14th International Symposium on the Packaging and Transportation of Radioactive Materials (PATRAM 2004), Berlin, Germany, September 20-24, 2004

Paper # 009

The Development of a Type B(U) Transport Container Design in Cast and Forged Stainless Steel for the Transport of Immobilised Intermediate Level Waste

Bill Sievwright - United Kingdom Nirex Ltd, Harwell, UK.
Paul Dixon - RWE NUKEM, Harwell, UK.
Chi-Fung Tso, Ove Arup and Partners, London, UK.

1. Background

United Kingdom Nirex Limited (Nirex) is responsible for providing the United Kingdom with safe, environmentally sound and publicly acceptable options for the long-term management of radioactive materials. This includes intermediate level (ILW) and some low level (LLW) wastes. As part of its role Nirex has defined standards and specifications for the conditioning and packaging of these wastes, and carries out assessments of packaging proposals to ensure compatibility with the requirements for future phases of waste management. In order to facilitate this process and to provide a basis for the production of waste package specifications, Nirex has developed the Phased Disposal Concept, and produced a suite of underpinning safety and performance assessments. It has also undertaken work to assess the compatibility of its waste packaging specifications with other waste management options. The Phased Disposal Concept continues to be developed and updated to incorporate issues arising from dialogue with stakeholders, including members of the public; future changes arising from Government policy, legislation and regulations; information from waste producers, and the results from on-going research and development.

One of the documents describing the Phased Disposal Concept is the Generic Transport System Design (GTSD) [1]. The GTSD outlines the range of waste packages to be transported and disposed of, and describes the design of the transport system needed to transport wastes from their sites of production or storage to a centralised phased disposal facility site. It also describes a range of re-usable transport containers which could be used to transport those waste packages, which require Type B standards [2] for transport, through the public domain. This paper describes the development to date of such a design of reusable transport container, known as the SWTC-285, the Standard Waste Transport Container (SWTC) with 285 mm of shielding.

2. The Waste Packages

The wastes to be transported to a facility in a SWTC will be ILW encapsulated in a cement grout. Because of the large volume of wastes involved a range of standard waste packages are defined to ensure the most efficient design and operation of the transport system. A limited range of different package types is required to best accommodate the many types of wastes and the needs of the plants producing the waste. These include the 500 litre drum Figure 1, the 3m^3 box (Figure 2) and the 3m^3 drum.

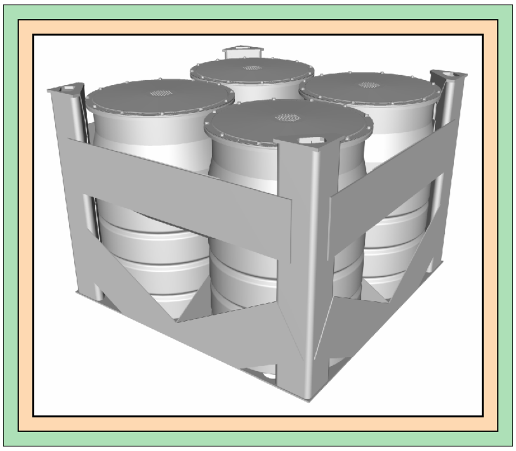


Figure 1: Four 500 Litre Drums in a Stillage

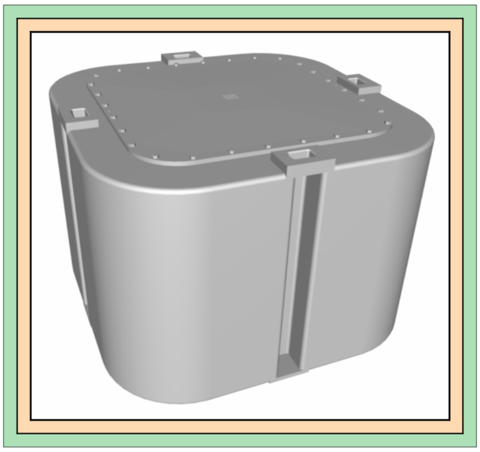


Figure 2: A 3m^3 Box

In order to transport these packages through the public domain a range of transport containers with different shielding thicknesses, known as the Standard Waste Transport Containers, have been defined. One such container, with 285mm of steel shielding, and designated as the SWTC-285, is currently being developed to meet the immediate needs of waste producers in the UK.

3. Transport Container Specification

A specification for the SWTC-285 was developed in consultation with UK waste producers. Key requirements of that specification were that the SWTC must:

- be capable of transporting four 500 litre drums of up to 2t in weight each, within a Nirex transport stillage or a BNFL compact stillage, or a $3m^3$ box of up to 12t in weight, or a $3m^3$ drum of up to 12t in weight;
- comply with the requirements of the IAEA Transport Regulations [2] as a Type B(U)F package for road, rail and sea transport;
- be transportable within the applicable UK rail gauges on a rail wagon with covers;
- provide containment such that the total leakage from the package will not exceed 1×10^{-3} bar cm^3/s SLR (Standardised Leak Rate), under normal conditions of transport, and 1×10^{-2} bar cm^3/s SLR under accident conditions of transport (to ensure compliance with IAEA Transport Regulations);
- be designed for minimum operating and maintenance cost, and ease of decontamination;
- have a gross weight not exceeding 65t to permit the transport on a four axle rail wagon.

4. Transport Container Concept Design

An initial SWTC design was developed to meet the design specification mentioned above. The maximum outside dimensions of the package were dictated by the need for the dynamic envelope of the rail wagon to fit within the rail gauges applicable to the UK rail network. When this was combined with the requirement to transport four 500 litre drums of waste, in a transport stillage, it meant that the maximum shielding which could be accommodated was 285mm. Such a thickness of steel has been found to provide adequate radiation shielding for the vast majority of UK ILW.

The space available for transport dictated that there was little room available for the inclusion of any large shock absorbing features on the outside of the package. Therefore, the design would have to be a robust one which could cope with high accelerations under impact, and one where the impact energy could be absorbed, and dissipated by the package itself. These stringent requirements dictated a design of monolithic construction with shock absorbing features concentrated around the most vulnerable area of the lid. It was judged that the most efficient way of doing this was to incorporate these features as part of the lid and body, thus the design became essentially a monolithic cuboidal box comprising a lid and body. At the conceptual stage the packaging body was to be made from forged austenitic (type 304) stainless steel to ensure compliance with the Type B(U) requirement not to exhibit brittle fracture at an operating temperature of -40°C. The key design data are listed in Table 1 below.

The main containment system is provided by the solid monolithic steel body, and the steel lid. The lid is fitted with two concentric elastomeric O-ring seals, seated within dovetail grooves to retain them during lid removal and replacement. The leak test point is situated on the lid, and is fitted with a quick-release self-seal coupling to facilitate remote operation. A vent/purge valve is provided in the lid close to one of the lid corners. This is required to allow equalisation of internal and ambient pressure before removal of the lid, and also to allow purging of the container cavity with nitrogen to prevent a flammable mixture forming in the package, during transport, should any of the wastes generate flammable gases. The valve is also provided with testable double O-rings for sealing purposes, and, for protection, is fitted with a very robust cover.

It was expected that the thermal capacity of the packaging structure alone would be sufficient to prevent the temperature of the O-ring seals from exceeding the acceptable material limit under fire accident conditions. However, experience with similar large monolithic packages has indicated that the thermal gradient across the package wall, and particularly across the lid, could result in the lid “dishing” with the possibility of subsequent seal face separation. To reduce this, it was proposed that the lid and all four vertical sides be protected with thermal insulation in the form of removable panels of resin-bonded cork, clad with type 304 stainless steel sheet. The panels were to be partially recessed into the body and lid, to resist sideways shear loads, and secured with a large number of bolts. On each vertical side of the packaging two bolted-on ribs absorb energy from flat-on-side impacts, and provide protection to the thermal insulation panels.

5. Material Selection

As discussed above, the container design concept was initially intended to be wholly of type 304 forged stainless steel construction, to be certain of satisfying the IAEA Type B(U) brittle fracture requirements at -40°C. However, forgings of the size required for a SWTC, in that material, are currently unavailable within the UK, and also, could be very expensive compared with other technically viable options. A study was therefore commissioned with Ove Arup and Partners [3] to determine which other materials could meet the technical requirements and to identify the most cost-effective material solution. A key technical requirement in selecting the material was the certainty of satisfying regulatory brittle fracture safety requirements, at the minimum normal operating temperature. The external size limitations imposed on the SWTC by UK rail transport meant that there was very limited scope for the addition of add-on shock absorbers to reduce the stresses associated with IAEA regulatory [2] impacts. Therefore, it was designed to absorb impact energy primarily by plastic deformation of the body material. That material would have to satisfy the brittle fracture criteria at high stresses and strains. This could potentially preclude materials that could possibly be satisfactory had the imposed stresses and strain rates been lower.

Two basic accepted methods were identified for demonstrating safety against brittle failure in a transport package. The US NRC's method [4] provides a criterion based upon the nil-ductility transition temperature (NDTT) of the material. The second method is given in an appendix to the IAEA's TS-G-1.1 [5], and is based upon ensuring that crack initiation does not occur by limiting the applied stress at a postulated crack.

A range of ferritic carbon steels were evaluated based upon the US NRC method and none of the ferritic carbon steel materials considered were found to be viable for this Type B(U) design. Had it been specified as a Type B(M) package, with a UK lowest service temperature (LST) of -10°C, the ferritic carbon steel SA-508-4A would comfortably satisfy the criterion, and SA-350-LF3 would be on the borderline of acceptability. The material SA-508-4N was believed to have very good properties, but no data on it's NDTT was available. The conclusion, therefore, was that ferritic carbon steel could not be proved acceptable for the SWTC design. It was, however, recognised that these materials could potentially be used if manufacturers would guarantee to supply forgings with the NDTT lower than the required values of -107°C for a Type B(U), or -76°C for a Type B(M) (with a LST of -10°C).

The option of using cast materials was also investigated. Both ductile cast iron (DCI), and the martensitic cast stainless steel CA6NM, to ASTM A352/A352M-93 (Steel No. 1.6982, to BS EN 10213-3, GX3 CrNi 13-4), were extensively researched and analysed by Nirex [6], [7]. DCI was rejected because analysis showed that it did not give sufficient margin of safety at -40°C at the high stresses and strain rates imposed. In addition, regulatory impact testing at -40°C, on full-size samples of typical designs of body corner shock absorbers, showed clear evidence that some brittle fracture did actually occur under real test conditions. By contrast, CA6NM was shown, in testing of full scale container sections, to be free from brittle fracture and was demonstrated, by analysis, to be capable of satisfying the IAEA brittle fracture criterion. It also appeared to provide a low cost option compared to a forged material solution. While it is known that this material is widely used for large castings it has not yet been used for the production of transport containers. However, it is believed that the risks associated with being able to obtain Competent Authority approval, because of its novelty in such an application, have been minimised by the extensive programme of work carried out by Nirex to date.

CA6NM was therefore considered as the most likely cost effective, lowest risk, option and was selected for the SWTC design.

6. The Brittle Fracture Case for CA6NM

As already discussed, a key requirement in the selection of the material of manufacture was the fact that Type B(U) approval would be sought for the SWTC design. This meant that a safety case had to be produced to demonstrate that the SWTC, with the body and lid manufactured from the cast steel CA6NM, would be resistant to brittle fracture when subject to 9 m drop tests onto an unyielding target at -40°C. Such a safety case was produced [8], and this may form part of a future application for Competent Authority Approval of the design.

The brittle fracture safety methodology used was based upon a development of IAEA TECDOC 717 [9], containing guidelines for design against brittle fracture. That document was used since [5] had not then been issued. The methodology of [9] was the basis for [5] and hence the use of [9] is still valid. The methodology was based upon the prevention of crack initiation in the material. The fundamental linear-elastic fracture mechanics (LEFM) equation which describes structural behaviour in terms of the crack tip driving force as a function of applied stress and flaw depth is given in [9] as follows:

$$K_I = Y\sigma\sqrt{\pi a} \qquad \text{where:}$$

K_I = applied stress intensity factor (MPa√m)
Y = constant base upon size, orientation and geometry of flaw and structure, and loading mode (i.e. bending or tension)
σ = applied nominal stress (MPa)
a = flaw depth, m (distance from the surface to the tip of the crack)

In order to preclude brittle fracture the applied stress intensity factor should satisfy the relationship $K_I < K_{I(mat)}$ where $K_{I(mat)}$ defines the fracture toughness which must be obtained from standard tests at the appropriate temperature and loading rate which will be experienced by the package. When the applied stress σ is sufficiently high (greater than about 60% of the yield stress according to [9]) significant yielding occurs at the crack tip, and the use of the LEFM approach described above may not be conservative. This can occur if the stress intensity factor is estimated only from the stress level and crack size without taking account of yielding. In these cases [9] recommends the use of elastic plastic fracture mechanics (EPFM) methods.

The EPFM method used was the one described in PD 6493 [10]. The first step was to calculate a Failure Assessment Diagram (FAD) using the true stress – true strain properties of the material obtained from [6]. The next step was to calculate the “assessment locus” for a given flaw size and applied stress, using the material toughness properties. The assessment locus lay entirely within the FAD for a 10mm reference flaw showing that there would be no crack extension, for that flaw size, and hence that flaw size would be acceptable. The case for the use of a 10m reference flaw size for the SWTC is presented in [8].

To determine the factor of safety against crack initiation, the size of flaw (critical crack depth) required to cause crack initiation under the materials true dynamic stress of 700 MPa [6] was calculated using the FAD approach. The crack depth was found to be 25mm, i.e. with a 25mm deep surface-breaking crack subject to a tensile stress of 700 MPa, the crack will be on the point of initiation. The factor of safety was calculated using the expression:

$$\text{Factor of safety} = \sqrt{\frac{critical\,crack\,depth}{reference\,crack\,depth}} = \sqrt{\frac{25}{10}} = 1.58$$

As the calculated factor of safety, 1.58, is greater than the acceptance criterion of 1.0 [8], the analysis demonstrates that a 10mm deep reference flaw is acceptable.

As stated above, the approach in [9] is to design for prevention of crack initiation. However, to illustrate the reserves of strength remaining in the transport container after crack initiation, a tearing instability analysis was also carried out. Using the FAD method, again, the flaw depth to cause tearing instability was calculated under an applied dynamic true tensile stress of 700 MPa. The result showed that a surface-breaking flaw 48.5mm deep, in a 285mm thick SWTC, would initially start to extend, if subjected to a 700 MPa applied stress - but would stabilise after a small amount of crack extension (about 2mm). If the initial crack were deeper than 48.5mm then the crack would not stabilise, but continue tearing. The calculated factor of safety against unstable tearing would be: $\sqrt{\frac{48.5}{10}} = 2.2$

In summary, a brittle fracture safety case has been produced which shows that the cast martensitic stainless steel CA6NM has very large reserves of strength, even if crack initiation were to occur, and is a suitable choice for the SWTC design.

7. Finite Element Design Analyses

With the concept design produced, and a robust case for the suitability of the material developed, the next step was to examine the overall performance of the design under IAEA regulatory [2] impact and fire accident conditions. This was done using finite element (FE) techniques, and assuming the contents were a 3 m^3 box of 12 t maximum weight. The 3 m^3 box was chosen as this was representative of the maximum weight that the design is intended to carry.

Analyses were performed assuming that the container body, and lid, would both be manufactured from type 304 stainless steel forgings. Following the materials selection process, discussed in Section 5, the material of both lid and body were changed to CA6NM. That material has very different mechanical properties from type 304 stainless steel, with a much higher yield stress and a lower strain-to-failure. Therefore, further analyses were carried out which incorporated the new material, and some detail design changes. The results of the finite element analyses showed that sealing integrity would be maintained during IAEA regulatory [2] impacts from 9 m when the SWTC-285 is constructed from CA6NM steel. The maximum permanent lid-to-body seal face separation was calculated to be about 0.2 mm maximum (Figure 3).

In order to examine the scope for possible optimisation of the design further FE impact analyses were carried out with various design changes incorporated. The inclusion of a modified body upstand (shock absorber) was examined as the original showed that some material tearing could occur with the original design. The new design proved more successful and had the added benefit of reducing the permanent seal face separation to a low and acceptable figure of < 0.1 mm (Figure 4). Analyses were also carried out with the number of lid-to-body bolts reduced from 48 to 32, and with the lid manufactured from a type 304 stainless steel. These analyses were successful in terms of effective containment being maintained following IAEA regulatory [2] impacts. However, in order to minimise the risks for the design the bolt number was fixed at 40.

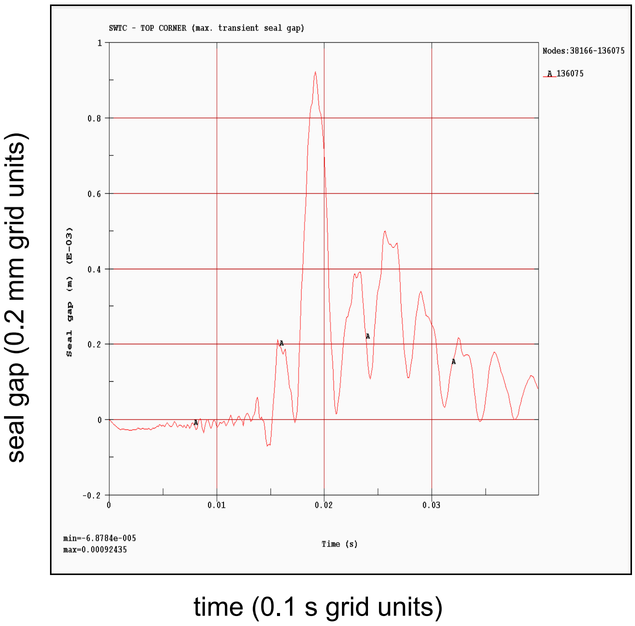


Figure 3: Main Seal Gaps (CA6NM body & lid) Original Corner Shock Absorber

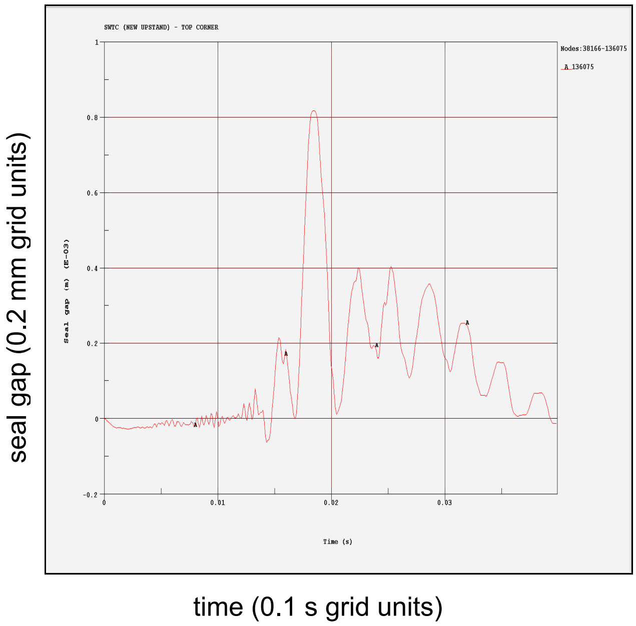


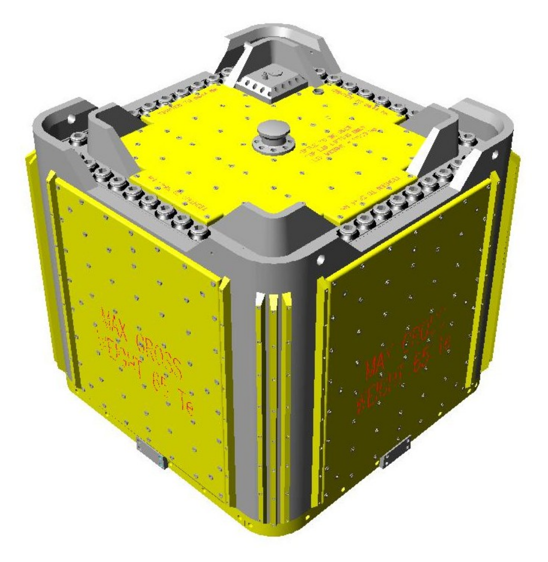
Figure 4: Main Seal Gaps (CA6NM body & type 304 s/s lid) - Improved Corner Shock Absorber

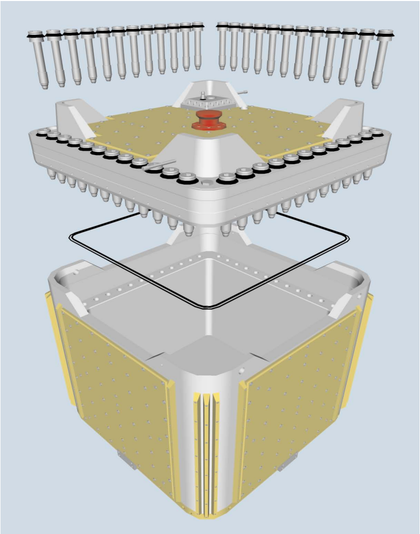
The thermal performance of the design was assessed against the IAEA regulatory [2] thermal performance criteria, including fire accidents. The assessments investigated material temperatures and thermal stresses, and covered both the transport container and its contents. Due to the large thermal capacity of the design and the relatively low heat generated by the contents (200W maximum), the predicted temperatures through the bulk of the container were found to be relatively low, both during normal transport and during the fire accident. The impact damage predicted to occur to the SWTC, under normal and accident conditions, had no significant effect upon its thermal performance, although predicted punch damage produced slightly higher temperatures and distortions, and thus represents a worst case. The peak temperatures at the inner lid seal, under fire accident conditions, was predicted to be 138°C. This is well below the upper temperature limit for the EPDM-30H seal material. The temperature difference between the inside and outside of the lid produced dishing of the lid which resulted in a transient gap of

0.51 mm developing between the lid and body. When this was added to the very small permanent gaps calculated in the impact analysis the resulting gaps were found to be well within values which would ensure the acceptable leak rates required. A detailed assessment was also carried out on the vent valve. The maximum temperature, of 130°C, and the maximum seal gap, of 0.03mm, which occurred under accident conditions, were both found to be acceptable.

8. Finalised Design

As a result of the analyses the design was optimised to produce the finalised design shown, and characterised by the information listed in Table 1.





External Dimensions(mm)	2450 x 2450 x 2320
Cavity Dimensions (mm)	1780 x 1780 (with 75 corner radius) x 1254
Shielding Thickness (mm of steel)	285
Maximum empty weight (t)	53 (Lid – 12, Body – 41)
Maximum payload (t)	12
Maximum gross weight (t)	65
Contents	Four 500l drums (up to 2 t each) in a Nirex transport or Compact stillage, or one 3m^3 box (up to 12 t), or one 3m^3 drum (up to 12 t)
IAEA package type	Type B(U)F
Main materials of manufacture	Body - cast martensitic stainless steel number 1.6982 to BS EN 10213-3, GX3 CrNi 13-4. The equivalent US standard is CA6NM, to ASTM A352/A352M-93 (ASME SA-352 CA6NM). Lid - forged stainless steel number 1.4307 to BS EN 10222-5. Thermal insulation panels of resin bonded cork clad in 5mm stainless steel number 1.4307 to BS EN 10088-2. O-ring Seal material - EPDM 30H.
Lid retention and sealing	Lid retained by M68 bolts (40 off), double O-ring seals
Lifting features	A lifting holes through each body corner impact limiter for lifting either the complete container or the body on its own. Male pintle provided in the middle of the lid for lifting the lid only.
Tie down features	Four feet provided on a square pitch of 1360 mm held down to the transport conveyance by sliding square bars on the conveyance.
Purge/vent valve	For controlled venting of the cavity prior to opening, and for purging with nitrogen before transport, if required,

Leak testing	Double O-ring seals on lid and purge/vent valve for leak testing by pressure drop method.
Maximum normal operating pressure (kPa g)	700

Table 1: SWTC-285 Summary Data

9. Scale Model for Regulatory Impact testing

The next stage in the programme is to prove the impact performance of the design by regulatory testing. The main reason for using a scale model for impact testing is to reduce costs. In the case of very large and expensive packages the use of a model can offer cost advantages with no reduction in proof of safety. Looking at the very approximate cost comparison between adopting a full scale and a scale model approach, shown in Table 2, then the case for using a scale model becomes clear. The savings from using a model are not confined to the manufacturing costs alone for such a large package as the SWTC-285. Using a model may allow more test facilities to quote for the testing work, thus providing a more competitive costing. Also, transport and handling costs would also be significantly reduced.

Cost driver	Full size prototype	Scale model prototype
Preparation of full scale manufacturing drawings	£50k	£50k
Preparation of scale model manufacturing drawings	0	£20k
Manufacture of one	£600k	£75K
Justifying the prototype against the production design	0	£15k
Hire of test facility	£150k	£100k
Hire of suitable handling equipment	£25k	£5k
Total	£825k	265k

Table 2: Approximate cost comparison between a full-size SWTC-285 and a scale model

With regard to which scaling factor to use for a model, there is a continuum of possibilities, and the optimum is not clearly defined. The problem of selecting the one to be adopted is addressed by considering, in turn, a number of constraints. It is stated in [5] that the maximum scaling factor should be 4. Theoretical and empirical analyses carried out, by many people, over a number of years, has shown that if a factor greater than 4 is used then discrepancies between the model and the production packaging become too great, and the model is not representative.

A scaling factor relates to linear dimensions, and so the weight varies as the cube of this factor. The familiar cube relationship is shown in Figure 5. It is evident by inspection that the main reduction in weight occurs for scaling factors between 1 and 2. Clearly, as a first step, it is reasonable to set a minimum scaling factor of 2.

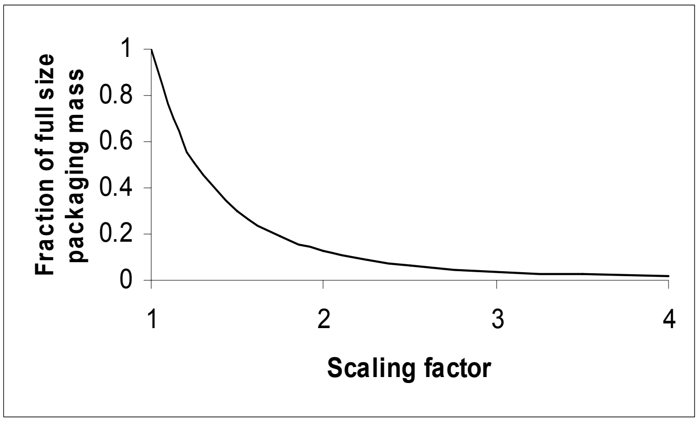


Figure 5: The effect of cubing the scaling factor

It is sensible to have the scaling factor as an integer, since this will make design and analysis easier and mistakes less likely to occur. Therefore the range of scaling factors is reduced to 2, 3 or 4.

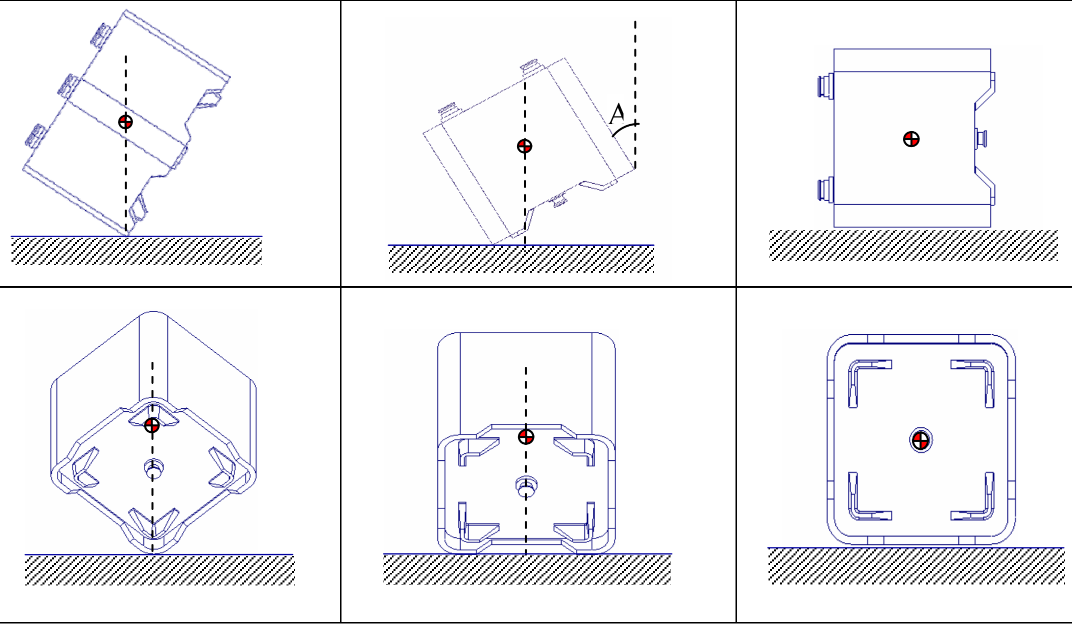
The approximate masses of a scale model SWTC-285 at these scaling factors are: SF = 2, mass = 8000 kg; SF = 3, mass = 2400 kg; SF = 4, mass= 200 kg. Each of these masses are reasonable for both manufacture (a number of companies would be capable of machining them) and testing (the masses are not excessive either for dropping or handling). However, the scaling factor of 4 is on the limit of what is acceptable, and it could be difficult to achieve the necessarily tight manufacturing tolerances on certain items, notably the vent valve and the O-rings. This scaling factor was, therfore, rejected. That left scaling factors of 2 and 3 as being the remaining practical options. The final deciding factor was cost. Budget costs for manufacture of a model with scaling factor 2 and 3 clearly showed a scale model, with a scaling factor of 3 would be significantly cheaper, and so a factor of 3 was chosen.

A one-third scale model has now been manufactured and is ready for testing. The scope of the test work is planned to be as follows:

Test 1	Lid-down drop from 0.3m on to a flat unyielding target
Test 2(a)	Centre of gravity over lid corner drop from 9m onto a flat unyielding target
Test 2(b)	Centre of gravity over vent valve cover plate drop from 1m onto a punch
Test 3(a)	Off-Centre of gravity over lid edge drop from 9m onto a flat unyielding target
Test 3(b)	Centre of gravity over lid insulation panel drop from 1m onto a punch
Test 4(a)	Centre of gravity over flat side drop from 9m onto a flat unyielding target
Test 4(b)	Centre of gravity over side insulation panel drop from 1m onto a punch

The model will be instrumented with both piezoresistive shock accelerometers and strain gauges.

Fig. 6 Test model orientation on the target - tests 2(a), 3(a) and 4(a)


Test 2(a)

Test 3(a)

Test 4(a)

10. Continuing Development Programme

The work reported in this paper is part of an on-going development programme for regulatory approval of the SWTC-285 transport container design. It is intended that the regulatory impact testing part of the work will be completed during 2004-05. Future work will be targeted on the preparation of the safety case required for UK Competent Authority approval of the design as part of a Type B(U)F transport package.

11. References

The references quoted in this paper (excluding standards and regulatory documents) can be obtained by accessing the Nirex web site: **www.nirex.co.uk**.

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