ASSESSMENT OF CASK-SPECIFIC QUESTIONS OF DRY INTERIM STORAGE OF SPENT FUEL ASSEMBLIES IN A SHIPPING-CASK STORAGE SITE AT AHAUS

BAM (Federal Institute for Material Examination)

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This Opinion consists of pages 1 to 127

[Translator's note: The last page in my copy is numbered 126]

1. Introduction

By letter of June 16/30, 1981, the Physikalisch-Technische Bundesanstalt [Federal Physical and Technical Institute] (PTB), Braunschweig, as regulatory authority in accordance with §§ 6, 23 Para. 1 No. 4 of the "Atomgesetz,"* directed the Bundesanstalt für Materialprüfung [Federal Institute for Material Examination] (BAM), in accordance with § 20 of the "Atomgesetz," to perform an expert examination of cask-specific matters for the dry interim storage of spent fuel assemblies in a shipping-cask storage site at Ahaus, State of Nordrhein-Westfalen, District of Borken. This assignment was given at the joint request of the Deutsche Gesellschaft für Wiederaufarbeitung von Kernbrennstoffen mbH [German Nuclear Fuel Reprocessing Company, Inc.] (DWK), Hannover, and STEAG Kernenergie GmbH [STEAG Nuclear Energy, Inc.], Essen, made to PTB on Oct. 3, 1979.

The applicant's plan is described in the DWK/STEAG "Safety Analysis Report: Ahaus Shipping-Cask Storage Site" [U 1].

Under the contract, the safety testing and evaluation extends to examining storage-specific matters of the CASTOR family of casks intended for storage use:

- special fittings for casks, especially seal rings, cover system and cask monitoring
- loads on casks and their components during normal service, especially with regard to radiation embrittlement, decay-heat output of fuel

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*Law on the Peaceful Use of Nuclear Energy and Protection from Its Dangers, version of the Notice of Oct. 31, 1976 ("Bundesgesetzblatt" I, p. 3053), last amended by the Law of Aug. 20, 1980 ("Bundesgesetzblatt" I, p. 1556).

assemblies, internal pressure, residual moisture, environmental effects, and creep behavior

loads on casks and their components under accident conditions, especially with regard to mechanical loads (generated by free drop tests onto an unyielding foundation and by penetration tests simulating an aircraft crash) and thermal loads (due to a fire and to impaired removal of fuel-assembly decay heat from the cask)

quality assurance in the fabrication, assembly and operation of casks and their components, as well as repair or restoration of suitability for storage after a single hypothetical failure of a seal barrier

Under the contract, military action, sabotage and the actions of third parties are not covered in this examination.

If effects on a cask due to its contents are to be considered, under the contract we also take into account the information provided by the other agency performing an examination, the Technischer Ueberwachungs-Verein Hannover e.V. [Hannover Technical Inspection Board, Inc.] (TUV Hannover) [L 1].

With regard to whether the penetration tests were representative as simulating loads due to an aircraft crash, the position of the Gesellschaft für Reaktorsicherheit [Reactor Safety Society] (GRS), Cologne, was adopted [L 17].

Statements in this Opinion refer to the CASTOR Ia, Ic and IIa cask types, which are based on the same design principle with respect to the arrangement and form of safety-relevant parts and components.

Effects of mechanical loads (resulting from drop tests) and of thermal loads are presented for the CASTOR Ic cask type by way of example. This cask type was tested under the provisions of the transportation laws for a Type B(U) packaging for the shipment of radioactive materials [L 8, L 9, L 14, L 23, L 24], with a positive result [L 39]. Because test certificates containing the assessments of drop tests and thermal loads are required for the other cask types before package type approval can be issued under the transportation laws, it is certain the statements made in this Opinion about the cask integrity, tightness, and activity release under the accident conditions cited above are also valid for the CASTOR Ia and IIa cask types.

The examination was based above all on the following documents:

- Safety Analysis Report on the Ahaus Shipping-Cask Storage Site [U 1]
- documents on the cask types CASTOR Ia [U 49], CASTOR Ic [U2, U 29 to U 37] and CASTOR IIa [U 51]
- revisions and supplements later issued to the documents identified above

These documents are explicitly listed in the appropriate sections of this Opinion.

The examination was performed in accordance with the laws, regulations, rules, guidelines and recommendations applicable to this activity. All documents used in the preparation of this Opinion are listed at the end of the Opinion; documents provided by the applicant have "U" numbers, while other documents and publications have "L" numbers. In addition, special knowledge of BAM, some of which has been set forth in Comments, was used in preparing the Opinion.

This Opinion is intended to aid the PTB in assessing whether, from the standpoint of the "Atomgesetz," the requirements for approval with respect to the safeguarding of irradiated fuel assemblies in a shipping-cask storage site are fulfilled.

This Opinion is based on the level of knowledge, testing and examination of documents supplied up to October 1982 inclusive. Further comments on documents and evidences that are subject to examination will be provided before storage begins, in the framework of continuing examination by an expert to be called in by the PTB. Such comments will be included in BAM Test

Certificates covering type testing of CASTOR Type B(U) packagings for the shipment of radioactive materials.

Fig. 1-1 is a schematic representation of the most important aspects of the safety examination of a cask for the dry interim storage of spent fuel assemblies.

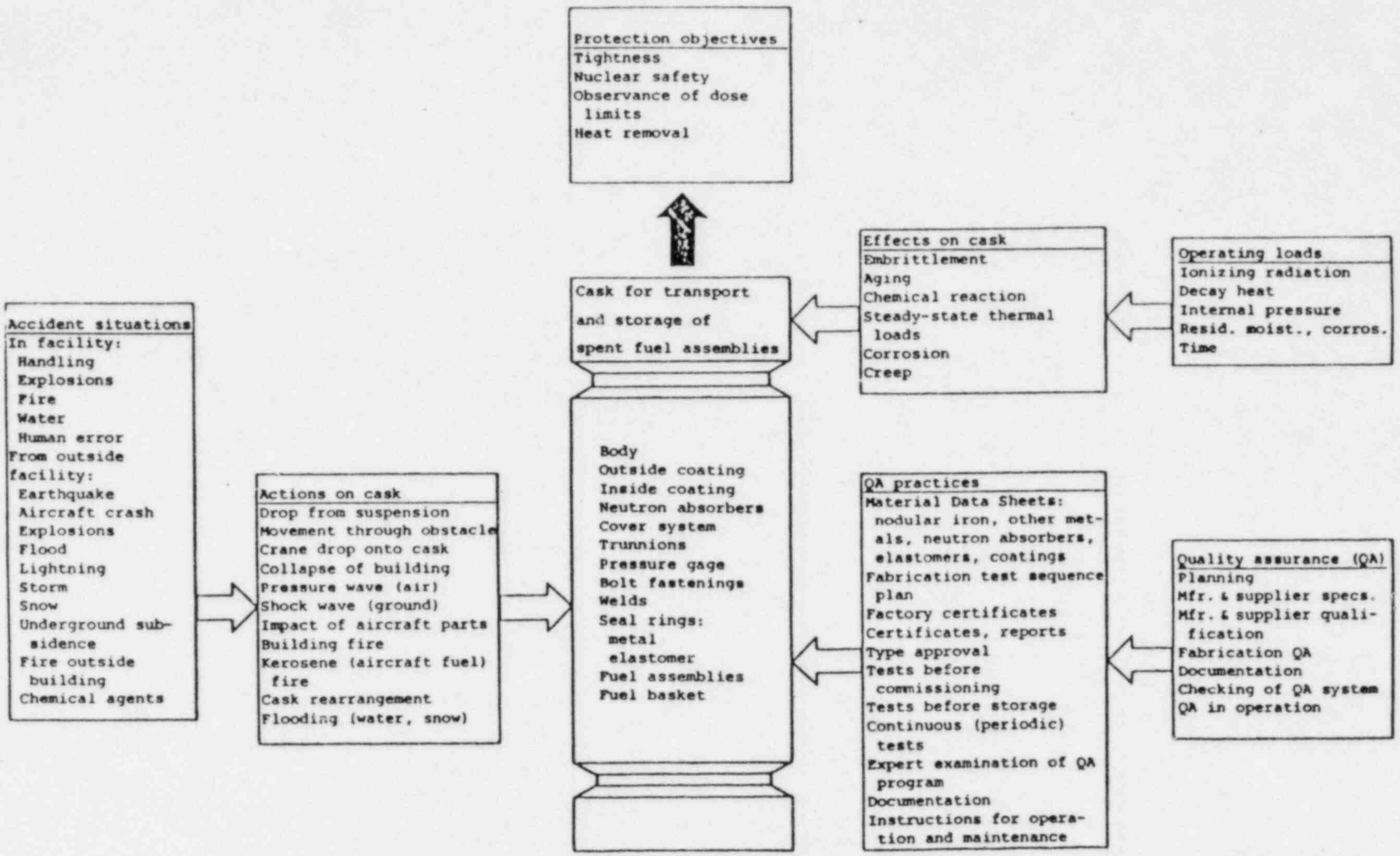

Fig. 1-1. Points considered in examination of casks for storage of spent fuel assemblies.

2. Description of the CASTOR Cask Design

The CASTOR (Ia, Ic, IIa) shipping and storage casks share a common design principle. They differ only in having the dimensions of the cask components altered to suit the several intended applications (numbers and types of fuel assemblies inserted).

The casks are described in the following documents: CASTOR Ic [U 29]; CASTOR Ia [U 49]; CASTOR IIa [U 51]. In the subsections of Section 3 we will go into more detail on the specifications and qualification of the components and materials.

The description that follows uses the CASTOR Ic cask as an example. Except for the measurements, the discussion of the cask body and the cover and seal system also applies to the CASTOR Ia and IIa types.

2.1. Cask Body

The body of the cask consists of a casting of GGG 40 (cast iron with nodular [spheroidal] graphite), produced in a single operation.

The cask body is square in cross section, both inside and outside, with the outside corners greatly rounded.

The interior and the top and bottom parts of the outside have a galvanically applied nickel coating. In the region of the seal surfaces this coating is intended to provide the needed surface finish and good corrosion resistance.

The cask has the following outside dimensions (without impact limiters):

Length, about 5500 mm. Cross section at base of fins, about 1580 mm x 1580 mm; at tip of fins, about 1780 mm x 1780 mm. Usable inside dimensions of shaft to accept fuel assemblies: length, about 4550 mm; cross section, about 670 mm x 670 mm. Wall thickness in side region (inside wall to base of fins), about 440 mm.

The outside of the body has lengthwise cooling fins to improve heat removal.

For improved neutron shielding, two concentric rows of axial holes in the wall of the cask body are filled with plastic rods (moderator material). The bottom and the secondary cover each have a slab of the same material inserted for the same purpose.

Two pairs of trunnions, one pair at the top end and one pair at the bottom end, are inserted into the cask body and bolted in place. Lifting tackle can be attached to the trunnions.

The finned part of the surface has several coats of epoxy-based decontaminable paint.

During shipping, the cask is also protected by an impact limiter (sheet-metal structure packed with wood) at either end (top and bottom).

2.2. Cover and Seal System

The "tight containment" is formed by the cask body together with two covers, one over the other. The covers are separately sealed and held in place by bolts and cap nuts. This cover and seal system is also protected from external effects by a guard plate.

The first seal barrier is the inner or primary cover, about 340 mm thick. It is a disk-shaped (cylindrical) body with an offset (shoulder) in the diameter and has grooves to accept elastomer seal rings (radial and axial seal rings or gaskets) as well as an axially positioned* metal gasket. The primary cover has the following penetrations for the performance of necessary handling operations during loading and unloading:

a hole for flooding and draining the inside of the cask. The continuation of this hole in the side wall of the cask body gives access to the interior from the bottom end. After loading, the hole is closed with a seal plug sealed with elastomer gaskets

a hole for evacuating the inside of the cask or filling it with helium through a vacuum valve inserted in the hole and sealed with a metal gasket

Both these holes are covered with seal covers, each with a metal gasket. This arrangement insures long-term sealing of the penetrations in the primary cover.

three test holes (A, B and C) giving access to the spaces between gaskets, so that instruments can be connected for tightness testing and the subsequent drying operations. The test holes are closed with seal bolts that have metal gaskets. Test holes A and B lead to the between-gasket spaces on the inside-cask side of the metal gasket position. The outer ends of these test holes are also covered by the seal covers mentioned above

The second seal barrier is the outer or secondary cover, about 130 mm thick. It is a disk-shaped (cylindrical) body and has grooves to accept an elastomer gasket and a metal gasket. Both gaskets are axial.

The secondary cover contains the following components and holes:

a layer of moderator material about 60 mm thick, which is penetrated

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*In this Opinion, gaskets are called "axially (radially) positioned" if the sealing force acts in the axial (radial) direction.

by a concentric web and is covered with a welded-in seal plate

a quick-release coupling valve, screwed into a hole that leads to the inaccessible space between the primary and secondary covers and closed by a bolted-on seal cover with a metal gasket

the cask monitoring system, which essentially consists of a pressure gage with which a drop in pressure in the inaccessible space can be detected. The pressure gage is bolted in and sealed with a metal gasket

a test hole for connecting measuring instruments so that the tightness of the secondary cover gaskets can be checked. This test hole extends into the space between the metal and elastomer gaskets and is closed with a seal bolt that has a metal gasket to seal it

A guard plate about 80 mm thick is placed on top of the secondary cover and sealed with two elastomer gaskets. The guard plate contains a ring of moderator material, which lies over the steel web in the secondary cover and is covered with a welded-in seal plate.

Under the repair concept [U 1, Sect. 4.1.3], if a metal gasket in the primary cover becomes leaky, the second barrier is to be restored by a welded-on "insert cover." Another guard plate is installed over the insert cover.

The metal gaskets used in the CASTOR casks for storage consist of a coil spring in O-ring form with a double metal jacket.

The effectiveness of the metal gaskets depends on plastic deformation of the outer jacket and elastic deformation of the spring core.

2.3. Monitoring System

The space between the primary and secondary covers (inaccessible space) is filled with inert gas (p_{abs} = 6 bar). The interior of the cask contain-helium (p_{abs} = 0.8 bar). The tightness of the two covers is monitored by surveillance of the pressure in the inaccessible space, which will decrease if one or both covers become leaky.

In the storage version of the cask, the secondary cover contains a pressure gage, which triggers an alarm if the pressure in the inaccessible space falls to p_{abs} = 3 bar* [U 1]. Section 3.1.7.4 of this Opinion describes the function.

2.4. Internals and Contents

A fuel basket inserted into the cask interior is made of borated stainless steel. It serves to fix the fuel assemblies in place and is intended to prevent a change in fuel assembly position (for reasons of criticality safety) even when the cask is flooded (loading and unloading at power plant).

The fuel basket is a welded structure with a square-cross-section grid corresponding to the shape and number of fuel assembly clusters.

According to data supplied by the applicant [U 1, Table 2.5-1.2], the CASTOR casks accept fuel assemblies from light-water reactors as follows:

CASTOR Ia: up to 4 PWR fuel assemblies (Biblis A)

CASTOR Ic: up to 16 BWR fuel assemblies (Würgassen)

CASTOR IIa: up to 9 PWR fuel assemblies (Biblis A)

The interior of the cask contains helium (p_{abs} = 0.8 bar); the inaccessible space is filled with inert gas (p_{abs} = 6 bar).

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*The reference pressure of the pressure gage is set to 3 bar at 293 K (20°C). This value may rise to about 3.7 bar at the beginning of storage because of the cask temperature increase; see Section 3.1.7.4.

3. Safety Testing and Assessment of Storage Casks

3.1. Loads under Normal Service Conditions

In the operation of the Ahaus Shipping-Cask Storage Site, loads are imposed on a storage cask on the basis of the following effects:

- ionizing radiation
- decay heat of fuel assemblies
- internal pressure, if fuel-rod cladding tubes are defective
- residual moisture in the cask interior and in the seal system
- fission products in the cask interior, if fuel-rod cladding tubes are defective
- corrosive environments
- length of storage period

3.1.1. Ionizing Radiation

In metallic materials, radiation damage is caused mainly by neutrons with energies of more than 100 keV ("fast" neutrons). In comparison with the neutron effect, the effect of alpha, beta or gamma radiation on metallic materials is negligible. A detrimental change in the mechanical properties of metals should not be expected until after a neutron fluence in excess of 10^{18} cm^{-2} [L 2 to L 7].

A document provided by the applicants [U 48] deals with the neutron fluence at the interior surface of a CASTOR Ic cask. According to that document, in 40 years the neutron fluence (for neutron energies greater than 100 keV) at the interior surface of the cask is less than $4 \cdot 10^{13}$ cm^{-2}. TUV Hannover estimates for this type of cask (loaded with Würgassen-type BWR fuel assemblies) give figures on the same order of magnitude [L 12]. The order of magnitude is also borne out by BAM estimates of the neutron fluence at the inner wall of a CASTOR IIa cask (loaded with Biblis-type PWR fuel assemblies). For casks of the CASTOR Ia type, the neutron fluence should not be expected to depart so far from these figures that the limiting value for a change in the properties of metallic materials, which lies some powers of ten higher, could be even approximately reached [L 12].

Once the neutron fluence at the interior surface of the cask expected in a storage time of 40 years (under 10^{14} cm^{-2}) is compared with the limit above which a negative effect on the material properties could be expected, it can be stated that damage to the metallic cask materials due to the effect of ionizing radiation is out of the question.

Radiation damage can also impair the shielding action of the moderator material used, primarily hydrogen being removed from the chain molecules of the material. The radicals generated can then continue to react. Because the moderator material is located in closed spaces, so that air cannot reach it, the only reactions of importance here are crosslinking and gas evolution.

At the energy-dose values expected here (156 Gy in the case of the moderator rods, 34 Gy for the moderator material in the secondary cover and the bottom [U 4, L 12]), the degree of crosslinking is so slight that no provision need be made for substantial changes in the mechanical and thermal properties of the moderator material [L 38].

Radiation damage can further impair the sealing action of the elastomer seal rings used. Since, however, the applicants do not wish to take any credit for the sealing action of these rings with respect to long-term behavior, radiation effects have been considered only to the extent that no degradation products are formed that themselves have detrimental effects on other cask components (e.g., the metal seal rings). In order to prevent the appearance of this type of aggressive degradation products as a result of radiation effects, only silicone rubber is employed for the elastomer seal rings; no corrosive degradation products are eliminated from this material [L 40].

3.1.2. Decay Heat of Fuel Assemblies

In the shipping cask, the decay heat generated by the fuel assemblies is transferred to the inner surface by thermal radiation, conduction and free convection, and from the inner surface is transported to the outer surface of the cask essentially by heat conduction. The heat is then dissipated by radiation and by convective flow of the surrounding air.

Under the specifications set forth by the transportation laws for a Type B(U) cask [L 8, L 9, L 23--Rn 1603 (8), L 24], the greatest permissible temperature difference between the accessible surface and the environment is 44 K, so that the temperature on the accessible surface of the cask must not exceed a value of 355 K (82°C). This requirement directly implies a limitation of the maximum heat output of the fuel assemblies to be stored for each individual cask in the Ahaus Shipping-Cask Storage Site [L 10, L 39].

After the loading of a shipping cask at the nuclear power plant, and after a steady thermal state has been established, surface-temperature measurements on every loaded cask are used to make certain that the maximum value of the temperature difference between the accessible surface and the environment does not exceed 44 K and that the temperature of the accessible surface does not exceed 355 K (82°C). This requirement is observed through the verifiable performance of an order (e.g., Proposed Order A2 in [L 39] for CASTOR Ic casks) applying to casks approved under the transportation laws.

The following additional boundary conditions are known:

According to data from TUV Hannover [L 1], a cask standing in the shipping-cask storage site building may have a cask surface temperature 10 K higher.

The temperature of a painted surface as determined by a contact thermometer is some 5 K lower than the temperature of the outer metal cask surface (a result confirmed by BAM measurements).

Given these conditions, if a shipping cask after loading at the nuclear power plant has the highest permissible surface temperature under the transportation laws--355 K (82°C)--as determined by a contact thermometer on the painted surface, then in the shipping-cask storage site a maximum temperature of about 370 K (97°C) at the outer (metal) cask surface is expected.

The highest permissible surface temperature under the transportation laws is based on a hypothetical ambient temperature of 311 K (38°C) at temperature equilibrium after the loading of a shipping cask at the nuclear power plant. If loading or the establishment of temperature equilibrium takes place at a lower ambient temperature (e.g., at $T_U = 311\ K - T_x$), then, to a first approximation, the cask surface temperature T_{BO} will also be lower by the same difference ($311\ K - T_x$).

Calculations on the dissipation of decay heat from the shipping cask, performed at TUV Hannover, have shown that the maximum surface temperature of a CASTOR Ic cask does not exceed a value of 369 K (96°C) when the ambient temperature is 300 K (27°C) and the decay-heat output is 30 kW. This same value is not exceeded in the cases of the CASTOR Ia and IIa casks either [L 1].

This calculated value is in good agreement with the maximum cask surface temperature in the shipping-cask storage site, determined on the basis of the specifications of the transportation laws. The TUV Hannover calculation is conservative, since it was based on a difference of

$$T = T_{BO} - T_U = 369\ K - 300\ K = \underline{69\ K}$$

between the surface and ambient temperatures, while the temperature derived from the specifications of the transportation laws is based on a smaller temperature difference of

$$T = T_{BO} - T_{U} = 370\ K - 311\ K = \underline{59\ K}.$$

We can state that--under the specifications of the transportation laws for Type B(U) packages--the maximum temperature of the metal cask surface (370 K (97°C)) cannot be exceeded for any of the CASTOR cask types in the shipping-cask storage site.

We point out that not only the highest permissible cask-surface temperature as cited above, but also the limit of the permissible cladding-tube temperatures, create a limitation on the decay-heat output. This is the position adopted by TUV Hannover in its Opinion [L 1].

With regard to the assessment of thermal loads on cask components under normal service conditions, the temperature gradient over the cask wall is also of importance. After evaluating the thermal calculations and measurements provided by the applicants [U 11, U 20, U 50, U 52, U 53, U 54, U 62, U 63, U 64, U 65], we took a maximum difference of 30 K between the inner and outer walls at the hottest point of an upright cask (top half of wall below cover region) as the basis for the analysis that follows. Through our calculations we are convinced that this difference of 30 K is a conservative value.

The cask-wall temperatures defined by the above limitation on cask-surface temperatures should be regarded as noncritical for a negative change in the mechanical properties of the <u>metallic materials</u> used--e.g., the casting, stainless-steel covers, fasteners, metal seal rings. In particular, for the metal seal rings that are responsible for the seal action, experimental studies have shown that the seal action does not diminish until substantially higher temperatures are reached [U 3]. The metal seal ring subjected to the highest temperature is (because of the geometry) the metal seal ring in the primary cover; however, because of the axial temperature profile [U 11, U 50] and its positioning, this component is subject only to temperatures $\leq$ 388 K (115°C). We have confirmed this by our own estimates.

With regard to the behavior of the moderator material in the bottom, secondary cover, guard plate, and lengthwise holes in the cask wall, we have checked whether the specified material values, component dimensions and cavity dimensions as provided by the applicants [U 5 to U 8, U 29, U 49, U 51] are sufficient to prevent undue thermal expansion of the moderator material as a result of a temperature rise under normal service conditions. A thermal expansion would be undue if the volume of the moderator material became larger than that of the corresponding cavity, so that the pressure built up in such a way that moderator material might escape from the cavity provided.

Through measurements of the thermal expansion on longitudinal and transverse specimens of the rod material intended for use, we were able to confirm the temperature dependence of the unit volume [U 7] employed in the subsequent analysis.

In an upright cask, because of the thermal conditions, an axial temperature profile comes into being; the bottom and top regions are at lower temperatures than the middle and, in part, the upper half of the wall region. This nonuniform temperature distribution has been confirmed by a number of measurements [U 11, U 50, U 52, U 54]. Employing the highest cask-surface temperature of 369 K (96°C) as calculated by TUV Hannover [L 1], the axial temperature profile from [U 11] normalized to this temperature, and a constant temperature difference of 30 K across the cask wall, and taking into consideration the position of the moderator rods (length and position in depth), we have determined the temperature distribution in a moderator rod. In this way the data on this point supplied by the applicants [U 7] have been essentially confirmed.

From the temperature distribution found and the unit-volume figures cited in [U 7], the coefficient of volume expansion (referred to an installation temperature of 293 K (20°C)) was calculated. We compared these values with the capacities available and found that the cavities meant to accept the moderator material (with the dimensions given in [U 8, U 29, U 49, U 51]) are adequately sized and can accommodate volume expansion resulting from the temperature under normal service conditions.

The seal action and geometry of the elastomer seal rings used can likewise be affected by service temperatures. The temperatures prevailing in the seal regions are below the failure threshold of the elastomer seal rings intended for use (< 473 K (200°C)) and, furthermore, will decline in the course of storage [L 11]; therefore temperature stress will not have a detrimental effect on the elastomer seal rings. However, as was mentioned in Section 3.1.1, the elastomer seal rings are not important for maintaining the long-term seal action, and so the elastomer seal rings were not assessed with regard to the additive loading due to temperature, time and ionizing radiation.

3.1.3. Internal Pressure If Fuel-Rod Cladding Tubes Are Defective

On the assumption of a 100% defect rate for fuel-rod cladding tubes, with the resulting release of radioactive fission gases and of the fill gas (He) from the fuel rods, according to our estimates for the CASTOR Ia cask type, the pressure in the cask interior will rise from p_{abs} = 0.8 bar (He, 513 K) to p_{abs} = 2.3 bar (He + fission gases, 513 K). The pressure rise will be smaller in casks of the CASTOR Ic and IIa types. The possibility of undue stress due to the internal pressure cited can be eliminated.

The cask body (CASTOR Ia prototype) has passed without damage a water-pressure test [U 66] in which a much higher internal pressure was imposed. A

CASTOR Ic with primary cover in place survived a pressure test with $p_{abs} = 3.6$ bar (N_2, held for 1 hr) [U 47] without impairment of the seal function.

3.1.4. Residual Moisture in the Cask Interior and in the Seal System

Because the cask must be loaded with fuel assemblies under water, the effects of residual moisture remaining in the cask (i.e., possible corrosion) must be considered.

Our analysis of corrosion problems relates to the cask body, the primary and secondary covers, the various seal plates in the primary and secondary covers, the outer guard plate and, particularly, the metallic seal systems. A distinction must be made among the corrosive stresses during the loading process (action of deionized water), the long-term service stresses occurring during subsequent storage or as a result of the loading process (residual moisture, atmosphere), and corrosion due to a supply of elemental corrosive fission products (see Section 3.1.5 for the action of corrosive fission products).

3.1.4.1. Cask Body

During the loading process, the cask body is exposed to the action of deionized water or moisture on all sides, for a maximum time on the order of about 20 hr. This length of time is not enough to bring about any kind of corrosion damage, given the wall thickness of about 440 mm, the inside protection by a thick coating of nickel, and the outside protection by an epoxy resin paint. After draining by pump and evacuation to 3 mbar, the quantity of residual water remaining inside the cask is small [U 9]; for this reason, even the direct reaction

$$mH_2O + nMe \rightarrow mH_2 + Me_nO_m$$

(where Me is metal and m and n are numbers of moles), assumed as the worst case for higher temperatures, represents no corrosion risk.

Because the inside of the cask is free of oxygen, oxygen corrosion in combination with the residual moisture is excluded. There is no need to consider an additional long-term release of water, for example from water included in damaged fuel assemblies, because--until appropriate evidence is presented that defective fuel assemblies are free of water--the applicants will place only undamaged fuel assemblies in the cask (for more detail on this point, see the TUV Hannover Opinion).

3.1.4.2. Covers

The discussion on corrosion hazards to the cask body during loading and in subsequent storage service applies, as appropriate, to the primary cover, secondary cover and guard plate. Neither external corrosive attack nor residual moisture in the interior represents a risk to the cover system; this statement takes in seals and seal plates on the holes in the primary cover, secondary cover and guard plate.

3.1.4.3. Seal Rings and Seal-Ring Region

In contrast to the cask walls and cover walls, whose thickness precludes corrosion damage, the seal rings or seal systems must be regarded in the overall cask concept as the most corrosion-sensitive region. All connecting paths between the cask interior and the environment must be secured, as provided in the design drawing [U 29], by at least two metallic seal rings (barriers) with aluminum outer jacketing and by additional elastomer seal rings. The long-term seal function is due to the metal seal rings alone. Because the bearing area between the metal seal ring and the seal surface is small, corrosion processes of all kinds (uniform attack, contact corrosion, stress corrosion cracking, pitting) at this point must be prevented. For the metals employed as seal-ring pairs (Al and Cr-Ni steel, Al and Ni), the conditions for prevention of corrosion are satisfied only if the possibility of deleterious quantities of moisture and/or deleterious quantities of other aggressive media being present or gaining access later is eliminated. With respect to the possible presence of deleterious quantities of moisture, the metal seal ring on the primary cover should be assessed as most critical, since the loading process, including the placement of the primary cover, takes place under water.

The drying process, to be carried out at the nuclear power plant according to data supplied by the applicants [U 34, U 37], should therefore be analyzed in detail.

A step-by-step description of the process follows.

After the cask is loaded in the fuel storage pool and the primary cover is set in place under water, the cask is lifted to the surface of the water; water left on top of the primary cover is drawn off and returned to the pool. The vacuum drying system is then connected to the holes, and vacuum drying is carried out between the seal rings of the primary cover; vacuum drying includes a vacuum retention test down to about 10^{-2} mbar. After the residual water has been pumped out of the cask interior through the drainage channel, a drying hood is mounted over the primary cover and the space so created is also dried with the vacuum system.

After the primary-cover cap nuts have been drawn down tight, the interior of the cask is vacuum-dried as well.

After the cask has been lifted out of the fuel storage pool, the secondary cover is put in place and the same drying process is carried out as for the primary cover.

According to our assessment, the design features (test holes A, B and C; see Section 2.2) together with appropriate procedures [U 37] insure that no residual moisture remains anywhere in the seal-ring region. We start with the assumption that, before the primary cover is finally pulled down tight, test holes A, B and C are used to perform vacuum drying down to 10^{-2} mbar between all the seal rings present, including the regions around the metal seal ring, and that the success of the procedure is verified by a vacuum retention test after loading.

By means of a subsequent vacuum drying operation on top of the primary cover, with the help of a vacuum drying hood, the seal surfaces for both seal plates in the primary cover and for the secondary cover are dried. The primary cover is then drawn down tight. All further operations are carried out with the seal-ring region concerned in a dry condition.

All drying operations have their effectiveness enhanced by the rising temperature of the cask and covers, any water present being baked out.

Therefore, there is no need to deal with any corrosion risk to the metal seal rings as a consequence of the loading process, provided all handling instructions relative to the drying operations have been followed, the effectiveness has been precisely checked, and any later admission of moisture to the seal surfaces for the secondary cover and for the seal plates in the primary cover has been prevented.

Inspection of handling operations during or after the loading of a shipping cask at the nuclear power plant is performed by specialists called in by the supervisory authority having jurisdiction in each case. This inspection, which also includes supervision of the effectiveness of drying operations and tightness tests, as well as the approval of handling instructions, are prerequisites that must be satisfied for the shipment of spent fuel assemblies. These requirements are met through the verifiable performance of appropriate orders applying to shipping casks approved in accordance with the transportation laws.

The short direct residence times of a few hours in the pool water or in the moist condition, before the performance of the first drying step, are not long enough to bring about corrosive attack on the metal seal ring of the primary cover that would threaten the seal function.

Degradation products of the elastomer seal rings generated upon radiation exposure must not attack the aluminum material employed as outer jacketing on the metal seal rings. If silicone rubber is used for the elastomer seal rings, as set forth in test certificates covering the type testing under the transportation laws (e.g., [L 39]), the possibility of such an attack is excluded (see Section 3.1.1).

3.1.5. Corrosion Due to Fission Products Released

It is further necessary to check whether volatile fission products released when fuel-rod cladding tubes fail can bring about corrosion effects on safety-relevant components, in particular the metal seal rings, that would unduly impair the required tightness. The treatment of this question is based essentially on statements by TUV Hannover [L 1], which cite the mass concentrations or vapor pressures of elements regarded as corrosive at the entrance to each cover clearance under consideration. From these data it is possible to estimate the maximum quantities of corrosive elements penetrating to the mounting groove of the metal seal ring, on the basis of a diffusion model with allowance for the regions of the cover clearance that are critical for diffusion, and thence to find the corrosion danger.

For the analysis of a hypothetical limiting case, therefore, the following assumptions, regarded as conservative, were made:

The failure rate of fuel-rod cladding tubes at the start of dry storage is 100%.

The formation or presence of chemical compounds with low vapor pressure in the fuel matrix is neglected, and thus the release of the inventory of volatile fission products regarded as corrosive (the elements cadmium, cesium, rubidium, selenium and tellurium) is assumed to be in elemental form and in accordance with the vapor pressure.

The adsorption capacities and reactivities of the fission products at the inside wall of the cask are neglected; in particular, the action of the cask bottom as a cold trap (coldest point of cask interior surface = region of preferential condensation of volatile substances) is neglected.

The seal function of the "upstream" elastomer seals is not assumed to continue indefinitely.

The halogens iodine and bromine in elemental form are not stable in the cask atmosphere; they combine with, for example, the alkali metals present in excess [L 1]. Thus the possibility of elemental halogens being transported to the metal seal rings can be ruled out.

The element krypton is of interest only insofar as its radioactive decay can produce the element rubidium. The mass of rubidium generated in this way can, however, be neglected in comparison with the mass of rubidium released from the fuel assemblies.

With regard to the other elements, cadmium, rubidium (released from fuel assemblies), cesium, selenium and tellurium, cesium and rubidium are dominant in terms of mass concentration. The concentration values for the elements cadmium, selenium and tellurium are several orders of magnitude lower [L 1], so that further investigations become superfluous.

For the elements cesium and rubidium, it is thus necessary to study whether significant quantities of these can pass through the cover clearance to the metal seal rings and give rise to corrosion processes.

The applicants have made appropriate calculations [U 46] available for the determination of fission-product diffusion at the primary-cover metal seal ring, and we have checked these. On the basis of the diffusion analysis contained in them, we have performed our own calculations, taking account of conservatively chosen diffusion coefficients as well as all diffusion paths in the primary cover of the CASTOR Ic and CASTOR IIa casks. These diffusion calculations concern transport by way of the cover clearances (metal-to-metal clearance 10 μm) and allow for differences in temperature and vapor pressure and for a time span of 40 years. They yield about $4 \cdot 10^{-5}$ g/cm^2 as the maximum quantity of the fission product cesium, referred to a unit area, that acts on the seal ring; the quantity of the fission product rubidium is about $1 \cdot 10^{-5}$ g/cm^2. These values are so low that, according to all available experience, it is not at all necessary to deal with any loss of seal action by the metal seal rings over a span of 40 years resulting from released fission products. This statement also holds for CASTOR Ia casks, since the geometry implies lower fission-product concentrations in this cask type.

Because the above statements relate to definite, verifiable parameters (e.g., the metal-to-metal clearance for the primary cover), we have written the following Proposed Order:

> It is to be ascertained that the internal metal-to-metal clearance is a maximum of 10 μm referred to the seal surface of the primary-cover metal seal ring. The determination is to be done during cask assembly and, in the framework of continuing examination, is to be made available for checking by a specialist to be called in by PTB. Presentation of proof of this determination may be dispensed with provided the applicants pres[illegible] proof that undue impairment of tightness by volatile [illegible] products can be precluded through

other measures, or if new knowledge is gained confirming that the seal action continues (Proposed Order AV 3.1-1).

3.1.6. Corrosive Environmental Influences

For the supposed interim storage period of up to 40 years, it must be expected that the cask will be subjected to external service stresses due to the ambient atmosphere, including aggressive air pollutants (e.g., SO_2) anticipated under normal conditions. Even in this case, the large wall thicknesses and the protective paint coating mean that there is no danger of serious loss of material from the cask wall as a result of corrosion.

During the intended storage period, the entry of moisture or corrosive agents from outside, through the doubly sealed guard plate, to the metal seal rings of the secondary cover that are the effective barriers (the cover seal ring itself and the seal rings of the pressure gage and the protective cap of the quick-release coupling), can be ruled out. This is all the more the case since the temperature of the outside of the cask is higher than the ambient temperature, so that condensation of an aqueous phase in the contact clearance between the guard plate and the cask is prevented.

3.1.7. Long-Term Effects

The supposed duration of interim storage, up to 40 years, creates the problem of the time dependence of safety-relevant values of properties. For the massive components, such as the cask body and the primary and secondary covers as well as the guard plate, the possibility of negative time-dependent effects can be excluded, since not only the decline in decay heat and radiation impact with time but also the predominantly stress-free condition of these components must be considered. But effects on the moderator material, should be expected at the service temperatures prevailing during the service period [L 25].

The maintenance of helium tightness (design standard helium leak rate $\leq 10^{-7}$ mbar·L·sec^{-1} for one barrier with metal seal rings) requires a pressing force as defined in Table 3.1-1. The force value is dictated by the seal-ring material, the mounting groove geometry adapted to each type of seal ring, and the pulling down of the covers metal-to-metal. After a check of the drawing documents [U 29], information provided by the seal-ring manufacturer being taken into account [L 26], the "optimum operating point" of the seal ring is insured by pulling down metal-to-metal.

For the example of a CASTOR Ic cask, Table 3.1-1 makes it clear that the relaxation behavior of the primary-cover, secondary-cover, pressure-gage, seal-plate and seal-cover bolts can be regarded as noncritical with regard to the maintenance of the required value that we calculated for the pressing force on the metal seal rings (the value such that helium tightness is lost if the pressing force is less).

Table 3.1-1.

Bolt fastening of	Minimum pressing (sealing) force required, kN	Pressing (sealing) force remaining after 20% relaxation of bolts, kN
Primary cover	about 130	about 1300
Secondary cover	about 160	about 1500
Valve seal cover	about 12	about 220
Valve seal plate	about 12	about 160
Pressure gage	about 8	about 90

Necked-down bolts are used for the primary and secondary covers. A diameter ratio of $d_T/d_3 = 0.9$ (where d_T is the shank diameter of the necked-down bolt and d_3 is the root diameter of the bolt thread) has proved a good test for the static stability of necked-down bolts under thermal stress [L 13]. The primary-cover bolts for the CASTOR Ic cask have a d_T/d_3 of 0.84, and the secondary-cover bolts have a d_T/d_3 of 0.88; thus the diameter ratio d_T/d_3 of 0.9 cited above should be considered fulfilled.

The pressing forces for the primary, secondary and seal covers and for the pressure gages are also maintained by the bolt elements of the CASTOR Ia and IIa cask types.

3.1.7.3. Metal Seal Rings

The continuation of the seal action during the time of storage through the metal seal rings to be used in the cask is an essential criterion for assessing the suitability of these cask types for the dry interim storage of spent fuel assemblies.

The seal action of the metal-seal-ring design being assessed here depends on the plastic deformation of its outer jacketing, effected by pressing. The plasticizability of this outer jacketing is greater than that of the materials adjacent to it, that is, the materials of which the flange seal surfaces, the inner jacketing and the elastic core (coil spring) of the metal seal ring are made.

The seal action is maintained if

- the required minimum pressing force is insured by the maintenance of the seal-ring geometry (mounting groove dimensions and "metal-to-metal" flange configuration; see Section 3.1.7.2 for the treatment of this problem);
- no undue damage occurs as a result of corrosive attack (see Sections

3.1.4.3 and 3.1.5 for the treatment of this problem);

the stress loss of the coil-spring material due to relaxation is non-critical with respect to the maintenance of the minimum pressing force, and "creep failure" of the coil spring does not take place during the service period. The present section treats this problem.

Two alternative spring materials (high-temperature nickel alloys) are to be used as coil-spring materials; they have high creep strengths even at high temperatures [U 41]. According to [L 27, L 32, L 33, L 36, L 37], the creep strength or yield strength diminishes only at temperatures $\geqq$ 873 K (600°C). On the other hand, we have determined that the highest temperature prevailing in the region of the metal seal rings at the beginning of service is $\leqq$ 388 K (115°C); after a storage period of five years, the corresponding figure is $\leqq$ 333 K (60°C).

The creep behavior of the coil-spring core is crucial for the maintenance of the long-term seal action for the seal system under consideration here [U 41], given a constant seal geometry at all times. The reaction force of the coil-spring core, after the seal ring is pressed, exerts the pressing force on the seal surfaces required to maintain a specified tightness. According to our calculations, the ratio between the pressing force after installation of the seal ring (Y 2) and the pressing force at which helium tightness is lost, 10^{-8} mbar·L·sec^{-1} (Y 1), is Y 2/Y 1 = 9.5 in the worst case (primary and secondary metal seal ring) [U 41, L 26]. Therefore, up to a 90% decrease in the initial spring load due to stress relaxation would be permissible without any loss of the tightness cited above.

For the assessment of the relaxation behavior, the applicants made available research results first for a spring material F 1* [U 41, L 33]. The

*Inconel X 750

stress-relaxation measurements presented therein were performed at high temperatures (> 700 K, > 427°C) on cold-wound and heat-treated wire springs. The results showed that:

- at the test temperature of 700 K (427°C), which is much higher than the maximum service temperature in the storage cask (388 K, 115°C), and for an initial stress of about 50% of the yield strength ($R_{p0.2}$) of the material, a stress relaxation of not more than 3% of the initial value is reached after a relatively short time (20 days) and does not increase further;
- only at higher temperatures and similar initial stresses can a more distinct increase in the stress-relaxation values ($\Delta\sigma$) with time be observed.

We plotted the measured values for T = 811 K (538°C) and T = 866 K (593°C) in log-log coordinates (log $\Delta\sigma$ versus log t), obtaining a straight line lending itself to extrapolation. If creep failure is neglected, extrapolation to $t = 3.5 \cdot 10^5$ hr (40 years) would lead to the result that the stress relaxation would reach 8% for T = 811 K and 25% for T = 866 K. This relaxation of $\leqq$ 25%, which is permissible for maintenance of the seal action, could also be extended to the second coil-spring material F 2,* since this material has slightly better creep-strength values [L 27, L 28, L 29.2, L 34]. What is more, a comparison was made with the stress-relaxation values extrapolated to 10^6 hr, which amounted to a maximum of 25% for unalloyed prestressing steels (T to 423 K (150°C), initial stress up to 95% of tensile strength) [L 25]. The results showed that a loss of tightness below the specified limit cannot occur as a result of undue stress relaxation of the coil-spring materials.

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*Nimonic 90

In addition to the analysis of stress relaxation, we employed [L 28 to L 37] in analyzing the problem of failure of the coil-spring materials through "creep failure." "Creep" denotes a continuing plastic deformation under static stress (DIN [German Industry Standard] 50119), which may lead to fracture (creep failure) under a given load after a given time [L 35]. The material parameter that characterizes the resistance to creep failure is the creep strength σ_B, defined as "that static stress, referred to the initial cross section of a specimen, that brings about fracture of the specimen after the passage of a given test time t_B" [L 28]. The creep strength depends on temperature and time, the creep function $\sigma_B(t_B,T)$ usually being stated in a form such that log σ_B is plotted in terms of a parameter $\Phi(t_B,T)$ that defines the time and temperature dependence (a "master curve"). The Larson-Miller parameter is most frequently used [L 28, L 29, L 30, L 33].

Empirically derived functional relations are known for both spring materials [L 28, L 29.2, L 33], so that extrapolation is possible.

For the service conditions (T_{max} = 388 K, t = $3.5 \cdot 10^5$ hr), we calculated the Larson-Miller parameters (in addition, calculations were done for material F 2 by the method of Orr, Sherby and Dorn and of Manson and Haferd [L 29.2]). The values obtained are much smaller than the values given by existing master curves. Since the creep strength increases as the parameter cited above decreases, it can be concluded that the creep strengths of the spring materials under service conditions are greater than the highest σ_B value from the master curves (σ_B > 540 N/mm^2 for material F 1, σ_B > 480 N/mm^2 for material F 2).

Within the range of validity of the existing master curves, the maximum service temperatures of the materials can be calculated for the above-cited creep strengths and a time of t = $3.5 \cdot 10^5$ hr. The results, according to our calculation from the Larson-Miller parameter, were T = 744 K (471°C) for F 1 and T = 785 K (512°C) for F 2.

From these sample calculations it follows that the coil-spring materials offer excellent creep behavior, and for this reason they are used under service conditions much more extreme than those in the storage cask, such as in aerospace applications (e.g., gas-turbine vanes) [L 27, L 31, L 32, L 36, L 37]. Because of these properties, the creep-strength values for F 1 and F2 should be taken from the specialist literature only for temperatures higher than 773 K (500°C).

As the weighting of time and temperature in the Larson-Miller parameter (proportional to T and to log t) implies, the temperature exerts a much stronger influence than the time, since creep is a thermally-activated process. Not until the temperature exceeds 40-50% of the melting point of a metal (in kelvins) does the transition take place from "primary creep" to "secondary creep" with a constant rate of creep strain [L 35]. For materials F 1 and F 2, this threshold is at $T > 653$ K (380°C); that is, for $T \leq 388$ K (115°C) primary creep will be the predominant creep process, so that the passage to tertiary creep (which precedes creep failure), in which the strain rate is accelerating, does not take place.

As further evidence of the positive long-term behavior of the metal seal rings to be used in the CASTOR casks, the applicants made available results from long-term studies already performed, and status reports on those still in progress, on metal seal rings of the same type (designated "HN" in what follows) and of similar type (designated "HL") [U 16, U 38, U 41].

One HL seal ring (about 1900 mm in diameter) has been under continuous testing since May 1973 and has gone through 513 temperature cycles (293 K (20°C) to 423 K (150°C)). This seal ring has been subjected to a total of 49,607 hr at a temperature of 423 K [U 38]. Four other HL seal rings (about 3600 mm in diameter) and one HN seal ring (about 3600 mm) have been under test since September 1977 and in this time have gone through 524 cycles (293 K

(20°C) to 403 K (130°C)). Their total residence time at 403 K is 10,407 hr [U 38].

Tightness tests have been performed at regular intervals during the tests, confirming that the leak rate was $\leqq 10^{-8}$ mbar·L·sec^{-1}. The last status report, dated August 1982, confirms this tightness, measured on July 31, 1982 [U 38]. Continuation of these trials until the end of 1983 and semiannual notification of the PTB and BAM (as consultant) are promised [U 43].

On the basis of the design and the principle of operation, in our estimation, the two types of seal rings under study are comparable. Because of their design, HL seal rings are actually subjected to greater stresses than the HN seal rings used in the CASTOR casks.

The boundary conditions selected for the long-term investigations have led to more severe loads, for the following reasons:

- the coil-spring material in the test seal rings was an unalloyed spring steel, which does not have creep properties as good as the nickel alloys intended for use;
- as a result of the cyclic thermal expansion, the temperature cycling brings about an alternating mechanical load;
- the seal lengths of the test seal rings (some of them a factor of two to three greater than in the storage casks) mean that the probability of leaks is higher.

In comparison with the service conditions in the storage cask (steady temperature, $T \leqq 388$ K, static load), the parameters selected for the long-term trials represent more severe conditions.

Thus the longest test time achieved up to now, 9 years 2 months (from May 1973 to July 1982), represents a conservatively fixed and proven service life.

From the discussion on the creep behavior of the coil-spring materials that are critical for the long-term function, and from the assessment of long-term studies on metal seal rings of the same and similar types, we can state that a loss of the seal action of the metal seal rings during the storage period of 40 years as a result of systematic undue alteration of the mechanical properties is precluded.

3.1.7.4. Cask Surveillance System

3.1.7.4.1. Functioning under Normal Service Conditions

In order to detect any loss of tightness that occurs in one of the two seal-system barriers, the applicants have provided for a cask surveillance system [U 1]. In the CASTOR casks, an "inaccessible space" is located between the primary and secondary covers; after the arrival of the cask at the shipping-cask storage site, this space is filled with inert gas (p_{abs} = 6 bar). A pressure gage, mounted in the secondary cover [U 12, U 57] and directly connected with the inaccessible space through a hole, is to transmit a signal if the pressure in the inaccessible space drops below the reference space pressure as explained below (indicating a leak in the seal system).

The pressure gage has the following functionally critical components:

a main contact (HS)

a control contact (KS)

a reference pressure space located between HS and KS

The switch point of the main contact is predetermined by the pressure in the reference space, since if the pressure in the inaccessible space drops below that in the reference space the deflection of the membrane causes the main contact to open, interrupting a steady current and triggering visual and acoustic signals.

We have verified that the pressure-gage design [U 12] insures--provided the pressure gage functions properly--that in every case where one of the seal barriers loses its tightness, a signal is transmitted when the pressure in the inaccessible space is greater than the highest possible internal pressure in the cask (see Section 3.1.3; this is the objective of cask surveillance). This important functional condition presumes a definite reference-space pressure that is higher than the pressure in the cask interior and represents a lower limit. For this reason, the control contact is provided to maintain surveillance on the reference-pressure space. The control contact functions as a differential pressure gage, which opens a normally closed contact when the pressure difference between the reference space and the atmosphere goes below $1.5\ ^{+0.25}_{-0}$ bar. According to our inspection, the design of the control contact [U 12, U 57] insures--provided the device functions properly--that a signal is transmitted before the pressure goes below the functionally critical reference-space pressure, so that the surveillance is effective.

3.1.7.4.2. Impairment of Function by Hypothetical Single Defect

In the sense of the single-defect concept [L 47, L 53], we assumed the following as single-defect criteria: "sticking" of contact springs to the main-contact or control-contact membrane and loss of pressure in the reference space. The effects of these events on the functioning of the cask surveillance system are analyzed in what follows.

"Sticking" denotes a connection, not yet known but possible, between the contact springs and the bearing areas of the membranes, resulting from diffusion or friction-welding effects due to vibration, standby current, time and temperature. Sticking of the main-contact springs would lead to a lowering of the main-contact switch point (i.e., the pressure in the inaccessible space at which a signal is transmitted) by the pressure difference required to unstick the contact.

The pressure-gage manufacturer has determined the unsticking forces and the corresponding pressure differences in tests using conservative boundary conditions with regard to making a weld between the contact springs and the bearing area (spot welding on stainless-steel wafers instead of on platinized ceramic) [U 45]. The switch point of the main contact, according to these tests, can be lowered by the maximum pressure difference found, 0.7 bar.

In the case of sticking of the control-contact springs, because of the manner in which the control contact functions [U 57], the change in travel of the control-contact membrane that may occur up to the unsticking of the contacts must be considered, as must the resulting pressure difference, by which value the switch point of the control contact would be lowered. Because of the design of the control contact, its switch point would be lowered by 1.2 bar if the control-contact springs were "sticking" only slightly [U 57].

On the assumption of the single defect "sticking of contact springs," we have verified that--for conceivable critical situations of the containment of the radioactive cask contents--a signal is transmitted when the pressure in the inaccessible space is higher than the pressure in the cask interior.

We employed the following hypothetical assumptions:

all the events listed below take place at the beginning of storage (at a later time, the same chain of events would not result in a more critical condition);

100% of the fuel-rod cladding tubes fail; the pressure inside the cask may then be up to a maximum of p_{abs} = 2.3 bar (see Section 3.1.3);

the primary- or secondary-cover seal system loses its tightness and the pressure of p_{abs} = 6 bar in the inaccessible space goes down to

$p_{abs} \approx 2.3$ bar (leak in primary-cover seal system) or to $p_{abs} = 1$ bar (leak in secondary-cover seal system);

the contact springs of the main contact stick so that the main contact does not switch until the pressure in the inaccessible space is 0.7 bar below the pressure in the reference-pressure space. Because the reference space is filled with air to $p_{abs} = 3$ bar at 293 K (20°C), and according to our estimates heating may generate a pressure of $p_{abs} \cong 3.7$ bar in the reference space at the beginning of storage, the main contact would switch when the pressure in the reference space was $p_{abs} \cong 3.0$ bar;

all the events listed above take place simultaneously.

We can state that even in the above scenario--regardless of whether the contact springs of the control contact "stick" at the same time--a signal is transmitted when the pressure goes below an inaccessible-space pressure that is at least some 0.7 bar higher than the highest possible pressure inside the cask.

This statement holds with allowance for the tightness of the reference-pressure space (standard helium leak rate $\leqq 10^{-9}$ mbar·L·sec^{-1} according to data provided by the applicants [U 55]), which must be insured for any pressure gage. Thus, even in the critical conditions described above for the pressure gage and the containments of the radioactive contents, the cask surveillance system functions properly.

Further, we have assessed the effect of the single defect "drop in pressure in the reference-pressure space," making use of the above hypothetical assumptions with regard to the time, failure of fuel-rod cladding tubes, and failure of seal system:

A drop in pressure in the reference-pressure space (due to a hypothetical leak in the reference-pressure space) is signaled by opening of the control contact at a minimum pressure of 2.5 bar in the reference-pressure space. If there is a leak in the primary-cover seal system, the pressure in the inaccessible space may drop to about 2.3 bar. If the reference-space pressure fails toward the inaccessible space, a signal will be transmitted at a minimum value of 2.5 bar (reference-space pressure = inaccessible-space pressure); that is, the pressure gage still functions as required.

This statement also holds for the possible cases of a leak in the secondary-cover seal system or a failure of the reference-space pressure toward the atmosphere, which in the present connection are not more critical than the case discussed above.

When the features of importance to the functioning of the pressure gage are inspected in the framework of quality assurance, the following points should be heeded:

A functional check is to be performed on every pressure gage to be used for cask surveillance at the Ahaus Shipping-Cask Storage Site. The check is to take place after fabrication and before installation on the cask. It should be demonstrated that the following standards are met:

integral standard helium leak rate of the reference-pressure space $\leq 10^{-9}$ mbar·L·sec^{-1}

pressure in reference-pressure space after filling with air p_{abs} = 3.0 bar (referred to a temperature of 293 K)

reproducibility of main-contact switch point ±0.05 bar

reproducibility of control-contact switch point $^{+0.25}_{-0}$ bar (Proposed Order AV 3.1-2)

The pressure-gage design intended for cask-surveillance use was assessed --again with the single-defect concept. Two critical single defects were assumed with regard to design and functioning. Even with allowance for these single defects, the pressure gage can perform its function properly. Thus it can be assumed with adequate confidence that the functioning of the pressure gage does not depend on random failure of one part of the system, and if functioning properly it should be considered suitable for a period of up to 40 years.

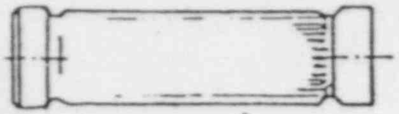
3.2. Accident Loads

Accidents not brought about by the intentional action of third parties (warfare, sabotage, etc.) involve mechanical and thermal loads which the CASTOR shipping and storage casks must be proved able to survive.

"Survivability" means maintenance of the cask's integrity, that is, maintenance of the "tight containment" in order to prevent the undue release of radioactive substances and retention of the shielding function needed for radiological safety. Furthermore, the integrity of the cask internals (fuel basket), which maintain criticality safety upon flooding during the loading process at the nuclear power plant, is to be analyzed.

Because some of the effects on the overall structure resulting from accidents, in particular effects on cask tightness, cannot be numerically or theoretically analyzed with sufficient accuracy, mainly experimental proof has been presented to show survival of severe mechanical and thermal loads. For the casks under consideration, experimental evidence has been obtained in a large number of tests, some of which have been run on model casks of similar design, full-size prototype casks of similar design, or full-scale sections of casks. Fig. 3.2-1 summarizes the load tests on the CASTOR casks.

An assessment of the accident scenarios to be considered (in which the accidents are simulated by the tests described and evaluated in what follows) is the subject of the expert Opinion by TUV Hannover.



CASTOR Ia

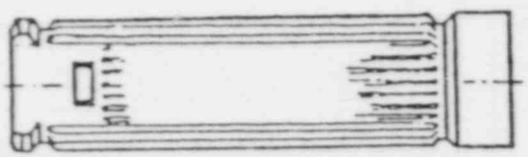
1/2 scale model

Drop tests from 9 m
<u>onto unyielding foundation</u>

Cover edge	233 K (-40°C)	w/ IL	5/9/78
Bottom	233 K (-40°C)	w/o IL	5/10/78
Trunnions	233 K (-40°C)	w/o IL	5/11/78
Cover edge	233 K (-40°C)	w/ IL	6/6/78
Cover edge	233 K (-40°C)	w/o IL	6/7/78
Bottom	233 K (-40°C)	w/ IL	4/19/79

<u>Fire tests (open fuel-oil fire)</u>

with IL	5/26/78
with IL	11/16/78
without IL	11/30/78



CASTOR Ia

prototype

Drop tests from 9 m
<u>on unyielding foundation</u>

Bottom	AT	w/ IL	11/9/78
Cover edge	AT	w/ IL	11/16/78
Trunnions	233 K (-40°C)	w/o IL	11/30/78
Trunnions	AT	w/o IL	4/25/80

Deformation check on dummy fuel assembly and spacing cross	4/5/79

<u>CASTOR Ia prototype</u> (continued from left column)

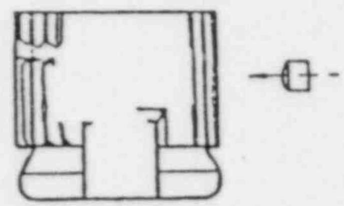
Suspension test from trunnions	4/23/80

<u>Fire test (open fuel-oil fire)</u>

without IL	12/13/78

<u>Thermal-load tests</u> (without impact limiters)

20.7 kW vertical	8/21/78
34.4 kW vertical	8/23/78
21.1 kW vertical	8/25/78
21.7 kW horizontal	8/29/78
32.7 kW horizontal	8/30/78
41.5 kW horizontal	9/1/78

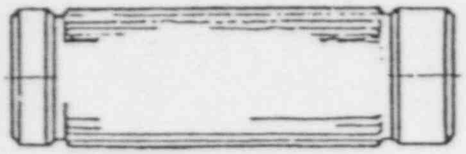


CASTOR Ia bottom end

(18 metric tons)

Thermal-load tests on insulated cask	10/1-19/79
Heating and fire test	4/20-27/78
Penetration test	12/14/78

Fig. 3.2-1 (page 1 of 2). Trials with specimen casks to test mechanical and thermal capacity of CASTOR shipping and storage casks. AT = ambient temperature, IL = impact limiter(s).



CASTOR Ic

full-size cask

Drop test from 19.5 m
onto real foundation 11/17/80

Drop test from 15 m onto power-plant impact limiter as foundation 12/5/80

Drop tests from 9 m
onto unyielding foundation

Trunnions	AT	w/o IL	4/21/82
Bottom/30°	AT	w/o IL	5/12/82
Trunnions	233 K (-40°C)	w/o IL	5/19/82

Drop tests from 1 m onto steel cylinder

Middle of cover	AT	w/ IL	10/12/82
Pressure-gage area	AT	w/ IL	10/14/82

CASTOR IIa
1/2 scale model
(two-barrier cover system,
metal gasket)

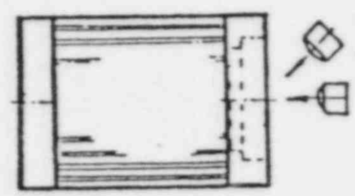
Drop tests from 9 m
onto unyielding foundation

Cover edge	AT	w/ IL	6/5/80
Bottom	AT	w/ IL	6/5/80
Trunnions	AT	w/o IL	6/9/80
Cover edge	AT	w/ IL	10/21/80
Trunnions	AT	w/o IL	10/22/80
Cover edge	AT	w/ IL	10/24/80

Drop tests from 1 m onto steel cylinder

Middle of cover	AT	w/ IL	6/10/80
Middle of cover	AT	w/ IL	10/23/80

CASTOR IIa
shortened cask



Two-barrier cover system,
metal gasket (old)

Two-barrier cover system,
metal gasket (new)

Penetration test on cover 12/20/79

Penetration test on middle of cover 6/6/80

Fig. 3.2-1 (page 2 of 2).

3.2.1. Mechanical Loads

3.2.1.1. Accident Situations

Tests to prove the mechanical integrity of the cask and its components, as well as the functioning of the seal system, are represented by two categories: drop tests and tests simulating an aircraft crash. The test conditions are chosen so that the (reproducibly generated) loads give a realistic simulation of severe drop and crash loads and take in the consequences of hypothetical accidents.

3.2.1.2. Drop Tests

As the schematic summary of load tests on CASTOR casks (Fig. 3.2-1) shows, many drop tests have been performed [U 13, U 14, U 58 to U 60, L 39, L 41]. These have served not only to verify that the required tightness is present after such loads [L 8, L 9, L 14, L 23, L 24], but also as mechanical tests.

3.2.1.2.1. Test Conditions

Four specimens were available for the drop tests (see also Fig. 3.2-1):

(a) CASTOR Ia, 1 : 2 scale model

Gesellschaft für Nuklear Service mbH (GNS) [L 41]

(b) CASTOR Ia, full-scale prototype

GNS [L 41]

(c) CASTOR IIa, 1 : 2 scale model

GNS (drop tests 1-4) [U 13, L 39]

(d) CASTOR IIa, 1 : 2 scale model (modified)

GNS (drop tests 5-8) [U 14, U 40]

(identical with (c) except for slight modifications)

(e) CASTOR Ic, full-scale cask

GNS [U 58 to U 61]

All the cask bodies featured the geometry typical of the CASTOR design, with lengthwise fins on the sides, and were cast in one piece from the material GGG 40.

As a rule, the drop height in drop tests with the casks listed above was 9 m, measured from the top of the foundation to the bottom surface of each test object (drop heights different from this are indicated below). The drop was onto a foundation designated "unyielding" in accordance with [L 14], so that as much of the total kinetic energy as possible acted on the cask.

The drop tests with the CASTOR Ia 1 : 2 scale model were performed on BAM Free Drop Test Stand 1. This test stand has a foundation measuring 5 m x 5.3 m and 1.1 m high, consisting of reinforced concrete with embedded steel scrap. A steel slab 0.06 m thick is anchored to the concrete. The whole foundation is embedded in the ground; its mass is about 80 metric tons.

The drop tests with the other cask types were carried out on BAM Free Drop Test Stand 2, which has a square foundation 10 m on a side and 4 m high, consisting of reinforced concrete. A steel slab (6 m x 2 m x 0.2 m), weighing about 20 metric tons, is mortised into the concrete and anchored. The foundation is entirely embedded in the ground; its mass is about 1000 metric tons.

Oscillation measurements in the tests with the CASTOR Ia prototype (b) showed that the foundation absorbs only about 2% of the kinetic energy, so that about 98% of this energy is transformed in the cask [L 41].

Unless otherwise noted, the following two kinds of measurements were performed in all the trials: Accelerometer curves were recorded at various points on the casks; before and after every trial, the tightness was measured with a helium leak tester (He mass spectrometer) or by other tightness-measuring methods.

Other techniques employed in the tests included mapping, documentation of the effects of the tests on the specimens by still or motion-picture photography, and checking of the cover-bolt tightening torques. BAM made use of numerous aids in preparing, implementing and executing the tests, such as Data Sheets, checklists for test sequence planning, and so forth; these are listed in the test reports.

Additional information on supplementary tests, drop positions, test temperatures and other boundary conditions can be found in the test descriptions that follow.

3.2.1.2.2. Drop Tests Performed

(a) Drop Tests with CASTOR Ia 1 : 2 Scale-Model Cask

The specimen cited above (weight about 6.5 metric tons, unloaded, without impact limiters; weight of load simulator about 1.4 metric ton; weight of cover impact limiter about 223 kg; weight of bottom impact limiter about 197 kg) was patterned, in all essential parts, on the full-scale CASTOR Ia cask that was later approved under the transportation laws; the scale was 1 : 2. The model cask was put through the following tests in succession:

Drop Test 1: impact on cover face with impact limiter, model cask cooled to 233 K (-40°C)

Drop Test 2: impact on bottom of cask without impact limiter, model cask cooled to 233 K (-40°C)

Drop Test 3: impact horizontally, on trunnions, model cask cooled to 233 K (-40°C)

Drop Test 4: impact on cover face with impact limiter, model cask cooled to 233 K (-40°C); repetition of Drop Test 1 with redesigned impact limiter

Drop Test 5: impact on cover face without impact limiter, model cask cooled to 233 K (-40°C)

Drop Test 6: impact on bottom of cask with impact limiter, model cask cooled to 233 K (-40°C)

The specimen cask retained its integrity and tightness after all the tests.

(b) Drop Tests with CASTOR Ia Prototype

With this specimen (weight about 65 metric tons, unloaded; total weight including load simulator and impact limiters 70.6 metric tons), the following tests were performed for the first time on a full-scale fuel-assembly cask of this order of magnitude:

Drop Test 1: impact on bottom of cask with impact limiter, ambient temperature

Drop Test 2: impact on cover face with impact limiter, ambient temperature

Drop Test 3: impact horizontally, on massive trunnions made of GGG 40, cask cooled to 233 K (-40°C)

In the above three trials, the cask was loaded with a simulated fuel basket for four Biblis-type fuel-assembly clusters from a pressurized-water reactor, and with appropriate dummy fuel assemblies in the form of bundles of steel pipes.

Drop Test 4: impact horizontally, on trunnions, ambient temperature; in this test, ferritic stainless-steel trunnions with conical recesses bored in them--corresponding to the CASTOR Ic design--were used.

The prototype retained its integrity and tightness after all the tests.

(c) Drop Tests with CASTOR IIa 1 : 2 Scale Model

The 1 : 2 scale specimen of the CASTOR IIa cask type, weighing about 14 metric tons, was subjected to the following tests in succession:

Drop Test 1: impact on cover face with impact limiter, ambient temperature

Drop Test 2: impact on cask bottom with impact limiter, ambient temperature

Drop Test 3: impact horizontally, on trunnions, ambient temperature

Drop Test 4: impact on cover with impact limiter, onto a cylinder (upright steel cylinder, h = 350 mm, diameter = 75 mm), drop from 1 m*

The cover and seal system comprised a massive welded-on insert cover, a secondary cover (with a pressure gage sealed by a metal seal ring, an aluminum-jacketed secondary-cover metal seal ring, and no elastomer seal ring), a primary cover (with aluminum-jacketed primary-cover metal seal ring and no elastomer seal ring), and two seal plates, sealed with metal seal rings, on the test holes in the primary cover. The design essentially matched the seal system used on the CASTOR casks after the installation of the insert cover.

(d) Drop Tests with CASTOR IIa 1 : 2 Scale Model (Modified)

For a second series of drop tests, the CASTOR IIa 1 : 2 scale model described under (c) had the cover system modified in the following way:

An additional guard plate with elastomer seal ring was installed under the welded-in insert cover, a concentric membrane being set into the insert cover to reduce stresses on the welds. Mounting straps were

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*In the drop tests onto a steel cylinder, the drop height in each case is measured from the top of the cylinder to the bottom of the test object.

employed to position the large metal seal rings in the grooves of the secondary and primary covers.

This second series of trials was performed under the supervision of BAM, which also carried out the tightness tests. No acceleration measurements wer made, since no new knowledge could be expected to come from them. Test connections made it possible to do tightness tests on individual components of the seal system after the tests cited above.

The following tests were performed at ambient temperature:

Drop Test 5: impact on cover face with impact limiter

Drop Test 6: impact horizontally, on trunnions

Drop Test 7: impact on cover with impact limiter, onto a cylinder (upright steel cylinder, h = 350 mm, diameter = 75 mm), drop from 1 m

Drop Test 8: impact on cover face with impact limiter

The specimen cask retained its integrity and tightness (integral standard helium leak rate of overall seal system < 10^{-7} mbar·L·sec^{-1}) after all the tests.

(e) Drop Tests with CASTOR Ic Full-Scale Cask

The full-scale CASTOR Ic cask weighed about 85 metric tons loaded and with impact limiters. The first two drop tests performed with it differed from the preceding and subsequent ones in that their purpose was to document the behavior of the cask when dropped from great heights onto real ground surfaces, such as are present during handling or when the casks are passed out through the lock at the nuclear power plant.

Drop Test 1: impact horizontally, without impact limiters, drop from about 19.5 m; simulated road-pavement foundation suitable for heavy truck traffic (gravely soil compacted in layers, reinforced-concrete slabs, several layers of bituminous topping), total height about 1.8 m, all placed atop the unyielding foundation

Drop Test 2: impact on cover edge without impact limiters, drop from about 15 m; energy-dissipating foundation in the form of a multi-layer impact-limiter structure (sandwich construction of aluminum honeycomb elements and steel and aluminum plates), total height about 2 m, placed atop the unyielding foundation

The cask exhibited no damage after these two tests. Proof of tightness was not the object of the investigations; that is, no tightness measurements were performed.

Afterward, the following drop tests (onto the unyielding foundation) were performed with the CASTOR Ic full-scale cask:

Drop Test 3: impact horizontally, on trunnions

Drop Test 4: impact horizontally at 30° inclination (impact on bottom trunnion first, then on cover-end trunnion), with impact limiters

Drop Test 5: impact horizontally, on trunnions

Drop Test 6: impact on cover (middle) with impact limiter, onto a cylinder (upright steel cylinder, h = 500 mm, diameter = 150 mm), drop from 1 m

Drop Test 7: impact on cover (edge of cover near pressure gage) with impact limiter, onto a cylinder (upright steel cylinder, h = 500 mm, diameter = 150 mm), drop from 1 m

Drop Tests 3, 4, 6 and 7 were conducted at ambient temperature, the cask was cooled to 233 K (-40°C) for Drop Test 5. In Drop Tests 6 and 7, the cask was fitted with an impact limiter on the cover end; the limiter design was modified from the design in the other tests. The purpose of the modification was to achieve a higher resistance in the drop test onto the cylinder. According to our assessment, no change in the cask behavior in the 9 m drop test is expected.

The cover and seal system design (starting with Drop Test 3) was the same as the version to be used in the Ahaus Shipping-Cask Storage Site (see Section 2.2). The cask was provided with primary cover, secondary cover, guard plate, and metal and elastomer seal rings. It was possible to test each metal seal ring of each of the two tightness barriers. The tests and the subsequent tightness tests were supervised by BAM specialists.

The CASTOR Ic cask retained its integrity and tightness (integral standard helium leak rate of the overall seal system $< 10^{-7}$ mbar·L·sec^{-1}) after the tests just cited.

3.2.1.2.3. Assessment of Drop Tests

The Introduction stated that, in the framework of type testing for approval of the CASTOR Ic cask under the transportation laws, the required evidence had been presented that the cask could survive mechanical accident loads (drop tests from 9 m onto an unyielding foundation and from 1 m onto a steel cylinder) and thermal ones (accidental fire, 1073 K (800°C)/0.5 hr) [L 39]. Similar test certificates must be presented for the CASTOR Ia and IIa cask designs before the beginning of storage of such casks in the Ahaus Shipping-Cask Storage Site.

The assessment of the drop tests that follows is done for the CASTOR Ic cask type as an example. An analogous assessment of the other cask types will be the subject of the test certificates cited above.

3.2.1.2.3.1. Cask Body

The seal system for the cask types being assessed here is designed in accordance with the two-barrier concept, having one metal seal ring each in the primary and secondary covers. This type of seal system was present only on the CASTOR IIa 1 : 2 scale model and the CASTOR Ic full-scale cask. The drop tests with the other test specimens, some of which had only a one-barrier cover system with elastomer seal rings, have therefore been used only for our analysis of mechanical integrity. Above all, they supply information on the integrity of the cask body, which is made of the material GGG 40.

To determine the forces acting during impact, the decelerations (i.e., negative acceleration values) caused by the impact are measured. From the maximum value a_{max}, if the mass m is known, the maximum force value can be calculated:

$$F_{max} = m \cdot a_{max}.$$

Two independent measuring techniques were available for measuring acceleration as a function of time:

- piezoelectric accelerometers, possibly with two separate means of recording (transient recorder and/or oscillograph)
- a high-speed rotating-prism camera linked with a computer program to determine the acceleration-time history

Our assessment of the data revealed that statements about the load levels can be made with confidence only when all the measured values have been combined and compared.

The results of acceleration measurements (accelerometer signals and film recordings) can be illustrated for the two drop tests that--according to our estimation, supported by ample experience from loading tests with the most varied cask designs--yielded the highest mechanical accident load on the type of cask body under consideration. These were Drop Tests 3 and 4 with the CASTOR Ia prototype (see Section 3.2.1.2.2(b)).

For several reasons, these trials embody extremely conservative boundary conditions, going far beyond the usual scope of component studies:

The bending stress resulting from the drop position (horizontal, simultaneous impact on two trunnions) means that, in the middle of the cask, a primary bending stress acts over the whole wall cross section. In the extreme fiber of the cask wall on the side toward the impact slab, the stress is a maximum and is tensile. Such a stress is much more critical for the cast material than a compressive stress of equal value.

The greater trunnion spacing means that the bending moment was larger in the tests on the CASTOR Ia prototype than would be the case for the CASTOR Ic. Because of its greater wall thickness, the CASTOR Ic cask has a considerably larger moment of resistance. Hence, not only is the maximum bending stress accordingly reduced, but also--given equal material properties--the safety is greater with respect to all the other stresses occurring in tests with the CASTOR Ia prototype.

In Drop Test 3 on the CASTOR Ia prototype, the whole cask was cooled to a temperature of 233 K (-40°C). The same was true in all the tests on the CASTOR Ia 1 : 2 scale model; by the mechanics of similitude, the stresses in the scale model are the same as in the full-scale cask, for constant drop height [L 15, L 42]. Therefore the survivability with respect to accident loads, as represented by the drop tests, is proven even for the material behavior corresponding to this temperature.

Since Drop Tests 3-5 with the CASTOR Ic full-scale cask yielded no data that could be used in a stress analysis, we have used the following analysis with respect to extending the CASTOR Ia prototype tests with the highest loads to the CASTOR Ic cask [L 39]:

The extension of mechanical loads is permissible if it is shown that the primary bending stresses, when design differences are taken into account, are at most equal in value.

Table 3.2-1 presents maximum deceleration values from piezoelectric acceleration-time curves for the drop tests with full-scale CASTOR casks (horizontal impact). The acceleration-time curves from which these values were taken had the high-frequency components superimposed on the fundamental vibration removed, since the high-frequency components have no effect on the integrity and tightness of the cask. The filtered values show adequate agreement with the values resulting from film interpretation (the distance-time curve was numerically differentiated twice).

The comparison in Table 3.2-1 with the CASTOR Ic trials shows that, even when the drop height is twice as great and impact is on a simulated road-pavement foundation, the stresses that occur are significantly smaller than those when the CASTOR Ia prototype impacts on the unyielding foundation of the drop test stand.

From a maximum deceleration value of $a_{max} = 1200\ m \cdot sec^{-2}$ and the relation

$$\sigma_M = M_M/W = \frac{m \cdot a_{max}}{2W}(\ell/4 - c),$$

the maximum tensile stress σ_M in the extreme fiber can be calculated.

In the above formula, M_M is the bending moment of a cantilever beam lying on two supports and loaded by a rectangular line load [L 16]; W is the moment of resistance of the cask cross section, represented by a box-shaped

Table 3.2-1. Maximum deceleration values in drop tests with full-scale CASTOR casks (horizontal impact simultaneously on trunnions).

CASTOR Ia prototype "unyielding" foundation drop height 9 m		CASTOR Ic "real" foundation drop height 19.5 m	
Drop Test 3 (b)		Drop Test 1 (d)	
Cover end	Bottom end*	Cover end	Bottom end
$a_{max} \cong 1200$ $m \cdot sec^{-2}$	$a_{max} \cong 3000$ $m \cdot sec^{-2}$	$a_{max} \cong 600$ $m \cdot sec^{-2}$	$a_{max} \cong 700$ $m \cdot sec^{-2}$
Drop Test 4 (b)			
Middle of cask			
$a_{max} \cong 1200$ $m \cdot sec^{-2}$			

*Our assessment is that this value came about through impact on a "bearing block," which is not present in this form in the CASTOR casks. The above value cannot be used as a reliable basis for deriving a higher stress level.

profile (the cooling fins are neglected); m is the mass of the cask with load; a_{max} is the peak deceleration value; ℓ is the length of the cask; and c is the length of the projecting ends of the cask.

The following values apply to the casks:

	CASTOR Ic	CASTOR Ia prototype
m	85,000 kg	70,600 kg
a_{max}	$1200\ m \cdot sec^{-2}$	$1200\ m \cdot sec^{-2}$
ℓ	5505 mm	5730 mm
c	200 mm (bottom)	300 mm
	750 mm (cover)	
W	$0.59\ m^3$	$0.37\ m^3$

For the CASTOR Ia prototype, the above figures give a value of $\sigma_M \approx 130\ N/mm^2$ for the maximum tensile stress in the extreme fiber of the side portion of the cask; for the CASTOR Ic (under the conservative assumption that c = 200 mm), $\sigma_M \approx 100\ N/mm^2$.

Thus, if equal maximum decelerations are assumed, the bending stress in the CASTOR Ic is about 20% less than in the CASTOR Ia prototype. The effect of the greater mass (about 20% more) and thus the greater kinetic energy in the drop is offset by higher plastic deformation of the trunnions, fins or impact limiter (in shipping); as a result, the travel during the deformation phase may be longer so that the deceleration will be lower.

Confirmation that the assumption $a_{max} \approx 1200\ m \cdot sec^{-2}$ is conservative comes from the interpretation of a similar drop test with the CASTOR IIa 1 : 2 scale model (Section 3.2.1.2.2(c), Drop Test 3). Using the same procedure as above, we calculated a bending stress of $\sigma_M \approx 68.5\ N/mm^2$ from the maximum deceleration values. This much of a load should also be expected for the full-soale CASTOR IIa cask, since--as can be shown through the use of model relations--the stresses upon impact are equally large in the model and full-scale casks dropped from the same height [L 42].

The three 9 m drop tests with a full-scale CASTOR Ic cask (Section 3.2.1.2.2(e), Drop Tests 3-5) have provided further evidence that the cask components offer adequate safety against undue deformation and failure under the accident loads simulated in the tests.

The failure (undue deformation or fracture) of the cask body and covers should not, according to our assessment, be expected under the accident loads considered here, provided the requirements on the material parameters (see Section 3.5.2) are satisfied.

3.2.1.2.3.2. Primary- and Secondary-Cover Bolt Fastening

In addition to the experimental test described above, in [U 30] the stress in the bolts of the CASTOR Ic primary- and secondary-cover fastenings was calculated under the assumption of an accident load bringing about a negative acceleration of 1962 $m \cdot sec^{-2}$.

This calculation, which we have checked, implies that the tensile stress in the bolts of the primary and secondary covers, with allowance for the possible action of inertial forces of the covers and cask internals (fuel basket and fuel assemblies), is below the yield strength of the bolt material.

The drop tests with the CASTOR IIa 1 : 2 scale-model cask and the CASTOR Ic full-scale cask provided experimental evidence that the primary- and secondary-cover bolt fastenings continue to function under the action of dropping loads assessed as representative. In the framework of testing under the transportation laws, the extension of this result to CASTOR Ia casks is also analyzed.

According to our assessment, the cover bolt fastenings thus offer adequate safety against failure under hypothetical shock loads due to dropping.

3.2.1.2.3.3. Cover and Seal System

After the drop tests with the CASTOR IIa 1 : 2 scale-model cask (see Section 3.2.1.2.2(c) and (d)), the following changes were observed in the cover and seal system being assessed here:

After the first drop test onto a cylinder (Drop Test 4), the insert cover displayed a dent in the middle with a depth of 10 mm and the secondary cover had a dent 8 mm deep.

After the drop tests onto the cover face during the second series of tests (Drop Tests 5 and 7), the insert-cover weld displayed a crack about 20 mm long in each case.

After the conclusion of the tests, no changes could be observed in the geometry of the primary-cover mounting and in its bolt fastenings.

The drop tests with the CASTOR IIa 1 : 2 scale model provided evidence of the tightness required under the transportation laws after mechanical tests (with allowance for a subsequent effect due to fire), because the primary cover remained tight (see Section 3.4.3).

The drop tests with the CASTOR Ic full-scale cask (Drop Tests 3-7) were intended to provide additional evidence that the second seal barrier alone (the secondary cover) satisfies the requirements of the transportation laws. No changes in the mounting geometry of the cover system were seen after the tests. After the drop tests onto a cylinder (Drop Tests 6 and 7), the secondary cover exhibited no permanent deformation; this finding confirmed that the resistance of the impact-limiter design to the loads imposed in the drop test onto a cylinder had been improved.

The assessment of the tightness of individual seal-system components is the subject of Section 3.4.1.

3.2.1.2.3.4. Cask Internals

Evidence that the fuel basket, which holds the fuel assemblies inside the cask, retains its integrity was to be presented; this point bears on the continued criticality safety, even when the cask is flooded during the loading and unloading processes in the nuclear power plant, after accidents that were simulated by the drop tests.

The following kinds of damage were seen in the inserted fuel basket after the first three drop tests with the CASTOR Ia prototype (the cask was not opened until after these tests): partial cracks in the structural welds in the fuel basket and slight deformations of the sheet-metal strips. The fuel-assembly simulators could, however, be unloaded in the proper manner and the geometry of their arrangement was maintained.

A GNS calculation [U 30], which we have checked, covers the maximum shear stress in a sheet of the fuel basket when an accident load is imposed that results in an acceleration of 1962 $m \cdot sec^{-2}$. In the calculation, a reference stress was determined; it is very much smaller than the yield strength of the fuel-basket material.

On the basis of the experimental proofs and the calculation, we consider the necessary evidence to have been presented that criticality safety, even when the cask is flooded during the loading and unloading processes at the nuclear power plant, is not impaired, that is, that no failure of the fuel-basket structure should be expected under the accident loads analyzed here.

3.2.1.3. Tests Simulating an Aircraft Crash

3.2.1.3.1. Test Conditions

A special penetration test, in which a heavy projectile was fired at a representative cask section, served as evidence that the cask could survive a mechanical load resulting from the crash of an aircraft [L 17].

A cylinder about 5000 mm long, about 600 mm in diameter, and weighing about 1000 kg was used as the projectile. It consisted of an outer sheet-steel jacket, with a convex head at the front, closed by a steel plate at the back. Inside the jacket was a massive steel pipe, about 3200 mm long, supported by crosswise braces.

After the projectile exited from the accelerating device, it flew free at a speed of about 300 $m \cdot sec^{-1}$ and impacted on the cask section.

After Test 3, tightness measurements were performed by BAM.

3.2.1.3.2. Tests Performed

Altogether three tests, described below, were performed to simulate an aircraft crash. The tests were conducted on CASTOR cask sections in the presence of BAM specialists.

Test 1

The projectile impacted perpendicularly on the cask-wall cooling fins of a freestanding bottom segment of the CASTOR Ia prototype, weighing 18 metric tons.

The cask was shifted about 4 m in the direction of the shot by the force of impact. The projectile was severely crushed and had a remaining length of about 1 m. Portions of the projectile were wedged between the cooling fins in the impact area. After these remains of the projectile were removed, no damage to the cask wall could be detected except for deformation of the cooling fins.

Test 2

The specimen was a CASTOR IIa cask section (weighing about 49 metric tons) with the bottom and cover portions like the original but with the middle section shortened. The specimen was set up at an angle of 60° to the horizontal and the projectile impacted on the face of the cover portion.

The seal and cover system used comprised guard cover, welded-in insert cover, a single main cover with two radial elastomer seal rings and one axial metal seal ring; there was one valve opening in the cover end of the cask body and this was closed with a valve guard cover with metal gaskets. The system described was not comparable with the seal system of the CASTOR casks, which was to be assessed. For this reason, we did not analyze the tightness of the test object.

The cask section was shifted about 1 m back by the force of the projectile, and the inclination of the cask cover was increased to about 125° from the horizontal.

The guard cover displayed only slight deformation on the surface where the projectile impacted. A crack about 200 mm long appeared in the weld of the insert cover in the region of projectile impact. There was no impairment of the mechanical integrity of the main cover and its bolt fastening.

Test 3 [U 15]

The projectile impacted perpendicularly on the middle of the cask cover system of the shortened CASTOR IIa section (total weight about 53 metric tons including internals). A concrete wall 200 mm thick stood immediately behind the horizontal cask, and the wall was backed with compacted earth.

The cover and seal system was of the same design as the CASTOR cask system as described in Section 2.2. The specimen cask contained internals in the form of a divider cross, simulating the fuel basket designed to accept nine PWR fuel assemblies, and the following items simulating the load: two shortened fuel-assembly simulators (one PWR fuel assembly 230 mm square and 880 mm long, one BWR fuel assembly 130 mm square and 888 mm long) and seven massive steel ballast pieces (190 mm in diameter and 850 mm long).

The force of the projectile shifted the cask about 400 mm backward, through the concrete wall; the angle between the cover surface and the horizontal was altered to 80°. The projectile was completely destroyed, leaving a piece about 1 m long.

Deformations caused by the massive pipe inside the projectile could be seen on the guard cover. After Test 3, the cask was sealed and taken to BAM Test Stand 2, where the other investigations were performed (inspection of damage, tightness test, measurement of tightening torques of bolts).

The deep impression in the middle of the guard cover had a diameter of 200 mm and depth of 73 mm. No visible cracks were found in the cover surface. After the guard cover had been removed, it exhibited a permanent bend.

The secondary cover displayed a dent 68 mm deep, which was visually crack-free, and proved to be permanently bent after removal. Rapid bubble formation in the bubble test indicated severe leaking of the secondary-cover metal seal ring. A function check of the contacts of the pressure gage mounted in the secondary cover came out negative.

The primary cover exhibited no deformations, except that its surface carried a faint impression of the concentric web of the secondary cover.

All cover bolt fastenings remained functional; only in the case of the guard cover could slight changes in the tightening torques be observed.

There was no damage to the cask internals (dividing cross, fuel-assembly simulators, ballast cylinders). The only features seen were faint impressions on the bottom side of the primary cover and a slight pressure mark on the top fitting of the BWR fuel-assembly simulator.

Tightness tests were also performed; these are discussed in Section 3.4.

3.2.1.3.3. Assessment of Tests

The penetration tests considered representative of an aircraft crash [L 17] provided evidence that

the cask wall retained its full integrity after this accident;

because of the two-barrier cover and seal system, at least the first barrier (the primary cover) retains its full integrity. Thus the second barrier (the secondary cover), if it is damaged, can be restored by replacing the guard plate and secondary cover or by welding in the insert cover (after establishing the actual leak rate or activity release of the primary cover);

the integrity of the cask internals is not impaired after this accident.

Sections 3.4.2 and 3.4.3.2 present the assessment of the tightness tests and the release rates derived from them.

Although Test 3 was performed on a section of a CASTOR IIa cask, the results can be extended to casks of the CASTOR Ia and Ic types, since these employ the same design principle for the seal and cover system but have smaller diameters, smaller weights, and roughly the same wall thickness.

Test 1 can also be extended to all casks of the CASTOR Ia, Ic and IIa types, because these casks have a greater wall thickness than the test specimen, and thus, with their similar geometry, a higher cross-sectional moment of resistance.

The penetration tests not only provide evidence of survival of the "aircraft crash" accident [L 17]. Through a comparison of the load assumptions or of the impact force-versus-time functions, they also give evidence of survival, without damage, of other accidents in which the load characteristics are similar, such as the collapse of the heaviest building roof structure components onto the cask [U 17]. This point is covered in the TUV Hannover Opinion [L 1].

3.2.2. Thermal Loads in Accidents

Both calculations and fire and thermal-load tests on CASTOR specimens served for the assessment of the effects of fire loads and disrupted decay-heat removal after accident events (see Fig. 3.2-1). We have assessed these calculations and tests with regard to the effects on the cask components that are important for tightness, shielding and criticality safety, taking the previous mechanical accident loads into account (see Section 3.2.1). The treatment of possible accident scenarios and thermal loads in the Ahaus Shipping-Cask Storage Site, as well as the effects on the fuel-assembly behavior, are covered in the expert Opinion of the TUV Hannover [L 1].

3.2.2.1. Effect of Fire

As evidence that fire loads are survived, the applicants have presented results of a fire test [U 32] and calculations on the cask-wall temperatures under the action of fire [U 18].

In the fire test [U 32], a CASTOR Ia bottom section weighing 18 metric tons, with electric heaters to simulate decay-heat output, was exposed to an open fuel-oil fire (mean flame temperature 1073 K (800°C)) that burned for 30 minutes.

According to data from TUV Hannover, a kerosene [aircraft fuel] fire lasting up to 1 hour with a mean flame temperature of 873 K (600°C) should be considered representative after an aircraft crash [L 1].

The applicants have presented a temperature calculation for the CASTOR IIa cask [U 18], in which they conclude that a fire load of 1073 K flame temperature/30 minutes fire duration is comparable with the loading due to 873 K (600°C) over 60 minutes.

A comparison of the experimental temperature curves with the calculated results showed that the temperature calculations yield higher values and thus should be regarded as conservative [L 41]. An important reason for the difference is the idealized heat-transport conditions assumed in the calculations, which cannot be fully realized in tests.

The maximum temperatures found through appropriate thermal calculations are thus suitable as bases for assessment of the properties with regard to the requirements imposed as to thermal loads in accidents with the CASTOR casks.

Fig. 3.2-2 shows maximum temperatures in the walls of a CASTOR Ic cask, found through our own thermal calculations. The fire parameters were 1073 K/ 0.5 hr (the test conditions set forth for an accidental fire in the IAEA Recommendations [L 14] and the transportation regulations, e.g., [L 8--Rn 1637]) and 873 K/1 hr.

Because the wall construction is the same and the wall thickness is nearly equal, the temperature conditions in CASTOR Ia and IIa casks after the action of a fire will be similar.

The design of the casks means that the assessment of the effects of a fire can be limited to the topics of tightness, shielding and internals.

3.2.2.1.1. Effects on Tightness

Because the applicants do not claim any long-term resistance for the elastomer seal rings used in the cover-seal system along with the metal seal rings, a conservative analysis should assume only the presence of both metal seal rings. (See Section 2.2 for the arrangement of the seal rings.)

For reasons of geometry, the seal region of the secondary cover is at a higher temperature than the seal region of the primary cover during a fire. With respect to continued functioning under the action of fire, the metal seal ring of the secondary cover can thus be assessed as representative for both metal seal rings. According to the calculations, this region heats up to about 473-483 K (200-210°C) (see Fig. 3.2-2). According to data supplied by the seal-ring manufacturer [L 26], a long-term load at temperatures of up to 523 K (250°C) is permissible. Tests with aluminum-jacketed metal seal rings, performed to establish the temperature stability, showed that the leak rate did not increase over the values measured before the test when a much higher

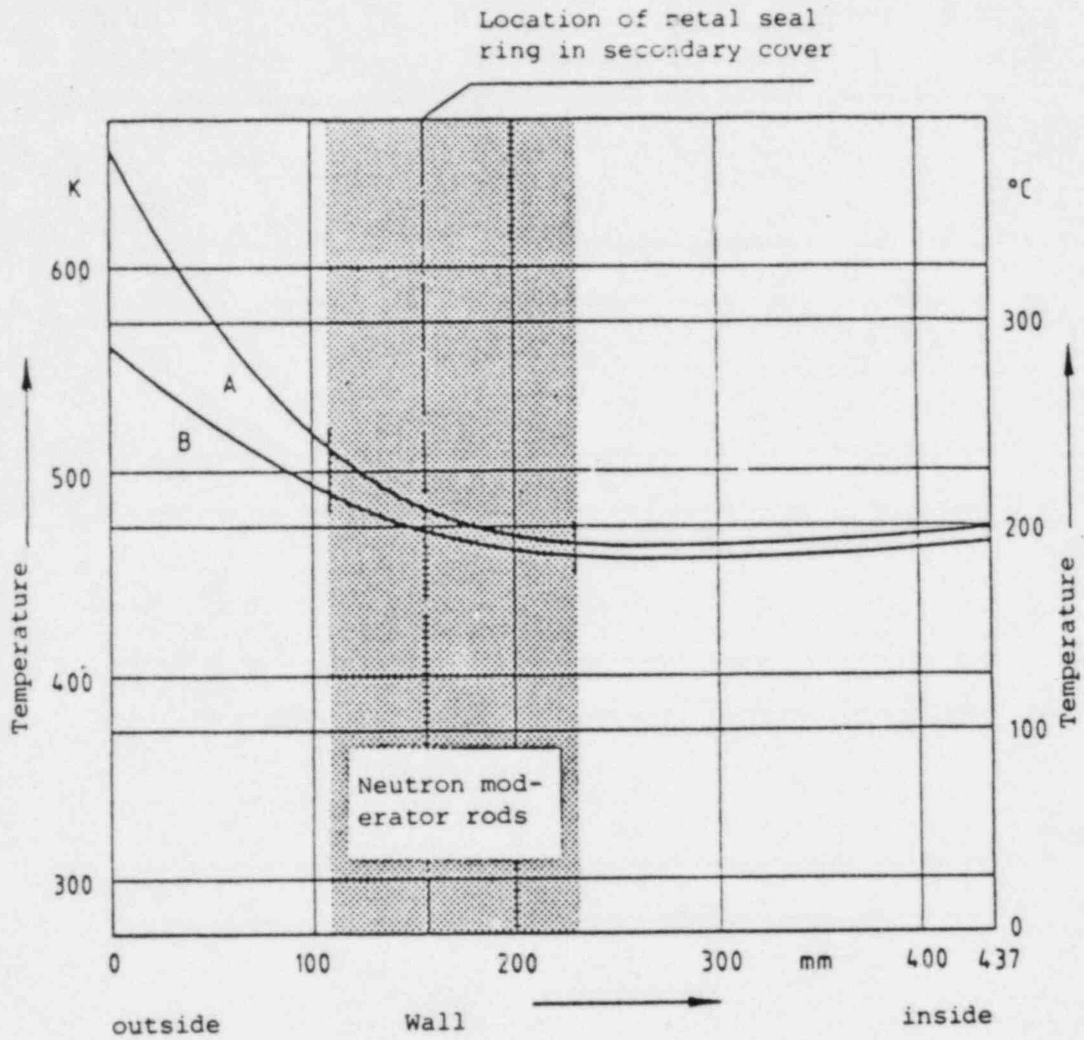

Fig. 3.2-2. Calculated temperature curves in the wall of a CASTOR Ic cask after a fire, showing maximum temperatures reached. Curve A is for a mean flame temperature of 1073 K and a duration of 30 minutes, curve B, for a mean flame temperature of 873 K and a duration of 60 minutes. It was observed that the maximum temperatures occurred at different times in different locations.

temperature was held for 4 hr [U 3]. The temperature effect due to a fire should thus, according to our assessment, be regarded as noncritical for the seal system.

3.2.2.1.2. Effects on Shielding

By virtue of the design, the integrity of metal cask components is not impaired by the action of fire [L 41]. The shielding action of these components can be viewed as adequately assured.

With respect to the neutron moderator material, however, a reduction in shielding against neutron radiation in the wall and in the bottom of the cask is to be expected after the action of a fire. The maximum temperature in the region of the moderator rods in the cask-body wall during a fire is between 458 K and 513 K (185°C and 240°C; see Fig. 3.2-2). For an upright cask, the temperature conditions in the regions of the moderator material in the top and bottom portions are roughly the same. In the case of a horizontal cask, the temperature in the bottom portion and in the guard-plate region may go even higher, since here the moderator is protected only by a seal plate 25 mm thick or by the remaining wall thickness (about 45 mm) of the guard plate remaining over the moderator ring. On the basis of the drastic increase in the unit volume of the moderator material used here at the temperatures to be expected after the action of a fire, the vacant volumes provided for expansion under normal service conditions are not sufficient for the increase in volume. We assume the following behavior to result from the expected pressure rise:

In the secondary cover, the seal-plate weld is expected to rupture, so that liquefied moderator material (the melting point of the moderator material is at about 393 K (120°C)) escapes into the inaccessible space between the primary and secondary covers. The possible pressure rise in the inaccessible space cannot, however, lead to impairment of the primary-cover seal system.

In the bottom portion and the region of the guard plate, likewise, cracking of the welds on the seal plates is expected, with escape of moderator material. The tightness of the cask is not impaired in this way.

Since the seal plugs of the moderator holes in the cask wall are only pressed in (transition fit), and thus can be squeezed out fairly easily when the internal pressure rises, moderator material can also be supposed to escape here.

Only part of the moderator material in the wall and in the bottom would escape from the cask, but because of the complicated thermal conditions (temperature distribution under the action of a fire) the fraction escaping cannot be stated quantitatively with much precision. For this reason, as a conservative assumption for the shielding calculation, we cannot rule the loss of all neutron moderator material out of the question (compare [U 39]).

The assessment of the shielding is covered in the expert Opinion of the TÜV Hannover.

3.2.2.1.3. Effects on Internals

Given the temperature rise expected at the inside wall of the cask after the action of a fire (see Fig. 3.2-2), no allowance need be made for impairment of the functioning of the internals (fuel basket).

3.2.2.2. Disruption of Decay-Heat Removal

In what follows, we analyze a long-term stoppage of decay-heat removal, such as might result from the cask being covered with debris after an aircraft crash, the collapse of the storage-building roof, or other hypothetical events.

On this point, the applicants conducted a test on the bottom section of a CASTOR Ia cask, weighing 18 metric tons, in which the debris or rubble cover was simulated by wrapping the test specimen in glass-wool mats [U 19]. The assessment of the test result with regard to its being representative for the accident to be analyzed here, as well as the treatment of effects on the behavior of the fuel assemblies, is covered in the Opinion by the TUV Hannover.

The internal cask temperature rise measured in this test, about 50 K, cannot cause functional impairment of the cask components or internals.

3.2.3. Combination of Mechanical and Thermal Loads in Accident

According to our assessment, even a combination of the mechanical and thermal accident loads that we have analyzed cannot result in more severe damage to the casks than the several individual events.

In the analysis of release after accidents in Section 3.4, the effect of combined mechanical and thermal accident loads is again considered.

3.3. Tightness and Activity Release in Normal Service

3.3.1. Introduction

At the beginning of storage, the fission products are tightly contained in the fuel rods. Because there is not yet any quantitative justification for assuming a given defect rate for the fuel-rod cladding tubes during storage, the co-expert TUV Hannover starts with the highest conceivable defect rate of 100% by way of a hypothetical limiting analysis [L 1]. In accordance with the agreement, our further estimates are based on this assumption.

The seal system (see Section 2.2) essentially consists of two metal seal rings with aluminum jacketing, which are located in the axial bearing regions of the primary and secondary covers, and the inaccessible space lying in between, which has a free volume of 13.8 L (CASTOR Ia), 15.2 L (CASTOR Ic) or 23.0 L (CASTOR IIa) [U 22].

In order to obtain conclusive information about the possible leak rates, the documents of TUV Hannover [L 1] and of the applicant [U 42, U 44] that were available to us were used. From them, mean time dependences were derived for the temperature of the gas in the cask interior, in the cask wall, and in the seal regions. These relations are adequately representative for the tightness analysis that follows.

The analysis carried out to assess the two-barrier seal system and the tritium permeation is likewise based on the documents available to us [U 42]; however, the analysis has been largely developed by us on the basis of our own theoretical knowledge and experimental background.

3.3.2. Radioactive Contents

The fission products generated during reactor operation are mainly bound in the fuel in solid form.

Roughly 30% of all nuclear fissions produce gaseous isotopes, either stable or radioactive with long half-lives, of the elements iodine, krypton and xenon, as well as much smaller quantities of bromine isotopes and the hydrogen isotope tritium. This means that about 30 mL of fission gases (under standard conditions, i.e., at 273 K and 1 bar) is produced per MWd of thermal energy generated. Of this, one year after removal from the reactor, a scant 3% of the volume content is still radioactive, essentially comprising $^{129}I_2$ (about 2%), ^{85}Kr (about 0.7%), and HT ($T = {}^{3}H$, about 0.05%); the calculation was done in accordance with [L 18] for a typical example with a PWR, 36,000 MWd/metric ton uranium burnup, 3.2% initial enrichment. A portion of the fission gases goes into the fission gas collecting plenums of the fuel rods during reactor service.

With regard to the releasable activity fractions from the fuel matrix, we follow the assumptions of the TUV Hannover [L 1].

Under these assumptions, 10% each of the ^{85}Kr and ^{129}I inventories are in the fission gas collecting plenums at the beginning of storage. In addition, TUV Hannover assumes gradual releases of ^{3}H and ^{85}Kr; with respect to the total free activities, each of these releases is competing with the radioactive decay of the gas. After a storage of about 1.5 yr, the free ^{3}H activity reaches its maximum, corresponding to about 28.6% of the ^{3}H inventory; after about 10 yr, the maximum relative release fraction of about 29.5% of the ^{3}H inventory is attained. The free ^{85}Kr activity reaches its maximum after about 3 yr, corresponding to about 16.2% of the ^{85}Kr inventory; toward the end of the service period of 40 yr, the maximum relative release fraction of about 19.2% of the ^{85}Kr inventory is reached.

Furthermore, stable or long-lived radioactive cesium isotopes are produced in nuclear fission events. Although cesium is one of the least noble metals and accordingly is extremely reactive, according to [L 1] it is hypothetically assumed that cesium is released in elemental form (volatile solid according to [L 43]), and that its concentration in the primary cover region is determined by the saturation vapor pressure prevailing there.

Elemental cesium melts at about 302 K (29°C) and boils at about 978 K (705°C). The relation [L 21]

$$\log p = 7.004 - 3750/T$$

describes the vapor pressure p (in mbar) as a function of the temperature T (in K).

3.3.3. Leak Rates

Given proper assembly of the cover and seal system of the CASTOR casks, we consider the design leak rate of $\leq 10^{-7}$ mbar·L·sec^{-1} (helium, 293 K, pressure difference 1 bar against vacuum) for each of the two metal seal barriers to be attainable. This design standard helium leak rate is to be demonstrated by measurements before storage (Proposed Order AV 3.3-1).

Leak rates of this order of magnitude virtually represent purely molecular flows. The leak rates Q_i are then proportional to the partial-pressure difference Δp_i for gas species i, and the dependence of leak rate on relative molecular weight M_i and gas temperature T is given by the following relation [L 19, L 20, L 44]:

$$Q_i \propto (T/M_i)^{1/2} \cdot \Delta p_i .$$

The free cask volume, between 1300 L (CASTOR Ia) and 3300 L (CASTOR IIa) [U 22], thus contains helium, the fission products released from defective fuel rods in gaseous form--tritium (as HT), krypton and iodine (as I_2)--and the fission product cesium in the form of a volatile solid. Cesium in proportion to its saturation vapor pressure, and the gases in proportion to the partial pressure of each one, would move against the total pressure gradient, through the primary-cover seal region, and into the inaccessible space, where they would accumulate. In proportion to the partial pressures set up in the inaccessible space in this way, these gases and the gaseous cesium would then be able to pass through the secondary-cover seal region and into the environment of the cask.

Our calculations showed that the partial pressures in the inaccessible space remain at least a factor of 10^{-3} to 10^{-2} smaller than those in the cask interior, depending on the gaseous species, so that Δp_i is practically equal to the partial pressure in the cask interior or in the inaccessible space. Under these conditions, the leak rate of the two-barrier seal system is proportional to the product of the leak rates for the two seal barriers. Given the above maximum design leak rate for one seal barrier, our calculations for helium yield a concentration rise of between 15 ppm and 25 ppm a year, depending on the cask-specific volume in inaccessible spaces that are filled with a helium-free inert gas. In sniffing tests with commercially available mass-spectrometric helium leak-detecting equipment, according to our experience, concentrations as low as 0.1-1 ppm can be detected with certainty. Thus, by measuring the helium content in an initially helium-free inaccessible space, it is possible in principle to establish, at any time of interest, the retrospective time average of the leak rate of the primary-cover seal system.

Using the activity inventories from TUV Hannover data [L 1], the release fractions described in Section 3.3.2, the free volumes of the cask interior and inaccessible space [U 22], and the mean curves of temperature versus time, we have calculated the time behaviors of the activities in the inaccessible spaces and the rates of activity leakage to the outside.

Fig. 3.3-1 shows the maximum activity inventories in the inaccessible spaces versus time. For ^{3}H, ^{85}Kr and ^{129}I, the cask-specific values are proportional to the activity inventory divided by the free cask volume; thus the values for the CASTOR Ic cask are largest. Because vapor saturation was assumed, the cesium inventory at equal cask temperatures and for equal design leak rates is identical for all the CASTOR casks.

Fig. 3.3-2 shows the time variation of the maximum activity leak rates outward through the two-barrier seal system. For ^{3}H, ^{85}Kr and ^{129}I, the cask-specific values are proportional to the activity inventory divided by the product of free cask volume and inaccessible-space volume; thus the values for the CASTOR Ic are largest and those for the CASTOR IIa are smallest (about 40% of the maximum leak rates). Although the inaccessible spaces contain relatively higher ^{85}Kr activities, the outward leak rates for tritium are greater because of the lower molecular weight. The cesium leak rates are inversely proportional to the inaccessible-space volume; thus the CASTOR Ia values are largest and, again, the CASTOR IIa values are smallest (about 60% of maximum).

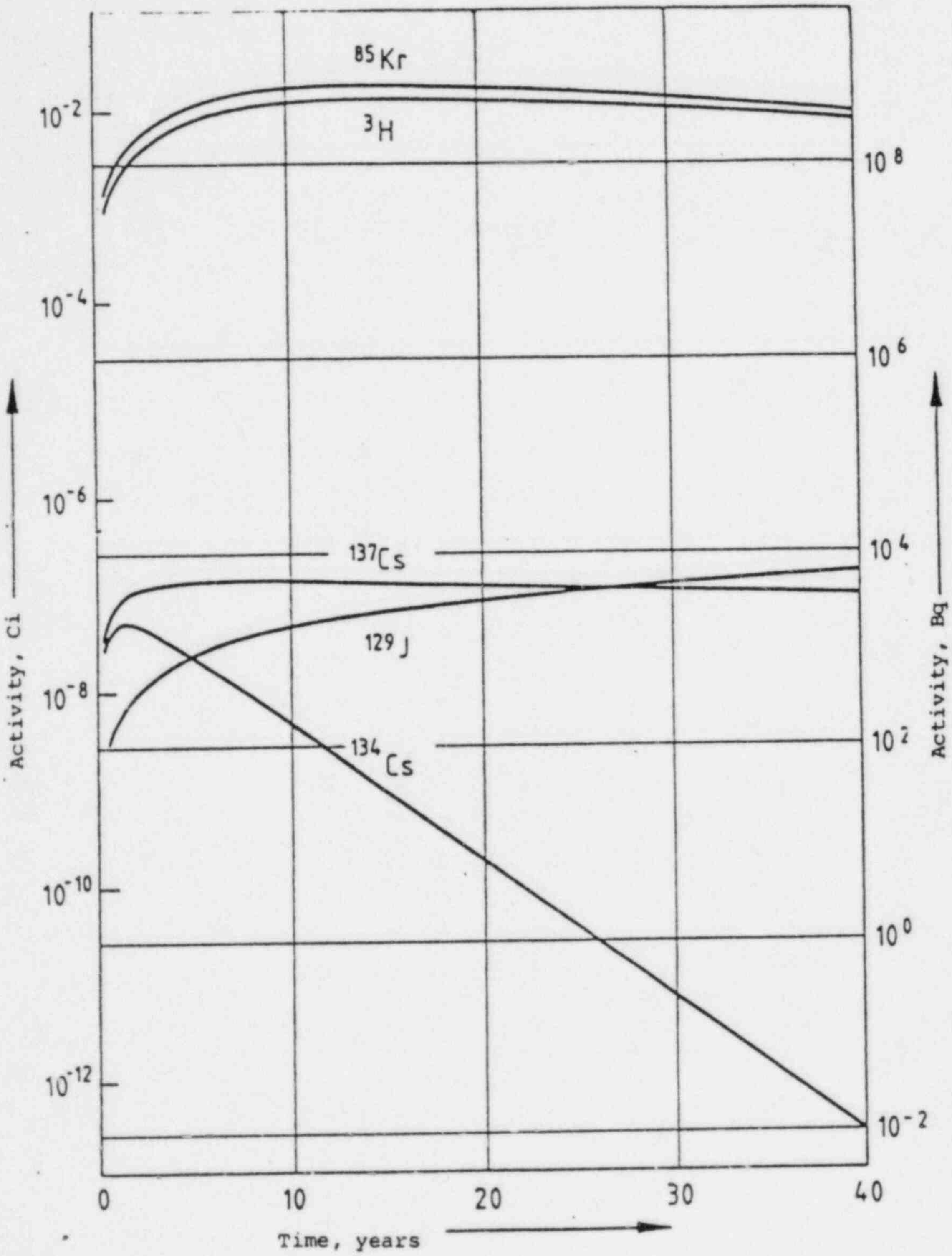

Fig. 3.3-1. Maximum activities in inaccessible space of CASTOR casks, versus storage time. ^{3}H, ^{85}Kr and ^{129}I for CASTOR Ic; ^{134}Cs and ^{137}Cs for all CASTOR types. Assumptions: (a) all fuel-rod cladding tubes become leaky at the beginning of storage; (2) both seal barriers have a constant standard helium leak rate of 10^{-7} mbar·L·sec^{-1}.

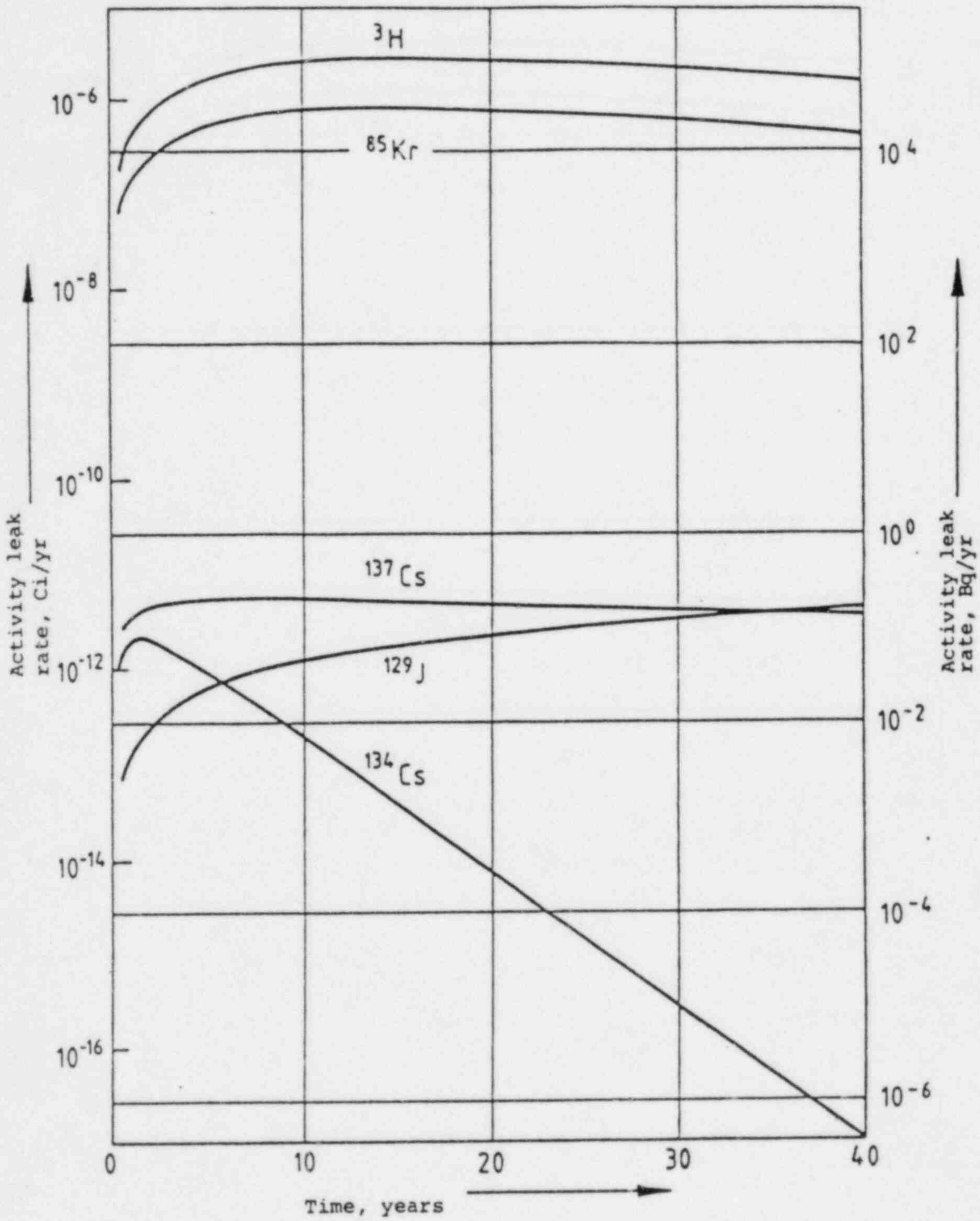

Fig. 3.3-2. Maximum activity leak rates from the two-barrier seal systems of CASTOR casks, versus time. ^{3}H, ^{85}Kr and ^{129}I for CASTOR Ic; ^{134}Cs and ^{137}Cs for CASTOR Ia. For assumptions, see Fig. 3.3-1.

The tabulations below give the maximum activities in the inaccessible spaces and the maximum activity leak rates for the CASTOR casks. The time of occurrence of each maximum is also stated.

Maximum activities in inaccessible space

$4.4 \cdot 10^{8}$ Bq ($1.2 \cdot 10^{-2}$ Ci)	^{3}H	after about	17	years	(CASTOR Ic)
$6.5 \cdot 10^{8}$ Bq ($1.7 \cdot 10^{-2}$ Ci)	^{85}Kr	after about	16	years	(CASTOR Ic)
$6.0 \cdot 10^{3}$ Bq ($1.6 \cdot 10^{-7}$ Ci)	^{129}I	after	40	years	(CASTOR Ic)
$1.8 \cdot 10^{3}$ Bq ($0.5 \cdot 10^{-7}$ Ci)	^{134}Cs	after about	1.2	years	(CASTOR Ia,
$5.0 \cdot 10^{3}$ Bq ($1.3 \cdot 10^{-7}$ Ci)	^{137}Cs	after about	8	years	Ic, IIa)

Maximum outward activity leak rates

$9.3 \cdot 10^{4}$ Bq/yr ($2.5 \cdot 10^{-6}$ Ci/yr)	^{3}H	after about	17	years	(CASTOR Ic)
$3.0 \cdot 10^{4}$ Bq/yr ($8.1 \cdot 10^{-7}$ Ci/yr)	^{85}Kr	after about	16	years	(CASTOR Ic)
$1.6 \cdot 10^{-1}$ Bq/yr ($4.3 \cdot 10^{-12}$ Ci/yr)	^{129}I	after	40	years	(CASTOR Ic)
$0.8 \cdot 10^{-1}$ Bq/yr ($2.1 \cdot 10^{-12}$ Ci/yr)	^{134}Cs	after about	1.2	years	(CASTOR Ia)
$2.0 \cdot 10^{-1}$ Bq/yr ($5.5 \cdot 10^{-12}$ Ci/yr)	^{137}Cs	after about	8	years	(CASTOR Ia)

3.3.4. Tritium Permeation

It is well known that hydrogen can penetrate metal walls relatively well. The literature data on the diffusion and permeation coefficients for hydrogen in iron, with its various phases and alloys, cover several orders of magnitude [U 23, L 22, L 45]; for this reason, measurements on the permeation of tritium (^{3}H) through original specimens of the cask material GGG 40 were performed at the Kernforschungsanlage Jülich [Jülich Nuclear Research Facility] [U 21].

Using the results, we have done calculations on the whereabouts of the tritium for a span of 40 years [L 46]. For simplicity, it was conservatively assumed that, at the beginning of storage, about 29.5% of the tritium inventory is free in the interior of the cask. This figure is the maximum releasable relative fraction of the tritium inventory after 10 years with all the fuel-rod cladding tubes defective, as assumed by TUV Hannover [L 1].

This analysis shows that some of the tritium dissolves in the inside wall of the cask (maximum absorbed activity in CASTOR IIa: $3.5 \cdot 10^{12}$ Bq = 10% of releasable inventory after about 1.2 years; in the 40 years covered by the analysis, the relative dissolved fraction increases to about 28% = $1.1 \cdot 10^{12}$ Bq). Most of this tritium, however, penetrates only a few centimeters into the cask wall, so that the outward leak rate is very small, several orders of magnitude below the seal-system leak rates shown in Fig. 3.3-2. By way of example: if the time behavior of the wall temperature on which this Opinion is based, together with a wall thickness of just 240 mm, is assumed, or if a uniform 27 K temperature rise is assumed throughout the storage period, then after 40 years the highest tritium permeation leak rate for the CASTOR IIa cask would increase in order of magnitude to about one tritium atom a year; that is, the permeation rate is negligible.

3.4. Tightness and Activity Release after Accidents

3.4.1. Tightness after Accidents as Simulated by Drop and Fire Tests

Because the test results can be compared and extended, here the tightness analysis after drop tests (Section 3.2.1.2.2) followed by fire loads (Section 3.2.2.1) is done for the CASTOR IIa 1 : 2 scale-model cask, since the seal system to be assessed is largely realized in this test specimen. Survivability with respect to this combination of accidents is also required by the specifications under the transportation laws [L 8, L 9, L 14, L 23, L 24].

The primary cover and secondary cover were placed tightly in the cask with the following seal-ring configuration:

Primary cover: one axial metal seal ring with aluminum jacketing

Secondary cover: one axial metal seal ring with aluminum jacketing

Because the possible leak rates are proportional to the seal-ring circumference in each case, it is simple to extend the test results to other CASTOR casks.

Tightness measurements on the metal seal rings (only these are considered here) after the drop tests described in Section 3.2.1.2.2(c) and (d) yielded the following results [U 13, U 14]:

- Except for the two seal rings mentioned below, it was established that, for all components of the seal system (except for the insert cover, which should not, according to our assessment, be regarded as accident-proof), the standard helium leak rate of $\leq 10^{-7}$ $mbar \cdot L \cdot sec^{-1}$, the value measured before the drop tests and on which the design was based, was not exceeded even after the series of drop tests.
- In the case of the metal seal ring on the small seal cover over the quick-disconnect coupling inserted into the secondary cover, a standard helium leak rate of $2 \cdot 10^{-7}$ $mbar \cdot L \cdot sec^{-1}$ was found after the drop onto the cylinder (Drop Test 4).
- After Drop Test 1 onto the cover face and the drop tests of the second series (Drop Tests 5-8), the large metal seal ring of the secondary cover exhibited a standard helium leak rate that could no longer be determined quantitatively with the measuring instrument used. According to our assessment, however, the rate was not greater than 10^{-1} $mbar \cdot L \cdot sec^{-1}$. We did not use this result for the purpose of assessment.

Tightness measurements after the drop tests with the CASTOR Ic full-scale cask (Section 3.2.1.2.2(e), Drop Tests 3-7), which provided a separate assessment of the secondary-cover seal system, yielded the following values [U 58, U 59, U 60]:

After Drop Test 3, the secondary-cover seal system exhibited a standard helium leak rate of $5 \cdot 10^{-5}$ $mbar \cdot L \cdot sec^{-1}$, which was essentially due to the leak rate of the secondary-cover metal seal ring.

After Drop Tests 4 and 5, the secondary-cover seal system exhibited a standard helium leak rate of $\leqq 6 \cdot 10^{-7}$ $mbar \cdot L \cdot sec^{-1}$; the highest leak rate of $\leqq 5 \cdot 10^{-7}$ $mbar \cdot L \cdot sec^{-1}$ was measured on the secondary-cover metal seal ring after Drop Test 5.

After Drop Tests 6 and 7, the secondary-cover seal system exhibited a standard helium leak rate of $\leqq 5 \cdot 10^{-7}$ $mbar \cdot L \cdot sec^{-1}$; this was essentially due to the leak rate of the metal seal ring of the pressure-gage flange after Drop Test 7.

3.4.2. Tightness after Tests Simulating an Aircraft Crash

After the penetration test to be assessed here (Section 3.2.1.3.2, Test 3), the guard plate and secondary cover of the test specimen showed large-scale leakiness.

In the nitrogen-filled cask interior, the pressure declined from 2 bar to 1.85 bar within 6 days. With the free internal volume of 530 L, this figure yields a mean nitrogen leak rate of about 0.15 $mbar \cdot L \cdot sec^{-1}$ for the primary-cover seal system. Allowing for uncertainties in measurement and the limits of error in the pressure measurements performed, we used a value of 0.3 $mbar \cdot L \cdot sec^{-1}$ in Section 3.4.3.2. This leak rate, determined on the seal system of a CASTOR IIa, was proportional to the cask-specific seal lengths for casks of the CASTOR Ia and Ic types.

3.4.3. Activity Release after Accidents

3.4.3.1. Activity Release after Accidents as Simulated by Drop and Fire Tests

The basis for assessing the activity release after accidents represented by drop tests (see Section 3.2.1.2) is as follows:

After all drop tests, the standard helium leak rate of the primary-cover seal system remained $< 10^{-7}$ mbar·L·sec^{-1}.

After the drop tests used for assessment of the secondary-cover qualification (see Section 3.2.1.2.2(e), Drop Tests 3-7 with CASTOR Ic full-scale cask), the highest standard helium leak rate was $5 \cdot 10^{-5}$ mbar·L·sec^{-1}.

As was shown in Section 3.2.3, the subsequent action of a fire does not result in any loss of this tightness.

3.4.3.1.1. Analysis of Primary-Cover Seal System

On the assumption that only the first seal barrier is functional (standard helium leak rate = 10^{-7} mbar·L·sec^{-1}, no seal action by the second barrier), in the framework of testing of the CASTOR Ic design under the provisions of the transportation laws [L 8, L 9, L 14, L 23, L 24], we have calculated the activity leak rates presented in Table 3.4-1 [L 39, L 48]. Leak rates this low correspond to molecular flows, and the relations given in Section 3.3.3 hold for them.

The calculation was done for the CASTOR Ic design (BWR fuel assemblies with 2.4% initial ^{235}U enrichment, 27,000 MWd/metric ton U burnup, 1 year decay time [L 39]), under the assumption of 100% defective fuel-rod cladding tubes, with a release of 10% of each of the radioactive gases ^{3}H, ^{85}Kr and ^{129}I and a concentration of ^{134}Cs and ^{137}Cs corresponding to the vapor pressure of free Cs in the region of the primary-cover metal seal ring. In contrast to the assumptions for normal service conditions, in the accident an immediate 50 K temperature rise was assumed in the whole cask, so that, because of the corresponding rise in vapor pressure, the Cs leak rate in particular is higher after an accident.

Table 3.4-1. Activity leak rates through a seal barrier of the CASTOR Ic type, with reference to the highest permissible limit of activity release under the transportation laws (standard helium leak rate = 10^{-7} mbar·L·sec^{-1}) [L 48]. 1 Ci = $3.7 \cdot 10^{10}$ Bq.

	Activity leak rate		A_2	Reserve factor	
	Normal service conditions	Accident (Notes 1, 4)	[L 8]	Normal service conditions (Note 2)	Accident (Note 3)
^{3}H	$6,6 \cdot 10^{-8}$ Ci/h	$1,2 \cdot 10^{-5}$ Ci/w	1000 Ci	$1,5 \cdot 10^{4}$	$8,3 \cdot 10^{4}$
^{85}Kr	$1,9 \cdot 10^{-7}$ Ci/h	$3,3 \cdot 10^{-5}$ Ci/w	1000 Ci	$5,2 \cdot 10^{3}$	$3,0 \cdot 10^{4}$
^{129}I	$4,6 \cdot 10^{-13}$ Ci/h	$8,0 \cdot 10^{-11}$ Ci/w	2 Ci	$4,3 \cdot 10^{6}$	$2,5 \cdot 10^{7}$
(Cs)	($8,0 \cdot 10^{-13}$ g/h)	($1,5 \cdot 10^{-9}$ g/w)	-	-	-
^{134}Cs	$3,0 \cdot 10^{-11}$ Ci/h	$5,8 \cdot 10^{-8}$ Ci/w	10 Ci	$3,3 \cdot 10^{5}$	$1,7 \cdot 10^{5}$
^{137}Cs	$3,0 \cdot 10^{-11}$ Ci/h	$5,8 \cdot 10^{-8}$ Ci/w	20 Ci	$6,6 \cdot 10^{5}$	$3,4 \cdot 10^{5}$

Notes: (1) Additional assumption: immediate 50 K temperature rise.

(2) Activity leak rate referred to permissible limit of $A_2 \cdot 10^{-6}$ per hour [L 8, L 9, L 14, L 23, L 24].

(3) Activity leak rate referred to permissible limit of $A_2 \cdot 10^{-3}$ per week [L 8, L 9, L 14, L 23, L 24].

(4) w = week.

Translator's note: In reproduced numbers, commas denote decimal points.

Section 3.2.2.1.1 gives an even higher temperature (up to 483 K (210°C)) in the seal region for an accidental fire (1073 K/0.5 hr). According to our calculations, these temperatures are present only for a short time, up to about 5% of the reference time span of one week. The temperature exceeding the calculated reference temperature for such a short time is offset by the temperature decline during cooling. Our assumption of an immediate temperature rise of 50 K, which remains constant in time for a week, allowed a simplified calculation yielding conservative values with respect to the leak rates.

As the results of these calculations (Table 3.4-1) show, the calculated activity leak rates are at least three orders of magnitude below the limits permitted under the transportation laws for Type B(U) packages. The "reserve factor" in Table 3.4-1 is the ratio of the permissible activity leak rate ($A_2 \cdot 10^{-6}$/hr for normal transport, $A_2 \cdot 10^{-3}$/week after accident loads) to the activity leak rate calculated by us from the barrier tightness (standard helium leak rate 10^{-7} mbar·L·sec^{-1}).

3.4.3.1.2. Analysis of Secondary-Cover Seal System

The highest standard helium leak rate determined after trials for the separate assessment of the secondary-cover seal system was $5 \cdot 10^{-5}$ mbar·L·sec^{-1} (see Section 3.4.1). This rate could be attributed to both molecular flow (very many small leaks distributed over the seal length, or one or several wide clearance leaks) and mixed flow in the transition region to laminar-viscous flow (one or several larger leaks). In the case of laminar-viscous flow, it would be proportional to the difference of squares between the total internal and external pressures and inversely proportional to the dynamic viscosity. With this type of flow, the composition of a gas mixture remains unchanged ahead of and behind a leak [L 19, L 20, L 44]--and thus the concentration of the released gaseous fission products, which is at issue in the problem as formulated here, also remains the same.

With regard to the pressure rise in casks when all the fuel-rod cladding tubes become leaky, we have worked with a fission-gas release of 10% (for the burnup considered here, and one year after withdrawal of the fuel assemblies from the reactor, about 95% by volume of the fission gas consists of the noble gases krypton and xenon [L 18], for which a released fraction of 10% is assumed in accordance with [L 43]). We have also assumed that all the helium charged under excess pressure into the fission-gas collecting plenum when the fuel rods were fabricated is still freely available. Under these assumptions, it is found that, when all the fuel-rod cladding tubes become leaky, the free gas inventory in the casks essentially consists of helium, so that the dynamic viscosity of helium remains decisive for our further analysis of laminar-viscous flow.

If TUV Hannover data [L 1] on the free activity inventory in CASTOR Ia, Ic and IIa casks are used, and if an immediate 50 K temperature rise is assumed, then the calculations we have performed yield the result that the highest activity leak rates for the CASTOR IIa design would be expected if gas escaped through a single leak by laminar-viscous flow.

In the case of disrupted decay-heat removal due to debris coverage, TUV Hannover assumes [L 1] that a temperature equilibrium at a maximum of 50 K higher is established after about 120 hr.

Our assumption of an immediate 50 K temperature rise, constant in time for one week, allowed a simplified calculation that yields conservative values with respect to the leak rates.

On the assumption that only the secondary cover, as the second seal barrier, is functional after accidents as simulated by drop tests (standard helium leak rate $5 \cdot 10^{-5}$ mbar·L·sec^{-1}, no seal action by primary cover), and with allowance for the boundary conditions stated above, we have calculated the maximum quantities of radiologically important fission products released in one week's time in the case of an accident event immediately after the beginning of storage:

a maximum of $5.8\cdot10^{-6}$ g of Cs

a maximum of $2.2\cdot10^{-5}$ of the content by volume = $2.2\cdot10^{-5}$ of the free inventory of ^{3}H, ^{85}Kr and ^{129}I

Each figure is for a CASTOR IIa cask.

Given these small leak rates, no significant drop in pressure would take place in the casks over one week; thus the activity leak rates would be constant in time.

By analogy with Section 3.4.3.1.1, we calculated the ratios of the activity leak rates permitted under the transportation laws ($A_2\cdot10^{-3}$/week after accident loads) to the activity leak rates corresponding to the highest measured standard helium leak rate of $5\cdot10^{-5}$ mbar·L·sec^{-1}. The decisive smallest value of the reserve factor from the calculations was about 9 with respect to the ^{85}Kr leak rate from casks of the CASTOR IIa type.

Thus we can state that the CASTOR Ia, Ic and IIa casks satisfy the requirements on tightness for a Type B(U) package when the primary-cover seal system is defective and the secondary-cover seal system is functional, when the guard plate is installed and the impact limiters are attached (this is true for the CASTOR Ic according to [U 61] and, accordingly, for the other designs).

3.4.3.2. Activity Release after Tests Simulating an Aircraft Crash

After the test simulating an aircraft crash, which is being assessed here, the nitrogen leak rate of the primary-cover seal system was determined to be 0.3 mbar·L·sec^{-1}. This leak rate could be attributed to both molecular and laminar-viscous flow. Making the simplified but conservative assumption of an immediate 50 K temperature rise due to obstruction of decay-heat removal (see Sections 3.2.2.3 and 3.4.3.1.2), and using the cask-specific seal lengths and pressure conditions, we have calculated the maximum released fractions of the gaseous cask inventory for each type of flow. If TUV Hannover data [L 1] on the free activity inventories in the CASTOR Ia, Ic and IIa casks are used, then according to our calculations the following inventory fractions correspond to the highest activities that would be released after the accident event named above occurring at the beginning of storage (release in the week following, through the primary-cover seal system):

a maximum of 10.8 mg of Cs from one CASTOR IIa cask, for molecular flow

a maximum of 20% of the ^{3}H inventory from one CASTOR Ic cask, for molecular flow

a maximum of 3.2% of the content by volume = 3.2% of the free inventory of ^{85}Kr and ^{129}I from one CASTOR IIa cask, for laminar-viscous flow

If the accident event (aircraft crash with obstruction of decay-heat removal) occurred at a later time, after the beginning of storage, then the released fractions stated above would be smaller because of the lower temperatures and pressures prevailing then. Radiological analyses connected with this discussion of release are covered in the Opinion of TUV Hannover [L 1].

3.5. Quality Assurance

3.5.1. Quality Assurance Concept

Because all safety-relevant functions for the "tight containment" of spent fuel assemblies at the shipping-cask storage site must be performed by the shipping and storage casks, quality assurance practices in the design, fabrication, tests before commissioning and after individual handling operations, and periodic tests during the operation of shipping casks take on the highest importance.

The purpose of testing in the areas named above is to cover every component or property of safety significance, so that every single mass-produced cask can be demonstrated to achieve the parameter values set forth or specified in the Opinion or in type tests.

The quality assurance system of the applicants, aimed at achieving the goals just stated, is set forth in [U 1--Section 2.3 and U 36]. The practices specified there apply to all casks of the CASTOR type.

The "Quality Assurance Handbook" [U 36] is, according to our assessment, suitable for regulating all administrative and management activities on the part of the applicants and manufacturers, establishing the application of portions of the "Quality Assurance Program" (QSP) covered by our Opinion, and establishing the application of portions of the QSP still to be checked as part of continuing examination by a specialist to be called in by PTB before the start of fabrication. Another contribution hereto is due to the "Quality Assurance Program for the Manufacture of Type B Packages--Requirements on Manufacturer's Quality Assurance" in [U 36], which obligates subcontractors and manufacturers of individual components to apply the above-cited Quality Assurance System.

Tests done as part of the preparation of this Opinion essentially related to establishing approval-relevant requirements and basic conditions of the QSP, such as

- qualification of materials used, hence statements of parameters and specifications
- type, scope and test personnel for fabrication tests aimed at proving the reproducibility of safety-relevant property values

specifications for manufacture and testing

documentation of quality assurance practices

The bulk of the requirements on quality assurance set forth in this Opinion are identical with the requirements established as part of type testing for approval under the transportation laws [L 39]. Requirements specific to shipping-cask storage sites must also be taken into account.

3.5.2. Qualification of GGG 40 Cask Body Material for CASTOR Shipping and Storage Casks

The body of a CASTOR cask is a large casting of GGG 40 cast iron with nodular [spheroidal] graphite. The design and material properties of the cask body must be such that it safely survives mechanical loads due to handling accidents and actions from outside (these alone result in significant loads).

The following criteria had to be taken into account in the safety testing of shipping and storage casks:

Every cask must safely survive accident loads as simulated by drop tests (9 m drop onto unyielding foundation and 1 m drop onto a steel cylinder 150 mm in diameter). Brittle failure must be precluded at low temperatures (down to 233 K (-40°C)).

On this point, evidence for four different test specimens must be presented (see Section 3.2.1.2) from drop tests performed in accordance with these requirements of the transportation laws [L 8, L 9, L 14, L 23, L 24].

The maximum loads due to handling accidents in the shipping-cask storage site are smaller than those in the 9 m drop tests onto the unyielding foundation of the drop test stand [L 1].

- Every cask must safely survive loads resulting from the events aircraft crash, explosion, and earthquake, including their consequences (collapse of building).
- The penetration tests (see Section 3.2.1.3), performed with two different test specimens, are representative with respect to loading level and type for the accident events just named [L 1, L 17].
- For the cask body, "safely surviving" the accident loads means that there may not be any loss of integrity or any deformation that results in undue lack of tightness.

All the test specimens that were subjected to the numerous loading tests had cask bodies made of cast iron with nodular graphite (GGG 40). These tests also demonstrated the fundamental suitability of this material, since in no case was any loss of integrity or undue deformation of the cask body observed.

In order, however, that the positive test results can be extended to the design type and to mass-produced CASTOR casks, the following conditions must be satisfied:

- The loads to be expected on the CASTOR casks under the same test conditions must be smaller than those imposed on the test specimens (or at most equally great).
- The level of material properties of safety significance must be comparable; that is, the factor of safety or (when the safety is not quantified) the material properties of the mass-produced casks must be higher or better than those of the test specimens that exhibit an adequate factor of safety.
- In the mass production of casks, the reproduction of properties of safety significance must be demonstrated through quality assurance practices carried out in conjunction with fabrication.

(The conditions just stated for the safety demonstration do not apply to the cask body alone; we have given them appropriate consideration in the assessment of all other cask components.)

According to the assessments performed in Sections 3.2.1.2.3.1 and 3.2.1.3.3, the test results with respect to mechanical loads on the cask body can be extended to the design of the CASTOR casks.

In order to secure the further conditions for extension of results concerning the material properties of safety significance, we have characterized these properties on the basis of extensive research on materials.

It was not possible to make reference to existing material standards, since these (e.g., [L 50]) do not cover the product form in question because of the great section thicknesses and product weights. In foundry practice, the usual way of determining material properties for castings of this size is to use integrally-cast specimens. According to our findings, this method when applied to CASTOR casks gives no information, or very uncertain information, about the material properties in safety-relevant regions (workpiece values in cask wall).

Because of this state of affairs, we have developed new evaluation scales with regard to the nature, level and determination of property values to be guaranteed for the cask body material GGG 40.

The starting point for our analysis was material research aimed at establishing the spectrum of properties of the CASTOR Ia prototype cask body. Not only does this cask body exhibit the fabrication-related characteristics typical of the GGG 40 product form under consideration (large casting with appropriate weight and dimensions); it also safely survived the most critical loading (9 m drop onto unyielding foundation with simultaneous impact on trunnions, test at 233 K (-40°C) among others). For the test material, the applicants made available four wall segments (about 200 mm x 200 mm) and two drilled cores (about 4.7 m long, 20 mm in diameter, depth in wall section roughly corresponding to that of moderator-rod holes) from the CASTOR Ia prototype.

BAM performed the following studies on this test material:

- tensile tests to determine mechanical properties (tensile strength R_m, 0.2% yield strength $R_{p0.2}$, elongation at fracture A_5, reduction of area Z)
- notched-bar impact bending tests to determine notch value A_v at various temperatures
- metallographic examinations to characterize the structure
- fractographic examinations under the scanning electron microscope to characterize the structure and the fracture surface
- chemical analyses to determine the most important alloying components

BAM also applied the above methods in systematic studies of two separately cast specimen blocks of GGG 40 (410 mm x 900 mm x 1300 mm) made available by the applicants. Static and dynamic three-point bending tests were also done on notched specimens of material from these test blocks in order to determine the fracture-mechanical parameters.

On the basis of these extensive material studies, we can make the following statements with regard to a practicable and secure assessment of the material quality in the mass production of CASTOR casks:

- In order to secure adequate safety against undue plastic deformation, it is sufficient to guarantee the yield strength of the material ($R_{p0.2}$). Local plastic deformations that may occur in external portions of the cover and bottom ends and on the cooling fins do not impair the functioning of the cask.

In order to provide adequate safety against loss of integrity through fracture, the material ductility needed for this kind of safety must be guaranteed.

It would not make sense to prescribe the ductility parameters A_5 and Z established on the assessment basis (CASTOR Ia prototype), because of the high values found, the associated difficulties in determining them with confidence by measurement, and the resulting scatter of values. A systematic relation, founded in the mechanics of the material, does, however, exist between A_5 and Z on the one hand and, on the other, the much more highly reproducible yield-strength ratio $(R_{p0.2}/R_m)$ [L 49]. For this reason, the yield-strength ratio can be employed as an auxiliary quantity for the ductility which is to be guaranteed in quality assurance practiced in conjunction with fabrication.

The inspection for freedom from larger macroscopic defects, which is required for establishing the integrity of the cask body, is accomplished through nondestructive tests (complete ultrasonic inspection and complete surface crack inspection). On the basis of a resolution adopted by the Reaktorsicherheitskommission [Reactor Safety Commission] at its 164th Session, March 18, 1981, we have not assumed, in the framework of the material assessment, the coincidence of an accident load with the presence of a crack-like or notch-like defect of critical size that has remained undiscovered.

The determination of structural parameters, chemical composition and notch value provides only a small amount of useful information for quality differentiation and should be employed only for quality surveillance.

Because of the thermal and metallurgical conditions during solidification of the casting, the most unfavorable properties in the casting occur roughly in the middle portion of the wall for the most part. From this region, with a technique developed by the applicants, it is possible to obtain drilled cores from the moderator-rod holes, so that determining the material parameters from the most unfavorable region (around the middle of the cask wall) over nearly the whole cask length is a feasible task.

The parameters to be guaranteed, $R_{p0.2}$ and $R_{p0.2}/R_m$ (or A_5 or Z, if these can be determined by measurement with confidence and with small scatter, given the appropriate level of the values), are specified in Material Data Sheets (see Section 3.5.3.1.2). In these Material Data Sheets, along with the parameters cited above, the continuing metallographic and chemical examinations, the type of tests to be performed, and the taking of samples from the drilled cores are set forth. The correlation between material parameters and modified fabrication procedures is to be verified through preliminary checking of the Quality Assurance Program (see Section 3.5.3.1) and continuing inspection during fabrication.

In summary, we can state that the qualification of the cask body material GGG 40 has been demonstrated, with regard to adequate safety of the CASTOR casks against failure in accidents, through appropriate loading tests; in addition, if safety-relevant material parameters are guaranteed in fabrication, at least equivalent safety can also be secured for the mass-produced casks.

3.5.3. Quality Assurance Program

3.5.3.1. Fabrication and Assembly Tests

The Quality Assurance Program (QSP) issued by the applicant [U 1--Section 2.3], which is to set forth all substantial quality characteristics and procedural specifications for fabrication quality assurance, is broken down into the following parts:

3.5.3.1.1. Design Drawings

The design drawings on which type testing for approval under the transportation laws is based give dimensions, tolerances and surface finish symbols; observance of these characteristics in fabrication is an important quality characteristic, which must be demonstrated by appropriate tests for safety-relevant data (see Section 3.5.3.1.3; [L 39]).

3.5.3.1.2. Material Data Sheets

In the parts list to the design drawings cited above, a standardized material code is sufficient to specify the material only for simple, smaller components. In the framework of type testing for approval under the transportation laws, requirements on the materials for the following cask components (including property values to be determined, guaranteed limits of these values, sampling plans, test methods, scope of testing, inspectors, and reference to applicable standards or regulations as appropriate) are set forth in Material Data Sheets [L 39]:

cask body

primary cover

secondary cover

seal covers for penetrations in covers

metal seal rings

cap nuts, studs and body-fit bolts

trunnions

trunnion bolts

fuel basket

For the components "neutron shielding (moderator material)" and "insert cover," the provisions of this Opinion and of the applicant documents checked by us [U 8, U 56] are to be taken into account.

Before the start of fabrication, in the framework of continuing examination, the Material Data Sheets for the components "neutron shielding (moderator material)" and "insert cover" must be subjected to a preliminary check by a specialist to be called in by PTB (Proposed Order AV 3.5-1).

3.5.3.1.3. Fabrication and Quality Control Plans

For the cask components listed in Section 3.5.3.1.2, the galvanic nickel coating of the seal region, and the pressure gage, the essential fabrication and testing steps are to be given, in technically correct sequence, in the Fabrication and Quality Control Plans. For quality assurance of components of safety significance, these plans are to state, for each operation or testing step, the applicable operational and testing specifications (these may also be drawings and Material Data Sheets), the form of testing with reference to the level of inspector (in-plant specialist, applicant's quality office, specialist called in by PTB), and the way in which the tests performed are to be supported (testing mark [stamp], test certificate, or the like) [L 39].

The testing effort should be dictated by the safety significance of the cask components or of their properties. A three-level classification is to be employed:

Class 1: Components or property values that directly affect the protection objectives of tightness and nuclear safety under normal service conditions and under well-defined accident loads. This class includes, first of all, any components (or values of their properties) that provide tight containment (cask body, all parts of the two-barrier cover and seal system). The trunnions and their fastening elements are to be included in Class 1 as a special case too.

Class 1 tests are to be supported by an acceptance test report A or C as provided in DIN 50,049 [L 51].

Class 2: Components or property values that directly affect the protection objective of shielding and only indirectly affect the achievement of the protection objectives listed in Class 1.

Class 2 tests are to be supported by an acceptance test report B as provided in DIN 50,049.

Class 3: All parts or properties not coming under Classes 1 and 2, whose testing may be performed at the applicant's request, by in-plant specialists if necessary.

Before the start of fabrication, in the framework of continuing examination, the Fabrication and Quality Control Plans for the components "neutron shielding (moderator material)," "insert cover," "pressure gage," and "galvanic nickel coating of the cask interior" must be subjected to a preliminary check by a specialist to be called in by PTB (Proposed Order AV 3.5-2).

3.5.3.1.4. Operational and Manufacturing Specifications

The operational and manufacturing specifications are instructions for the manufacturer, which contain requirements on personnel, apparatus, material and fabrication procedures, as well as specifications for the workpiece, particularly when safety-relevant property values are distinctly fabrication-dependent. This relation between fabrication procedure and properties is especially marked in the case of the cask body [L 39]; for this reason, all fabrication practices in the body-casting technology--on the basis of what the applicants and manufacturers report to BAM--are covered in the Opinion. For inclusion in the Quality Assurance System, however, the respective operational and manufacturing specifications with detailed information are to be submitted to the specialist called in by PTB for checking, and the reproducibility of manufacture must be demonstrated through tests at crucial delay points in fabrication [L 39].

Before the start of fabrication, in the framework of continuing examination, the Operational and Manufacturing Specifications to which reference must be made in the Fabrication and Quality Control Plans must be subjected to a preliminary check by a specialist to be called in by PTB (Proposed Order AV 3.5-3).

3.5.3.1.5. Test Specifications

For all tests performed to demonstrate essential quality characteristics, Test Specifications are to be prepared by the applicants or manufacturers when it is impossible to make reference to recognized engineering rules. The Test Specifications are to contain complete information on the qualification of testing personnel, testing apparatus, evaluation method, scope of testing, limits of test criteria to be observed, and required documentation or reporting of test results; see also [L 39].

Before the start of fabrication, in the framework of continuing examination, the Test Specifications of the applicants or manufacturers to which reference must be made in the Fabrication and Quality Control Plans must be subjected to a preliminary check by a specialist to be called in by PTB (Proposed Order AV 3.5-4).

3.5.3.2. Tests before Commissioning (Assembly Testing)

After a final check of cask components with the purpose of verifying and demonstrating the properties defined, the assembly of the cask system is to be carried out in accordance with Operational Specifications to be devised, and an inspection is then to be performed in accordance with Test Specifications to be prepared (assembly testing).

Before the start of fabrication, in the framework of continuing examination, these Assembly, Operational and Test Specifications must be subjected to a preliminary check by a specialist to be called in by PTB. They enjoin compliance with the respective Operational and Test Specifications (function check) and have the purpose of assuring the performance and verification of cask assembly according to proper procedures (Proposed Order AV 3.5-5).

3.5.3.3. Tests on Cask before Storage in Shipping-Cask Storage Site

Here a distinction must be made between tests during the loading of the cask at the nuclear power plant (e.g., [U 37]) in accordance with the requirements of the transportation laws, and the tests that must be performed after the entry of a shipping cask and before placement in the shipping-cask storage site.

These tests have the purpose of demonstrating (1) the correct assembly of the cover and seal system, the tightness of the individual components of the cask seal system (design standard helium leak rate $\leq 10^{-7}$ mbar·L·sec^{-1} for each seal barrier), and the complete drying of the cask and the seal system; (2) the maintenance of the specified tightness after transport into the shipping-cask storage site and the functioning of the cask surveillance system.

With regard to tests on each shipping cask after arrival at the site, the applicant has supplied the documents [U 1, U 24].

The handling and testing instructions given herein state, in general form, the possible measures for individual testing of the seal-system components. According to our assessment, these tests for the purpose of guaranteeing the design helium leak rate for each of the two seal barriers are feasible; however, the measures listed in [U 24] with respect to the sequence of testing steps to be employed should be expanded and suitable testing procedures should be added.

For the purpose of guaranteeing tight containment, detailed and complete handling and testing instructions should be prepared for the handling and testing of casks after arrival at the shipping-cask storage site. Before the beginning of storage, these instructions must be subjected to a check by a specialist to be called in by PTB (Proposed Order AV 3.5-6).

3.5.3.4. Documentation

The results of tests during fabrication, before commissioning, during and after loading at the nuclear power plant, before storage at the shipping-cask storage site, and, for example, after special incidents during service, are to be documented for each individual cask in accordance with the provisions of the instructions stated in the preceding Sections, and preserved during the period of service. The nature and scope of this documentation (test book) are given in the respective test certificates covering type testing (e.g., [L 39]).

3.6. Actions after a Hypothetical Loss of Required Tightness of the Storage Cask

According to our assessment and with allowance for the discussion presented above, tightness loss of a barrier in the cask seal system should not be expected to occur as a systematic failure in a large number of casks. Because a quantified failure rate cannot be stated, a single failure of a seal barrier is assumed. After a signal is transmitted by the cask surveillance system or after an accident, the applicants are to undertake suitable reconditioning work in the framework of a repair concept. The applicants have submitted test programs for this purpose [U 25, U 26, U 27].

Our statements on handling procedures and tests relate only to measures for restoring and verifying tightness. Other safety aspects of cask handling are covered in the TUV Hannover Opinion [L 1].

The test programs, on the basis of the cask design and available apparatus at the shipping-cask storage site (maintenance and repair area), specify the following for the restoration of two seal barriers:

- retightening of fastening elements or replacement of seal rings in the secondary-cover seal system, if this system is leaky and the primary-cover seal system still remains adequately tight
- installation of the insert cover by gastight welding, if the primary cover has become leaky

In the case where a standard helium leak rate to be guaranteed for the secondary-cover seal system is exceeded, restoration of this seal barrier at the shipping-cask storage site is possible provided the primary-cover seal system remains fully functional.

In contrast, leaks that may occur in the primary-cover seal system cannot be remedied directly, that is, by replacement of metal seal rings. In this case, the two-barrier seal system should be restored through the installation of an insert cover. Under the conditions stated by the applicants [U 56], and with observance of the general rules of welding, we consider it feasible to make a weld between cask body and insert cover that will be gastight (design standard helium leak rate $\leq 10^{-7}$ mbar·L·sec^{-1}) under normal service conditions (static internal pressure load, p_{abs} = 6 bar).

In accordance with usual practice in the assessment of welding methods (see, e.g., [L 52]), we require demonstration of a secure command of the welding technology on the basis of procedural tests with all the parameters affecting the weld properties taken into account.

Before the beginning of storage, procedural tests for the cask body/ insert cover weld are to be performed in coordination with BAM (Proposed Order AV 3.7-1).

Repair welding at the shipping-cask storage site is to be carried out in accordance with an operational and testing program to be prepared. The program is to contain, in suitable form, all needed measures for the fabrication and inspection of the welding in an orderly manner. Before the beginning of storage, this program must be inspected by a specialist to be called in by PTB (Proposed Order AV 3.7-2).

The handling sequence to be followed, according to [U 27], is to set forth in detail in an appropriate way which operational and test specifications are to be employed after a signal is transmitted by the indicating device of the cask surveillance system.

A detailed and complete handling specification for the performance of maintenance and repair work is to be prepared before the beginning of storage. The handling specification should contain, in suitable form, all measures by which, in case the tightness of a metal seal barrier is lost, it can be restored and the restored tightness verified.

Before the beginning of storage, these measures must be inspected by a specialist to be called in by PTB (Proposed Order AV 3.7-3).

4. Proposed Orders

AV 3.1-1

It is to be ascertained that the internal metal-to-metal clearance is a maximum of 10 μm referred to the seal surface of the primary-cover metal seal ring. The determination is to be done during cask assembly and, in the framework of continuing examination, is to be made available for checking by a specialist to be called in by PTB. Presentation of proof of this determination may be dispensed with provided the applicants present proof that undue impairment of tightness by volatile fission products can be precluded through other measures, or if new knowledge is gained confirming that the seal action continues.

AV 3.1-2

A functional check is to be performed on every pressure gage to be used for cask surveillance at the Ahaus Shipping-Cask Storage Site. The check is to take place after fabrication and before installation on the cask. It should be demonstrated that the following standards are met:

integral standard helium leak rate of the reference-pressure space $\leq 10^{-9}$ mbar·L·sec^{-1}

pressure in reference-pressure space after filling with air = 3.0 bar (referred to a temperature of 293 K)

reproducibility of main-contact switch point ±0.05 bar

reproducibility of control-contact switch point $^{+0.25}_{-0}$ bar.

AV 3.3-1

For each of the two metal seal barriers, the design standard helium leak rate of $\leq 10^{-7}$ mbar·L·sec^{-1} is to be demonstrated by measurements before storage.

AV 3.5-1

Before the start of fabrication, in the framework of continuing examination, the Material Data Sheets for the components

neutron shielding (moderator material)

insert cover

must be subjected to a preliminary check by a specialist to be called in by PTB.

AV 3.5-2

Before the start of fabrication, in the framework of continuing examination, the Fabrication and Quality Control Plans for the components "neutron shielding (moderator material)," "insert cover," "pressure gage," and "galvanic nickel coating of the cask interior" must be subjected to a preliminary check by a specialist to be called in by PTB.

AV 3.5-3

Before the start of fabrication, in the framework of continuing examination, the Operational and Manufacturing Specifications to which reference must be made in the Fabrication and Quality Control Plans must be subjected to a preliminary check by a specialist to be called in by PTB.

AV 3.5-4

Before the start of fabrication, in the framework of continuing examination, the Test Specifications of the applicants or manufacturers to which reference must be made in the Fabrication and Quality Control Plans must be subjected to a preliminary check by a specialist to be called in by PTB.

AV 3.5-5

Before the start of fabrication, in the framework of continuing examination, the Assembly, Operational and Test Specifications must be subjected to a preliminary check by a specialist to be called in by PTB.

AV 3.5-6

For the purpose of guaranteeing tight containment, detailed and complete handling and testing instructions should be prepared for the handling and testing of casks after arrival at the shipping-cask storage site. Before the beginning of storage, these instructions must be subjected to a check by a specialist to be called in by PTB.

AV 3.7-1

Before the beginning of storage, procedural tests for the cask body/insert cover weld are to be performed in coordination with BAM.

AV 3.7-2

Repair welding at the shipping-cask storage site is to be carried out in accordance with an operational and testing program to be prepared. The program is to contain, in suitable form, all needed measures for the fabrication and inspection of the welding in an orderly manner. Before the beginning of storage, this program must be inspected by a specialist to be called in by PTB.

AV 3.7-3

A detailed and complete handling specification for the performance of maintenance and repair work is to be prepared before the beginning of storage. The handling specification should contain, in suitable form, all measures by which, in case the tightness of a metal seal barrier is lost, it can be restored and the restored tightness verified. Before the beginning of storage, these measures must be inspected by a specialist to be called in by PTB.

5. Summary Statement

In the present Opinion, we have assessed the qualification of the shipping-cask designs CASTOR Ia, Ic and IIa, intended for the dry interim storage of spent fuel assemblies from light-water reactors.

In the assessment, experience and knowledge gained by BAM in the testing of shipping casks under the requirements of the transportation laws and in questions of material and component qualifications relevant to the Opinion were considered. As required, new criteria for assessment were devised; among the information considered was that provided by TUV Hannover, the co-assessor, about the cask contents.

Safety testing and assessment included the investigation of cask-specific questions with regard to the attainment of the protection objectives --tightness, nuclear safety, and heat removal--under normal service conditions and under accident loads. Furthermore, quality assurance (i.e., practices aimed at establishing and guaranteeing safety-relevant properties in the fabrication and operation of the casks) was covered in the assessment.

Because the protection objectives named above are carried out by the cask itself during interim storage, stringent requirements were imposed on the cask and its components with regard to maintenance of integrity, tightness, and long-term suitability.

The following actions on the cask parts, components and materials, in particular the seal system and the cask surveillance system, were considered in the case of normal operation:

ionizing radiation and decay-heat output of fuel assemblies

internal pressure and fission product release in case of defective fuel-rod cladding tubes corrosive effects of residual moisture in the cask and from the environment of the cask

long-term effects for a storage period of up to 40 years

In the assessment of cask integrity and tightness after accident events, the results of experimental studies on representative test specimens were taken into account, as were calculations. The effect of mechanical accident loads was studied in drop tests onto an unyielding foundation and in special penetration tests simulating an aircraft crash. The effects of an accidental fire were represented by fire tests and fire calculations.

On the basis of the tightness of the cask seal system, we derived the maximum expected nuclide-specific release fractions under normal service conditions and after accidents. This information is being used by TUV Hannover in assessing the radiological impacts of the Ahaus Shipping-Cask Storage Site.

Taking into consideration the above-cited loads due to normal operation and accidents, as well as the component and material specifications necessary to maintain the secure containment of the radioactive contents, on which the assessment was based and which are to be demonstrated for each individual cask in the framework of quality assurance, on the basis of our tests we conclude that the cask system continues to carry out its intended function over the intended service period and that adequate safety is guaranteed in case of accident.

If the orders proposed by us, which we consider feasible, are complied with, we are of the view that the required protective measures have been taken with respect to tightness, nuclear safety and heat removal, so that the use of casks of the CASTOR (Ia, Ic, IIa) type for the dry storage of spent fuel assemblies at the Ahaus Shipping-Cask Storage Site constitutes the precaution against harm needed in accordance with the state of the art.

6. List of Documents and References

6.1. Documents of Applicant Firms

[U 1] Deutsche Gesellschaft für Wiederaufbereitung von Kernbrennstoffen mbH (DWK) and STEAG Kernenergie GmbH
Ahaus Shipping-Cask Storage Site, Safety Analysis Report
SB-TBL A 07.82

[U 2] Gesellschaft für Nuklear-Service mbH (GNS)
Report No. GNS B 3/79, reissued 11/80 (Rev. 0)
1.2 Contents of Package Type (CASTOR Ic)
November 1980

[U 3] DWK
CEA Temperature Tests on Metal Gaskets at Pierrelatte
Report No. F 4 20 H 1551 BH (Rev. 0)
Date: March 18, 1981

[U 4] Arbeitsgemeinschaft (ARGE) DWK-STEAG
Ahaus Shipping-Cask Storage Site: Long-Term Behavior of Neutron Moderator Material
OS No. 0812.03.7860.00.ME 1 Index 2
GNS July 31, 1980

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