ANALYSIS OF DROP TESTS

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SUMMARY

This document presents the analysis of drop tests performed on a ½ mockup of the TN-MTR packaging that demonstrated that the packaging on which the drop sequences defined by IAEA rules <1> and <2> were carried out complies with assumptions made for the thermal, radiation protection, release and criticality safety- analysis calculations.
It provides the following additional information:

- The analysis of drops made at a temperature of approximately 20°C and the analysis of the behaviour of the TN-MTR packaging between–40°C and the maximum temperature under NTC (Normal Transport Conditions) include a calculation of the accelerations to be assumed for mechanical analyses of the packaging (chapter 1) and the basket (chapter 1A) under accident transport conditions:

  - ♦ Acceleration along the longitudinal axis of the full scale packaging = [redacted]
  - ♦ Acceleration along a radial axis of the full scale packaging = [redacted]

- Leak-tightness is demonstrated after each possible drop case either by leak-tightness checks made during the tests or by comparison with a more severe drop case made on the TN-MTR or with the RD 30 packaging for drops that are not made.

- Sections in IAEA rules <1> <2> that require drop tests are mentioned in this document to demonstrate that the requirements contained in the sections are satisfied and to mention the chapters that deal specifically with the subject.

In particular, this analysis demonstrates that:

◊ deformations of the packaging and particularly of the containment are small under normal and accident transport conditions, and thermal calculations and dose equivalent rate calculations and the nuclear safety analysis of the package may be made based on the packaging as described in chapter O, depending on the results of the thermal calculations for the fire test.

◊ Leak-tightness of the packaging is maintained, even after a drop sequence much more severe than the regulatory sequence, which validates the global allowable leak-tightness criterion produced for analysing the activity release.

- The analysis of the behaviour of the MTR-68 basket shows that the basket resists the worst lateral drop case (only drop case tested for the basket) for the most damaging orientation and with severe conditions for the load, materials and dimensions of load-bearing structures.

  The local deformation observed on the basket when the packaging was opened after drop 2 is small and is caused by deformation of the cavity during drop 1.
  Accelerations used for the design of the basket taking account of dynamic amplification and produced as a function of the response spectrum on accelerometers on the packaging body are:

  - ♦ Acceleration along the longitudinal axis of the full scale basket = 350 g
  - ♦ Acceleration along a radial axis of the full scale MTR-68 basket = 300 g

1. INTRODUCTION

This document presents the analysis of drop tests with regard to regulatory requirements <1> <2>.

The purpose of these drop tests is to demonstrate the resistance of the TN-MTR packaging to tests as defined by regulations <1> and<2> for type B packages and packages containing fissile material.

The sections mentioned below refer to the IAEA regulation in reference <1>. Refer to chapter 00-2 for the correspondence between these sections and the sections in the regulations in reference <2>.

2 ACCELERATIONS ON THE FULL SCALE PACKAGING

The accelerations undergone by the drop mockup and by the full scale packaging are inversely proportional to the scale ratio:

$$\gamma_{mockup} = \gamma_{full\ scale} / \eta$$

Stress values are unchanged between the mockup and the full scale packaging.
Accelerations are in N/kg.
Keeping pressure values means that forces are proportional to the square of the scale ratio.
Masses are proportional to the cube of the scale ratios.
Therefore the N/kg ratio is inversely proportional to the scale ratio.

Data in table 1-6.6 are used to calculate the maximum accelerations to be assumed for a drop of the TN-MTR packaging.

- Acceleration along the vertical axis of the packaging, 0.3 m drop
  γ_{ymax} = [redacted]
- Acceleration along the longitudinal axis of the packaging, 9 m drop on bottom
  γ_{ymax} = [redacted]
- Acceleration of top end of the packaging along a radial axis, 9 m lateral drop
  γx =
- Acceleration of bottom end of the packaging along a radial axis, 9 m lateral drop
  γ_x = [redacted]
- Acceleration along the longitudinal axis of the packaging, 9 m drop on shock absorbing cover
  γ_{ymax} = [redacted]
- Acceleration of top end of packaging along longitudinal axis, 9 m drop on corner of the shock absorbing cover
  γ_y = [redacted]

- Acceleration of bottom end of packaging along longitudinal axis, 9 m drop on corner of the shock absorbing cover
  γ_y = [redacted]

3 LEAK-TIGHTNESS

- The drop tests demonstrated that there is no loss of leak tightness caused by a regulatory drop sequence, a 9-metre drop coupled with a drop on a bar on a bar. Variations in measurements of leakage rates through lid and plug internal seals, and welds, presented in table 1-6.3 are due to either residual helium present in the cavity or to permeation through seals (leakage rate, always less than 8.6 x 10^{-8} Pa.m^3/s, or a total leakage rate always less than 8/6 x $10^{-8} \times 3$ = 2.6 x10^{-7} Pa.m^3/s for the 3 orifices).

  This value remains far below the minimum leakage rate value selected for the confinement analysis (see chapter 3A).

  The leakage rate measured after drop No. 2 on the representative orifice plug (8.6 x 10-^{8} Pa m^3 /s) is due to the seal groove not being suitable for the seal used, which caused an abnormal leakage rate for the seal type used, although without causing loss of leak-tightness. After a plug conforming with the design drawing for the mockup presented in Appendix 4 to Chapter 1 was installed, the measured leakage rate was once again correct for the seal type used. This new plug used for drops No 3 to No. 9 demonstrated that leak-tightness was maintained in a configuration similar to the drop No. 1 configuration and for the most severe cases for the plug: axial drop on shock absorbing cover.

- Drop tests demonstrated that leak-tightness is maintained not only after the series of 2 drops required by the regulations (one 9-meter drop and one drop on a bar on a bar), but also after a series of 5 9-meter drops and two drop on a bardrops on a bar on a bar. Although the shock absorbing covers were replaced during the drop tests, all the tests were carried out on the body and the lid, and the packaging remained leak-tight even after the combined drops, and showed no incipient loss of leak-tightness.

- The estimate of loosening torques of lid and plug screws (see table 1-6.5) shows that the threshold value (1.5 kg.m for lid screws and 0.2 kg.m for plug attachment screws) defined in Appendix 5 to Chapter 1 is always guaranteed.

- The 9-meter drop on the bottom corner was not done because:

  ◊ Accelerations during this drop along packaging axes are lower than during the 9 m axial drops (on the bottom of the packaging) or the 9 m lateral drop (along the longitudinal line of the packaging when laid flat).

  ◊ The strength of the packaging is confirmed by comparison with packaging RD 30 <3>.

  The diameter of the RD 30 drop test mockup is 697.5 mm. The scale of the TN-MTR is calculated such that the outside diameter is the same, to obtain comparable values:

$\eta_{TN\text{-}MTR}$ = 697.5/1480 = 0.471

The mass of the RD 30 mockup is 1135 kg. The mass of the TN-MTR mockup at scale 0.471 is at most: 23400 x 0.471^3 = 2445 kg, which is 2.15 times more than the mass of the RD 30 (1135 kg), for the same outside diameter

The thicknesses of RD 30 layers are:

- inner steel containment: 4 mm,
- lead containment: 20 mm,
- Insulation containment: 10 mm,
- outer steel containment: 5 mm.

The corresponding thicknesses of the 0.471 scale TN-MTR are:

- inner containment and bottom: 20 x 0.471 = 9.42 mm, or 30 x 0.471 = 14.1 mm,
- lead containment: [redacted] x 0.471 = [redacted] mm,
- Insulation containment: [redacted] x 0.471 = [redacted] mm,
- outer steel containment: 25 x 0.471 = 11.8 mm.

In the case of a drop on a corner, the mockup of the RD 30 packaging was deformed by bending of the bottom and compression or buckling of the shell.

The strength depends on the properties and thicknesses of the materials of the two mockups (see table 1-6.4).

The ultimate strength of the TN-MTR packaging is higher than that of the RD 30.

The strength of the packaging is proportional to the modulus of inertia of the bottom (bending), the cross-section of the shells (compression), or the moment of inertia of the shells (buckling).

The ratios of the moduli of inertia and cross-sections of the outer containment of each packaging are compared to the ratio of the masses.

Bottom modulus of inertia:

$$\frac{I_{TN-MTR}}{I_{RD30}} = \left(\frac{e_{TN-MTR}}{e_{RD30}}\right)^2 = \left(\frac{14{,}1}{5}\right)^2 = 7.9$$

Considering the mass ratio $M_{TN\text{-}MTR} / M_{RD\ 30}$ = 2.15, this ratio remains favourable to the TN-MTR.

The ratio of outer steel shell cross-sections is equal to:

$$\frac{S_{TN-MTR}}{S_{RD30}} = \frac{(1480\ x\ 0{,}471)^2 - (1480\ x\ 0{,}471 - 2\ x\ 11{,}8)^2}{697{,}5^2 - (697{,}5 - 2\ x\ 5)^2} = 2.33$$

This ratio is also favourable to the TN-MTR.

Moment of inertia of the shells:

The moment of inertia of a disk with inside diameter d and outside diameter D is:

$I = \pi (D^4 - d^4) / 64$

The ratio of the moments of inertia is:

$$\frac{I_{TN-MTR}}{I_{RD\,30}} = \frac{(1480 \times 0{,}471)^4 - (1480 \times 0{,}471 - 2 \times 11{,}8)^4}{697{,}5^4 - (697{,}5 - 2 \times 5)^4} = 2.28$$

This ratio is also favourable to the MTR.

The strength in the case of a corner drop is better for the TN-MTR than for the RD-30, so that the deformation is less and therefore the strength is higher including for the case of a drop on a bar on a bar.

Keeping in mind that the RD-30 successfully passed this drop case, it is concluded that the TN-MTR packaging is sufficiently strong to resist a 9-metre drop on the corner without loss of leak-tightness (in the impact zone). The leak-tightness of components that are not directly subjected to impact is verified by axial and lateral drops that cause maximum accelerations on these components.

- The following analysis shows that regulatory 0.3-meter drops described in sections 622 (free drop test), subparagraph a) for a packaging mass of more than 15 tonnes, and subparagraph b), do not lead to loss of leak-tightness.

  ◊ In the case of a axial drop on bottom, a 9-metre drop did not cause any loss of leak-tightness and accelerations measured during a 0.3-meter drop are significantly lower than accelerations measured for a 9-meter drop (see table 1-6.6).

  ◊ In the case of a bottom corner drop, accelerations measured during drop No. 9 projected onto the principal axes of the container (vertical and horizontal axes of the container under normal transport conditions), are less than accelerations observed during the 9-meter drops (axial drop on bottom No. 5, and lateral drop No. 1 or 3). The fact that leak-tightness is maintained during 9-meter drops combined with lower accelerations guarantees that leak-tightness will be maintained for the 0.3-meter drop case on a bottom corner.

  ◊ Accelerations due to the impact of a lateral drop and a corner drop on the shock absorbing cover will be lower for a 0.3-meter drop than for a 9-meter drop.

  The presence of wood in the shock absorbing cover means that the cover will be compressed more as the energy to be dissipated during the impact increases. Since the energy during a 0.3-meter drop is 30 (= 9 / 0.3) times lower than during a 9-meter drop, the accelerations will also be lower.

Accelerations due to the impact of an axial drop on the shock absorbing cover will be lower for a 0.3-meter drop than for a 9-meter drop.

The relation between the force (F), the mass (m), the acceleration(γ), the stress (σ which is a function increasing with the compression of the wood) and the area (S) is:

$F = m\,\gamma = \sigma\,S$

Therefore $\gamma = \sigma\,S / m$

The area (S) and the mass (m) remain constant.

The stress (σ) increases with compression of the wood, and compression increases with the energy absorbed during the impact.

Since the impact energy reduces as the drop height reduces, the acceleration is lower when the drop height is lower. Therefore the acceleration during a 0.3- m drop is lower than during a 9-meter drop.

Considering that the accelerations and the energy are lower in the case of a 0.3 metre drop than in the case of a 9-meter drop, the fact that leak-tightness is maintained after drops No. 1, No. 3, No. 4 and No. 7 ensures that leak-tightness will be maintained in the case of a lateral drop, a drop on the corner of the shock absorbing cover and a 0.3 m axial drop on the shock absorbing cover.

4 ANALYSIS OF DROPS REGARDING REGULATORY REQUIREMENTS

This section describes the analysis of requirements in IAEA rules <1> concerning mechanical tests of packages under normal and accident transport conditions.

The regulatory drop sequences are mentioned for each normal and accident transport condition, and then the safety analysis for each section in IAEA rules <1> referring to drop tests is presented, and the chapter dealing specifically with the subject is mentioned.

4.1 Normal conditions of transport

- Regulatory drop sequence

The regulatory drop sequence for type B(U) F packagings as defined by the IAEA rules includes the following (section 622 in <1>):

◊ a 0.3 m drop on each quadrant of the circular edges of the packaging (drops only for packagings transporting fissile materials)

Free drop test: a 0.3 m drop (for a mass of more than 15000 kg), so that the maximum damage occurs.

- Criteria and analysis

◊ Section 537 in IAEA rules <1>: Packages shall be designed such that under ambient thermal conditions, allowing for the heat generated inside the package on which the tests described in sections 619 (presentation of tests), 620 and 621 (spraying with water), 622 (free drop), 623 (stacking), 624 (penetration) are performed, they will prevent:

a) loss or dispersal of the radioactive contents

b) loss of integrity of the shielding that would result in an increase of more than 20% of the radiation intensity on any outside surface.

0.,3 m drops on bottom (drop height imposed in section 622) demonstrated that:

- leak-tightness of the packaging is maintained (see section 3) and consequently the confinement analysis presented in chapter 3A is valid even after the 0.3-meter drops.

- deformations on the packaging after the 0.3-meter drops and even the 9-meter drops do not significantly change the geometry of the packaging and consequently, calculations of the dose equivalent rates around the packaging given in chapter 4A are valid. Therefore the increase in the radiation intensity on any outside surface is negligible.

◊ Sections 543 and 547 in IAEA rules <1>: Packages shall be designed such that, under ambient thermal conditions, heat generated inside the package on which the tests in sections 619 (presentation of tests), 620 and 621 (spraying with water), 622 (free drop), 623 (stacking), 624 (penetration) are carried out, does not have any adverse effects on the package in such a way that it would fail to meet the applicable requirements for confinement and shielding if left unattended for one week.

Considering the very small deformations observed after 0.3-meter drops and even after 9-meter drops, the drops do not significantly modify the geometry of the packaging. Therefore the assumptions made for the thermal analysis of the packaging (geometry and materials as defined in chapter 0) are validated.

◊ Section 548 a) in IAEA rules <1>: Packages shall be designed such that, if the tests described in sections 619 (presentation of tests), 620 and 621 (spraying with water), 622 (free drop), 623 (stacking), 624 (penetration) were performed on them, the loss of radioactive contents would not exceed $A_2 \times 10^{-6}$ per hour.

It is shown in section 3 that the packaging remains leak-tight after the 0.3-meter drops and in particular, that the leakage rate defined for the confinement analysis (chapter 3A) is correct. Therefore the loss of radioactive content is less than $A_2 \times 10^{-6}$ per hour.

◊ Section 552 in IAEA rules <1>: the package must not contain any containment depressurisation system that would allow the release of radioactive materials. Since the packaging is not transported with overpressure, this criterion is not applicable.

◊ Section 553 in IAEA rules <1> : packages shall be designed such that if they were at the maximum normal operating pressure and were subjected to the tests specified in sections 619 (presentation of tests), 620 and 621 (spraying with water), 622 (free drop), 623 (stacking), 624 (penetration), stresses in the containment would not reach values which would adversely affect the package such that it would no longer satisfy applicable requirements.

The packaging is not transported with overpressure, therefore the tests described in sections 619 to 624 (normal conditions) do not lead to effects worse than when the pressure is ignored.

◊ Section 563 a) in IAEA rules <1>: The volume and the space used to evaluate nuclear criticality control are not reduced by more than 5%, when the tests defined in sections 619 (presentation of tests), 620 and 621 (spraying with water), 622 (free drop), 623 (stacking), 624 (penetration) are carried out on the packaging.

The following drop tests can be envisaged:

- Axial drop on bottom: the drop performed (drop No. 8) did not cause any deformation of the mockup.

- Axial drop on shock absorbing cover: drop not done, but it would cause lower accelerations and deformations than the axial drop on bottom.

- Drop on bottom corner: drop done (drop No. 9) and only caused minimal deformation on the truncated cone that has no influence on the dimensions of the cavity.

- Drop on corner of shock absorbing cover: drop not done, but it would cause lower accelerations and deformations than the axial drop on bottom.

- Lateral drop: Drop not done, but due to the drop inclination, the resulting deformations would be less than in the case of the drop on bottom corner.

  Furthermore, the 9 m drop on the shock absorbing cover did cause deformation of the cavity.

  Due to the energies involved in the case of the 9 m or 0.3 m drop, deformations caused by the 9 m drop are obviously greater than for the 0.3 m drop.

  According to dimensional measurements made after drop No. 2, the minimum measured diameter is 476.7 mm, for a maximum initial diameter of 482.5 mm.

  The calculated volume variation using very conservative assumptions is less than 5%.

Assumptions:

⇒ cavity initial diameter equal to the measured maximum diameter and applied over the entire height of the cavity.

⇒ cavity diameter after deformation equal to the minimum diameter, although the deformation is only effective on one axis

⇒ minimum cavity diameter along the entire height of the cavity, although the deformation is only effective over a small height at the bottom of the packaging.

Calculation of the change in the cavity volume:

V_{ini}: Initial volume of the mockup cavity = $\pi/4\ D_{ini}^2\ h$

where:

D_{ini}^2: initial diameter of the mockup cavity = 482.5 mm

h: height of the mockup cavity = 540 mm

$V_{ini} = \pi/4\ 0.4825^2 \times 0.54 = 0.0987\ m^3$

V_{def}: Deformed volume of the mockup cavity = $\pi/4\ D_{def}^2\ h$

where:

D_{def}^2: deformed diameter of the mockup cavity = 476.7 mm

h: height of the mockup cavity = 540 mm

$V_{ini} = \pi/4\ 0.4767^2 \times 0.54 = 0.0964\ m^3$

The volume change is therefore:

$\Delta V = (V_{ini} - V_{def}) / V_{ini} = (0.0987 - 0.0964) / 0.0987 = 2.3\%$

This value, calculated from a drop height of 9 m instead of 0.3 m and using very conservative assumptions, is less than the 5% limiting criterion fixed by IAEA rules.

◊ Section 563 b) in IAEA rules <1> states that water cannot enter any part of the package when the tests defined in sections 619 (presentation of tests), 620 and 621 (spraying with water), 622 (free drop), 623 (stacking), 624 (penetration) are carried out on the packaging.

After the drop tests, it is found that:

- ♦ 0.3 m drops result in only minor damage, considerably less than the damage caused by 9 m drops.

- ♦ The container remains leak-tight after a series of 5 9-meter drops and two 1 m drop on a bardrops on a bar on a bar.

It is deduced that the container remains leak-tight after the series of free drops as described in section 622 in <1> (mentioned in the previous analysis),and that the criterion is respected.

◊ Section 563 c) in IAEA rules <1> states than the configuration of the radioactive content and the geometry of the containment would not be changed such that there is a significant increase in neutron multiplication when the tests defined in sections 619 (presentation of tests), 620 and 621 (spraying with water), 622 (free drop), 623 (stacking), 624 (penetration) are carried out on the packaging.

Packaging deformations observed during 0.3-meter drops are very small and have no consequence on the geometry of the cavity.

The analysis presented in chapter 1A on the mechanical strength shows that the baskets are not deformed by tests under normal transport conditions, and particularly by the free drop test (section 622).

The geometry of the packaging and its basket are unchanged during free drop tests and assumptions for criticality calculations (presented in chapter 5A) are respected after this drop sequence.

Therefore neutron multiplication is not increased and the criterion is respected.

4.2 Accident conditions of transport

- The condition of the damaged package defined for accident drop conditions is the condition of the package after the tests listed in section 564 of IAEA rules <1> have been carried out:
  Concerning drops, the tests are the succession of tests defined in sections 622 and 627 in <1>

◊ A 0.3 m drop on each quadrant of the circular edges of the packaging (drops only for packagings transporting fissile materials)

Free drop test: a 0.3 m drop (for a package with a mass of more than 15000 kg), so that the maximum damage occurs.

◊ The sequence of one 9-meter drop (section 627 a)) and one drop on a bar on a bar (section 627 b)), in the order that leads to the maximum damage.

- Criteria and analysis

◊ Section 542 in IAEA rules <1>: Packages shall be designed such that they would maintain a sufficient shielding function when the tests described in sections 627 (mechanical test), 628 (thermal test) and 629 (immersion test) are carried out on them, to guarantee that the radiation intensity for the maximum radioactive content is acceptable.

Drop tests showed that the geometry of the packaging is globally unchanged after 5 9-meter drops and 2 drop on a bardrops on a bar.

Therefore this justifies the assumptions made for the calculations of dose equivalent rates around the packaging that are given in chapter 4A.

◊ Section 547 in IAEA rules <1>: A package that includes thermal protection to satisfy the fire test (case of resin thickness surrounding the lead) must be designed such that this protection remains effective when the tests for normal transport conditions and the tests in section 627 in <1> (mechanical test) are carried out on the package.

Considering the small deformations observed after 9-meter drops, this requirement is respected.

Consequently, the thermal calculations for the package under fire conditions are carried out with the packaging geometry as defined in chapter 0.

◊ Section 548 b) in IAEA rules <1>: Packages shall be designed such that the accumulated loss of radioactive content after one week following the tests described in 627 (mechanical test) does not exceed 10 A_2 for krypton and 1 A_2 for other radionuclides.

It is shown in section 3 that the container remains leak-tight after the 9-meter drops and in particular, that the leakage rate defined for the confinement analysis (chapter 3A) is correct. Therefore the accumulated loss of radioactive content after one week is less than 1 A_2 for radionuclides other than krypton.

◊ Section 552 in IAEA rules <1>: the package must not contain any containment depressurisation system that would allow the release of radioactive materials. Since the packaging is not transported with overpressure, this criterion is not applicable.

◊ Section 553 in IAEA rules <1>: packages shall be designed so that if they were at the maximum normal operating pressure and were subjected to the tests described in section 627 (mechanical test), stresses in the containment would not reach values which would adversely affect the package such that it would no longer satisfy applicable requirements.

There is no overpressure in the transported packaging, therefore the tests described in section 627 (mechanical test) do not lead to any effects worse than when the pressure is ignored (case for the drop tests done for the TN-MTR).

◊ Section 566 in IAEA rules 1>: the damaged package (particularly after the mechanical test defined in section 627 in <1>) must be sub-critical, considering the physical and chemical characteristics, including any variation in these characteristics that could occur when the package is damaged, and under moderation and reflection conditions specified for materials located inside the containment.

Drops demonstrated little damage for the MTR-68 basket leading to geometric change that has no influence on assumptions made for criticality calculations, based on severe conditions for the load (see Appendix 5 to Chapter 1), the yield stress of the material (see Appendix 5 to Chapter 1) and the thickness of the compartment cores (see table 1-6.8). Chapter 1A also demonstrates the strength of the different baskets used in the TN-MTR and their compatibility with the assumptions made in Chapter 5A for the criticality calculations for the analysis of nuclear safety of the package.

5. BEHAVIOUR OF LEAD DURING DROPS

A visual inspection of the mockup after the drops confirmed that there is no deformation (swelling). Therefore no significant settling of the lead radiation shielding shell had occurred.
However, according to reference <4>, the lead shielding will undergo settling during the axial drop of the packaging. Determination of the displacement will be used to estimate the radiological consequences of the radiation leak.

The variation of the length (ΔL) of the lead shielding of a packaging for which the variation in the shell diameter is negligible (this is verified by the check to assure that there is no deformation observed on the mockup after the drops), satisfies the following equation:

$$\Delta L = \frac{R.M.g.H}{\pi.(R^2 - r^2).(e.\sigma + R.\sigma_{Pb})}$$ equation 2.16 in <4>

where:

R = outside radius of lead shielding
r = inside radius of lead shielding
M = mass of package shielding
e = thickness of the outer shell
H = drop height,

σ = compression strength of the steel in the shell taken to be equal to Re at a temperature of 140°C (upper-bound temperature of the packaging outer shell under Normal Transport Conditions) (see Chapter 2-1).

σ_{Pb} =compression strength of confined lead

The dimensions of the ring that forms the shielding are (see Chapter 0-1):

R = [redacted]
r = [redacted]

Therefore its mass over a length of 1.28 m is (ρ = 11300 kg/m^3, see Chapter 0):

M = 1.28 x [redacted]

The other parameters are:

e = 25 mm
H = 9 M = 9000 MM
σ = 135 MPa at 140°C (interpolated using table 0.7).
σ_{Pb} = 35 MPa according to <4>

hence ΔL = [redacted]

The above demonstration is valid regardless of the condition of the lead. Energy absorption due to deformation of a solid depends on the value of its modulus of elasticity (Chapter 11 in <6>). This characteristic does not change much as a function of the temperature for lead. Reference <7> gives the following for the tensile modulus:

Temperature	20°C	100°C	200°C
Modulus	16,700 MPa	16,200 MPa	14,000 MPa
Evolution	-	= 3%	= 16%

The temperature of 150°C bounds the maximum lead temperature under normal transport conditions (see Chapter 2-1).

The maximum variation of the modulus of elasticity of lead assuming a parabolic variation is equal to 8% at 150°C (E = 15395 MPa).

The calculated settling height of the lead forming the radiological shielding of the TN MTR following a 9-meter drop is limited to 32 mm. The influence of this settling of lead on maximum dose rates around the TN-MTR packaging will be studied in Chapter 4A.

6. BEHAVIOUR OF THE BASKET DURING DROPS

During the drop tests on the TN-MTR packaging mockup, the content was chosen to be representative of the method of application of the load on the packaging cavity, and also the mechanical strength of the MTR-68 basket and the load that the basket would resist due to the fuel assemblies.

6.1 Main characteristics of the content

Appendix 5 to Chapter 1 contains a description and choices made for the content of the drop test mockup.

- The mechanically resisting structure (stainless steel disks) for lateral drops is scrupulously reproduced.
- The mechanical strength in the case of an axial drop is not representative. This is reflected in the fact that the aluminium disks are modelled by rings.

- The mass per unit length for a lateral drop is conservative:

  Packaging: Maximum mass per unit length per compartment: 20.4 kg/m per complete compartment (see table 1-5.8).

  Mockup: Mass per unit length per compartment corrected to full scale:

  $M_{per\ unit\ length} = 7.99 / 0.5^2 = 32$ kg/m (see Appendix 5 in Chapter 1).

  Considering the increases applied to the mass per unit length of assemblies to take account of compartments left empty for instrumentation and expected differences in Young's modulus (when the basket is at temperature), the mass per unit length of the pins simulating the assemblies is 30% higher than the value of the predicted mass per unit length (see Appendix 5 to Chapter 1).

- The yield stress of the basket mockup is lower than the minimum guaranteed yield stress of the steel used in the MTR-68 basket.

  ◊ Guaranteed minimum value of the yield stress of the steel used for the MTR-68 basket, given in Chapter OA, for a temperature of 315.5°C (although the maximum temperature of the basket calculated in Chapter 2A is less than 300°C):

  $\sigma_{e\ MTR68} = 584$ MPa.

  ◊ Value of the yield stress of steel used for the basket mockup, measured on materials used for fabrication, at ambient temperature:

  $\sigma_{e\ mockup} = 552$ MPa.

  Ignoring the conservative value of the temperature, the strength of the mockup basket is (1 - 552 / 584 =) 5.5% lower than the strength of the MTR-68 basket.

- The method of application of the load on the basket load bearing structure is conservative: the pins distribute the force over the length of the compartment whereas the assemblies apply the force close to the corners of the compartment (see Appendix 5 to Chapter 1).

- The orientation of the basket in the drop mockup corresponds to the lower strength of the basket disks.

- The fabrication of the basket mockup is also conservative: table 1-6.8 shows that the average thickness of compartment cores is equal to 2.96 mm, although the minimum thickness of cores for the MTR-68 basket will be 3 mm.

6.2 Drops 1 and 2

During drop 1, the mockup impacts the shock absorbing cover first and then the bottom. The impact on the bottom caused deformation of the bottom.

Drop 2 is a drop on a bar on the same axis as drop 1.

When the mockup was opened after drops 1 and 2, it was found that deformations had occurred in the cavity (see photo 1-6.12) and 3 cores of the basket (see figures 1-6.15, 1-6.16 and photos 1-6.16 to 1-6.19). These three cores are located around the compartment left empty for instrumentation of the basket close to the bottom of the mockup.

The cause of these deformations is presented below.

6.2.1 Deformation of the cavity

Deformation of the cavity is due to deformation of the bottom of the mockup during drop 1 (see figures 1-6.2, 1-6.4 and photos 1-6.2, 1-6.4 and 1-6.5), or to the impact on a bar (see figures 1-6.12 to 1-6.14, photos 1-6.7 and 1-6.8).

The shape of the cavity after the two drops could be due to either of the drops or the combination of the two.

The cavity is only slightly deformed at the bottom disk and it is slightly ovalled (see figure 1-6.13). The maximum deformation is located at approximately 75 mm above the bottom of the cavity.

This deformation is due either to the deformation of the outer containment of the mockup during the 9 m drop, explaining that the lack of deformation at the level of the bottom disk is due to the stiffness of this disk, or to the deformation imposed by the drop on a bar.

Figure 1-6.13 presents the survey of representative heights of maximum deformations of the outer containment and the cavity, and demonstrates that they are at the same elevation. Considering the drop angle (30°), if the deformation were due to the bar, it would be expected to have been in line with the drop axis.

Drop 3 caused deformation of the outer containment of the packaging similar to the deformation caused by drop 1, and deformation of the cavity also similar to the deformation observed after the pair of drops 1 and 2, for the height of the deformation and also for the minimum value of the diameter (see surveys made after drops 2 and 4).

Therefore the deformation of the basket is due to the deformation of the cavity as demonstrated in the following section, and records of stresses in the basket show that this deformation occurs during drop 1 (see figures 1-6.9 to 1-6.11 and 1-6.21 to 1-6.23).

In conclusion, the deformation of the cavity is due to drop 1.

6.2.2 Deformation of the basket

Deformation of the basket is shown in figures 1-6.15 to 1-6.16.

An exception is made for the deformation of the basket bottom disk (see photo 1-6.13), which is caused by friction forces during extraction of the basket from the cavity.

Stress readings in the deformed compartment cores (presented in figure 1-6.22), show that plastic deformation occurred on this compartment during drop 1 (see readings made during drop 1) and that stresses recorded during drop 2 are lower than the yield stress (see readings made during drop 2).

Therefore the deformation was caused by drop 1.

It may be due either to accelerations applied to the basket and the pins, or due to the displacement imposed by deformation of the cavity.

Photos 1-6.14, 1-6.16 and 1-6.17 show that this deformation occurs on only one compartment and is located on the deformation zone of the cavity. If this deformation were due to accelerations experienced by the basket, damage to the compartments would certainly have been better distributed, and the disks on each side of disk 7 would also have been deformed. The only exception is disk 8 for which the deformation is much smaller, although the accelerations on this disk are higher because it is closer to the bottom of the mockup.

After taking the basket out of the cavity, the basket relaxed (according to the records made after drop 2, the smallest outside diameter of the deformed disk is 477.7 mm, and the diameter of the cavity is 476,7 mm). This behaviour is more like the behaviour of a compressed object than a buckling deformation (buckling would be the failure mode resulting from accelerations).

In conclusion, deformation of the basket is due to the displacement imposed by deformation of the cavity.

6.2.3 Conclusion

Deformations of the packaging and especially of the containment are small following these accident drops. Therefore thermal calculations and dose equivalent rate calculations and the nuclear criticality safety analysis of the packaging can be made based on the packaging as described in chapter O, depending on the results of the thermal calculations for the fire test.

6.3 Other drops

During other drops, the basket mockup is not representative of the mechanical strength of the full scale basket.

However it is observed that the basket was not damaged by the drops, even in the case of an axial drop on bottom, for which the basket resisted the mass of the spacer.

6.4 Accelerations

- Longitudinal accelerations: Maximum longitudinal accelerations are obtained as expected in the case of an axial drop on the bottom of the mockup.

  In this case, the maximum acceleration measured on the body of the mockup is 642 g (see figure 1-6.42).

  Due to the very high stiffness of the basket along this axis, it experiences the same acceleration.

  Therefore the value of the longitudinal acceleration used for the design is:

  γ_{longi} = 642 / 2 = 321 g

- Radial accelerations: maximum accelerations are obtained for drop 3 (angle +5°, impact on shock absorbing cover along the axis of the trunnions).

  The accelerations used are derived from response spectra for accelerometers 1Ax (figure 1-6.5) and 1Dx (figure 1-6.6).

  Since the natural frequency of the full scale basket is 283 Hz (see section 5.2.5 in Chapter 1-6), the acceleration to be considered is the maximum value of response spectra for accelerometers 1Ax and 1Dx, for the natural frequency corrected to ½ scale.

  Thus f = 283 × 2 = 566 Hz.

  We then obtain:

  γ_{1Ax} = 420 g (see figure 1-6.5)

  γ_{1Dx} = 600 g (see figure 1-6.6)

  It is also necessary to take account of the variation in the natural frequency due to the difference in Young's modulus of steel when cold and when hot.

  The difference on the frequency is:

  $$f_T = f_{20°C} \times \sqrt{\frac{E_T}{E_{20°C}}}$$

  Where:

  f_T: natural frequency when hot, the temperature being increased to 300°C, for which the Young's modulus is $E_{300°C}$:

  $E_{300°C}$ = 185 000 MPa

  $f_{20°C}$: natural frequency calculated with Young's modulus at 20°C:

$f_{20°C}$ = 283 Hz

$E_{20°C}$: Young's modulus at 20°C = 200 000 MPa.

Therefore f_T = 272 Hz.

This variation is small and even negligible considering the logarithmic scale of the response spectra in figures 1-6.5 and 1-6.6.

The acceleration calculated from a radial acceleration of [redacted] on the mockup will be used for the design of the basket, i.e.:

γ_{radial} = [redacted]

- Drop 2: accelerations during this drop are measured both on the body of the mockup and the basket.

  In the same way as for drop 1, the accelerometer cables are either stretched or cut, except for accelerometer L_u (see figure 1-6.17) for which the acceleration curve is acceptable.

  The maximum measured acceleration is:

  γ_{Lu} = [redacted]

  Response spectra for accelerometer 2Bx (placed on the mockup body), corresponding to the section of basket accelerometer L_u give the acceleration given below for a frequency of 566 Hz (2 × 283 Hz):

  $\gamma_{response}$ = [redacted] (see figure 1-6.65)

  This acceleration should be compared with γ_{Lu} (=[redacted], figure 1-6.17) and γ_{2Bx} (= [redacted], figure 1-6.19).

  The curve presented in figure 1-6.65 gives an increase in the response when the frequency increases from 566 Hz to 630 Hz, for which the curve shows a relative maximum at [redacted]

  This means that the real frequency of the basket under these drop conditions (the frequency is modified by the manner in which the pins apply load to the structures) is higher than that determined by calculation and is equal to 630 Hz.

  Compared with drop 1 (spectra shown on figures 1-6.5 and 1-6.6), the response remains stable or is lower when the frequency increases from 566 Hz to 630 Hz, therefore the accelerations corresponding to the frequency determined for drop 2 (630 Hz) are equal to or lower than the accelerations defined in the previous section.

  It is thus demonstrated that the method of determining design accelerations is valid and that accelerations defined for lateral drops are conservative.

7. CONCLUSION

Drop tests performed on a ½ scale mockup of the TN-MTR packaging demonstrated that this packaging can resist drop sequences like those defined by IAEA regulations <1> and <2>, and that the container remains leak-tight after the tests.

Drop tests demonstrated that deformations of the packaging after the drops are low.

This analysis thus shows that the assumptions made for the thermal and dose equivalent rate calculations,, and the confinement and nuclear safety analyses for the package are respected.

Finally, this appendix determines accelerations to be considered for mechanical analyses of the strength of the packaging and the baskets:

- ◊ Packaging design:
  - ♦ Acceleration along the longitudinal axis of the full scale packaging (drop on bottom)= [redacted]
  - ♦ Acceleration along the longitudinal axis of the full scale packaging (drop on shock absorbing cover)= [redacted]
  - ♦ Acceleration along a radial axis of the full scale packaging = [redacted]
- ◊ Basket design:
  - ♦ Acceleration along the longitudinal axis of the full scale packaging = [redacted]
  - ♦ Acceleration along a radial axis of the full scale packaging = [redacted]

The calculated settling height of the lead forming the radiological shielding of the TN MTR following a 9-meter drop is 32 mm.

8. REFERENCES

<1> IAEA Safety Collection No. 6 – Rules for the Transportation of Radioactive Materials – 1985 Edition (Amended 1990)

<2> IAEA Safety standards series N°TS-R-1- Regulations for the safe transport of radioactive material - 1996 Edition (ST-1 revised)

<3> TRANSNUCLEAIRE document: 3051-Z-1-6: RD30 PACKAGING - DROP TEST REPORT AND ANALYSIS OF REGULATORY DROPS.

<4> Cask Designer Guide by L.B. Shappert – ORNL-NSIC 68

<5> Reactor Shielding Design Manual – T. Rockwell III

<6> Strength of Materials – S. Timoshenko – Ed. DUNOD

<7> Properties of Lead – Lead Information Centre