Safety Analysis Aspects of CASTOR V Spent-Fuel Transport and Storage Casks

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INTRODUCTION

GNB Gesellschaft für Nuklear Behälter mbH has a long-term experience in developing casks for the transport and storage of spent-fuel assemblies. A main type of casks built by GNB is the CASTOR type made of ductile cast iron GGG 40. All design criteria including all tests according to the IAEA regulations as a type B(U) F package (IAEA) and the acceptance criteria for the German storage sites (e.g. BLG) are fulfilled by the CASTOR V casks family which has been shown by calculational analysis and by analog evaluations on the base of experiments.

The most modern high-capacity casks of the CASTOR V type family have been developed for transport and long-term interim storage of 19 PWR or 52 BWR spent-fuel assemblies. The new casks of the CASTOR V type family are, according to the decay time of approximately 5 years and the number of fuel assemblies to be put in the cask, called CASTOR V/19 and CASTOR V/52.

The mechanical and thermal layout of the CASTOR V family are mainly focused in this report.

GENERAL DESCRIPTION

The cask body consists of a thick walled, cylindrical cask body made in one piece of ductile cast iron (DCI). DCI exhibits sufficient ductility and resistance to corrosion. The inner surfaces of the cask are nickel coated; the outer surfaces have an easily decontaminating paint on the basis of epoxy resin. For a better passive heat removal off the casks, there are machined radial fins with a height of 60 mm on the cylindrical outer surface of the cask.

The primary and the secondary lid are made of stainless steel and have separate metallic and elastomer seals to secure leaktightness. Both lids are fitted by screws.

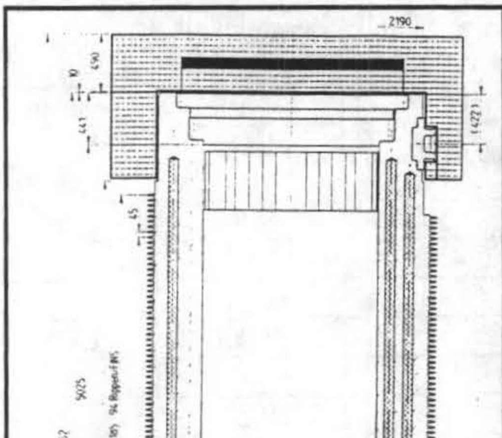
For handling operations four trunnions, two each, are placed at the top and bottom ends of the cask. The trunnions are designed according to the German KTA regulation 3905.

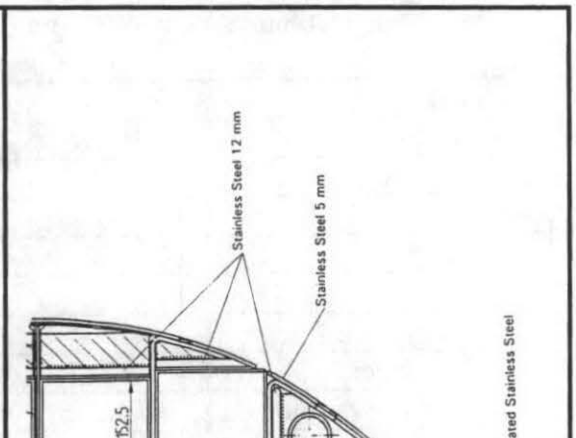
For a better neutron shielding there are moderator rods within the cask wall and moderator plates on the bottom and lid side of the cask. The material of the moderator is polyethylene.

In the cask cavity, a fuel basket made of partly boronated stainless steel is located. The basket provides fuel assembly support, criticality control, and heat conduction paths. The cask body together with the lids and seals is used as the confinement system.

During transport on the wagon, wooden shock absorbers coated by steel are fitted to the CASTOR V cask at both ends.

Figure 1 shows the transport configuration of the cask CASTOR V/19 for PWR fuel assemblies, which is 400 mm longer than the CASTOR V/52 for BWR fuel assemblies. Figure 2 shows as an example the cross section of the CASTOR V/52 basket.





GNB	CASTOR V/19 Transport config.	**Figure** **1**	**GNB**	CASTOR V/52 Basket	**Figure** **2**

The masses of the CASTOR V/19 (GNS B 98/92) and V/52 (GNB B 110/94) are summarized in the following table:

CASTOR		V/19	V/52
Weight of fuel assemblies	kg	15 900	16 640
Transport weight (loaded)	kg	136 440	135 250
Storage weight	kg	123 200	123 590

DESIGN CRITERIA

The main mechanical and thermal test respectively accident design criteria defined by the IAEA regulations and the German storage criteria are the following:

a)	mechanical tests	- transport (IAEA):	drop tets
		- storage (BLG):	earthquake, side impact, aircraft crash, gas cloud explosion
b)	thermal tests	- transport (IAEA):	800 °C for ½ hour
		- storage (BLG):	600 °C for 1 hour

CASK INVENTORY

The casks can accomodate the following types of fuel assemblies:

CASTOR V/19		homog.	heterog.	heterog.
Type of FA	**PWR**	**UO_2**	**UO_2**	**UO_2**
Max. no. UO_2-FA		19	15	15
Max. average burnup	GWd/t_{HM}	55	55	55
Initial enrichment in U_{235}	%	4.05	4.05	4.05
and				
Type of special FA	**PWR**	**-**	**MOX**	**UO_2**
Max. no. special FA		-	4	4
Max. average burnup	GWd/t_{HM}	-	55	65
Initial enrichment in U_{235}	%	-	3.95 / 3.7 *)	4.05

CASTOR V/52		homog.	heterog.
Type of FA	**BWR**	**UO_2**	**UO_2**
Max. no. UO_2-FA		52	52
Max. average burnup	GWd/t_{HM}	55	55
Initial enrichment in U_{235}	%	4.05	4.05
and			
Type of special FA	**BWR**	**-**	**MOX**
Max. no. special FA		-	16
Max. average burnup	GWd/t_{HM}	-	50
Initial enrichment in U_{235}	%	-	5.7 / 5.5 *)

*) content of (Pu-fiss + U-235) respectively Pu-fiss

The mass of heavy metal per fuel assembly is 542 kg for the CASTOR V/19 and 187 kg for the CASTOR V/52. The maximum allowable heating per cask is 40 kW.

DESIGN OF THE IMPACT LIMITERS AND STRESS ANALYSIS OF THE CASK BODY

The aim of the impact limiters is to reduce the decelerations on the cask caused by the above-mentioned drop tests in such a way that the stresses in the cask remain lower than the allowable values. The analysis is based on the law of energy conservation:

$$E_{pot} = E_{kin}(t) + E_V(t)$$

$$E_{pot} = \frac{1}{2} m v^2(t) + \int_0^t \int_0^{A(x)} \sigma(x, A) . dA \ v(t) . dt$$

With E_{pot} potential enery,
$E_{kin}(t)$ kinetic energy in the cask at the moment t,
$E_V(t)$ deformation energy in the impact limiter at a moment t,
m mass of the cask,
v(t) velocity at a moment t,
$\sigma(x,A)$ local compressive stress in the impact limiter material within an area A with a deformation path x,
A(x) local deformation contact area of the impact limiter with a deformation path x,
t impact duration up to a deformation x.

Because of the unyielding and rigid surface of the IAEA drop test foundation, the basis for the analysis is that the whole impact energy will be dissipated by plastic deformation of the impact limiter. During the impact process kinetic energy decreases in the same amount that the part of deformation work increases during the impact. The compressive stresses are calculated from the local deformations according to the stress-compression characteristics of the wooden impact limiter which have been investigated by experiments. The compression characteristic of different wood types has been implemented into the software called DROP which is calculating according to the above-mentioned model. DROP has been benchmarked by several experimental drop tests. Conservatively, the steel coat of the impact limiters has been neglected.

To verify the results calculated with the DROP-code and to get the maximum stresses, additional comparisons of the CASTOR V types with experimental results of several drop tests with other, very similar CASTOR casks were made (GNS B 98/92; GNB B 110/94). The results show differences of maximum 11 % in the deceleration between the calculation and the experimental drop tests, which is within the usual tolerance range of designing impact limiters, especially taking into account the range of tolerances of wood characteristics. The following table shows the maximum decelerations and deformations of the CASTOR V/19 respectively V/52:

	Drop on side wall	Drop on bottom side	Drop on lid side	Drop on lid/bottom side
Maximum deceleration	110 g	95 g	88 g	70 g
Maximum deformation	195 mm	220 mm	216 mm	560 mm

For the maximum deceleration of 110 g, the maximum bending stress was calculated according to the one-dimensional transverse beam model, which has been benchmarked by several drop tests (GNB B 2/93):

$$\sigma_{b,max} = M_{b,max}/W$$

with

$\sigma_{b,max}$ as maximum bending stress; $M_{b,max}$ as maximum bending moment;
W as moment of resistance under consideration of the weakening by the moderator boreholes.

The maximum tensile stress of the CASTOR V casks is 81 N/mm^2, which is well below the half of the yield stress Rp of the cask material DCI under accident conditions at the design temperature of 130 °C (GNS B 98/92; GNB B 110/94):

Temperature [°C]	Tensile stress of DCI [N/mm^2]	Yield stress of DCI [N/mm$^{2]}$	Allowable yield stress ½ Rp(T) [N/mm^2]
20	300	230	115
130	281	215	108

MECHANICAL ANALYSIS OF THE FUEL BASKET

The baskets are made of stainless steel, boronated stainless steel, aluminum, and copper. Boronated steel is used for subcriticality; aluminum and copper, for the improvement of heat removal.

The analyses of the fuel baskets are conducted using the ANSYS finite element program. ANSYS has been validated by SANDIA benchmark calculations as well as for comparisons to real drop tests which have been done for several CASTOR casks (R. Diersch et al. 1993). The analyses consist of reviewing the stresses and displacements in the baskets when the loads occur on those orientations which represent the extremes. The maximum deformations are 1 mm, which has been taken into consideration in the criticality calculations. The integrity of the fuel basket and the positions of the fuel assemblies remain unchanged, and criticality safety is sufficiantly guaranteed.

THERMAL LAYOUT

The heat dissipation of the CASTOR V packages is performed in a passive manner according to the design principle of all CASTOR casks so that an active heat dissipation system is not necessary, neither under transport nor under storage conditions.

To prove that the maximum heat inventory can be dissipated without influencing the contents, the confinement, and the shielding, the load case is analysed which leads to the maximum temperatures in the components. For the normal transport conditions, this is the transport of the horizontal cask under a transport hood taking into account the insolation, with the assumption that the cask will not be supervised for 1 week. During the transport the cask is lying in the transport cradle and equipped with impact limiters under a hood. The calculation has been done in several steps from outside to inside of the cask by calculating the following:

- the temperature of the outer side wall of the cask at the ground of the fins;
- the temperatures in the components, taking into account the reduced heat conductivity in the area of the moderator bore holes; and
- the fuel element and basket temperatures, taking into account the special geometries and heat transfer mechanism in this area.

THERMAL CALCULATIONS OF TRANSPORT HOOD AND COMPONENTS

The calculation of the temperatures at the transport hood and the cask surface is based on the determination of the thermal equilibrium between cask, hood, and environment, taking into account the insolation on the hood surface.

For the formulation of a calculation model, the following conservative assumptions were made:

- The cask dissipates its heat by convection and radiation. Therefore only the area between the impact limiters is taken into account.
- The heat radiation of the cask is completely absorbed by the transport hood; only the surface adjacent to the cask surface is taken into account.
- At the outer side of the hood the heat is dissipated by radiation and convection. At the inner side of the hood, convective heat is dissipated to the environment over the hood ventilation. No heat resistance between hood inside and outside is considered.
- For the heat dissipation off the transport hood, conservatively, only that surface of the hood (inside and outside) adjacent to the cask surface is considered.
- The insolation required according to IAEA for a duration of 12 hours per day is conservatively regarded as constant and lasting 24 hours.
- As the maximum temperatures of the components for unsupervised transportation phases have to be considered, a stationary transport cask is assumed; i.e., cooling due to airstream is neglected.

The temperatures of the hood and the cask surfaces can be determined from energy equilibrium:

Cask:	Q_I	$= Q_{C,CS} + Q_{R,CS}$
Transport hood:	$Q_S + Q_{R,CS}$	$= Q_{R,H} + Q_{C,H,i} + Q_{C,H,a}$
Hood ventilation:	$Q_{C,CS} + Q_{C,H,i}$	$= Q_L$

With Q_I : heat of the cask contents, Q_s : insolation to the hood,
$Q_{C,CS}$: heat flow from the cask surface by convection
$Q_{R,CS}$: heat flow from the cask surface to the hood by radiation,
$Q_{R,H}$: heat flow from the hood to the environment by radiation,
$Q_{C,H,I}$: heat flow from the hood into the wagon by convection,
$Q_{C,H,a}$: heat flow from the hood to the environment by convection,
Q_L : heat flow from the wagon to the environment by airstream.

The thermal analysis of the basket and the cask body has been done by the benchmarked Finite Element Code TOPAZ2D. For the calculation the following assumptions were made:

- Only the cask cross section of the uncovered side wall surface is considered.
- The heat transfer in the wall of the cask is performed by heat conduction. The effective heat conductivity of the moderator zone is determined by precalculations also with the Finite Element Code TOPAZ2D.
- The inventory of the cask has also been taken into account. Precalculations were done to get the effective conductivities radial as well as axial.
- In the area above the basket the conductivity increases by convection of the helium in the cavity. The equivalent conductivity coefficient was therefore calculated according to the rule from Nusselt for heat transport in vertical layers.

The time-depending calculations of the heating test were done according to the IAEA regulations and the German regulations for the storage sites. Therefore the load case with the maximum temperatures of the stationary calculated temperatures during normal transport has been used. The caloric material properties relevant to the calculation were taken into account in dependency of the temperature. Shielding and confinement must be maintained during the test.

The maximum temperatures of the components of the CASTOR V/19 respectively V/52 are calculated as follows:

	Normal transport [°C]	Fire test [°C]	Normal storage [°C]	Allowable temperature [°C]
Hood	66	-	-	85
Outer surface of cask	104	370	104	-
Lid seals	118	206	84	280; 204/288
Moderator material	125	259	134	300
Inner side wall	139	205	137	-

So,

- the temperature of 66°C is below the maximum allowable temperature at the easily touchable surface of the package (85°C, IAEA)
- the maximum temperature of the moderator zone with 259°C is below 300°C, which is the temperature when the material of the moderator starts to decompose the low-molecular polyethylene and other carbon hybrids. Thus, the neutron shielding is guaranteed even for the heating test;
- the maximum temperatures at the lid seals during normal transport are with 118°C below the temperatures for which the tightness of metal and elastomer seals is guaranteed (280-380°C for metal seals depending on the torus diameter, 204°C for elastomer seals). During the heating test the temperatures of the seals in the primary and secondary lid are maximum 206°C, which is lower than the allowed maximum temperatures of 280°C for metal seals and 288°C during maximum100 h for elastomer seals.

The maximum temperatures of the fuel rods are 362°C under normal transport, 392°C at the heating test, and 354°C under normal storage conditions. The temperature of 392°C only appears during the heating test for a short while.

CONCLUSIONS

The design of the CASTOR V casks is highly qualified. Due to the above mentioned calculation models, which were qualified by several benchmark calculations as well as comparisons to a lot of experiments with other CASTOR casks, the time and the costs of developing have been minimized.

The CASTOR V/19 has already been licensed for transport and storage by the German authorities.

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