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# TN®24E: An AREVA TN International Spent Fuel Transport and Interim Storage Cask for the German Market

**Authors:**

**Christophe VALLENTIN**
AREVA TN International

**Jochen SEIDEL**
E.ON Kernkraft GmbH

**Pierre CAVELIUS**
AREVA TN International

**Dr. Frank GUTERMUTH**
EnBW Kernkraft GmbH

## ABSTRACT

In response to the needs of the German utilities E.ON and EnBW, AREVA TN has designed and manufactured the TN® 24E cask offering a high level performance in the following:

- Transport and storage over a period of 40 years of up to 21 PWR spent fuel assemblies (SFA)
- High SFA loading performance for up to 17 MOX SFAs and 4 UOX SFAs
- High flexibility in the SFA loading plans, with predefined constraints limited to some configurations with regards to the MOX or UOX SFA positions in the basket of the cask
- A maximum allowable enrichment of the fuel as high as 4.65%
- A minimum cooling time as low as 2 years

The TN® 24E cask includes several significant technological advances, among which:

- Proven high mechanical performance of A 508 steel for the forged shell and its welding to the bottom of the cask
- The shielding performance of the AREVA TN Vyal B™ resin
- The use of burnup credit including, for the first time, 6 fission products to demonstrate criticality safety
- Depletion codes validated for high burnup, up to 65 GWd/t

The TN® 24E is now entering its industrial phase. In addition to meeting the initial needs of the German utilities, it will be used to meet other requirements from utilities such as the management of failed fuel rods.

## INTRODUCTION

AREVA TN, a subsidiary of the AREVA group, offers a complete range of transport and interim storage solutions for radioactive materials throughout the entire nuclear fuel cycle. Being a world leader in its sector, AREVA TN has supported the expansion of the nuclear industry for 50 years, in particular by providing expertise in secure packaging systems for the storage of spent fuel assemblies.

Responding to the specific requirements of the German market, AREVA TN has designed the TN® 24E package offering high performance in terms of the loading of spent fuel elements with a high level of flexibility and efficiency attaining a state-of-the-art safety level. It meets all the current safety requirements.

The need of E.ON and EnBW was to load the fuel under the best possible conditions:

- mixed populations of PWR assemblies for UOx and MOX fuel
- U-235 enrichment for UOx fuel of up to 4.65%
- short cooling times, starting from 2 years (vs. 5 years typically)
- high burnup fuel of up to 65 GWd/tU
- flexible loading options taking advantage of the cask performance

Furthermore, an interim storage period of 40 years had to be guaranteed as well as the compliance with regulations for the safe transport of radioactive material in Germany.

In response to these criteria, AREVA TN developed the TN®24E package design which is based on the association of well proven technology improved by innovations in technology and safety analysis.

Figure 1. View of the TN® 24E cask

The TN®24E can contain up to 21 PWR spent fuel assemblies and up to 17 MOX fuel assemblies. The following diagrams show the configurations.

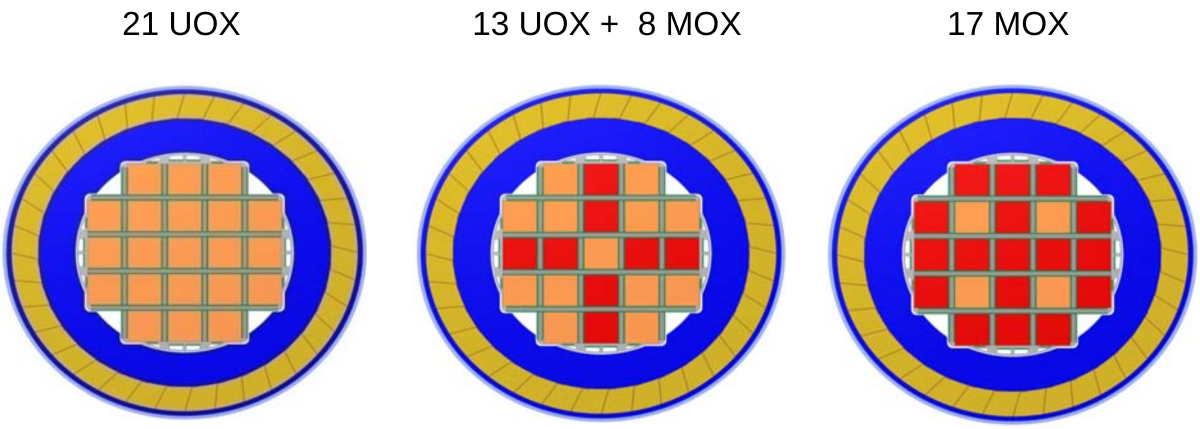


Figure 2. Example of allowed configurations in the TN®24E cask

These loading configurations allow a high thermal power of up to 39 kW and a high radioactive inventory including high gamma and neutron source terms.

The challenges that were overcome to ensure the loading flexibility and compliance to the current German safety standards are described below.

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## FOCUS ON CRITICALITY PERFORMANCE

The high criticality performance was reached with AREVA TN's cutting edge technologies based on the following principles:

- Detailed knowledge of fuel assembly behavior after regulatory drop tests: A methodology based on experimental tests on real unirradiated and irradiated fuel assemblies was developed and qualified by AREVA TN to predict the mechanical behavior of the fuel assembly after the 9-meter drop test. The knowledge of the status of the radioactive content after the regulatory drop test enabled AREVA TN to perform the criticality calculations with adequate and justified assumptions.

- Advanced safety demonstration on the criticality evaluation based on the use of a qualified Burnup Credit methodology: From the 12 actinides and 15 fission products recommended by the OECD, the following actinides and fission products were considered in the criticality calculations:

  - 9 actinides: 235U, 236U, 238U, 238Pu, 239Pu, 240Pu, 241Pu, 242Pu, 241Am
  - 6 fission products: 103Rh, 133Cs, 143Nd, 149Sm, 152Sm, 155Gd

  The preselection of 9 actinides and 6 fission products used in the BUC methodology for the TN®24E criticality calculation is conservative compared to the OECD recommendation and represents, as far as FPs are concerned, approximately 50% of the total contribution of all fission products.

For the qualification, the demonstration of the similarity between a selected set of critical experiments (Haut “Taux de Combustion” (HTC) and Fission Product (FP) experiments, co-funded by the AREVA Group and IRSN) and cask configuration were performed. A set of 111 experiments from HTC and FP series was selected for the validation of the criticality code package CRISTAL V1.0 to be applied on the AREVA TN TN®24E transport and storage cask loaded with 21 irradiated UO2 fuel assemblies (minimum required average fuel assembly burnup of 12 GWd/tHM). The similarity analysis was completed by various and numerous sensitivity analyses to confirm the application of the burnup credit on the TN®24E cask.

- Special design of the TN®24E basket: The basket is composed of interlaced profiles made of a borated aluminum profile (MMC) and reinforced by stainless steel. The design of the basket ensures the non modification of geometry and integrity of the basket material after the 9-meter regulatory drop test. Therefore credit of the presence of neutron absorbing capabilities at the expected and known position inside the cavity can be taken in order to ensure the sub-criticality thus ensuring the safety of the cask. The optimal design of the TN®24E basket is based on AREVA TN experience in designing baskets and accumulated experience on drop tests on other TN casks (TN 81, TN®24 D, TN®24 G). Due to the extensive experience of AREVA TN, the assessment of the design of the TN®24E cask could be conducted with advanced and benchmarked dynamic and numerical calculations.

The design of the basket was improved through the study of the delayed impact phenomenon without operational consequences on the loading activities. The delayed impact analysis concerns the assessment of a 9-meter axial drop on the top side where the kinetic of the impact may induce a delay between the moment of the impact of the cask on the unyielding target and the moment of the basket impact on the lid inside. The challenge was to design a bumper capable of absorbing this additional energy as needed to guarantee no damage to the closure system while avoiding potential disadvantages of such a solution:

- increase in the package weight linked to additional cavity length if needed
- impact on sub-criticality linked to the crushed height in accidental conditions
- reduction of the lodgment accessibility

This solution avoids the above disadvantages as:

- the absorber is entirely included in the top of the basket without restriction of the lodgment size or increased cavity length
- the advanced criticality analysis and basket material performance demonstrated sufficient margin to deal with an increased non borated length inside the cavity

The corresponding crushing characteristic of this bumper was qualified and introduced to the global dynamical analysis of the drop consequences.

## FOCUS ON THE HIGH FLEXIBILITY AND PERFORMANCE OF THE SHIELDING

The high flexibility of loading in terms of radioactive content of the TN® 24E cask design is the result of:

- the use of high performance and qualified shielding material such as the Vyal B® resin which was developed by AREVA TN

- sophisticated engineering for flexible loading options that allow to get out of the predefined and restricted loading plans, in compliance with the high safety standard described in the IAEA regulation .

The neutron shielding performance is mainly based on the properties of the resin Vyal B®. It was qualified for its technical properties (chemical composition and physical properties) over a large range of temperature (up to 180°C) and its long-term behavior in interim storage for a period of 40 years. Additionally, all the steps of the manufacturing process of the Vyal B resin® were qualified by the German Authorities ensuring the highest quality level of the TN®24E cask.

The loading strategy does not impose a predefined position of fuel assemblies regarding the shielding criteria thus providing high flexibility as requested by E.ON and EnBW. AREVA TN developed a methodology, Term Source Reference, for the easy verification of real loading plans that could be applied in the TN®24E cask to meet the transport and storage shielding criteria. The Term Source Reference methodology, which establishes the maximal loading capacity of the TN®24E cask, is based on inequations involving the comparison of real sources of fuel assemblies to be loaded with cask specific reference source terms associated to the TN®24E package design. These inequations are defined in such a way as to generate conservative neutron and gamma dose rates at the TN®24E relevant outer surfaces. The main terms of the inequations are mainly dependant on:

- the real sources “S” of the fuel assemblies to be loaded in the TN® 24E cask

- the reference source term corresponding to the maximal shielding capacity of the cask regarding dose rate criteria

- the lodgement factor which determines the contribution of each basket lodgement: A complete set of calculations with the 3D transport code is necessary to evaluate the contribution of the each basket lodgement. The calculations are repeated for each lodgement taking credit of the geometrical symmetries thus ensuring the management of incomplete loading plans.

The reference source terms, real sources and lodgement factor are calculated for:

- neutron generation reactions: spontaneous fission and (α, n) reaction
- each gamma energy group of the TN®24E shielding relevant gamma energy spectrum
- gamma sources of $^{60}Co$ activation located in fuel assembly ends

One set of inequations is determined for each criterion and each shielding relevant area. These areas correspond to zones on the cask surface or in the flask vicinity where relative maximum dose rates occur. They are determined by performing dose rate calculations around the cask using a 3D transport code.

This methodology entirely satisfies the IAEA regulation for the Safe Transport of Radioactive Material concerning the “maximum radioactive content” definition to assess the design compliance with the radiation level criteria under routine conditions of transport.

The Term Source Reference methodology requires significant engineering resources and investment: more than 300 calculations to determine the inequations for transport and more than 300 calculations to determine the inequations in storage are necessary to obtain correct, optimized, safety-oriented results. Thus, the Term Source Reference methodology constitutes a pillar in the establishment of the high performance and flexibility (managing both complete and incomplete loading plans) of the TN® 24E cask.

## FOCUS ON HIGH THERMAL PERFORMANCE AND FLEXIBILITY

The thermal performance and flexibility is based on similar principles to the shielding:

- Robust basket and cask design for heat removal: The design of the cask limits the gaps between the cask components to ensure the most efficient conduction path through efficient thermal material. Inside the cavity the heat power is removed from the fuel assemblies mainly through the continuous MMC plates (MMC plates are made of aluminium with a very good thermal conductivity), which are connected to closing plates made of aluminum by a system of elastic connections, also limiting the gaps. In the cask, the heat is transferred from the forged shell through the external plates by copper conductors.

- No fixed boundary values are specified for the heat thermal power regarding the position of a particular fuel assembly. A specific thermal heterogeneous loading plan methodology is implemented and qualified by AREVA TN for verification of a given heterogeneous loading plan from a thermal point of view. This methodology was implemented with a simple procedure to verify the transport. A methodology, taking into account the specificity of the interim storage requirements such as for the fuel rods (limiting creep strain and tensile stress in the cladding material), has been developed by AREVA TN and is under qualification.

The thermal heterogeneous loading plan methodology for both transport and storage has been extensively benchmarked with 3D calculations taking into account numerous different parameters such as different total heat power, different heat power per fuel assembly with different positions in the basket. The thermal heterogeneous loading plan requires more than 50 complete 3D calculations to obtain correct and optimized results. The benchmark confirms the accuracy of the thermal heterogeneous loading plan methodology. Below is presented a comparison of the temperatures obtained with the thermal heterogeneous loading plan methodology and the 3D finite element calculation for the same heterogeneous loading plan.

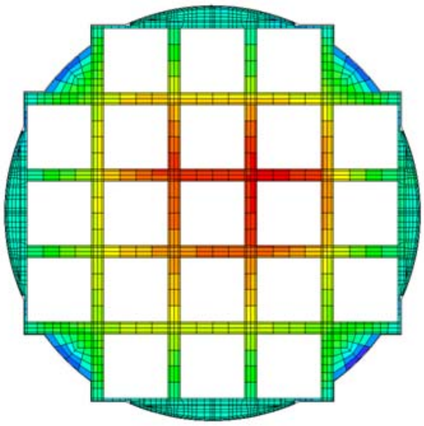

Figure 3. Isotherm of the hottest section of the basket with the 3D calculation

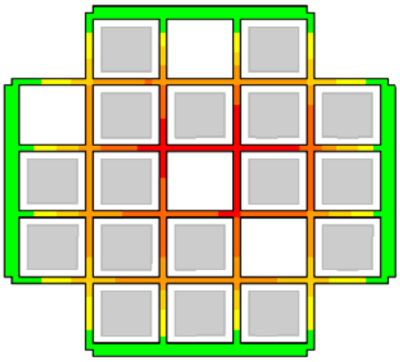

Figure 4. Isotherm of the hottest section of the basket with the thermal heterogeneous loading plan methodology

To optimize interim storage, this methodology enables operators to predict the maximum temperature for each fuel assembly and temperature of each basket lodgment depending on the loading plan, even considering incomplete loading plans. The knowledge of these parameters is helpful e.g. for the assessment of the maximum cumulated creep strain over 40 years for each fuel assembly.

The development of the Term Source Reference and the Thermal Heterogeneous Loading Plan methodologies required substantial engineering resources. However, once defined and coupled, the methodologies determine optimized loading plans for the TN® 24E cask very quickly, very easily and with a high level of flexibility and performance. These methodologies support optimized usability (complete loading plans including very hot fuel assemblies are possible) which enable the consignor to save time during the loading preparation, limit the space needed for the dry storage and limit the cooling time of fuel assemblies in the pool.

Having achieved this flexibility in the loading of the TN® 24E, the industrial phase has been lunched. Manufacturing activities are in progress. Furthermore, based on AREVA's joint expertise in both package design and fuel management, a fully integrated offer is possible. Extension of the product to meet additional needs of our German utilities is under way. For instance, the TN® 24E is foreseen to provide an appropriate solution to the management of leaking fuel rods in compliance with storage and transport safety requirements.

The TN®24E package design has recently received the German Federal Office for Radiation Protection (BfS) approval for transport, thus, confirming the validity of the methodologies presented above.

## CONCLUSIONS

State-of-the-art engineering and innovative technologies applied in the TN® 24E package design associated with new safety analysis methods resulted in a high performance of the cask in terms of:

- flexibility in the spent fuel assembly loading plan
- characteristics of fuel authorized to be loaded, including large amounts of MOX fuel

The high flexibility of the TN® 24E cask will enable the German utilities to define optimized loadings and unloadings for pool management and safety.

The performance of the TN® 24E cask offers the possibility to adapt the use of the cask for other potential applications:

- The cask is currently designed for 16 x 16 and 18 x 18 fuel assemblies (with high content of fissile material with high enrichment) but can be adapted for other types of PWR fuel assemblies employed in Germany.

- The TN® 24E cask can easily be adapted for other inventories, e.g. leaking fuel rods due to AREVA TN's advanced knowledge of special fuel assembly characteristics.