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Material Issues in Manufacturing and Operation of Transport and Storage Spent Fuel Casks

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ABSTRACT

The paper will concentrate on discussion of material and technological issues of fabrication of the transport and storage spent fuel containers components.It will also be present material problems some additional parts concerning to special properties requirements.The paper provides comparison of three different material and technological alternates container bodies fabrication.This includes cast ductile iron bodies made of GGG 40 for CASTOR containers, forging and welded parts for container of WEC and MC-10 type and application of cast manganese steel for developed project ŠKODA container.

Material properties especially fracture toughness will be discussed with regards to IAEA TECDOC 717 requirements, including comparison with RPV material requirements.There will be presented austenitic chromium-nickel special steel with boron additions as metallic absorption material.This material is used under the identification ATABOR especially in hexagonal tubes for spent fuel assemblies of compact storage and also for container inner parts.

From material point of view, there will be assessed the nine meter drop test and one meter thorn drop test results for 1 : 2,5 ŠKODA 440/84 model container.These tests demonstrated convenient cover and screen ability of these containers according to requirements of international safety regulations.Ageing of these containers materials and potential necessity of implementation of a special surveillance programme similar to the one applied for nuclear reactor pressure vessels.

INTRODUCTION

Operation of nuclear reactors requires periodic exchange of fuel. Immediately after removing spent fuel assemblies from the reactor they are stored in the interim storage facilities at NPPs. Mostly high-density racks for storage in pools are used for this purpose. Casks of various types which have to meet strict requirements for safety and reliability of the operation as well as any equipment working with radioactive materials are used for transport and permanent storage. Currently, ŠKODA JS manufacture and supply high-density storage racks for type VVER 440 and 1000 reactor, and type CASTOR cask for transport and storage of 84 spent fuel assemblies from VVER 440 reactor. Castor casks are made under the licence of GNB company (Gesellschaft fur Nuklear-Behalter mbH, Essen, Germany). In addition to that, our company has developed ŠKODA 440/84 cask of its own design which is currently in the licensing stage at SÚJB (State Office for Nuclear Safety).

The question of material which has to be solved in connection with equipment for spent nuclear fuel transport and storage is one of the cardinal matters. For this production and development our company utilize long-term experience gained during research and development works and during manufacture of type VVER pressure vessels and reactor internals.

MATERIAL ISSUE OF CASK BODIES

Solution of the material issue for cask bodies as the most important components is really varied. Currently, there is a number of projects world-wide solving this issue in different ways. Not considering projects using concrete parts, or double-shell designs with pouring the interspace with concrete mixture or lead, there are three obviously most frequent alternatives. All of them are based on the application of metal materials - steel and ductile cast iron, and their manufacture requires different technological procedures which in final stage must provide required properties of these components. They are cast bodies of ductile cast iron GGG40 used for the manufacture of CASTOR casks, forged and welded parts for Westinghouse and others cask projects, and application of cast manganese steel for ŠKODA design cask which is being developed. Further on, we will try to characterize these three material and technological alternatives and consider their advantages and disadvantages in relation to properties required with respect to the assurance of safe transport and long term storage of spent nuclear fuel.

Ductile cast iron GGG 40 (per DIN Standard) is used for the manufacture of CASTOR cask bodies according to GNB project. Ductile cast iron can be characterized as a heterogeneous material the properties of which are significantly effected by size, quantity and shape of separated nodular graphite. Chemical composition, particularly carbon and silicon content, has a major effect here. Si content is in the range of 1.2 to 2.4%, and increasing silicon concentration escalates eutecticum temperature, stabilizes ferrite in the structure, and during heat treatment extinguishes formation of pearlite. Strength properties increase and at the same time ductility decreases. In addition to that, properties of ductile cast iron are significantly dependent on the content of some impurities (Bi, Ti, Sb, Al,V) which even with low concentrations can lead to changes in graphite morphology and reduction of ductility and fracture toughness. As shown in Table 1, DIN Standard allows ratio value of yield point to tensile strength on the level of 0.8 and more. Minimum ductility value is required 6% with unguaranteed notch impact strength values. It is very demanding to assure required properties in a thick-wall vessel with respect to the technological procedures which have to be followed in the entire course of fabrication. As mentioned in Gunter's and other author's work, there were many problems in the past to meet plastic properties during the manufacture, and average ductility reached values only around 3%. Currently, with the process acquired, this value is 15% and higher.

Cask body of ductile cast iron is covered on its inside surface after machining with galvanically applied layer of nickel. The nickel layer of thickness between 0.5 to 2.0 mm serves for additional sealing of the cask and for anticorrosion protection of the cask body during loading of fuel assemblies under water. Such electroplating represents another very demanding technological process which must be met during the manufacture. Nickel layer shall meet very stringent requirements for thickness uniformity, homogeneity, hardness and adhesion to the base ductile cast iron material. Everything is checked because in the duration of the process taking about 150 hours there must not be any deviations from the process parameters, nor its interruption. For this purpose ŠKODA JS have developed and use a monitoring system which enables monitoring and control of the entire nickel-plating process.

According to Westinghouse and recently also TEPCO (Japan) projects, cask bodies are made of forged and welded parts. This design, with respect to material and technology, is very similar to the manufacture of reactor pressure vessels. E.g. ring forgings of steel SA 508 Cl.4b and Cl.5 are used for cask MC-10. It is a high-strength CrNiMoV steel with 3.5% of nickel and 1.5% of chromium for which a special method of welding under preheating shall be applied. Required properties are determined by ASME Code and particularly brittle-fracture characteristics are on a high level. According to available material specifications, carbon steels SA 350 Gr.LF1 are used in Japan. To achieve uniform properties in high thicknesses (300 mm) holow ingot technique (2) is used for the manufacture of rings. The application of forgings for cask bodies has indisputable advantages in reliable assurance of high strength and plastic properties, however, naturally with much higher production costs in comparison with the application of ductile cast iron. Certain mistrust of casks was obvious at the time of the licensing process of CASTOR cask for the use in the U.S.A. Despite of extent experimental program of testing of these ductile cast iron casks which showed excellent properties, they were not approved for transport in the territory of the U.S.A. They can be used only for storage.

Quite different solution of the material issue for casks was proposed and processed after a proper analysis in ŠKODA Plzeň. It was enabled by the cask design itself which differs significantly from the previous designs by its double-barrier design. The cask body of thickness 260 mm is made of cast manganese steel ČSN 42 27 07. 9. Inside the body there is a canister made of CrNi austenitic steel and after filling it with spent fuel assemblies it is welded. Casting material of the cask body was tested first of all from the point of view of achieving more advantageous brittle-fracture and plastic properties in comparison with other materials used for these bodies. It was found that mechanical properties reached high values also in the half of the wall thickness, yield point Rp0.2 is in the level between 276 to 290 MPa and detected tensile values are 40 to 43% at the testing temperature 20°C. Tensile force value remains on a relatively high level also at the testing temperature -40°C (24.6 and 28%). The performed calculation of ŠKODA 440/84 cask of brittle failure resistance met the required criteria of IAEA-TECDOC-717 (3) for a design defect equal to 1/4 of the body wall thickness, i.e. 65 mm with the safety coefficient $K_B = 1.463$. This evaluation included also drop test of the cask from the height of 9 m.

RADIATION SITUATION OF THE CASK AND REACTOR PRESSURE VESSEL FROM THE POINT OF VIEW OF MATERIAL DAMAGE

Radiation damage caused by high-energy nuclear radiation was notices at numerous metals and alloys. From the point of view of engineering consideration it is necessary that the extent and principle of irradiation and resulting from it degree of metal damage was such that it makes reliability of the irradiated design component with respect to integrity conservation questionable. Therefore, the most sophisticated from this point of view are steels and weld material for nuclear pressure vessels where chemical composition, particularly concentration of certain impurities has a significant role with respect to sensitivity to radiation damage. To assess a damaging potential of a given neutron environment, the principle of interaction atom-neutron as a function of neutron energy, number of neutrons according to the energy (or an energy group) and a possibility of their interaction with the atoms of irradiated metal should be known. The experiment proved that neutrons with lower energy contributed only little to this kind of damage. Neutron fluency which is an expression of neutron flow time integral and considers neutron from a certain energy, has a significant effect for radiation damage of steels. The irradiation temperature is another significant factor of the operation environment. With increasing temperature a minor radiation damage occurs above a certain temperature threshold due to thermally activated processes and recombination of grid failures. For a reactor vessel this threshold temperature is 200 to 235°C and at operation temperature 290°C a significant reduction of radiation embrittlement occurs. It can be stated that for steels with identical neutron fluency, higher radiation damage occurs at material which was subject to irradiation at lower temperature. According to design values and verification calculations it is obvious that radiation loading of the cask is 5x lower than of a reactor pressure vessel (considering the initial value of fast neutron fluency having more distinct importance in degradation mechanisms of the VVER440 reactor pressure vessel material) in comparison with designed and calculated value at the end the cask life, i.e. assumed 50 years. However, comparing the value of fluency in the RPV wall at the expected end of the RPV life, i.e. 30 or 40 years, this value is even more distinct. Moreover, relation of the cask life to RPV life is 50/30, 50/40 respectively. Evaluation from the point of view of thermal mechanical loading and mainly by the character of loading would be similar. The cask can be considered a stationary vessel without dynamic effects of loading while during the reactor operation the RPV is subject to thermal mechanical dynamic regimes of loading with incomparably higher inside overpressure.

A critical point in the assessment of the cask life is not a stable condition during the storage but possible emergency situations during the cask transport. For this reason all safety regulations emphasize verification of material properties in the initial condition first of all from the view point of static and dynamic brittle fracture characteristics in comparison with the critical embrittlement value. These values are verified by calculation codes modelling mainly dynamic loading, respectively crash tests with factual drop and fire tests on a model or possibly on actual cask bodies where the cask leak-proof is the main aspect..

ŠKODA JS paid special attention to this question also with respect to development, calculation and experimental works on the ŠKODA 440/84 cask itself on which a number of design, development and experimental works were performed in a comparable scale with world leading manufacturers of casks, and currently, licensing of the cask is in process.

DROP TEST OF CASKS

A necessary condition to obtain the licence for the manufacture and use of the cask is, besides others, to perform drop tests. Cask properties in possible extreme conditions which may occur during the transport of spent nuclear fuel are tested by such tests. Drop tests are performed according to requirements stipulated in IAEA document - "Rules for safety transport of radioactive materials" (Safety Series No. 6). A cask is dropped during such tests from a defined height (9 or 18 meters) on a massive base plate, and preservation of leak-proof is the main criterium. In order to detect leakage, the cask is filled with helium the possible leakage of which is monitored using special devices. Besides verification of sealing properties, also tensometric measurements are performed during the drop tests. These measurements can detect to what mechanical loading the cask material is subject during the drop test. The measurement results are then used for verification of calculations which document reliability and safety of produced casks.

To perform the tests a drop test facility has been built in ŠKODA JS, Plzeň. It includes a special steel plate of weight 14 tons under which there is a 450t ferroconcrete monoblock for damping the drop reaction. In 1997 drop tests of ŠKODA 440/84 cask model were performed in this facility; the model was a replica of an actual cask, only reduced in size in scale 1 : 2.5. A drop from 9 m height on the edge, and also a flat drop on a spine protruding from the base plate from 1 m height were performed there. During the tests and after them all the above measurements were performed and it could be stated that there was no leakage and no plastic deformations on the critical components of the cask. Successful drop test results of the cask were included in the safety documentation file which is submitted to the Regulatory Body for licensing.

ATABOR STEEL FOR SPENT FUEL STORAGE RACKS ABSORPTION TUBES

Austenitic corrosion-resistant 1% boronated Cr-Ni steel is used for the manufacture of high-density storage racks tubes intended for temporary storage of spent nuclear fuel. Thus modified steel serves as absorption material for entrapping of neutrons, and it is used for the manufacture of capsules into which the fuel assemblies are inserted. The most important property of the capsules made of this material is besides a sufficient capability to absorb neutrons also their corrosion resistance in a given medium, i.e. demineralized water with an addition of boric acid. Addition of 1% of boron provides sufficient absorption properties of this material. Boron is present in the steel in the form of borides $(FeCr)_2B$, and its uniform distribution in the basic austenitic die is given by meeting all the metallurgical procedures of the manufacture including heat treatment. In the final stage of the absorption tubes manufacture a 100% inspection of the shielding function from the view point of neutron absorptivity is performed. Equipment developed particularly for this purpose works on the principle of thermal neutron absorption during irradiation of material. In addition to that, also metallographic methods of inspection are used. Steels of this type with similar chemical composition are used for the construction of such storage racks in Germany, USA and other countries of the world, mainly under the name of NeutroSorb.

Corrosion resistance of produced tubes was subject to a thorough inspection already during development works, and later it was verified also abroad (4),(5). In addition to that, corrosion and gamma radiation effects to corrosion of ATABOR steel were evaluated by long-term tests directly in the high-density storage rack pool at Dukovany NPP. Samples of a plate with different surface quality were for a long time exposed in water with 16g of boric acid and 0.15 mg chlorides per 1 liter of water, at pH = 4.3 and temperature 40°C. By evaluation of corrosion losses maximum corrosion rate of $4.7.10^{-5}$mm/year was detected. One-sided corrosion loss of size $2.1.10^{-2}$mm leading to 1% loss of boron content in plate of thickness 4.2 could theoretically occur after 470 years.

Recently, a draft of the continuous corrosion monitoring system and periodic inspection of the shielding capability of ATABOR material absorption tubes system has been elaborated. The system enables to indicate occurrence or absence of non-uniform corrosion including local attack using electrochemical measurements. Necessary cleanliness and quality of the surface in the course of manufacture is sharply inspected according to generally applicable regulations and requirements for the work, handling and storage of parts of austenitic Cr-Ni steels. Questions of pickling, passivation and methods for detection of ferritic impurities are part of these regulations. Doubting the life time of ATABOR steel absorption tubes in high-density spent fuel storage racks is a problem which repeatedly occurs a number of years during tender procedures and realization of supplies of this equipment to nuclear power plants inland and abroad. Corrosion resistance and permanent screening capability had to be often defended for the used technology of these tubes manufacture against customers and also against judgements of various organizations. For the supplies of high-density storage racks to Dukovany NPP, the life time of the equipment was guaranteed for 30 years according to technical documentation, including the stability of dimensional tolerances.

CONCLUSION

All countries operating nuclear power plants have to deal with the question of spent nuclear fuel storage. The use of casks designed for transport and permanent storage seems to be the most economical solution. The casks have to meet a number of requirements resulting from international regulations for equipment working with radioactive materials. Materials used for the manufacture of casks are chosen and tested so that they meet all these demanding regulations assuring a long-term safety operation. A critical point when assessing safety and life of the cask, is not a stable condition during the storage in the storage facility but possible emergency situations during the transport. For this reason all safety regulations strongly emphasize verification of material properties in the initial state, first of all from the point of view of static and dynamic brittle-fracture characteristics. ŠKODA JS paid a special attention to the question of its cask material, and all performed tests including drop tests met the requirements of IAEA TECDOC-717 regulation.

Austenitic corrosion-resistant CrNi steel with addition of 1% of boron is used as absorption material for entrapping of neutrons in high-density storage racks and for parts of the transport and storage casks internals. Corrosion tests of this material performed in our country and abroad demonstrated sufficient resistance in the medium of demineralized water with the addition of boric acid in the high-density storage racks pools. In the final stage of the manufacture a 100% inspection of shielding function with respect to neutron absorptivity is performed on the parts made of this material.

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(4) Certification of ATABOR Steel at Siemens, Report No. KWU E121/91086, Erlangen, July 1991

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CHEMICAL COMPOSITION (weight %)
(Requirements)

TYPE / MATERIAL	C max	Mn	P max	S max	Si	Ni	Cr	Mo	Cu	V	Cr+Ni+Cu max
CASTOR/GGG 40 cast iron	3,30 3,80	0,60 max	0,03	0,01	1,30 2,40	1,30	-	-	0,15 max	-	
TEPCO/A 350 Gr.LF1 carbon steel	0,30	0,60 1,35	0,035	0,04	0,15 0,30	0,40 max	0,30 max	0,12 max	0,40 max	0,03 max	
SKODA/ Mn- cast manganese steel CSN	0,12	1,00 1,60	0,025	0,02	0,20 0,50	0,40 max	0,30 max	0,15 max		0,03 max	0,70

MECHANICAL PROPERTIES
(Requirements)

TYPE / MATERIAL	Yield strengh $R_p0,2$ [MPa]	Tensile strengh Rm [MPa]	A5 [%]	Z [%]	KV -40°C [J]	KV 20°C [J]
CASTOR/GGG 40 cast iron	200 min	250 min	6 min			
TEPCO/A 350 Gr.LF1 carbon steel	205	415 585	25	38		
SKODA/ Mn- cast manganese steel, CSN	270 min	420 570	25 min	50 min	45 min	80