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Aging Management in the Design and Operation of Dual-Purpose Casks

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Abstract

CASTOR® casks are dual-purpose casks for high active nuclear waste that have to fulfill the requirements from both transport (acc. to IAEA regulations) and storage (acc. to national regulations). The first CASTOR® cask was loaded with spent nuclear fuel in 1983 in Switzerland. Since the 1990s, casks of the CASTOR® type with high active waste from reprocessing plants have been stored in Germany. According to the storage licenses in Germany, the CASTOR® casks are licensed for a storage period of 40 years.

By now more than 1000 casks have been loaded and stored worldwide. GNS is both supplier of the casks and operator of the two centralized storage facilities. In combination with the continued longtime use of CASTOR® casks GNS has unique operational experience covering the entire lifetime cycle: from design, licensing, via manufacturing, loading, and transport up to storage.

The main approach for long-term storage is to prevent or to minimize the aging effects by design or maintenance measures. In general durable materials are used which are not subject to corrosion or the degradation mechanism by irradiation. The cask body consists of ductile cast iron and its surfaces which may be in contact with corrosive atmospheres are protected by a multilayer paint system. Furthermore, critical material combinations which may lead to degradations should be excluded.

For components which are affected by aging, the change of its properties is considered in the design.

1 Introduction - Aging Management for Dual-Purpose Casks

Dual-purpose casks have to fulfill the requirements of both fields of operation – long-term-interim storage and public transport in accordance with the IAEA regulations, even after storage. As illustrated in Figure 1, directly after loading, the casks are transported to a storage facility with original, non-degraded material properties. Within the storage facility the dual-purpose casks stay for a minimum period of 40 years under quasi-static conditions without any external load but the time. In case this storage facility is not in the vicinity of the final repository, a last transport has to be carried out with the same requirements as for new casks. This is particularly challenging, since the aging effects of the single components of the cask have to be considerate for the safety case.

Some of the main components (cask body, basket, primary lid with bolts and metallic gasket and of course the fuel) cannot be substituted after the storage period and thus at least for those components aging management is already necessary in the design phase casks to avoid later interventions. Here the term aging means changes of characteristics of the cask, its components or the inventory with time or use. It is the task of the designer and user to take engineering, operation and maintenance actions to control the aging effects of the cask and its components within acceptable limits in order to ensure the specified characteristics and functionality over the complete lifetime cycle.

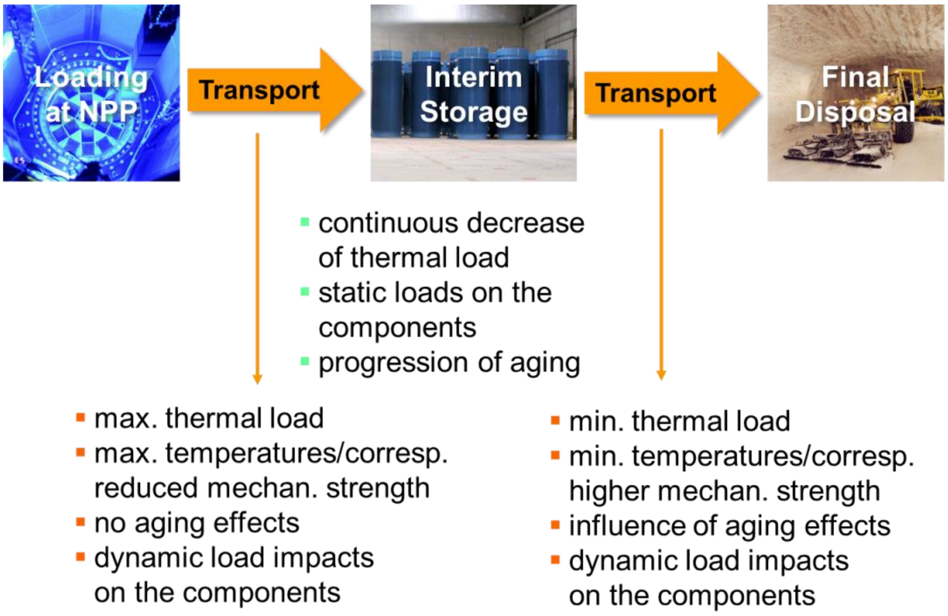

Figure 1 Operation cycle of dual-purpose casks

During their service time, dual-purpose casks are principally affected by the following stressors, which are crucial for the rate of aging:

- Radiation,
- Thermal and mechanical loads,
- Corrosion

Subsequently, the single stressors are evaluated with respect to the resulting degradation effects on the casks. Feasible design measures are introduced.

2 Degradation by Radiation

Due to the radioactive decay all kinds of radiation are emitted from the spent nuclear fuel (SNF). The only radiation types to be considered for the cask design are the neutron and gamma radiation, as all other types are completely shielded by the cladding material of the SNF.

2.1 Neutron Radiation

Embrittlement Caused by Neutron Irradiation

The energy of fast neutrons, as submitted from the SNF, is high enough to cause defects in the lattice of metallic materials. The defects are generated by displacement cascades of recoil atoms from scattering and neutron reactions. Due to the formation of defect clusters the material is hardened which is associated with an embrittlement of the metallic material.

All components of the cask are affected by interactions with neutrons because of their long range in matter. The SNF is surrounded by different metallic materials: The cask body of a CASTOR® cask is typically made of cast iron, the basket consists of components made of stainless steel or aluminum alloys (mainly for heat dissipation), the lid system is made of forged steel and the bolts are made of stainless steel or coated carbon steel.

Radiation damages in cast iron and carbon steel result mainly from fast neutrons, thus neutrons with energies above 100 keV. A considerable modification of the mechanical properties of the metals is expected at neutron fluxes above 10^{18} n/cm^2. In typical aluminum alloys changes of mechanical properties do not occur at neutron fluxes below 10^{20} n/cm^2.

However, the typical total amount of emitted neutrons during a storage period of 40 years is at least four magnitudes below the given thresholds for fast neutrons. Therefore no radiation damages due to neutrons are expected for all components of the cask.

In consequence, no specific design measures are needed to control the effect of embrittlement by neutron radiation in metallic material.

Depletion of Neutron Absorber Material

The neutron radiation must also be considered with respect to the depletion of neutron absorbers. After each capture of a neutron the respective atomic nucleus is depleted. As a consequence, the amount of the relevant neutron absorbing isotopes within the material must be high enough to compensate the losses by neutron reaction.

All absorber materials within the basket, mainly borated alloys are of relevance.

It has to be considered that boron has an absorption cross section which is proportional to the inverse of the velocity of the incident neutron. In case of dry storage under normal conditions no moderator material (water) is available in the cask cavity which could slow down the neutrons. Without moderation the energy distribution is shifted to faster neutrons and therewith fewer neutrons are absorbed. This fact is without significant consequence with respect to the criticality safety as the reactivity without moderator is considerably below the limit. However, with the lower absorption rate the depletion of the boron is decreased significantly under normal conditions of storage and reduces the need for compensating absorber material.

2.2 Gamma Radiation

The gamma energy is too low to generate substantial damages in metallic material, but is high enough for degradation effects of polymers. The energy of the gamma photons exceeds the covalent bond of the main carbon chain. The carbon chains can be cracked and new cross-links can be formed.

Degradation of Polymers by Gamma Irradiation

As a result of the formation of additional cross-links the material changes its mechanical properties: on the one hand it loses elasticity and on the other hand embrittlement is pushed forward. Due to the cracking of long chains by gamma irradiation the polymer can also be decomposed by the formation of new composites from the ruptured parts (radiolysis). The new composites can be volatile and released from the polymer.

Affected components are elastomer seals and moderator materials like polyethylene or resin.

As a consequence of the possible aging effects it is recommended for the cask design, to expose as little as possible polymer material to significant gamma dose rates. Even if the component has no direct safety related function, decomposition under irradiation may lead to the release of substances which could result in further degradation interactions with material in the vicinity. If the use is inevitable polymers with higher radiation resistance should be chosen.

In the CASTOR® design the functionality of elastomer seals is only needed during the loading of the cask and the elastomer seals are not part of the containment. For example, elastomer seals are used for the confinement of the test volume in order to carry out the helium leak test of the metallic gaskets directly after the loading with SNF. The verification of the leak-tightness after long-term storage is feasible also without the auxiliary seals, but only more complex.

Hydrogen Generation by Radiolysis

Components which can be a source of hydrogen generation are the moderator material and the remaining water within the cavity of the cask. In polymers the hydrogen can be generated by the combination of two ruptured H-C bonds. In water the deposed energy of gamma irradiation initiates the radiolysis of water by formation of ionized or excited water molecules followed by cascades of physical-chemical reactions which finally lead to the generation of hydrogen.

Beside the direct degradation effects of gamma radiation illustrated above, the generated hydrogen causes secondary effects which have to be considered in the cask design and handling:

- Hydrogen uptake and incorporation into the lattice of metals which result in embrittlement of the affected material,
- Pressure build-up due to release of additional gas,
- Possible generation of an explosive gas mixture.

The first design measures are the already described minimization of polymer components or - if feasible - a complete exclusion. Additionally, the amount of water in the cavity as radiolysis source is very limited due to the strict drying criterion which is mandatory for CASTOR® casks.

Due to the fact, that after a wet loading always a specific amount of water remains and the polymers are inevitably necessary for moderation also the generation of hydrogen by radiolysis has to be considered. This means the consequences from the hydrogen generation have to be mitigated:

- Inertization of the cask cavity before closing the lid system during the loading and a controlled dilution at the moment of opening after long-term storage to prevent explosive gas mixtures,
- Due to the limitation of hydrogen supply, the condition of the surfaces and the selection of the used alloys, the hydrogen uptake and the embrittlement can be neglected,
- The pressure build-up within the containment is negligible in relation to the maximum normal operational pressure of 0.7 MPa to be considered for transport packages according to the IAEA regulations. Outside the containment it is possible to limit the pressure build-up by means of over-pressure valves.

3 Thermo-Mechanical Degradation

Under steady structural loads and high temperatures creep effects occur before the yield strength of the material is reached. Internal stress in highly pre-loaded components is relieved by plastic flow of the material, which results in deformation (creeping) of components like gaskets or in loss of pre-tension (relaxation) in bolting.

At the beginning of the operation, after application of the load, the creep induced strain rate is relatively high, but it significantly slows down with increasing storage time due to strengthening by accumulative strain hardening. The strain rate increases with temperature, but at normal operation temperatures of the bolts in the lid system (in CASTOR® casks below 120 °C) the influence of the temperature on the creep rate is to be considered as insignificant.

Relaxation of Bolted Joints

The acting stress and therewith the strain rate can be influenced by the geometry or the number of the bolts and the applied tightening torque (pre-stress).

In the cask design the mechanical load of the bolting must be balanced between the necessary pre-stress to compress the metallic gasket and to compensate relaxation and stress reserves to carry the additional dynamical loads under storage and transport conditions.

As a consequence, the pre-stress applied for bolted joints of the CASTOR® is limited to a maximum utilization of the yield strength depending on bolt material (strength class) and application (lid system/load attaching points).

Aging of Metal Gaskets

In the containment system of CASTOR® casks HELICOFLEX® gaskets are used. Metal gaskets of this type are characterized by excellent resilient properties which ensure useful elastic recovery. This elastic recovery is the precondition to accommodate minor distortions in the flange assembly due to changes in external loads, like under conditions of transport.

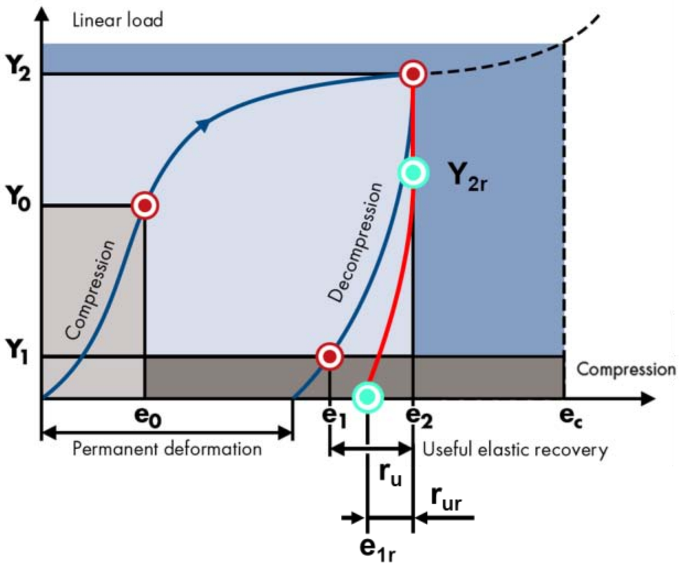

Figure 2 Compression and decompression cycle of metal gaskets with long-term drift of the useful recovery r_u (Picture based on manufacturer's informatory material)

Figure 2 shows the compression and decompression cycle of the HELICOFLEX® gaskets. The run of the decompression curve is the result of a hysteresis effect and permanent deformation of the spring and jacket. Due to creep effects the point of optimum compression drifts toward lower load values Y_{2r} with time of operation. The additional permanent deformation of the gasket reduces the useful elastic recovery. The reduced useful elastic recovery r_{ur} at the end of the storage period has no influence under static loads during storage. But under the conditions of transport the lower elastic recovery r_{ur} must be considered in the design of the flange assembly. The gapping of the flanges must be limited to less than the elastic recovery remaining after the storage period.

4 Corrosion

Established measures to prevent corrosion are the use of noncorrosive components or corrosion protection with self-passivation or anodization of surfaces (aluminum). A common method which is also used in the CASTOR® design is the coating of surfaces by noncorrosive materials (nickel) or by cathodic protections (zinc).

Corrosion in the cask cavity is excluded since the cavity is dried, evaporated and filled with inert gas after the loading procedure. In addition, casks intended for underwater loading have a nickel coating to prevent corrosion in the cavity and the sealing surfaces. In case the inventory is not leak-tight, the escape of water must be prevented by encapsulation of the leaking fuel. Or, in case this is not feasible, drying agents can be implemented to receive the water escaping during the long-time storage period.

Possible corrosion on the outside of the cask is excluded by a multilayer paint system, which can be easily monitored over the interim storage period. Gaps in the cask body due to construction are permanently sealed with silicone. Due to the cask design the influence of corrosion is negligible or can be managed by suitable maintenance measurers.

5 Compensatory Effects

As known, the degradation rate increases with the temperature of the components and the dose deposed in the material. With respect to the radioactive decay the temperatures and dose rates decrease most rapidly directly after loading and as a consequence the highest and most serious aging rates occur in the first two decades of storage. Especially when the temperatures fall short of critical values the reaction kinetics of degradation processes is significantly decreased, often by magnitudes.

This physical effect is overlapped by conservative assumptions along with the methodology of the verification for transport and storage licensing. The licenses are normally granted for generic reference inventory, which covers the real inventory parameters. The design temperatures and dose rates calculated for the reference inventory usually overestimate the actually realized loadings; which offers additional safety margins.

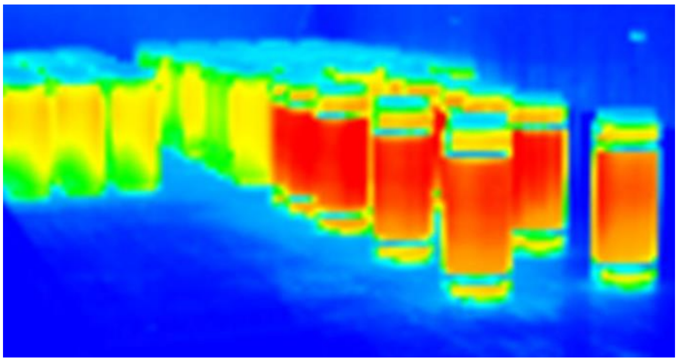

Figure 3 Thermography of dual-purpose casks in a storage facility

In addition, the thermal design of the casks considers that the casks in the storage facility are positioned in an array of casks with each at a maximum heat load. In reality fresh casks can be separately positioned or with larger distance to neighbor casks (see also Figure 3).

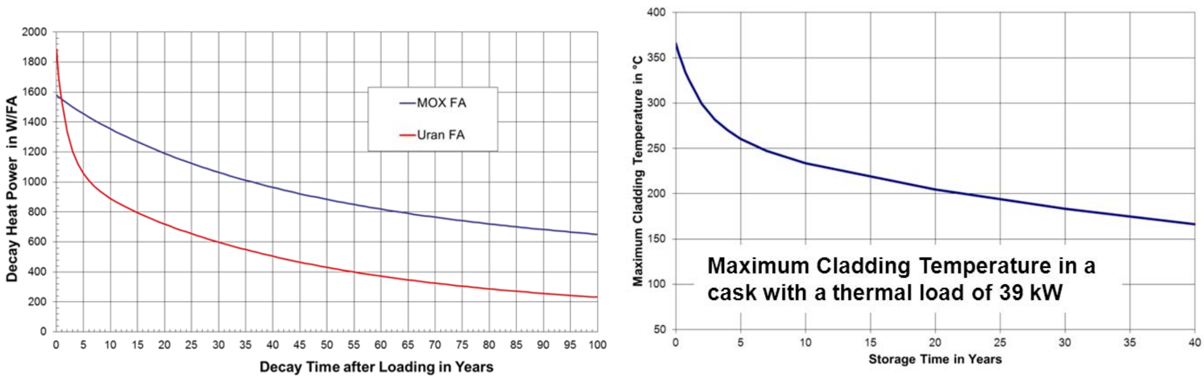

Figure 4 Temporal progression of heat power and maximum cladding temperature

This consideration for single casks can be transmitted to the total heat inventory of a storage facility. As a storage facility is not loaded at once, but in many stages with each cask less than its maximum thermal and radioactive inventory and taking into account that the already stored inventory continuously decays (see Figure 4), the actual total heat load within the facility is significantly less than the design load during the complete operation period.

Consequently, the ambient temperature in the facility is significantly reduced whereby the cask temperatures are equally reduced. As shown in Figure 5, the surface temperatures of the casks follow the ambient temperature according to the cask's thermal inertia.

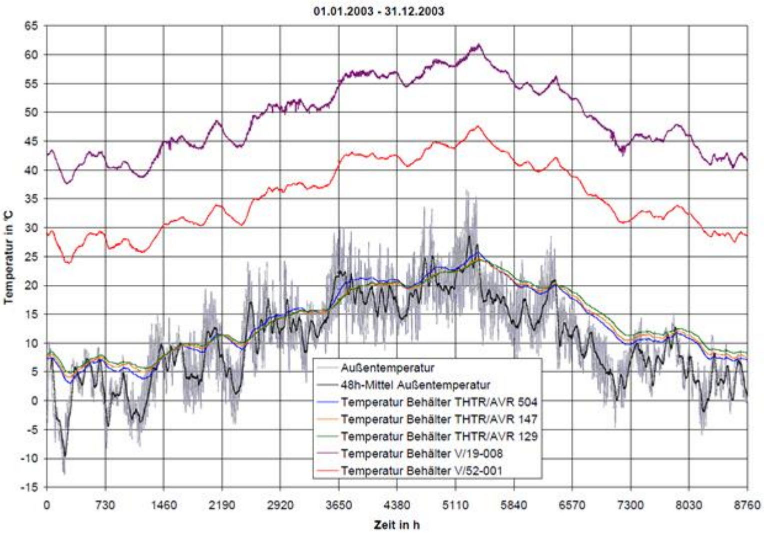

Figure 5 Cask surface temperature vs. ambient temperature in the storage facility

For example, at casks of the type CASTOR® V/19, CASTOR® V/52 and CASTOR® THTR/AVR stored in the centralized storage facility Ahaus (operated by GNS) the measured temperatures at the cask surface are significantly below the design temperature calculated for the approval:

Cask Type	Design Temperature	Measured Temperature
CASTOR® V/19 and V/52	max. 105 °C	< 65 °C
CASTOR® THTR/AVR	max. 60 °C	< 30 °C

6 Increasing Requirements

Before transportation or in course of Periodic Safety Review it has to be demonstrated, that the Safety Analysis Report of the dual-purpose cask meets the state of the art. The state of the art permanently progresses. But new analysis methods require specific material parameters which often cannot be determined afterwards on the basis of available data. Due to this fact, the progression of the state of the art is one of the most challenging aspects in the long-term storage.

Active measures can be taken to increase the existing safety margins. Direct measures could be the re-design of the shock absorber or the introduction of an additional over-pack.

Indirect measures could be the mitigation of accident scenarios by new handling equipment/ procedures or structural strengthening of the facility against outside impacts.

7 Possible Maintenance Actions to Control Aging

As a consequence of the storage requirements dual-purpose casks must have a double lid system, which is permanently monitored. Due to the double-lid design, the outer barrier (consisting of the secondary lid system and associated bolts and gaskets) can completely be removed without opening the inner containment of the radioactive material.

If the outer barrier would show any sign of intolerable aging effects, there is the opportunity to change or rework the affected components. Moreover, also the bolting of the primary lid system is completely accessible to test or to apply the specified torque of the bolting. The loss of pre-stress due to relaxation can be easily compensated.

For removable parts of the transport package aging effect can be eliminated by maintenance measures in advance. Only for the cask body, the basket and the primary lid system the influence of aging on specified characteristics must be ruled-out.

8 Practical Experiences

By now, more than 1,000 CASTOR® casks are in operation, about half of them in storage facilities operated by GNS. The overall storage time of CASTOR® casks worldwide sums up to more than 10,000 years (see Figure 6), while the storage period of single casks reaches up to 30 years. With this huge operational experience the CASTOR® design has got an in-service proof of its long-term operational reliability.

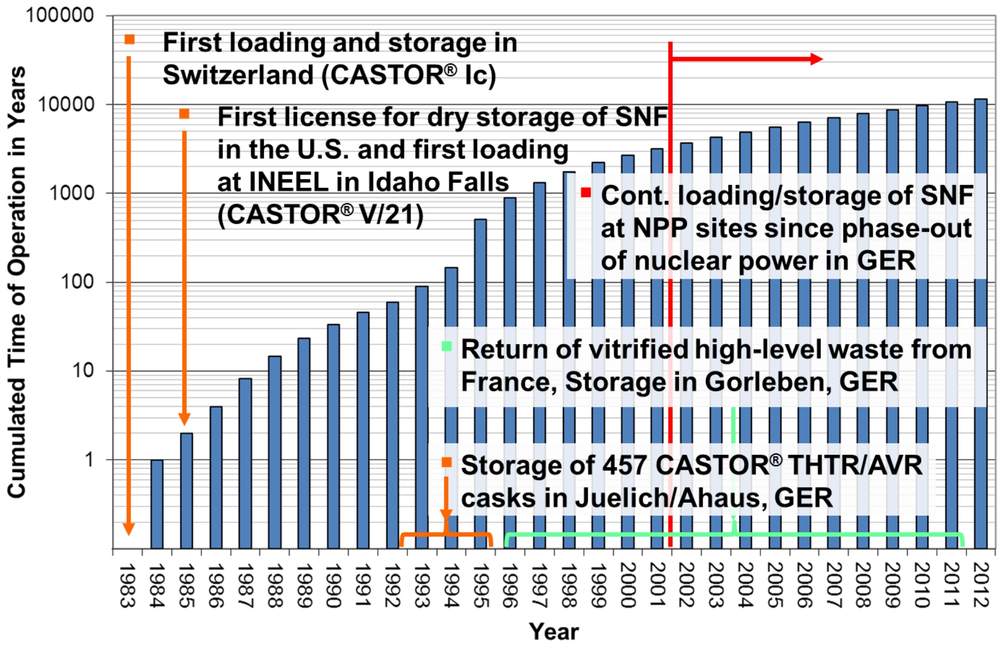

Figure 6 Cumulated time of operation of CASTOR® casks worldwide

On the basis of the operational experiences it can be concluded, that design and operation of CASTOR® casks is appropriate to keep the effects of aging within acceptable limits and to ensure the required functionality over the complete life cycle.

9 Conclusions

The relevant aging effects are considered in the design of dual-purpose casks by effective measures. The efficiency of these measures has been proven not at least by the service experiences of GNS. 30 years after loading of the first CASTOR® cask, there are no indications for the influence of aging effects on the characteristics and functionality of the casks. With respect to the real loads and the low utilization of design limits the actual degradation rates of loaded casks are significantly overestimated by the pessimistic assumptions in the safety case.

The double-lid system of dual-purpose casks provides the advantage that essential parts of the containment are accessible for inspection or maintenance actions. Based on this, evidence about the state of safety related parts can be provided. If necessary, the secondary lid system can be completely restored to the original state. In order to increase the existing safety margins it is possible to take active measures either to improve the robustness of the package under conditions of transport or to mitigate accident scenarios under conditions of storage.

As the above mentioned examples underline, GNS is engaged in the complete lifetime cycle of the casks, and gets the feedback of experience. In principle all the information which are necessary for aging management are accumulated at GNS as designer, manufacturer, and operator of dual-purpose casks. The challenge is to transfer all the existing information for such a complex product to the next generation. Aging management is first and foremost the management of knowledge transfer.