# Verification of activity release compliance with regulatory limits within spent fuel transport cask assessment

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**Content:**

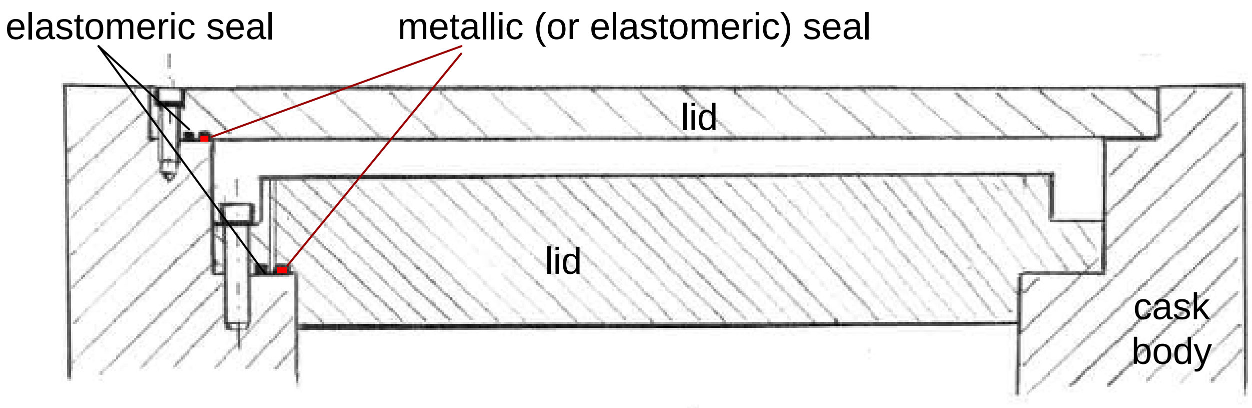
1. Sealing system
2. Leakage mechanism and methods of calculation
3. Design leakage rates
4. Releasable radioactive content
   - effects of higher burn-ups

# Limits for activity release from Type (B) packages

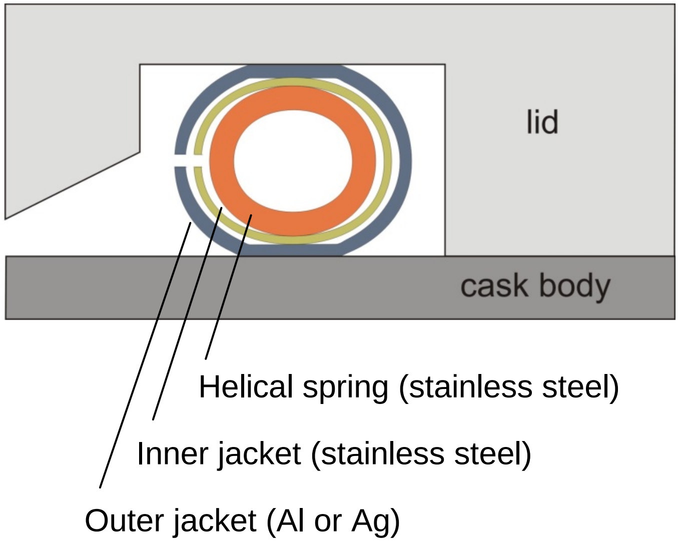
## (IAEA Safety Standards TS-R-1, § 657):

| | | |
|---|---|---|
| Normal conditions of transport (**NCT**): | **$10^{-6}$ $A_2$ per hour** | **[Bq]** |
| Accidental conditions of transport (**ACT**): | **$A_2$ per week** | **[Bq]** |
| | **(10 $A_2$ per week for Kr-85)** | |

# Sealing system of transport and storage casks

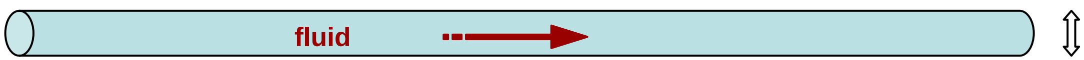



Metallic gasket, Helicoflex[R] -type



# One capillary leak model

$p_u$




Capillary diameter $p_d$

$p_u$ - upstream pressure
$p_d$ - downstream pressure
( $p_u > p_d$ )

***Standardized leakage rate $Q_{SLR}$***

$Q_{SLR} = 10^{-8}$ $Pam^3s^{-1}$
$Q_{SLR} = 10^{-5}$ $Pam^3s^{-1}$
$Q_{SLR} = 10^{-2}$ $Pam^3s^{-1}$

**correspond to**

***Capillary diameter D***

D= 1.5µm
D= 10µm
D= 60µm

# Modes of flow

**Gas flow**
KNUDSEN

$$Q = \frac{\pi}{128} \cdot \frac{D^4}{\mu \cdot a} \cdot \frac{(p_u^2 - p_d^2)}{2} + \frac{\sqrt{2\pi}}{6} \cdot \sqrt{\frac{R \cdot T}{M}} \cdot \frac{D^3}{a}$$

a - Capillary length (m)
D - Capillary leak diameter (m)
M - Relative molecular mass (kg $mol^{-1}$)
$p_d$ - Downstream pressure (Pa)
$p_u$ - Upstream pressure (Pa)
R - Universal Gas constant (8.31J $mol^{-1}K^{-1}$)
T- Temperature fluid (K)
µ - Dynamic viscosity of fluid (Pa s)

**particle-tight: $Q_{SLR}$<1E-4 $Pam^3s^{-1}$**

**Liquid flow**
POISEUILLE

$$L = \frac{\pi}{128} \cdot \frac{D^4}{\mu \cdot a} \ (p_u - p_d)$$

**liquid-tight: $Q_{SLR}$<1E-5 $Pam^3s^{-1}$**

**Permeation**

$$Q_P = P \cdot \frac{A}{l} \cdot \Delta p$$

P - Coefficient of permeation ($m^2 s^{-1}$)
A - Area normal to gas flow ($m^2$)
$l_p$ -Thickness of permeable material (m)
^p- Partial pressure difference (Pa)

# Steps of release calculation (ISO 12807)

Step 1: Determination of the total releasable activity

Step 2: Determination of the equivalent $A_2$

Step 3: Determination of the permissible activity release rate

Step 4: Determination of the activity release rate due to permeation

Step 5: Determination of the maximum permissible volumetric leakage rate

Step 6: Determination of the maximum permissible equivalent capillary diameter

Step 7: Determination of the permissible standardized leakage rate

Assessment criterion:

***Permissible standardized leakage rate > Design leakage rate***

# Deducing of conservative design leakage rates

***Design leakage rates:***

- identify the efficiency limit of the sealing system
- must not exeeded under routine (RTC), normal (NCT) or accidental (ACT) conditions of transport
- deduced from tests with real casks and cask components relating to normal and accidental transport conditions

# *Impacts to be considered (according to IAEA TS-R-1):*

Routine condition of transport **(RCT):** §612, §615

-acceleration (2g) in radial and axial directions
-operational temperature and pressure

Normal conditions of transport (**NCT**): §722

-free drop from 0.3m in transport position

Accidental conditions of transport (**ACT**): §726-728

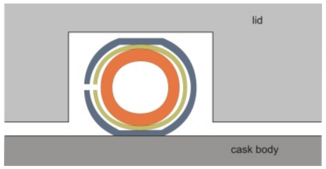
-free drop from 9m
-1m puncture test
- 800°C, 30min
-water immersion test

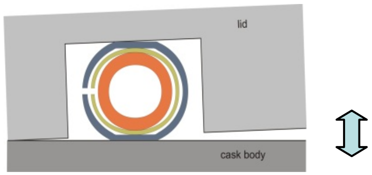
***Possible effects on sealing system:***

**- deformation or displacements of cask components**

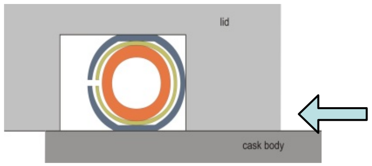
**-unloading and/or moving of the seal (rotation or lateral sliding)**

**unloading, rotation possible**



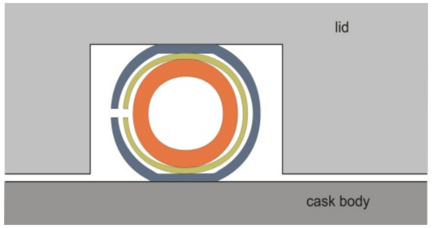

**lateral sliding after lid displacement**



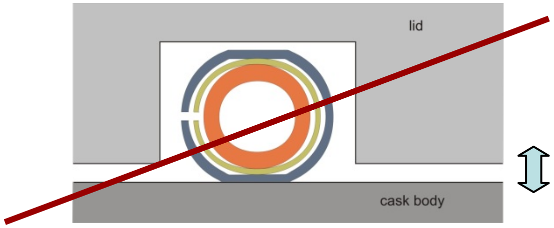
# Design leakage rates ($Q_{DLR}$) for metallic seals:

***RTC*:** $Q_{DLR} < 10^{-8} Pam^3 s^{-1}$ (attests the sealing system the regular assembly status)

***NCT,ACT:*** $Q_{DLR}$ depends on test results




**widening < $r_u$**




**widening > $r_u$**

**No widening permitted above $r_u$ !!!**
(except for short-term decompression during NCT or ACT impacts)

**$r_u$**= useful elastic recovery of the seal

# Illustration of the usuable resilience $r_u$ of a metallic seal

(Garlock Sealing Technologies, Helicoflex High performance sealing)

## Definition of Terms

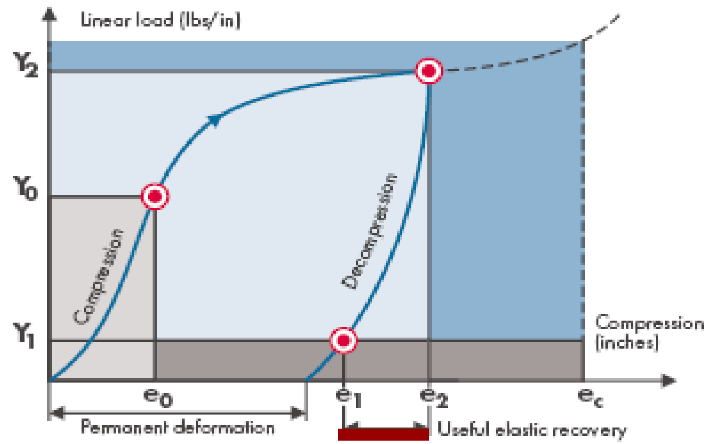
$Y_0$ = load on the compression curve above which leak rate is at required level

$Y_2$ = load required to reach optimum compression e2

$Y_1$ = load on the decompression curve below which leak rate exceeds required level

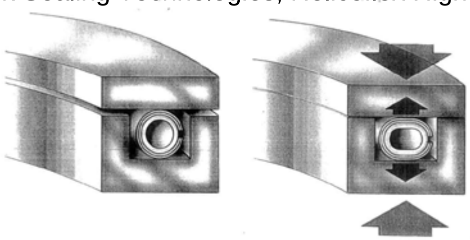
$e_2$ = optimum compression

$e_c$ = compression limit beyond which there is risk of damaging the spring




$r_u$

(Garlock Sealing Technologies, Helicoflex High performance sealing)



- $r_u = e_2 - e_1$ characterizes the efficency of the seal to absorb decompression,
- below $Y_1$ the leakage rate exceeds the level of 1E-8 $Pam^3s^{-1}$
- Influence of time and temperature on $r_u$ ?

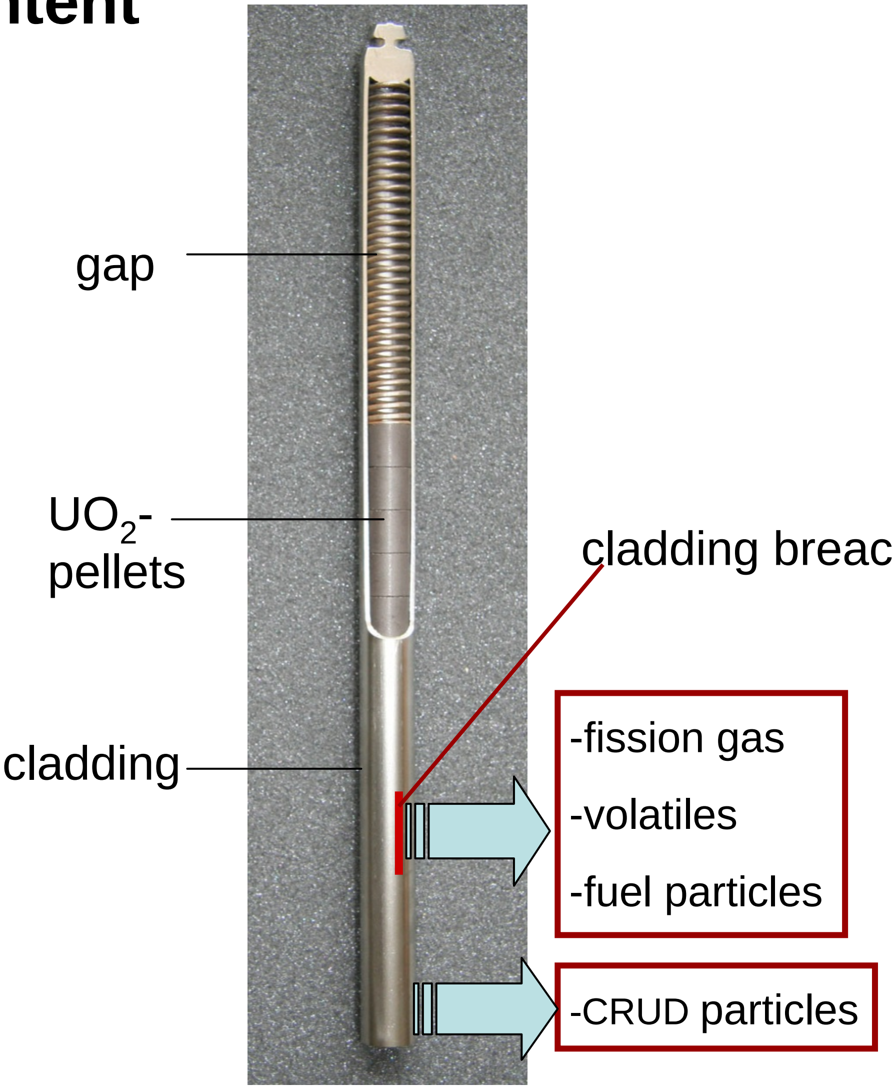
# Design leakage rates for elastomeric seals (fluorocarbon - or EPDM-rubber):

***RTC, NCT, ACT:*** $Q_{DLR} < 10^{-5}$ Pa $m^3 s^{-1}$ (limited by permeation)

- BAM test program about time and temperature depending behaviour of new material mixtures

# Releasable radioactive content

Section of a fuel assembly




Section of a rod

# Fractions of releasable radioactive content

| | | NCT | ACT |
|---|---|---|---|
| -fraction of gases that are released due to a cladding breach | $f_G$ | 0.3 | 0.3 |
| -fraction of volatiles that are released due to a cladding breach | $f_V$ | 2E-4 | 2E-4 |
| -fraction of fuel fines that are released due to a cladding breach | $f_F$ | 3E-5 | 3E-5 |
| -fraction of CRUD that spalls off of rods | $f_C$ | 0.15 | 1.0 |
| -fraction of rods that developing cladding breaches | $f_B$ | 0.03 | 1.0 |

( Values determined for burn-ups of 33 to 38 GWd/tU in Bl. Anderson, R.W.Carlson,L.E.Fisher: „Containment Analysis for Type B Packages used for Transport Various Contents“, NUREG/CR-487, November 1996)

# Do higher burn-ups have an effect on the release fraction of gases and volatiles?

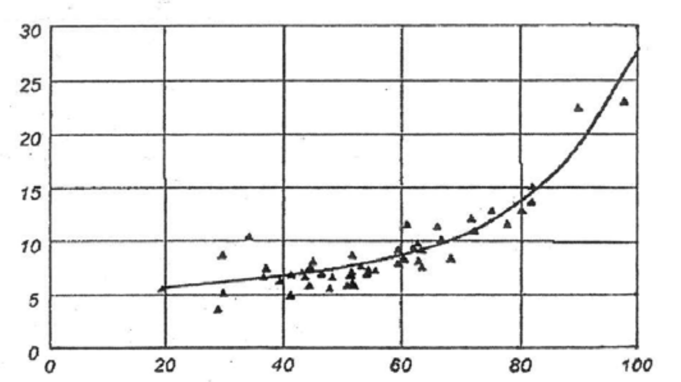
***Gases***

- dominated by Kr-85 and H-3
- generation increases linear with burnup
- release depends on temperature and fuel microstucture
- $\mathbf{f_G}$ < 0.30 up to 100 GWd/tU

  <0.15 up to 80 GWd/tU

→ **BAM accepts a release fraction of $f_G$= 0.15 up to 80 GWd/tU**

**Fission gas release (%)**




[Source: E.Weber,atw (2005), Heft11]

**Burnup (GWd/tU)**

***Volatiles***

- potentially volatile nuclides Cs-137, Cs-134, Ru-106, Sr-90
- vapour pressures of relevant compounds like CsOH, $RuO_2$ and SrO are very low
- $RuO_4$ do not exist below 600°C

→ **BAM accepts a release fraction of $f_V$=2E-4 as conservatively also for higher burnups**

# How do higher burn-ups could influence the fraction of rods developing cladding breaches?

***Two effects of cladding breaches :*** - release of gas, volatiles and fuel particles

- increase of cask internal pressure

***Higher burn-ups can cause :***

- increasing embrittlement of cladding material by hydrogen uptaken and hydride reorientation
- increasing thickness of the oxid layer resulting in a cladding thinning and higher cladding stress
- increasing closing of fuel pellet –cladding gap and formation of bondings

**BAM requires at higher burn-ups additional examination of cladding failure probability during NCT**

Current measurements: - sufficient safety margin

- limited number per transport
- encapsulation

# Summary

- Standardized method for release analysis through a capillary leak is in ISO 12807.
- $Q_{SLR}$<1E-4Pam$^3$s$^{-1}$ imply no particle release.
- $Q_{SLR}$<1E-5Pam$^3$s$^{-1}$ imply liquid- tightness.
- Design leakage rates for NCT and ACT are deduced from real cask and component tests.
- Maximum permissible widening of sealing system is < $r_u$ (except for short-term during NCT or ACT impacts).
- Influence of time and temperature on $r_u$ has to be considered.
- Release fractions for gases and volatiles for burnups about 40 GWd/tU are also applicable for higher burn-ups up to 80 GWd/tU.
- Fraction of higher burn-up rods developing cladding breaches under NCT is still an open question.