough to withstand such effects. Inner primary packagings should be protected from vibration and the sealing system in particular protected to ensure there is no reduction in the effectiveness of the seal.

[613] **Compatibility of packaging/contents**

The materials of the packaging shall be compatible with the radioactive contents. This mainly concerns the primary containment system for the amounts of activity in Type A packages. The materials of the packaging and closure seal should be carefully selected to ensure they are compatible both in terms of the radioactive product not attacking or dissolving the containment materials, and also that these materials should not absorb the radioactive product. For many products and packaging materials the permeability of the materials may need to be considered.

The outer packaging materials should also be chosen to be compatible with the product in that should the product escape the containment system, there should be no chemical reaction between the two that could generate heat or gas etc or other potentially harmful product. Outer packaging materials (eg expanded polystyrene) that are simply dissolved by the product would be considered acceptable as the dissolved material would be no more harmful than the escaping product (and may well be less so).

[614] **Security seal on valves**

Any valves, such as gas valves, used to contain the product must be protected against unauthorised operation. This will usually entail providing a security seal to ensure the valve cannot be opened without destroying the seal.

[616] **Other dangerous properties of the contents**

If the radioactive material has other dangerous properties then these should be taken into account within the design. For instance, the material may react with atmospheric moisture and generate a flammable gas etc.

If another hazard exists that can be identified as such for the mode of transport being used then the packaging design must meet any additional requirements defined by the regulations controlling this.

It should be remembered that radioactivity is the primary hazard for Type A packages. For excepted package designs hazards other than radioactivity may take precedence, in which case `UN approved' packaging may be required.

[617] **Surface temperature**

For packages to be transported by air, the temperature of the surface of the package shall not exceed 50°C at an ambient temperature of 38°C with no account taken for insolation (solar heating). For Type A packs there will be no significant internal heating effects for activities up to the A_1 value of the nuclide.

[618] **Effect of -40°C to +55°C**

See [637] below.

[619] **Leakage with a differential pressure of 95 kPa (0.95 kg/cm^2)**

For packages containing liquid radioactive materials being shipped by air then the containment system shall withstand a pressure differential of 95 kPa (95% of a full vacuum) without leakage. Crimped or screw capped glass and plastic packagings can provide this level of seal.

[634] **Minimum external dimensions**

All packages must have a minimum external dimension of not less than 100 mm. However, in order to be able to apply the radioactive category label then the height and width will need to be approximately 150 mm to accept it in the correct orientation.

[635] **External security seal**

The package shall incorporate a seal which will provide evidence that the package has not been opened. Polypropylene tape on the outside of corrugated cases is considered acceptable, alternatively other tamper evident features can be used such as security seals, frangible tapes etc.

[636] **Strength of tie-down attachments**

Not appropriate for the lightweight package designs. If a tie-down facility is incorporated then its strength must be assessed.

[637] **Effect of -40°C to +70°C**

All the packaging components shall be selected such that they withstand this temperature range. Most of the common materials used such as fibreboard cases, tinplate cans, expanded polystyrene cushioning, lead pots etc will withstand this temperature range.

[638] **QA of design and manufacture**

A quality system should be in place that controls the design and manufacture of the packaging, and this system should be acceptable to the Competent Authority.

[639] **Containment system**

There shall be a containment system securely closed by a positive fastening device which cannot be opened unintentionally. Containment systems such as crimped vials, flame sealed ampoules, screw cap vials, heat-sealed membranes, sealed sources, special form capsules and lead pots or other vessels incorporating seals and positive closing devices will be suitable.

[641] **Independence of containment system**

If the containment system forms a separate unit of the package it shall be securely closed and independent of any other feature of the packaging. For instance, the process of removal of the lead shielding around a product should not result in the seal on the primary packaging being removed within the same process. The primary packaging seal should be removable as a totally separate operation to the radiation shielding being removed.

[642] **Effect of radiolytic decomposition etc**

The design of the containment system should take into account radiolytic decomposition of liquids and the generation of gases by chemical reaction and radiolysis. This is not usually significant for solutions containing up to the A_2 value of the nuclide.

[643] **Containment with ambient reduction to 60 kPa**

The containment system shall retain its contents if the outside pressure is reduced to 60 kPa. See [619] and containment.

[644] **Enclosure for any valve leakage**

If a valve is incorporated in the design (other than a pressure relief valve) then it shall be provided with an enclosure, sealed cap, blanking piece etc to retain any leakage.

[645] **Closure of radiation shield**

The radiation shield enclosing the containment system shall be designed to prevent the unintentional release of that containment system. Lead pots held together by tape, screw threads or bolted together will satisfy this requirement. There is a further requirement that the closing of the radiation shield shall be independent of any other packaging structure. For example, opening the outer packaging on a corrugated case should not release the two halves of a lead pot within that package, the lead pot should independently be held together with adhesive tape or other closing device.

[646] **Test performance**

After the tests described in [719-724] the package design should demonstrate it is able to prevent:

a) loss or dispersal of the radioactive contents and

b) loss of shielding integrity which would result in more than 20% increase in the radiation level at any external surface of the package.

There is no requirement within the regulations for all the tests to be performed on the same package. The regulations do require that the package is tested in its most vulnerable orientation. For many designs this is difficult to assess with any accuracy or conviction, hence it is often easier to test packages in all major orientations in each of the tests in order to ensure that the most vulnerable orientation was achieved. Again, a new package may be used for each test in each orientation if required.

[647] **Ullage**

For liquid products then sufficient ullage should be provided to allow for such effects as temperature etc. For most packagings, including glass, containing aqueous solutions the 10% ullage should be adequate to compensate for the liquid freezing.

[648] **Liquid Products**

For liquid products there needs to be sufficient absorbent material provided to absorb twice the volume of the liquid content and positioned such that it will contact the liquid on leakage <u>or</u> it should have a secondary containment system outside the primary containment system designed to retain the liquid contents even if the primary packaging leaks. See Section 8.5 "Absorbers" for more details on absorbent material and secondary containment.

Liquids will need to pass the test requirements of paragraph [725] (9 m drop, 1.7 m penetration test).

[649] **Compressed/uncompressed gases**

Packages for compressed or uncompressed gases will need to pass the test requirement of paragraph [725] (9 m drop, 1.7 m penetration). A Type A package designed for tritium gas or noble gases shall be excepted from this requirement.

APPENDIX B, SECTION 8 - SHIELDING DATA

A very common form of Type A packaging is cylindrical, and uses lead for shielding. The information provided in this Appendix allows quick shielding related calculations to be made for a package of this generic form.

The tables at the back of this Appendix are based on a reference design of a package with an external radius of 254 mm and lead shielding in a range of thicknesses up to 203 mm. The tables list the activities that will give a surface dose rate of 1.6 mSv/h for a wide range of nuclides. This base data can be manipulated to accommodate different situations as follows:

- Activity for shielding thicknesses other than those given can be found by interpolation.
- The activity to give the reference surface dose rate for a package radius other than 254 mm can be found using the Multiplication Factor, see below.
- Surface dose rate is directly proportional to activity, and can be found by simple proportion.

The Multiplication Factor (MF) applies the inverse square law to the reference radius of 254 mm and the true package radius:

$$MF = \frac{Packaging\ radius^2}{254^2}$$

The Transport Index (TI) is also found using the inverse square law:

$$TI = Surface\ dose\ rate\ (mSv/h)\ x\ \frac{Packaging\ radius\ (mm)^2}{(Packaging\ radius + 1000)^2}\ x100$$

MF and TI for the activity content of packages with radius 50 mm to 350 mm are given in Table 1 below:

Table 1

Package radius mm	MF	TI* (surface dose rate 1.6 mSv/h)
50	0.0387	0.36
75	0.0872	0.78
100	0.155	1.32
125	0.242	1.96
150	0.349	2.72
175	0.475	3.55
200	0.620	4.58
225	0.785	5.40
254	1.000	6.56
275	1.08	7.44
300	1.40	8.52
325	1.64	9.63
350	1.90	(10.75)

*** Note**: The declared TI is rounded up to first decimal place.

Example 1 What is the surface dose and TI of a 150 mm radius package containing 200 MBq ^{60}Co in a lead pot with wall thickness 25.4 mm ?

From the table for ^{60}Co, the wall thickness of 25.4 mm gives the following figures:

Radius – mm	Activity - GBq	Shielding - mm	Surface dose rate mSv/h	TI
254	0.89	25.4	1.6	?

Use the MF corresponding to a packaging radius of 150 mm to find the activity that will give a surface dose rate of 1.6 mSv/h for that packaging radius:

$= 0.89 \times 0.349 \quad = 0.311$ GBq

Radius – mm	Activity - GBq	Shielding - mm	Surface dose rate mSv/h	TI
150	0.311	25.4	1.6	?

The surface dose rate is proportional to activity. Therefore for contents of 200 MBq the surface dose rate is:

$= \frac{200}{311} \times 1600 \quad = 1.029$ mSv/h

Radius – mm	Activity - GBq	Shielding - mm	Surface dose rate mSv/h	TI
150	0.2	25.4	1.03	?

Hence:

$$TI = 1.029x\frac{150^2}{(1000+150)^2}x100 = 1.75$$

Radius – mm	Activity - GBq	Shielding - mm	Surface dose rate mSv/h	TI
150	0.2	25.4	1.03	1.8

Example 2 **A packaging has lead shielding 50.8 mm thick and an external radius of 100 mm. What is the largest ^{137}Cs source that can be carried without the surface dose rate exceeding 1 mSv/h ?**

From the table for ^{137}Cs, the wall thickness of 50.8 mm gives the following figures:

Radius - mm	Activity - GBq	Shielding - mm	Surface dose rate mSv/h
254	0.211	50.8	1.6

Correct the packaging radius using the MF:

$$= 0.211 \times 0.155 = 0.033 \text{ GBq}$$

Radius - mm	Activity - GBq	Shielding - mm	Surface dose rate mSv/h
100	0.033	50.8	1.6

The required surface dose rate is 1 mSv/h, hence the maximum activity is:

$$= 0.033 \times \frac{1.0}{1.6} = 0.02 \text{ GBq}$$

Radius - mm	Activity - GBq	Shielding - mm	Surface dose rate mSv/h
100	0.02	50.8	1.0

Example 3: The dose rate 300 mm from an unshielded ^{60}Co source is 10 mSv/h. A packaging of radius 150 mm and lead shielding thickness 50.8 mm is available. What will the surface dose rate be when the packaging is loaded?

From the table for ^{60}Co, the wall thickness of 50.8 mm gives the following figures:

Radius - mm	Activity - GBq	Shielding - mm	Surface dose rate mSv/h
254	3.33	50.8	1.6

Use the MF corresponding to a packaging radius of 150 mm to find the activity that will give a surface dose rate of 1.6 mSv/h for that packaging radius:

$= 0.349 \times 3.33 \quad = 1.16$ GBq

Radius - mm	Activity - GBq	Shielding - mm	Surface dose rate mSv/h
125	1.16	50.8	1.6

From the ^{60}Co table, for shielding of zero thickness:

Radius - mm	Activity - GBq	Shielding - mm	Surface dose rate mSv/h
254	0.28	0	1.6

Use the MF to correct the activity to the packaging radius:

$= 0.349 \times 0.28 = 0.098$ GBq

Radius - mm	Activity - GBq	Shielding - mm	Surface dose rate mSv/h
150	0.098	0	1.6

Calculate the source activity by first finding the dose rate from the unshielded source at the packaging radius of 150 mm:

$$= 10 \times \frac{300^2}{150^2} = 40 \text{ mSv/h}$$

Now find the true source activity:

$$= 0.098 \times \frac{40}{1.6} = 2.44 \text{ GBq}$$

Now find the package surface using the ratio of the true source activity to the activity that gives 1.6 mSv/h:

$$= \frac{2.44}{1.16} \times 1.6 = 3.37 \text{ mSv}$$

Radius - mm	Activity - GBq	Shielding - mm	Surface dose rate mSv/h
150	2.44	50.8	3.37

That is, the packaging is not adequate.

Table 2 Limiting activities to give a surface dose rate of 1.6 μSv/h

	Ac-227	Ag-105	Ag-110m	Ag-111	Am-241
mm Lead	**GBq**	**GBq**	**GBq**	**GBq**	**GBq**
0	2.04	1.55	0.25	26.6	27.0
3.2	4.07	3.11	0.31	70.3	592,000
6.4	6.66	5.18	0.37	170	
12.7	13.0	11.8	0.59	1,070	
25.4	37.0	37.0	1.33	48,100	
50.8	300	229	6.66		
101.6	22,200	6,290	126		
203.2			33,300		

	Ar-41	As-71	As-72	As-73	As-74
mm Lead	**GBq**	**GBq**	**GBq**	**GBq**	**GBq**
0	0.56	1.22	0.41	104	0.89
3.2	0.63	2.39	0.59	59,200	1.30
6.4	0.74	3.52	0.78		1.85
12.7	0.96	7.40	1.44		4.07
25.4	1.70	28.5	4.44		18.5
50.8	6.29	200	32.9		370
101.6	99.9	5,180	77.7		27,700
203.2	33,300		88,800		

	As-76	Au-195	Au-198	Au-199	Ba-133
mm Lead	**GBq**	**GBq**	**GBq**	**GBq**	**GBq**
0	1.63	11.8	1.70	8.14	1.33
3.2	2.18	592,000	3.11	555	4.81
6.4	2.89		5.55	12,600	11.5
12.7	4.81		20.0		62.9
25.4	12.9		207		1,924
50.8	59.2		3,370		592,000
101.6	888		111,000		
203.2	148,000				

	Ba-140	Be-7	Bi-206	Bi-207	Br-82
mm Lead	**GBq**	**GBq**	**GBq**	**GBq**	**GBq**
0	0.29	13.7	0.25	0.44	0.26
3.2	0.36	21.8	0.32	0.59	0.33
6.4	0.44	35.2	0.41	0.74	0.41
12.7	0.59	96.2	0.59	1.11	0.63
25.4	1.07	777	1.33	2.48	1.48
50.8	3.52	62,900	6.29	11.1	7.03
101.6	40.7		92.5	211	137
203.2	6,290		15,200	48,100	40,700

mm Lead	Ca-47 GBq	Cd-109 GBq	Cd-115 GBq	Cd-115m GBq	Ce-139 GBq
0	0.67	270	3.15	23.3	3.18
3.2	0.78	592,000	4.81	27.8	851
6.4	0.89		7.40	32.6	148,000
12.7	1.18		17.7	44.4	
25.4	2.15		111	92.5	
50.8	7.77		4810	407	
101.6	126		592,000	8,880	
203.2	44,400				

mm Lead	Ce-141 GBq	Ce-144 GBq	Co-56 GBq	Co-57 GBq	Co-58 GBq
0	8.51	15.9	0.21	6.29	0.70
3.2	14,400	28.5	0.25	629	0.89
6.4	592,000	33.3	0.30	851	1.15
12.7		44.4	0.41	1,480	1.89
25.4		85.1	0.74	4,810	5.18
50.8		259	2.48	62,900	40.7
101.6		2,330	25.5		2,480
203.2		215,000	2,220		

mm Lead	Co-60 GBq	Cr-51 GBq	Cs-131 GBq	Cs-132 GBq	Cs-134 GBq
0	0.28	21.8	7.03	1.00	0.44
3.2	0.33	59.2	592,000	1.29	0.59
6.4	0.37	166.5		1.74	0.74
12.7	0.48	1,400		3.11	1.30
25.4	0.89	111,000		10.7	3.70
50.8	3.33			133	31.8
101.6	55.5			8,800	1,260
203.2	20,000				555,000

mm Lead	Cs-137 GBq	Cu-64 GBq	Cu-67 GBq	Eu-152 GBq	Fe-59 GBq
0	1.18	3.48	6.66	0.70	0.59
3.2	1.59	5.18	214	0.89	0.70
6.4	2.15	7.77	1,510	1.07	0.78
12.7	3.70	18.1	10,300	1.55	1.07
25.4	14.1	92.5		3.03	2.00
50.8	211	851		12.6	7.77
101.6	59,200	14,800		225	148
203.2				74,000	74,000

mm Lead	Ga-66 GBq	Ga-67 GBq	Ga-72 GBq	Hf-175 GBq	Hf-181 GBq
0	0.34	4.81	0.31	1.89	1.41
3.2	0.40	24.4	0.36	5.18	2.59
6.4	0.52	62.9	0.41	12.6	4.44
12.7	0.70	277	0.60	77.7	11.8
25.4	1.30	1,590	1.07	3,260	96.2
50.8	3.70	13,300	3.48	592,000	7,400
101.6	30.3		32.2		
203.2	2,030		2,660		

mm Lead	Hg-197 GBq	Hg-197m GBq	Hg-203 GBq	Ho-166 GBq	I-123 GBq
0	12.9	8.88	2.96	24.4	2.63
3.2	5,180	200	12.2	44.4	96.2
6.4	51,800	851	51.8	51.8	159
12.7		17,000	1,030	66.6	370
25.4			481,000	111	2,400
50.8				370	107,300
101.6				4,810	
203.2					

mm Lead	I-125 GBq	I-126 GBq	I-129 GBq	I-131 GBq	I-132 GBq
0	2.52	1.52	7.03	1.81	0.33
3.2	592,000	2.63	592,000	3.62	0.40
6.4		3.70		7.03	0.55
12.7		7.40		21.8	0.89
25.4		27.0		126	2.33
50.8		303		2,030	14.8
101.6		15,900		481,000	307
203.2					62,900

mm Lead	In-111 GBq	In-113m GBq	In-114m GBq	In-115m GBq	Ir-192 GBq
0	1.22	2.26	4.44	4.44	0.85
3.2	20.0	5.18	17.8	11.1	1.81
6.4	155	10.4	24.8	27.8	3.44
12.7	9,620	44.4	44.4	185	10.4
25.4		851	144	9.600	62.9
50.8		370,000	1,400		1,550
101.6			55,500		233,000
203.2					

	K-40	K-42	K-43	Kr-85	La-140
mm Lead	**GBq**	**GBq**	**GBq**	**GBq**	**GBq**
0	4.81	2.70	0.70	307	0.32
3.2	5.55	3.03	1.11	480	0.37
6.4	6.29	3.40	1.70	703	0.44
12.7	7.77	4.44	3.70	1,700	0.59
25.4	13.7	7.40	15.5	11,100	1.07
50.8	44.4	23.3	226		3.51
101.6	592	285	16,300		40.7
203.2		55,500			6,290

	Lu-177	Mg-28	Mn-52	Mn-54	Mn-56
mm Lead	**GBq**	**GBq**	**GBq**	**GBq**	**GBq**
0	23.7	0.23	0.21	0.81	0.41
3.2	444	0.27	0.25	1.00	0.48
6.4	4,070	0.31	0.30	1.26	0.59
12.7	62,900	0.41	0.44	1.92	0.78
25.4		0.70	0.85	4.81	1.48
50.8		2.15	3.52	37.0	5.18
101.6		24.4	55.5	2,740	51.8
203.2		3,630	14,800		5,550

	Mo-99	Na-22	Na-24	Nb-95	Nb-97
mm Lead	**GBq**	**GBq**	**GBq**	**GBq**	**GBq**
0	2.52	0.32	0.21	0.89	1.04
3.2	5.92	0.41	0.23	1.11	1.37
6.4	7.77	0.52	0.26	1.41	1.81
12.7	12.9	0.78	0.32	2.29	3.29
25.4	37.0	1.63	0.52	6.29	11.5
50.8	355	6.29	1.41	59.2	152
101.6	40,700	104	11.8	6,290	12,200
203.2		37,000	888		

	Nd-147	Np-237	Os-185	Os-191	P-32
mm Lead	**GBq**	**GBq**	**GBq**	**GBq**	**GBq**
0	5.92	20.7	0.96	12.9	40.7
3.2	11.5	6,660	1.33	481,000	155
6.4	17.4	133,000	1.78		266
12.7	40.7		3.14		592
25.4	229		10.4		2,070
50.8	7030		118		18,800
101.6			11,100		
203.2					

	Pa-233	Pb-201	Pb-203	Pb-210	Pd-103
mm Lead	**GBq**	**GBq**	**GBq**	**GBq**	**GBq**
0	4.07	1.04	2.74	240	1,810
3.2	11.1	1.63	9.62	592,000	4,810
6.4	31.1	2.37	31.1		
12.7	226	4.07	170		
25.4	7,770	7.02	1,040		
50.8		48.1	15,500		
101.6		1,260			
203.2					

	Pm-147	Pm-149	Pm-151	Pr-142	Pt-195m
mm Lead	**GBq**	**GBq**	**GBq**	**GBq**	**GBq**
0	888	66.6	5.92	12.9	10.7
3.2	592,000	174	21.1	14.4	28,100
6.4		344	55.5	16.3	
12.7		740	363	20.3	
25.4		2,220	17,000	34.0	
50.8		18,100		107	
101.6				1,260	
203.2					

	Pt-197	Ra-226	Rb-86	Re-186	Re-188
mm Lead	**GBq**	**GBq**	**GBq**	**GBq**	**GBq**
0	36.6	0.41	7.40	55.5	12.9
3.2	1,550	0.52	8.51	1,810	30.3
6.4	15,900	0.67	10.0	2,400	40.7
12.7		0.92	13.7	4,070	70.3
25.4		1.78	27.4	13,700	207
50.8		5.92	126		1,660
101.6		66.6	3,260		92,500
203.2		8,510			

	Rh-105	Ru-97	Ru-103	Ru-106	Sb-122
mm Lead	**GBq**	**GBq**	**GBq**	**GBq**	**GBq**
0	8.88	3.14	1.41	3.44	1.55
3.2	24.8	22.9	2.07	4.81	2.18
6.4	70.3	81.4	3.37	6.66	3.11
12.7	629	370	8.51	13.3	6.29
25.4	48,100	2,740	55.5	48.1	26.6
50.8		81,400	2,520	366	322
101.6				9,250	9,620
203.2					

mm Lead	Sb-124 GBq	Sb-125 GBq	Sc-46 GBq	Sc-47 GBq	Se-75 GBq
0	0.41	1.26	0.35	6.66	1.92
3.2	0.48	2.55	0.41	1,850	9.25
6.4	0.55	3.70	0.48	592,000	30.0
12.7	0.81	8.51	0.70		189
25.4	1.59	40.7	1.44		3,700
50.8	5.18	888	7.03		592,000
101.6	55.5	407,000	189		
203.2	8,140		144,000		

mm Lead	Sm-153 GBq	Sn-113 GBq	Sn-119m GBq	Sr-85 GBq	Sr-87m GBq
0	24.4	129	17.0	1.33	2.15
3.2	3,140	740	592,000	2.00	4.07
6.4	4,810	4,440		3.07	8.51
12.7	10,700	192,000		7.40	35.5
25.4				48.1	703
50.8				2,330	348,000
101.6				592,000	
203.2					

mm Lead	Sr-89 GBq	Sr-90 GBq	Ta-182 GBq	Tb-160 GBq	Tc-99m GBq
0	7,770	20.7	0.59	0.67	5.92
3.2	9,250	66.6	0.74	0.85	14,400
6.4	11,100	104	0.85	1.00	592,000
12.7	16,300	203	1.15	1.44	
25.4	37,000	592	2.11	3.00	
50.8		3,590	8.51	14.4	
101.6		85,100	166	351	
203.2			81,400	185,000	

mm Lead	Te-123m GBq	Te-125m GBq	Te-127m GBq	Te-132 GBq	Th-228 GBq
0	3.44	4.07	133	3.29	0.59
3.2	1,550	592,000	274	34.8	0.74
6.4	518,000		518	370	0.89
12.7			1,810	48,100	1.18
25.4			23,300		2.00
50.8					5.18
101.6					40.7
203.2					

mm Lead	Ti-44 GBq	Tl-200 GBq	Tl-201 GBq	Tl-202 GBq	Tl-204 GBq
0	0.31	0.44	8.88	1.63	814
3.2	0.40	0.59	4,440	2.85	592,000
6.4	0.55	0.78	592,000	4.81	
12.7	0.85	1.18		15.5	
25.4	1.89	2.48		166	
50.8	8.14	10.4		9,250	
101.6	170	181		592,000	
203.2	88,800	59,200			

mm Lead	Tm-170 GBq	V-48 GBq	W-181 GBq	W-187 GBq	Xe-133 GBq
0	133	0.24	18.9	1.48	8.51
3.2	148,000	0.29	592,000	2.15	31,800
6.4		0.35		2.96	592,000
12.7		0.48		5.55	
25.4		1.00		20.7	
50.8		4.07		281	
101.6		70.3		44,400	
203.2		19,600			

mm Lead	Xe-133m GBq	Y-87 GBq	Y-87m GBq	Y-88 GBq	Y-91 GBq
0	7.4	0.89	2.26	0.28	196
3.2	337	1.52	4.44	0.32	225
6.4	3,260	2.59	9.25	0.36	259
12.7	333,000	7.77	37.0	0.48	344
25.4		70.3	740	0.85	629
50.8		5,550	133,000	2.66	2,480
101.6				27.7	48,100
203.2				340	

mm Lead	Yb-169 GBq	Yb-175 GBq	Zn-65 GBq	Zr-95 GBq	Zr-97 GBq
0	2.26	19.6	1.22	0.92	0.81
3.2	44.4	48.1	1.41	1.18	1.04
6.4	181	104	1.63	1.48	1.29
12.7	1,960	444	2.26	2.48	2.11
25.4	240,000	8,880	4.44	7.4	5.55
50.8			19.2	74	40.7
101.6			444	8,880	1,073
203.2			314,000		248,000

9 MISCELLANEOUS ISSUES

9.1 PACKAGING SIZE, SHAPE AND SURFACE FINISH

Size and shape
The Regulations discuss size and shape in general terms, requiring it to be easily handled and transported [606] and, as far as practicable, being free from protruding features [609]. A packaging's size is largely dictated by the contents and the shielding (if any). In general, the total cost to build and operate a packaging is directly proportional to, among other things, its size. Consequently the designer's aim should be to minimise a packaging's overall dimensions. Similar practical and economic concerns should lead to a package that is easily lifted and secured to the conveyance, and that load and unload operations that are straightforward and as fast as reasonably practicable. In addition, decontamination should be as easy as possible by minimising surface irregularities and ensuring access to all surfaces.

The Regulations only specifically mention size in [634] which requires the minimum external dimension to be not less than 10 cm. This applies to all other than excepted packages.

The Regulations para [610] requires a package to be designed to shed water readily. It is usually self-evident whether a packaging design will shed water or not and often it comes down to details, such as the judicious drilling of drain holes or the addition of features such as seals to keep water out of bolt holes or lid seal gaps.

Surface finish
Surface finish is an issue where contamination is likely to occur. This requirement is expressed in general terms in [609], though this requirement can be extended to cover not only surface finish, but also the need to avoid inaccessible areas. Generally speaking, austenitic stainless steel is the most favoured material since it is largely corrosion-free and resists the adsorption of contaminants. (Aluminium alloys lack the latter property and are consequently difficult to decontaminate.) Cold-rolled stainless steel sheet has a good surface finish, and can be used without additional treatment. Where machined surfaces are involved the designer needs to trade off specifying a high surface finish to improve the ease of decontamination against the cost of producing that surface. Experience has shown that a finish of 1.6μm usually provides the optimum. In the case of rolled sheet and plate, the finish should be at least 2B.

If carbon steel is to be used, it is almost invariably given a suitable surface treatment (usually by being painted) to prevent the rusting that makes decontamination difficult. TCSC1080 provides detailed advice on a wide range of appropriate coatings.

9.2 MATERIALS

The choice of the material of construction is influenced by a number of factors, chiefly:

Strength.
This will be determined by the designer to suit the packaging under consideration. TCSC1042 Part 6 provides advice on calculating the loads and stresses arising during drop testing.

Ductility
It is not specifically required for a packaging material to be ductile (though this is advisable). Package drop-testing is most commonly carried out at ambient temperatures,

so to satisfy the IAEA regulations the properties need to be largely constant across the required operating temperature range. For IP-3, Type A and Type B(U) this means from -40°C to +70°C [637]. For Type B(M) packages restricted to surface transport in the UK the temperature range is -10°C to +26°C [665], and with the insolation values given in TS-R-1 Table XI halved. What is of key importance is that there must not be a significant change in properties, such as the change from ductile to brittle failure mode seen in some steels at low temperatures. It is frequently said that to be satisfactory a material should have a Charpy toughness of 27 J at -40°C. Whereas this property may be quite acceptable, in fact it is consistency across the temperature range that is important rather than an absolute value.

It is generally accepted that ferritic material will not fail in a brittle way at -40° if its thickness is less than 6 mm.

Plastics such as polyethylene and PVC usually remain ductile to temperatures well below -40°C, though it is prudent to confirm that this is so before specifying a particular material. It is at the upper bound that particular care needs to be taken since their strength generally falls away sharply at temperatures above 60-70°C

Corrosion resistance
This property was discussed above in the context of maintaining a decontaminable surface. It does of course impact on other packaging performance factors, such as strength and containment.

Austenitic stainless steel tends to corrode in specific areas, most notably in crevices or where contaminants can collect and become concentrated. Under particularly unfavourable conditions corrosion can be very rapid, though this more usually seen in process plant rather than transport packagings. This is a complex and sometimes unpredictable process, but corrosion resistance is improved by:

- Using the more expensive 316 grade in place of 304.
- Ensuring that contamination with carbon steel is prevented. This is frequently a result of using contaminated grinders and other tooling during manufacture.
- Treating it with one of the commercial pickling and passivating processes
- Using good design to minimise concealed areas where crevice corrosion can initiate
- Being aware that the heat-affected zone around a weld is particularly vulnerable
- Trying to design-out areas where chloride-contamination can accumulate, especially around areas where there are residual stresses, e.g. welded or formed parts

Although carbon steel also corrodes preferentially in stressed areas, it has a greater tendency to generalised corrosion across a whole surface. Corrosion resistance is most commonly achieved through painting.

Particular care needs to be taken where different metals are in contact, since one will always corrode. The material that suffers is dependant on the relative positions of the two within the electro-chemical series, see below. The more electro-positive material will corrode, and the more electro-positive it is, the faster the corrosion process. If two metals in contact have a difference of electrolytic potential greater than about 0.6 V there is a risk of serious electolytic corrosion. This may of course be used to good effect – a surface coating of zinc protects the steel substrate by sacrificial corrosion.

Magnesium	+ 2.40 V
Aluminium	+ 1.7 V
Zinc	+ 0.76 V

Chromium	+ 0.56 V
Iron	+ 0.44 V
Cadmium	+ 0.42 V
Nickel	+ 0.23 V
Lead	+ 0.12 V
Copper	- 0.34 V

Note: voltages are relative to hydrogen, which is arbitrarily taken as zero.

For materials to corrode there must be four conditions: another electrode, an electrically conducting path between the two, an electrolyte, and oxygen. The elimination of any one of these will prevent corrosion from taking place.

Resistance to radiation damage
The Regulations require the designer to take this into account [613]. Steels used in packaging construction are unlikely to be subjected to a sufficiently high dose for long enough to suffer significant radiation damage. The designer should, however, consider what damage could occur to non-metallic parts. O-rings may be susceptible and may need to be changed regularly. Generally elastomers can absorb doses of up to 10 kGy without losing their elastic properties, though at 100 kGy they are likely to be affected. The most resistant material is EPDM, and in particular the grade EPDM-30H (see BNFL specification NF 0115/1).

Non-metals incorporated into the structure are more difficult – a typical example might involve polyethylene used as a neutron moderator. In cases such as this changes in material properties over an extended period may occur (usually embrittlement) that could impair the packaging's resistance to impact damage. In severe cases there will be an increase in overall dimensions as the material swells. There is also the possibility of hydrogen evolution, and this may be significant if the material is within the containment boundary allowing an explosive mixture to build up.

Seizing of mating parts
Austenitic stainless steel is notoriously prone to galling and does not need particularly high loads to be initiated – on occasions a stainless bolt can seize in a hole tapped in a stainless flange when no more than finger-tight.

Seizing can be combated by using proprietary lubricant, such Neverseize. A more permanent strategy is to use dissimilar materials. For example, aluminium-bronze is good with austenitic stainless steel. In the case of bolts, there are a range of suitable alternatives to austenitic stainless steel, e.g. ASTM A320/320M-01 Gr L7. Bolts can also be nickel-plated: note however that there is a possibility of hydrogen embrittlement, and plating should not be used for strength grades above 8.8. Alternatively phosphor-bronze thread inserts can be used.

9.3 DESIGNING TO COMBAT HAZARDS ARISING FROM THE CONTENTS

The designer should be aware of hazards (other than radioactivity) arising from the contents and take due account of them. Typically such hazards may be that:

- the material is pyrophoric, that is it may spontaneously combust. This is usually countered by transporting the material in an inert environment – typically oil in the case of finely divided uranium. Alternatively, the package may be filled with an inert gas such as argon. In this case the designer must ensure that there is a means of introducing the gas (and sealing off the entry point with a testable seal) and monitoring to ensure that the required concentration is present.

- hydrogen is evolved, typically as a result of radiolysis of water that is present either deliberately or left behind following a wet loading process. The designer must ensure that the concentration never approaches the lower explosive limit of 4% hydrogen in air. This may be achieved, again, by pumping down the package and introducing an inert gas, or by venting at regular intervals. It must be noted that the later process is only permitted for Type B(M) packages [666]. Again, a test point must be made available so that the internal atmosphere can be tested prior to opening.
- a build-up of daughter products leads to an increase in radiation level. Clearly the only means of mitigating against this is through the use of shielding, so the designer must either base calculations on the maximum inventory (not the nominal inventory) or ensure that the activity in the package as a starting condition is limited so that under the worst case the external radiation is not excessive.
- the contents are chemically corrosive. The designer must provide suitable internal containment and/or absorbent material to cope with spillage. It is good practice to ensure that a prominent notice is fixed to the inner packaging as warning.
- ullage to cope with freezing liquid. Water increases its volume by 4% as it freezes, so the designer must take account of this if the package is to contain aqueous solutions.
- ullage to cope with gas evolution and limit pressurisation. The maximum normal operating pressure allowable inside a B(U) package is 700 kPa [661]. The designer must ensure that he has allowed for any gas production and factored in the increase in pressure that results from the contents and solar heating and (if applicable) a reduction in external pressure.

9.4 SECURITY AND PHYSICAL PROTECTION ISSUES

Type A and Type B packages must be designed such that an attempt to open it by an unauthorised person is evident [635]. Typically, such evidence is provided by using:

- locking wire and a crimp seal. The wire is often threaded through two or more of the bolt securing the containment – the bolt heads being specially drilled for this purpose.
- numbered PVC cable ties, a more convenient method than the wire and crimp seal.
- security tape on cardboard boxes. The tape should be suitably printed (e.g. with the name and logo of the consigning organisation) to prevent resealing with a commonly available tape.
- a padlock that prevents the containment from being broken.
- a locked cover over the containment.
- a locked bar to obstruct lid removal.
- being inherently tamper-proof. For example, the package containment may only be able to be opened using special tools or equipment.

9.5 TRANSPORT MODAL CONSIDERATIONS

HGV LIMITATIONS

The Road Vehicles (authorised weights) (amendment no.1) Regulations came into effect on 1 February 2001. This amendment allows 3-axle articulated tractors and three or more axle drawbar rigid vehicles fitted with Euro 2 (low-emission) engines to operate at 44,000 kg gross train weight. As with the 41 t legislation, the combination must consist of a drawing vehicle with three or more axles, and a trailer with three or more axles. When operating at this weight the drive axle weight must not exceed 10,500 kg. Road friendly suspension is required on the motor vehicle, unless the rear axle weights do not exceed 8,500 kg when operating at this weight. The trailer must have at least three axles and must be fitted with road friendly suspension. The distance between the coupling centre and the centre of the rearmost axle of a semi-trailer must be at least 8 m.

All goods vehicles registered on or after 1 October 1997 are required to be fitted with a Euro 2 engine.

For loads which are greater than 2.9 m in width or 18.3 m overall length the police in every area that the vehicle is passing through must receive two days prior notice. If the load exceeds 5 m in width the Department for Transport must be informed.

An abnormal indivisible load may be abnormal on account of its weight or size. It is likely that, in the case of radioactive material transport packages, only the latter will apply. Vehicles to transport these loads are classified into three groups according to the total laden weight. Within each group there is a series of weight limits based on axle spacing. The maximum weight within each group is: Category 1 – 46 t; Category 2 – 80 t; Category 3 – 150 t. The overall width of a vehicle or load must not exceed 6.1 m, and the overall length must not exceed 27.4 m.

9.6 RAIL WAGON AND RAIL LINE GAUGE/WEIGHT LIMITS

These gauges are mainly for freight wagons. They represent the maximum height and width to which vehicles can be constructed or loaded and can only be used for vehicles of a certain length - vehicles which are longer must be built and loaded to slightly narrower dimensions. In 1999, Railtrack devised a new nomenclature for the freight vehicle loading gauges used on Britain's national railways. The following summary is taken from the 1999 Network Management Statement. Heights and widths are in millimetres.

British Rail code	Railtrack code	UIC* height equivalent	Height above rail	Width
W6	W6		3320	2700
W6A (Freightliner 8')	W7		3448	2500
W6A (Freightliner 8' 6")	W8		3600	2500
SB1c	W9		3715	2600
n/a	W10	UIC "A"	3896	2500
n/a	W10w	UIC "A"	3896	2600
n/a	W11	UIC "B"	4130	2500
n/a	W11w	UIC "B"	4130	2600

* Union Internationale des Chemins de Fer.

More details can be found at Railtrack's web site www.freightcommercial.co.uk. This includes maps of the British railway network showing which routes are cleared to the different gauges. It also explains the varying combinations of loading gauge and low platform wagon which can be used to move tall packagings safely. It should be emphasised that this is a complex subject, and designers are advised to seek early advice if they feel that the size of a packaging may approach the limits of the rail gauge.

These remarks apply equally to the payload that can be carried. Typically, a 2-axle wagon will accept a payload of up to 28 t, and a 4-axle flat-bed wagon will take 66 t. These figures are for guidance only – limits to weight and speed are applied to certain parts of the track and consultation with Railtrack is recommended at an early stage in the design of a large packaging that is to travel by rail.

Air/sea transport
The state and airline variations for, in particular, air transport can be complex and the regulations governing them should be consulted directly.

International air transport regulations are “The Technical Instructions For The Safe Transport of Dangerous Goods By Air”, International Civil Aviation Organisation (ICAO). The working document is “International Air Transport Association Dangerous Goods Regulations” (IATA). These regulations are revised every year.

Transport by sea is governed by “International Maritime Dangerous Goods Code”, International Maritime Organisation.