The TN 84: A Dual-Purpose Cask for VVER-440 Nuclear Power Plants

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INTRODUCTION

As the previous arrangements between the former USSR and some East-European countries are no longer valid, the return of their spent fuel to reprocessing is hampered by political and economic obstacles, and several Eastern Europe NPP operators must develop new back end strategies. As many other utilities in the world, they are facing a dilemma: either selecting the way of reprocessing/recycling, which indeed is already an industrial reality, or studying burial in a geologic disposal, which is certainly a questionable method and anyhow a faraway project. As a result, most of these countries have been adopting a "wait and see" policy, in providing additional means of interim storage for the spent fuel discharged in excess of reactor pool capacity in order to keep the possibility to select later on the most appropriate back end strategy.

To meet the needs of VVER 440 nuclear power plants, Transnucléaire has designed the TN 84 transport/storage cask.

The TN 84 is based on the forged steel technology as numerous other TN casks which have been proved for almost two decades as trouble free means to transport and/or store spent fuel assemblies (SFAs) on an industrial scale. This technology is particularly appropriate to store the spent fuel under totally safe conditions for a very long duration, e.g. fifty years or even more.

A specific advantage offered by this steel cask technology is the possibility of easily adapting the gamma and neutron shield thicknesses for several batches of SFAs with different average burnups and cooling times, while keeping the same basic concept so that both the safety analysis necessary for licensing and the equipment needed for manufacturing will remain practically identical.

Thus, instead of covering the whole population of SFAs with only one concept which should therefore be designed for the most demanding case (highest burnup associated to the shortest cooling time), the steel cask technology allows to produce two (or more) very similar cask designs :

- one tailored to the large majority of SFAs with average burnup and cooling time, and offering the largest storage capacity,

- one tailored to the most severe expected case resulting in a smaller capacity, which will seldom be needed, but which nevertheless might have to be covered for any possible emergency situation.

The TN 84 cask corresponds to this second case. It can accommodate up to 91 VVER 440 SFAs with 42,000 MW.d/tU burnup and 4 year cooling time. Now, if the peripheral lodgement row of the basket is left empty, then it can accommodate up to 61 SFAs with 42,000 MW.d/tU burnup and only 3 year cooling time.

Such large capacities associated with high performances can be achieved thanks to our new basket described in more details hereafter. This basket concept has been derived from the reactor core configuration, which is not only the most compact possible, but also the safest since the fuel assembly has been precisely designed to be fully and safely controlled for criticality under that configuration just by dropping control assemblies. Thus, with a basket configuration undermoderated at the same level as in the reactor core, as soon as the poisoning ratio is higher than in the reactor at shut down, nuclear safety is ensured.

GENERAL DESCRIPTION OF THE TN 84

In storage configuration, i.e. when standing vertically and equipped with its primary closure system, the overall height of the cask is 4 m, its maximum transverse dimension 2.6 m and its total weight lower than 110 Mt , including the weight of 91 SFAs (corresponding to roughly 20 Mt, among which 11 MtHM). If required, a secondary lid and even an anti-aircraft crash cover might be added: this would increase the cask height by 0.3 m and its weight by about 12 metric tons.

In transport configuration, with the primary lid only and shock absorbing covers, the overall length of the cask is 4.6 m, its maximum transverse dimension is 3.0 m (across the shock absorbing covers) and its total loaded weight is around 112 metric tons.

The main gamma shielding is provided by the forged steel shell, approximately 32 cm thick, connected to a forged steel bottom, approximately 34 cm thick. Additional lateral gamma shielding is provided by the 10 cm thick resin layer (used as the main neutron shielding) crossed by copper heat conductors, and by the external steel shell also acting against secondary gamma rays.

The main features of the TN 84 (see attached figure) are similar to those of many other TN casks, in particular:

- a cask body made from a thick forged carbon steel shell with a thick forged bottom of the same grade attached to it and surrounded by the hydrogenous resin layer enclosed within the outer steel shell and crossed by copper plates acting as heat conductors;

- a closure system including one or several lids under transport or storage configuration, depending on customer's requirements, but incorporating at least in transport configuration one leaktightness barrier with checkable interspace allowing to guarantee that the Transport Regulations criteria for activity release are met under type B(U) regulatory accident conditions.
  In storage configuration, the closure system includes two leaktightness barriers using metallic gaskets, each of which being checked for a leaktightness better than 10^{-7} mbar.l/s , with a continuously monitored interspace pressurized with helium, allowing to guarantee zero-release over a period of 50 years and more;

- a boronated aluminium basket designed to convey the decay heat of the SFAs toward the cavity wall and to control criticality under both normal and accident conditions.

NEW FEATURES INCORPORATED INTO THE TN 84

With a view to improve the cask design, i.e. to increase the safety and/or to reduce the cost, three new features have been introduced. They concern the bottom-to-shell connection, the basket concept and the basket-cavity interface.

Bottom-to-Shell Connection

The idea was to design the cask bottom in a similar way as the lid. This led to a thick forged bottom with a flange totally recessed within the forged shell where it is shrink-fitted over most of its thickness, then welded around its outer edge over a 40 mm depth. Since the cask is intended to be loaded in a pool, it is wise to complement the bottom-to-shell attachment by a thin leaktightness weld between the bottom inner edge and the cavity wall.

As soon as the strength of the bottom-to-shell weld exceeds that of the lid bolts, such a design can be easily justified, even without taking any credit for shrink-fit.

Compared to the previously used bottom-to-shell connection with a full penetration radial weld, this solution brings several significant advantages:

- under horizontal drop conditions, no mechanical solicitation affects the bottom-to-shell connection, and in particular the welds, while the thick radial weld of the former design is heavily strained under these conditions,

- under vertical drop on the bottom side, even with the bottom center impacting the regulatory punch, again the welds are not at all strained providing that the flange is thick enough to withstand the shear stress,

- the only case in which strain is induced on the welds is the vertical drop on lid side, but then the force involved is limited to the rebound of the contents.

The proposed design change of the bottom-to-shell connection therefore constitutes a significant safety improvement while proving cost-effective. This is why a patent has been applied for.

Basket Concept

The basket must ensure two functions : control criticality and convey the residual heat power of the spent fuel to the cask body wall.

These two functions shall be fulfilled under any conditions, including under the most severe accident.

It should be noted that it does not matter whether the basket has been deformed or not: indeed, the possible difficulty in removing a fuel assembly from the basket after an accident is not a safety related concern, since subcriticality and heat dissipation remain ensured; and it is not justified to overburden the basket design with an important additional requirement, applicable to all units produced, with a view to only make easier an operation whose probability is very low. As a consequense, one must keep in mind that withstanding the regulatory drops without any plastic deformation of the basket constitutes neither a basic function nor even a requirement as soon as subcriticality and heat dissipation are guaranteed under any conditions. It cannot be too strongly emphasized that nowhere in IAEA Safety Series n° 6 can be found a requirement specifying the absence of basket deformation after regulatory drop.

On the other hand, looking for the most compact basket design, we observed that the best example was certainly the reactor core configuration which has been designed as undermoderated for safety purposes, and which is therefore the safest one.

From there, we conceived a basket made up of hexagonal lodgements separated by heat conducting and poisoned partitions, for instance in boronated aluminium, in such a way that the moderation ratio is similar to that in the reactor core configuration and that the poisoning ratio is higher than in the reactor core at shut down. Practically, this could be achieved using an assembly of hexagonal tubes made of boronated aluminium, complemented at its periphery with aluminium profiles, hooped together and turned in a lathe, then fixed on a bottom plate equipped with tie-rods, and designed so that it can be installed and removed easily when empty and cold, while it becomes seized in the cask cavity when hot due to the differential thermal expansion between the aluminium tubes and the forged steel shell. Thus, heat dissipation through the basket partitions and toward the cask body is further improved when temperature increases. As a consequence, the thermal performances of the TN 84 are excellent (this has been confirmed by a scale 1 test) and the thickness of its basket hexagonal tubes can be precisely adjusted to meet the specified temperature limitations. Then, for a given aluminium partition thickness needed for heat transfer, the content required in Boron-10 of the aluminium can be determined to control criticality.

As regards the criticality issue, the justification will be based on a comparison of both the undermoderation ratio and poisoning ratio within the TN 84 on one side and on the other side within a reference VVER 440 reactor core at shut down, i.e. after all control assemblies have been dropped.

In principle, this comparison is sufficient to demonstrate the safety of this basket design under any conditions. Indeed such a basket concept based on an undermoderated configuration is intrinsically safe, and a patent has been applied for.

A preliminary investigation has shown that, using the same unit (i.e. mg of natural Boron per mm of VVER 440 fuel assembly height), the poisoning ratio is in the range of 7 to 10 within the in-service reactor core (depending on both burnup and power level), and in the range of 97 to 102 at shut down assuming that all control assemblies have been dropped. For comparison, we calculated the poisoning ratio existing in several VVER 440 baskets which had been qualified against the usual criterion $k_{eff} + 3\sigma \leq 0.95$, and we found values spread out between 220 and 360. This shows that within currently used baskets, the boron content is needlessly high. And most often such a high boron content prejudicial to the material soundness is not even a guarantee against the criticality hazard, since most basket designs existing today are based on an overmoderated configuration (contrary to all good and safe reactor core designs), i.e. they include the so-called "neutron flux traps" that could disappear suddenly in the event of an "off standard" accident.

But we have to take into account that changing a habit of mind might be difficult, even when the proposed change improves the safety. This is why we intend to additionally give for comparison the k_{eff} value (calculated through the classical method) corresponding to each case considered, and to increase the poisoning ratio so as to meet the usual criterion $k_{eff} + 3\sigma \leq 0.95$ when required.

Basket-Cavity Interface

The basket-cavity interface is another area where improvements can take place.

Indeed, in the case of dry storage, it is always important, from the viewpoint of thermal performances, to reduce the need for heat conduction in gas that is very poor compared to heat conduction in any metal. As a consequence the space between the basket outer lodgements and the cavity wall should be as far as possible filled up by a metal, for instance aluminium like the basket, or steel like the forged shell according to the purposes.

As the boronated aluminium tubes making up the basket lodgements have a regular hexagonal shape, it is easy to machine aluminium or steel plates longitudinally so that they can fit with a sector of the basket periphery (here 1/6 of the circumference) along the whole basket length. Then these aluminim or steel plates can be installed either on an appropriate jig, or on the basket itself, and turned in a lathe to a very precise external diameter that exactly fits the cask cavity.

As a result, along its entire length, the cask cavity will be filled up with solid material everywhere, except the void space around the fuel rods inside the basket lodgements. This arrangement, favourable as already seen for heat transfer, also highly enhances the nuclear safety of the concept: indeed, the more compact the cavity contents are, the safer the fissile package is, because not only this is the best guarantee of an undermoderated configuration, but furthermore there is much less possibility left for relative movements between fissile material, neutron poison material, and heat conducting material even under the most severe accident conditions.

One should also observe that such an internal arrangement does work in a way where any deviation from normal operating conditions will lead to a correction toward more safety for the two major aspects involved of criticality and heat transfer. Thus, if the cask contents are subjected to any mechanical solicitation leading to a plastic deformation of the basket partitions, the reactivity of the fissile material contained can only decrease. As well, if for any reason the basket temperature exceeds the normal operating temperature, then the heat transfer toward the cavity wall, related to the differential thermal expansion between the aluminium of the basket and the forged steel shell, will be improved.

FUNCTIONS AND PERFORMANCES OF THE TN 84

As a transportable storage cask, the TN 84 fulfils three basic functions:

- protection of the neighborhood against the radiations emitted and activity released by the radioactive materials contained,
- protection of the irradiated fuel assemblies against any external aggression,
- retrieval of the contents after storage over a very long period of time.

The TN 84 cask will fulfil these functions over a long period of time, even much more than 50 years, thanks to the following features:

- effective containment of the radioactive contents by means of metallic gaskets arranged according to the "zero-release";
- efficient shielding capabilities against the gamma and neutron radiations from the SFAs, using appropriate thicknesses of durable materials: principally steel for the gamma rays and solid hydrogenated resin for the neutrons;
- adequate dissipation of the decay heat thanks to the use of materials with high thermal conductivity such as aluminium for the basket, carbon steel for the forged body and copper plates as heat conductors across the external layer of resin and because of relying on passive heat transfer modes only (radiation, conduction and natural convection);
- guarantee of subcriticality under both normal and accident conditions, based on an appropriate distribution of neutron poison within the undermoderated fuel medium so that subcriticality is maintained whatever the water content within and between the SFAs (before, during or after any accident) might be: this indeed corresponds to an intrinsically safe concept;
- mechanical resistance as appropriate to allow any normal operations implemented according to specified procedures and to guarantee that all safety functions are satisfied also under accident conditions.

CONCLUSION

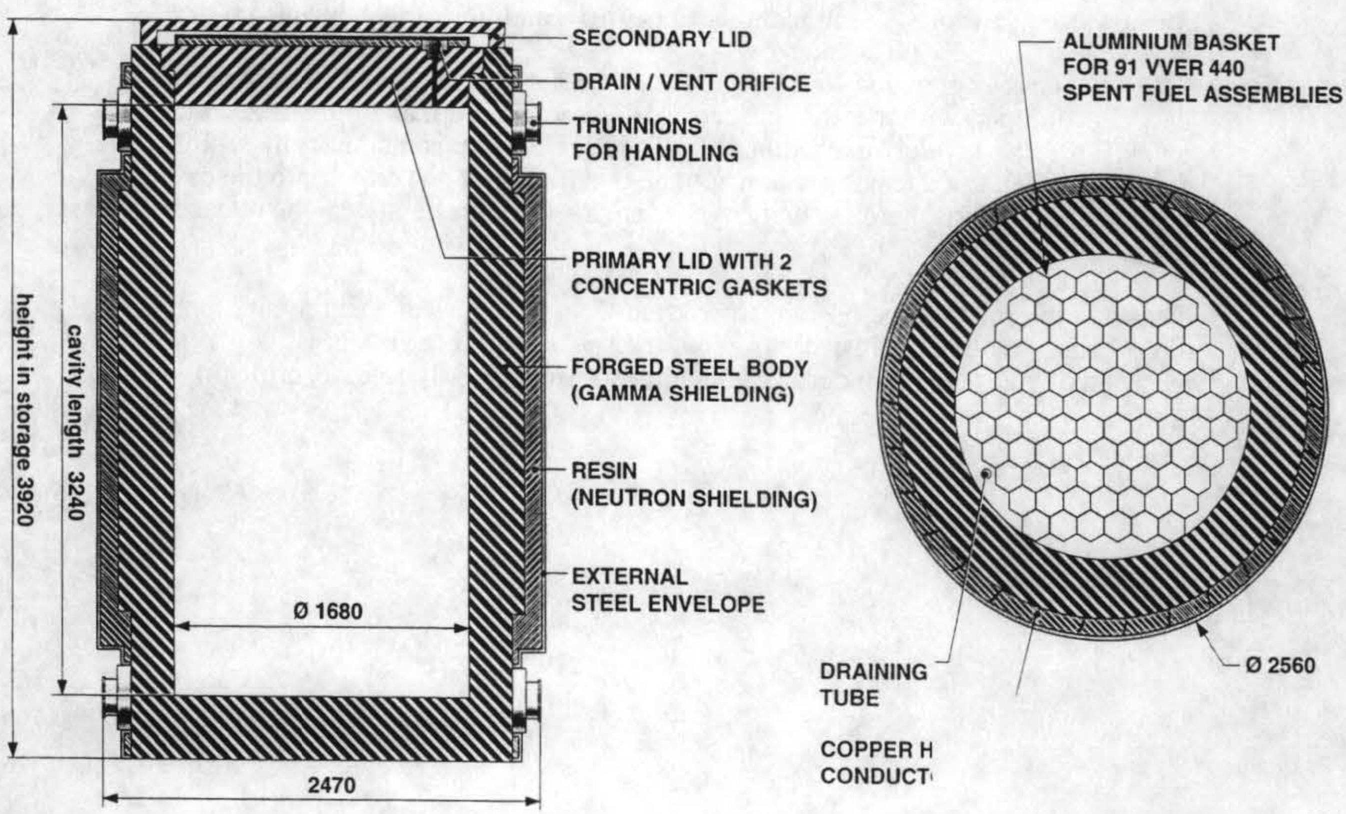
The TN 84 cask can be used either at a VVER 440 reactor site or at an independent spent fuel storage facility (ISFSF). Moreover its interface characteristics (such as the detail design of trunnions as well as lid and basket handling attachments) may be adjusted to fit the existing equipments perfectly, thus allowing to proceed with all usual loading/unloading operations required on the nuclear site.

The cask is intented to be loaded under water in a reactor cooling pool or in an ISFSF pool along the well established procedures routinely used with standard transport casks for 15 years. It might be unloaded either in the same way in a pool, for instance at a reprocessing plant, or under dry conditions in a hot cell.

When the cask is prepared for storage, the space between the two leaktightness barriers equipped with metallic gaskets is filled with helium and pressurized at a level (7 bar abs.) widely exceeding that of the cavity. In this manner, any sealing defect would cause a leak of uncontaminated helium (not air) either into the cavity or toward the atmosphere, so that anyhow no gas from the cavity can be released to the atmosphere.

Thus any interim storage or transport system for spent nuclear fuel relying upon TN 84 casks will be intrinsically safe with respect to all three major risks associated with nuclear material: radiation exposure, activity release, criticality.

FIGURE 1: TN 81 TRANSPORT/STORAGE CASK



Session III-3: Structural Analysis