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Customization of ENUN 24P Cask for Transport of High Burnup Spent Fuel in China

A. Palacio
Ensa, Spain

G. Calleja
Ensa, Spain

D. Garrido
Ensa, Spain

D. Castrillón
Ensa, Spain

V. Gómez
Ensa, Spain

R. Muñoz
Ensa, Spain

R. Miguel
Ensa, Spain

L. Moreno
Ensa, Spain

E.G. Poncela
Ensa, Spain

Abstract

The ENUN 24P dual-purpose metal cask has been adapted from the ENUN cask series concept developed by Ensa, to fulfil specific spent fuel transport requirements across People's Republic of China. Among those, it is designed to allow the transportation of spent nuclear fuel from Ling Ao and Daya Bay Nuclear Power Plants (NPPs) located in southeast China, to Lanzhou storage facility (long distance until almost 4000 km) crossing China in different regions and climate conditions through road & rail transportation.

During the development of this project, Ensa's skilled staff from the Design & Engineering, Project Management and Field Services departments has faced several technical challenges in order to customize an existing solution licensed in Spain (the ENUN 32P), for the particular specifications and requirements of the Chinese scenario. Within those technical solutions provided, the following are highlighted and described along this paper:

– The structural design of the impact limiters was slightly modified to considerably reduce its maximum diameter, because of constrained limits of the transport route while maintaining the same cask center of gravity maximum acceleration. Through detailed scoping analyses, Ensa was able to assure the original G load limit suffered by the cask to comply with the requirements stated by the principal international standards (IAEA SSR-6 [1], 10 CFR 71 [2] and ADR 2015 [3]) for the hypothetical accident conditions.

– An innovative trunnion design concept was implemented to fit in the cask with the reduced impact limiters and assure enough energy absorbing material to avoid contact between the trunnions and the rigid target (i.e. the transport road) during postulated hypothetical impact accidents. This new trunnions design concept implied the development of a new lifting yoke and transportation skid, customized for the loading and transport operations of the cask.

- Since the burnup credit methodology was not already allowed to use by the Chinese nuclear regulator at the time of ENUN 24P design, the configuration of the basket implied several design modifications to assure the subcriticality of the high burnup fuel with very low cooling time.

Ensa has performed deep evaluations of all the safety functions of the customized ENUN 24P cask to assure full compliance with the international transportation regulations, for high radioactive spent fuel (IAEA SSR-6 [1], 10 CFR 71 [2] and ADR 2015 [3])). Ensa is currently in the last step of the processes for licensing the cask in Spain and in People's Republic of China for transportation. In addition, the manufacturing work flow at Ensa workshop has been carefully planned and fixed to be able to supply the first unit of the ENUN 24P customized cask within a very constrained time schedule, and comply with the customer agenda for the transportation of high burnup spent fuel across China in the beginning of 2017.

Introduction

People's Republic of China has not already established a unified and definitive strategy for the high level waste management, and more especially the spent fuel irradiated in its great number of operating nuclear reactors and the numerous under construction. Reprocessing and recycling has been under study for several years but a commercial-scale reprocessing plant and a fast-neutron breeder reactor has not being built yet, since among other reasons, the large economical investment is necessary to be done and the technical challenges still to be solved. Furthermore, final disposal is forecasted in the long term scenario and first sitting studies are being carried out at a specific location in the north of the country. Current deep technical, economic and social studies performed by the international community recommend China to allocate its economic resources in research and development projects for the time being, and allow more time for technology to develop. And nowadays, rely in the benefits and flexibility of at-reactor and centralized dry casks storage facilities, for any fuel cycle option chosen in the future [4].

For any fuel cycle option and waste management strategies, transportation of the spent fuel is considered a critical step in the back end of the Chinese nuclear fuel cycle, with the particularity that distances between the different facilities are usually huge (several thousands of kilometers).

Since 2003, used fuel from Daya Bay nuclear power plant located in the south east of the country near Shenzhen in the province of Guangdong, has been transported to Lanzhou interim wet storage facility, and located in the province of Gansu in the central part of the country (see Figure 1). For that purpose, Ensa had agreed a contract together with NAC International Inc. to manufacture two units of the STC transport spent fuel cask, to be supplied to CNNC Everclean. In addition to the material purchase, the complete manufacturing and the casks supply, Ensa already provided technical support to improve the design and solve several technical issues in a first of a kind fabrication project. The two cask units are currently in operation performing several transportations campaigns per year of spent fuel, to release space in Daya Bay NPP fuel pool. The STC is a stainless steel and lead ‘bare-fuel’ type cask system, designed to transport up to 26 PWR spent fuel assemblies with a maximum burnup (BU) of 45 GWd/tU.

However, by 2013 CGNPC Uranium Resources Company Co., Ltd. studied the necessity to request an improved and cheaper solution for the transportation of spent fuel. Improved in terms of allowing the possibility to transport high burnup spent fuel (BU > 45 GWd/tU) in a package with limited outer dimensions, and also with a more competitive cost in comparison with that of previous casks manufactured in 2003 for the same purpose. In addition, the cask should be designed for intermodal transportation, by road and by rail.

Figure 1 Transportation of Spent Nuclear Fuel across People’s Republic of China

Finally, by the end of 2013 ENSA was awarded with a contract to supply initially one unit of the ENUN 24P cask, the ancillary equipment and training services to the operating personnel at Daya Bay and Ling Ao NPPs, and obtain the Certificate of Compliance for transport of high burnup spent fuel from the Spanish (CSN) and Chinese (NNSA) nuclear authorities. The ENUN 24P was the specific solution developed by Ensa within a very tight schedule to comply with all challenging technical requirements from the client and the aforementioned NPPs. The ENUN 24P design is based on the established ENUN cask concept developed by Ensa, initially for the spent fuel management of all the Spanish NPPs, after Ensa’s long and proven experience of more than 40 years in the design, manufacturing and operating of nuclear equipment. However, the ENUN 24P includes some technical modifications which involved technical challenges for Ensa's Design & Engineering team, that have been successfully solved and implemented during the fabrication of the first unit of the cask at Ensa facilities. The fabrication and supply of the first unit of the cask is currently being completed and will be finished just at the time of the expected issuance of the Certificate of Compliance for Transportation as a type B(U) package from the Chinese regulator (NNSA), to perform the new first spent fuel loading campaign at Day Bay NPP.

Initial Design

The New Ensa ENUN Spent Fuel Cask Series

The ENUN 24P design was adapted by Ensa from the reference ENUN 32P dual-purpose cask (see Figure 2), already licensed in Spain, but including some technical modifications. All systems from the new ENUN spent fuel casks series developed by Ensa share the same concept design of 'bare-fuel' type dual-purpose metal casks, but each one includes specific features depending on the type of fuel it is going to allocate, the interfaces of the nuclear power plants where they will be used or other specific customer requirements.

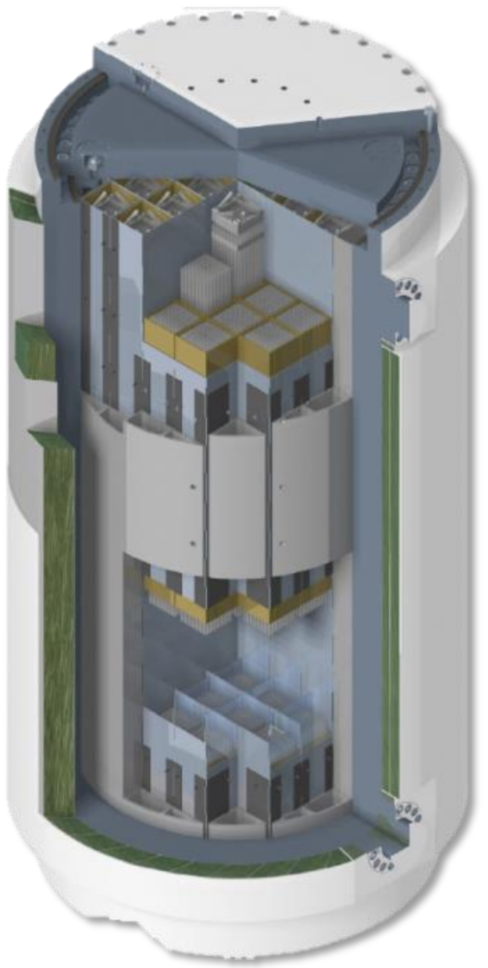


Figure 2 The Reference Cask: the ENUN 32P Dual-Purpose Cask

Origin of the ENUN 24P

The ENUN 24P has been specifically designed for transportation of high burnup PWR type spent nuclear fuel of the following designs: AFA 2G, AFA 3G and AFA 3GAA. It fulfills all the specific requirements of a Type B(U) package indicated in the international transport regulation IAEA No. SSR-6 [1] for the safe transport of radioactive material[1].

The ENUN 24P is designed for a uniform fuel loading strategy, where any authorized fuel assembly can be loaded in any of the 24 basket cells positions. The design basis fuel bounding parameters of the authorized content that can be transported in the ENUN 24P cask are indicated in Table 1. These parameters comply with the most limiting of the spent fuel intended to be transported from Daya Bay and Ling Ao NPPs.

Table 1 ENUN 24P Design Fuel Basis Bounding Parameters

Parameter	ENUN 24P
Fuel design	AFA 2G, AFA 3G, AFA 3GAA
Maximum burnup	Up to 57000 MWd/tU
Minimum cooling time	Up to 3 years
Maximum initial enrichment	Up to 4.5 % wt U-235
Type of loading	Uniform
Burnup credit	No

For the development process of the ENUN 24P to comply with the Chinese requirements, Ensa set out its established ENUN 32P dual-purpose cask as the referenced cask design, and included some technical modifications. The ENUN 32P is licensed in Spain for dry storage and transportation of PWR type spent fuel from the following Spanish NPPs: Trillo NPP (KWU 16x16 fuel design), Ascó I & II NPPs, Almaraz I & II NPPs and Vandellós II NPP (Westinghouse 17x17 fuel design). It allows two different basket configurations in order to allocate both allowed fuel designs, KWU 16x16 and Westinghouse 17x17.

The principal design change introduced for the development of the ENUN 24P project has been the maximum capacity of the cask. The ENUN 32P was designed to allocate up to 32 PWR type fuel assemblies. The criticality evaluation was performed giving credit to the burnup of the spent fuel, to

[1] Additionally, the ENUN 24P is perfectly suitable for dry storage of spent fuel, since it has been designed as a dual-purpose cask. Ensa plans to start soon the licensing process also for storage in Spain.

the actinides according to ISG-8, Rev. 3 [5]. Therefore, the basket layout was optimized to a capacity of 32 fuel positions. However, since the Chinese client and nuclear authority did not initially allow the application of the burnup credit methodology, for the ENUN 24P cask Ensa decided to include a “flux trap” concept in the basket layout to increase the gap between adjacent fuel cell positions, and assure the subcritical condition of the spent fuel considering it as fresh fuel for the criticality evaluations. Consequently, the maximum capacity of the cask had to be reduced up to 24 fuel positions.

This reduction in the maximum capacity of the cask gave Ensa the possibility of slightly reduce the inner cavity diameter of the ENUN 24P respect to the reference ENUN 32P, from 1866 mm to 1669 mm but maintaining the inner shell thickness that provides the majority shielding against the radial gamma radiations. Therefore, the weight of the cask was reduced. The maximum loaded cask weight was another limitation imposed by the Chinese customer, since the maximum lifting capacity of the cranes in all fuel buildings was limited to 130 tons.

A second important design modification was in the shielding capabilities of the cask. The design basis fuel parameters, specifically the high burnup and the very short cooling time detailed in Table 1, produced very high gamma and neutron fluxes and elevated decay heat that the cask had to dissipate. Furthermore, although IAEA SSR-6 [1] requires ‘exclusive use’ transportation mode for these type of radioactive packages and consequently allow maximum dose rates in the package surface of 10 mSv/h (see paragraph 573 of [1]), the Chinese client imposed another challenging requisite to the Ensa team. The maximum dose rates in the package surface had to be conservatively reduced to 2 mSv/h. This additional demand forced Ensa engineers to increase the gamma and the neutron shielding capabilities of the cask, but without penalizing in excess the overall weight and the supply chain for the fabrication of the cask: supply of the raw materials (mainly the forgings that constitute the inner shell), planning of the principal and secondary production lines, development of the ancillary equipment, fulfillment of the licensing schedules, etc. The following technical solutions were adopted by the Ensa team:

- <u>Increase the thickness of the aluminium profiles in the basket.</u> This modification looked for two different goals: firstly, to increase the material thickness in the periphery of the basket and reinforce the gamma shielding capabilities. Secondly, to increase the volume of aluminium in the basket and enhance the heat rejection capability of the cask.
- <u>Weld a set of stainless steel plates in the periphery of the basket</u>, in the squared fuel cell structure formed by the assembly of plates (‘egg-crate’ structure). This additional set of plates provided additional gamma shielding but closer to the fuel, without increasing the cask weight in excess.
- <u>Triplicate the thickness of the outer shell</u> that envelopes the neutron shielding profiles and

constitute the outer surface of the cask, to complete the enhancement of the gamma shielding capabilities of the ENUN 24P respect to the former ENUN 32P design.

- Increase the inner volume of the aluminium fins, to pour more neutron shielding resin and enhance the neutron shielding capabilities.
- Add discs of solid neutron shielding material at the centre of both impact limiters, to reduce the contribution of the neutron source in the axial dose rates, and comply with the conservative limit of 2 mSv/h.

All these new features proposed by Ensa during the pre-design phase of the ENUN 24P project finally convinced the client with the enhanced cask design. At that time, it allowed Ensa the start of the detailed design evaluations and the kick off for the development of the manufacturing documentation (material purchase specifications, fabrication drawings, welding qualifications, etc.). The tight schedule agreed in the contract to comply with the established date for the first fuel loading and transportation campaigns from Daya Bay NPP, obligated Ensa to start the fabrication activities in parallel with the completion of the detailed design evaluation and the issuance of the licensing documentation, in Spain and in China. This imposed high risk on the success of the project, but Ensa performed a specific and detailed risk analysis of the overall project, studied and implemented appropriate measures, resources and project deadlines to mitigate those risks.

Cask Design Changes Due to Client Additional Requirements

However, once the pre-design phase had been completed and the start of the elaboration of the manufacturing documentation had been approved, the client requested Ensa to perform additional design modifications in the cask. There were principally two important issues that had to be addressed by Ensa engineers within a very short time, in order to not affect the licensing, manufacturing and fuel loading schedules:

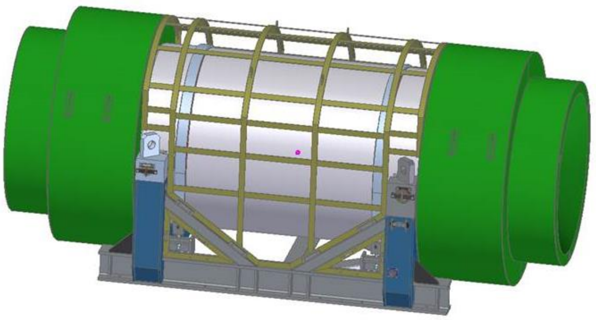
I. The client wanted to reduce the maximum diameter of the transportation package, limiting it to 3300 mm. During the bidding phase of the contract a maximum outer dimension of 3400 mm was proposed by Ensa. However, due to geometrical restrictions imposed later in the transport route of the cask from Daya Bay and Ling Ao NPPs to Lanzhou storage facility (see Figure 1), a package with an outer diameter over 3300 would not receive the appropriate transportation permits.

II. An anti-corrosion coating should be applied to the inner metal surfaces of cask that were going to be in contact with water from the spent fuel pools. Ensa defended and technically justified that ‘bare-fuel’ type metal casks made of carbon steel do not require the application of any anti-corrosion coating as long as an appropriate pressure of the inner cavity is performed with inert gas (i.e. helium) after any fuel loading and unloading operation, and the operating and maintenance activities are strictly performed as indicated in the operating manual of the cask. Finally, an agreement was achieved to apply an aluminum based anti-corrosion treatment to the inner cavity and the inner lid, to mitigate any potential risk of corrosion since the cask was going to be used for several transportation campaigns per year.

After these design modifications required by the client, Ensa started immediately a process to re-design some of the components of the cask and analyze its implication in all the safety functions, in parallel to continue with the development of the manufacturing documentation by Ensa's Engineering department. The principal modifications and analyses performed from the initial pre-design of the ENUN 24P are briefly explained in the following subsections.

Implications of the Reduction of the Outer Diameter of the Package

The transportation package of the ENUN 24P (Figure 3) is constituted by the cask and the impact limiters attached to the outer lid and the bottom of the cask. The package is also protected with a protective barrier to avoid that any person could access the outer surface of the cask. The outer dimension of the protective barrier is limited by the outer diameter of the impact limiters. The package is attached to a transportation skid through its four trunnions fixed to the rail car or truck used for transportation.



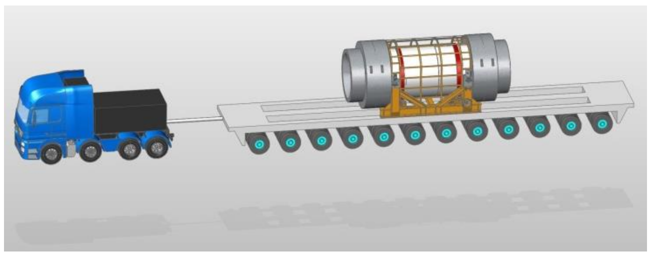


Figure 3 Transportation Package of the ENUN 24P

Therefore, in order to reduce the outer diameter of the package, Ensa had to reduce the diameter of the impact limiters. The impact limiters of all the ENUN casks have been developed in collaboration with Sandia National Laboratories in the U.S.A. They are constituted of two different types of energy absorbing materials (polyurethane foam and aluminum honeycomb blocks) enveloped by a stainless steel cover. They were tested using a mock-up of the ENUN 32P cask from 9 m free drop and 1 m puncture impact tests, in 'cold' and 'hot' testing conditions and different cask orientations as required by IAEA SSR-6 [1]. These tests were also performed at Sandia National Laboratories (see Figure 4). After that, they were validated through detailed finite element analysis, and adapted to fit other casks designs from the ENUN series, including the initial ENUN 24P pre-design with a 3400 mm outer diameter.

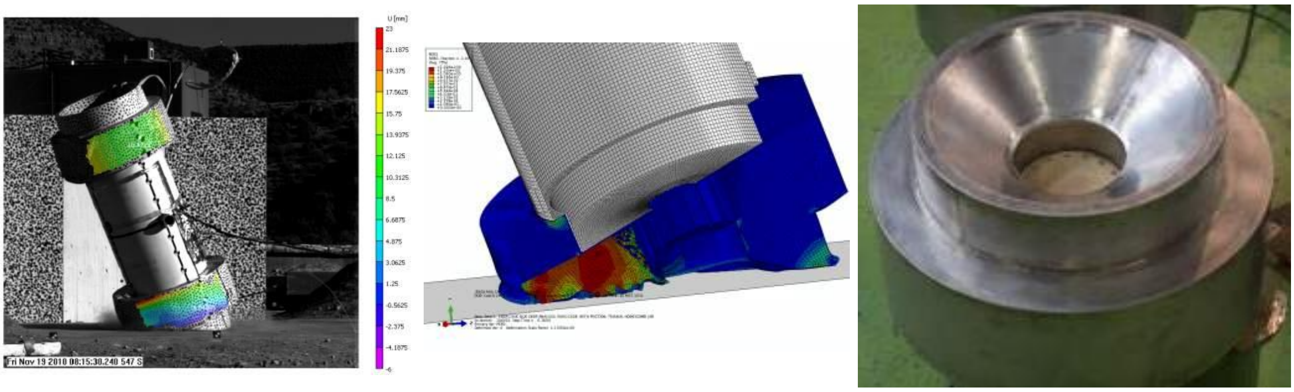


Figure 4 Impact Limiters, Drop Tests and Component Validation of the ENUN Casks

Therefore, the first set of drop analyses performed on the ENUN 24P cask using impact limiters with reduced diameter (3300 mm) led to accelerations in the center of gravity of the package (and therefore in the spent fuel assemblies) in the ‘cold test condition’ over the 60 G design limit, and to avoid the complete depletion of the impact absorbing material in the ‘hot test condition’, provoking a very hard impact between the cask trunnions and the flat surface.

At this critical point of the development, Ensa started a close working relationship with Sandia National Laboratories and the supplier of the aluminum honeycomb energy absorbing material, in order to search and test enhanced properties materials to absorb more impact energy and redistribute it, trying to comply with the two main functions of the impact limiters when tested from 9 m free drops: reduce the maximum acceleration of the cask center of gravity in the ‘cold test condition’ and avoid the complete depletion of the energy absorbing material in the ‘hot test condition’, avoiding damage in the spent fuel. Several scoping analyses were performed with the cask and the impact limiters that covered a complete range of the following parameters, but assuring any impact on the validated methodology for the ENUN casks drop tests:

- Cask orientations: horizontal, vertical, slap-down, etc.;
- Cask temperature:
- Impact limiter honeycomb absorbing material crush strength: better characterization;

After these intense work and components evaluation, where a vast amount of data was obtained and carefully evaluated Ensa finally decided to maintain the same type of honeycomb absorbing material used in the rest of impact limiters of all ENUN cask (and tested at Sandia National Laboratories).

However, a slight modification was performed in the geometry of the internal structure of the impact limiters that allowed the installation of higher volume of honeycomb absorbing material, thereby reducing the maximum acceleration of the cask centre of gravity within the design limits. Since this solution was not enough to avoid the complete depletion of the energy absorbing material in the 9 m free drop 'slap down event' under 'hot testing conditions', because of the harsh contact between the cask trunnions and the flat surface, and innovative technical solution was proposed by Ensa: substituting the traditional trunnion concept protruding out of the outer surface of the cask (commonly named as 'trunnion male concept') by drilling an inner cavity in the trunnion block (see Figure 5). This has named by Ensa team as 'trunnion female concept'.

This technical solution implied also the modification of the ancillary equipment for the fuel loading and unloading operations of the cask, principally the lifting yoke and the transport skid. Ensa has developed a sophisticated device driven by a pneumatic actuator system (but including also an additional countermeasure actioned manually in case of off-normal or accident conditions) and a double blade system to reinforce the structural behaviour of the lifting yoke (see Figure 6).

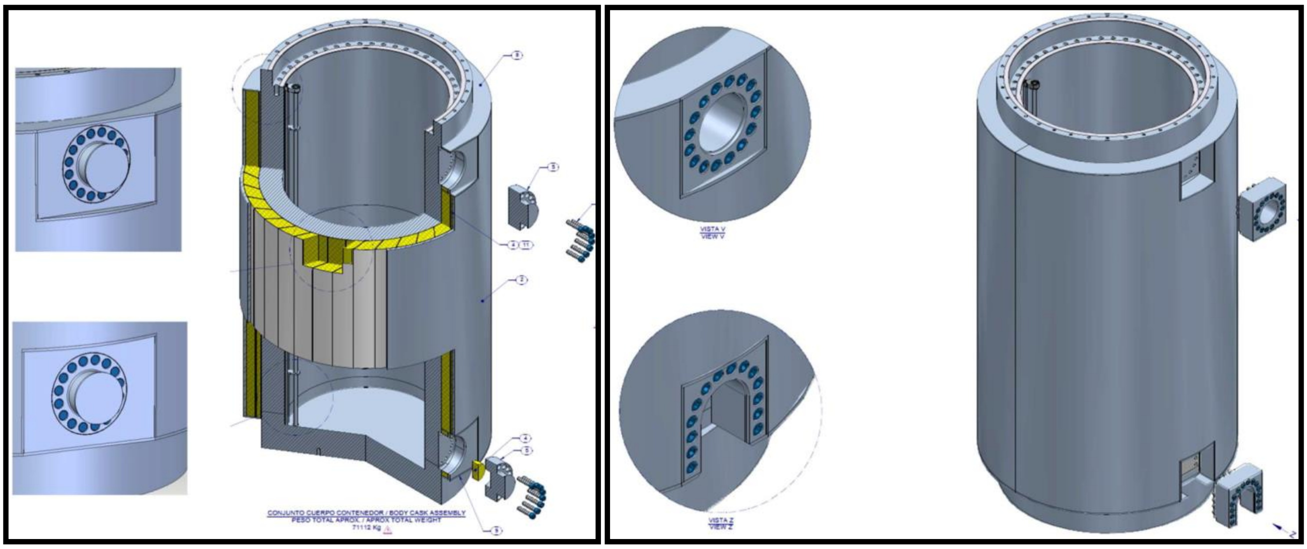


Figure 5 Modification of the Trunnions in the ENUN 24P: From 'Male' to 'Female' Concept

This innovative 'female trunnion concept' has allowed Ensa to remove any protruding from the outer surface of the cask and avoid the harsh impact with the flat surface. The complete depletion of the energy absorbing material during any cask orientation in 9 m free drop tests was completely avoided and the successful performance of the impact limiters was validated at any postulated accident condition, according to IAEA SSR-6 [1].

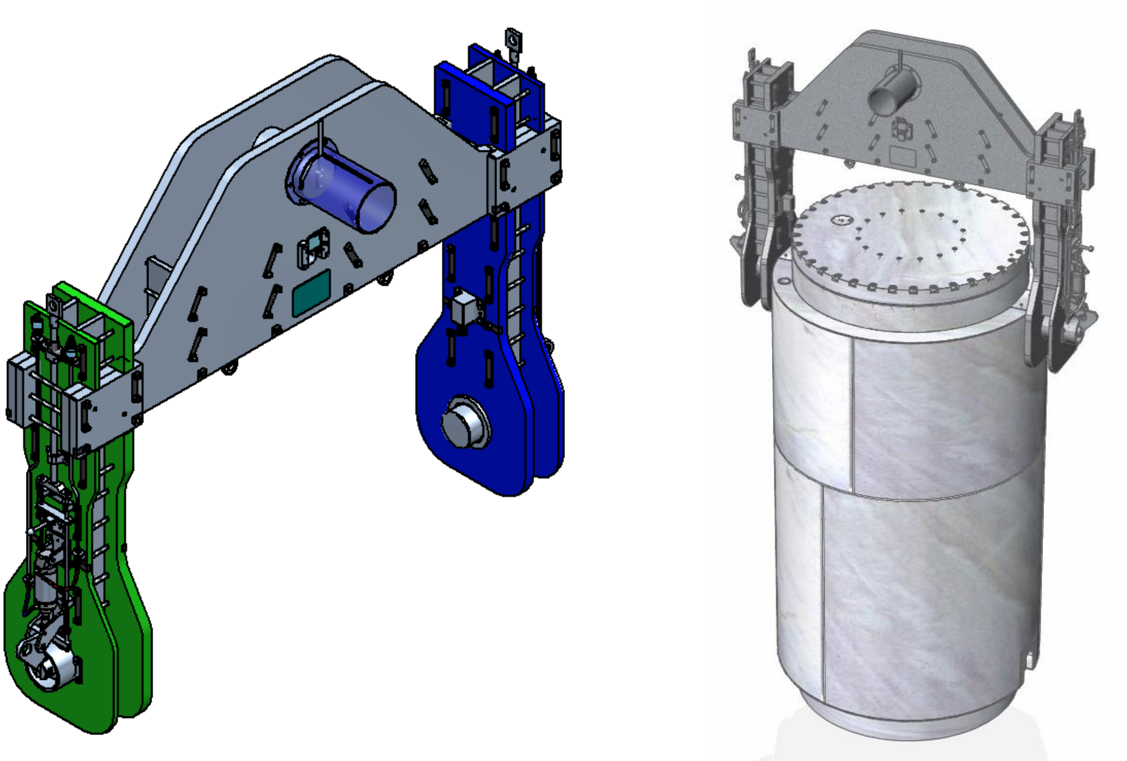


Figure 6 Specific Lifting Yoke Developed for the ENUN 24P

Conclusions

By 2013 Ensa accepted the challenge to adapt the design of the ENUN 32P cask and comply with the specific requirements of a cask required by a Chinese customer, for the transportation of high burnup spent nuclear fuel from Ling Ao and Daya Bay Nuclear Power Plants (NPPs) located in southeast China, to Lanzhou storage facility (long distance until almost 4000 km), crossing China in different regions and climate conditions through road & rail transportation. The challenge implied re-design a cask and the appropriate ancillary equipment, get the license approval both in Spain and in People's Republic of China, manufacture all the equipment, supply it to China and perform specific training to the operational staff of the Chinese plants. All these activities within a very tight schedule, to arrive on time to the forecasted fuel loading campaign to remove space from Daya Bay NPP spent fuel pool.

This project has entailed the need to implement important and innovative technical solutions in the design of spent fuel casks, both before and during the development of the project, such as the basket configuration, the trunnions and the impact limiters design, the shielding capabilities, etc. The ENUN 24P project has brought to Ensa's Design & Engineering department the experience to cope with specific customer requirements respect to the base design of the ENUN casks series.

Additionally, this project is showing the how a timely and coordinated work between the different Ensa's departments involved, the client, and subcontractors can satisfactorily meet the new challenging technical and schedule requirements of China's ambitious nuclear high level waste management program.

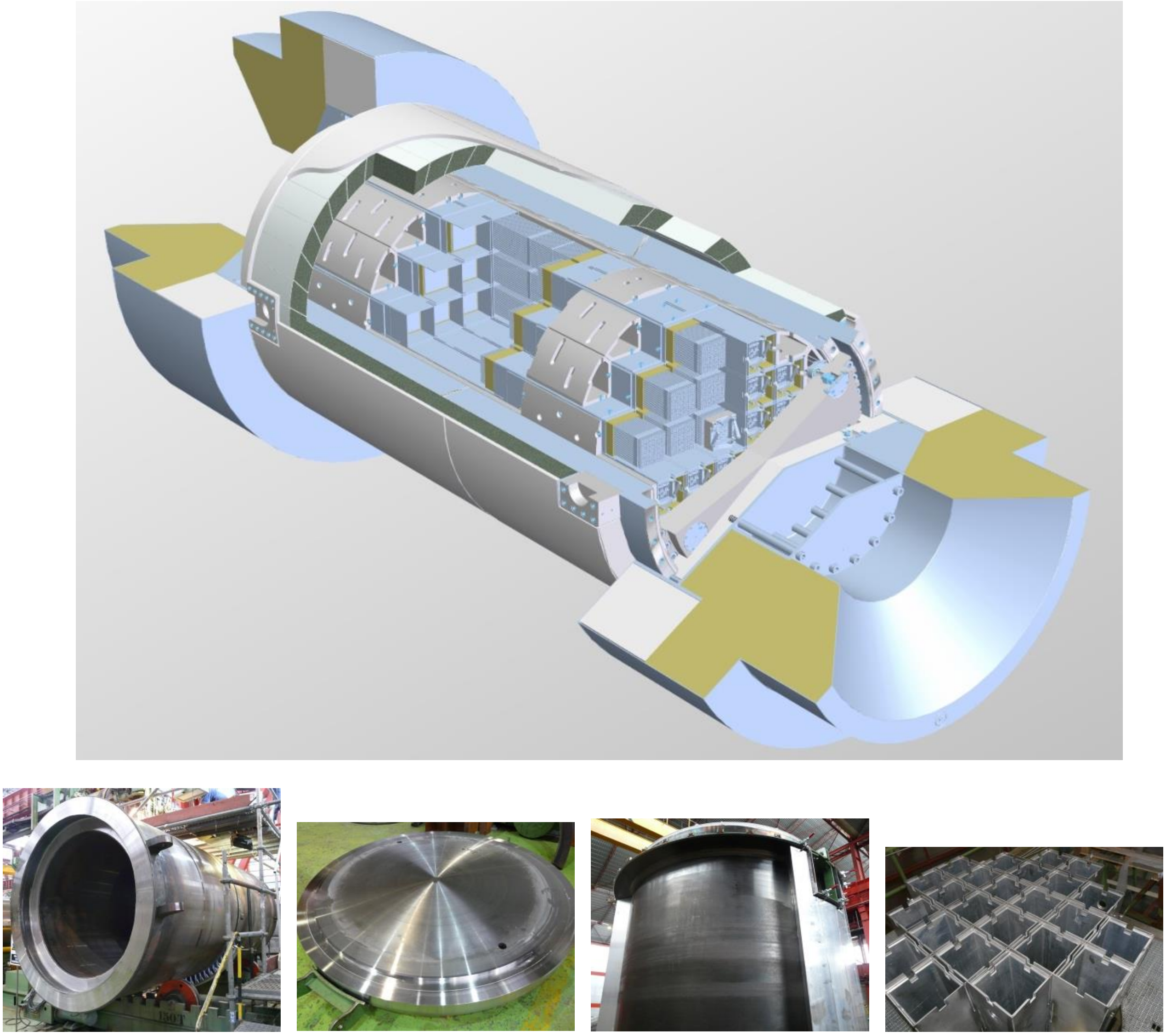


Figure 7 Final Design and Manufacturing Sequences of the ENUN 24P

Acknowledgments

I would like to acknowledge the principal members of Ensa's ENUN 24P cask project for its dedication to successfully solve all the challenging technical issues of this project. Specially, my colleagues from the Spent Fuel Design & Engineering area (David Garrido, David Castrillón, Víctor Gómez, Raúl Muñoz, Roberto Miguel, Luis Moreno, Virginia Madrazo, David Pondal, Alejandro Lanza, Jesús Fernández and Enrique Gómez Poncela), from the Project Management area (Tan Lin, Roberto Diego and Cynthia Sacristán), from the Field Services area (Álvaro Soto, David de Francisco and Pablo Echaure), Guillermo Calleja from the Commercial area and Francisco Javier Maldonado as Engineering Manager.

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