Conception of transport cask with advanced safety, aimed at transportation and storage of spent nuclear fuel of power reactors, which meets the requirements of IAEA in terms of safety and increased stability during beyond-design-basis accidents and acts of terrorism

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Abstract

The report is devoted to the problem of creation of a new generation of multi-purpose universal transport cask with advanced safety, aimed at transportation and storage of spent nuclear fuel (SNF) of power reactors, which meets all requirements of IAEA in terms of safety and increased stability during beyond-design-basis accidents and acts of terrorism. Meeting all IAEA requirements in terms of safety both in normal operation conditions and accidents, as well as increased stability of transport cask (TC) with SNF under the conditions of beyond-design-basis accidents and acts of terrorism has been achieved in the design of multi-purpose universal TC due to the use of DU (depleted uranium) in it. At that, it is suggested to use DU in TC, which acts as effective gamma shield and constructional material in the form of both metallic depleted uranium and metal-ceramic mixture (cermet), based on stainless or carbon steel and DU dioxide. The metal in the cermet is chosen to optimize cask performance. The use of DU in the design of multi-purpose universal TC enables getting maximum load of the container for spent nuclear fuel when meeting IAEA requirements in terms of safety and providing increased stability of the container with SNF under conditions of beyond-design-basis accident and acts of terrorism.

1. Introduction

Currently due to acts of terrorism, which became more frequent all around the world, the problem of SNF safety and preservation became burning in countries with developed atomic power engineering.

Russian and American specialists think that one of the possible ways of solving the problem of safe and reliable storage of SNF is creation of multi-purpose universal TC, aimed at transportation, storage and disposal of SNF. Such transport casks are much more reliable and safe under conditions of beyond-design-basis accident and acts of terrorism. The main advantage of multi-purpose universal container is safety and preservation of SNF in comparison with spent nuclear fuel storage facilities: SNF is treated only once, when it is loaded into the container. At that, it should be taken into account that the amount of SNF loaded into each separate container is limited, thus the after-effects of each incident are also limited. At the same time, multi-purpose universal TC, having rather great sizes, is easily watched from space orbit, which makes it possible to control the state of both container and fuel in it.

There has been developed the conception of dual-purpose universal transport cask with advanced safety level, aimed at transportation and storage of SNF of power reactors, which corresponds to all IAEA safety requirements and which has increased stability under conditions of beyond-design-basis accidents and acts of terrorism. Meeting all IAEA safety requirements as well as increased stability of TC with SNF under conditions of beyond-design-basis accidents and acts of terrorism was achieved due to the use of DU in TC design. At that, it is suggested to use depleted uranium in TC, which acts as effective gamma shield and constructional material in the form of both depleted uranium metallic and metal-ceramic mixture based on stainless or carbon steel and DU dioxide. For Minatom, which has accumulated a great amount of depleted uranium in the form of utilizable metal devices and wastes of isotope separation enterprises, the creation of a new generation of double-purpose universal transport cask for SNF of power reactors on the base of DU is the most rational and forward-looking method. It allows solving the problem of DU stocks utilization rather efficiently and economically sound. Huge supplies of depleted uranium do not find application and cause problems for the environment.

Exactly such technical policy regarding the new generation of TC for SNF is being carried out in the US now, which possess great amount of DU stocks, formed as a result of military programs and nuclear fuel production.

Department of Energy of the USA has developed R&D program on creation of DU cask for storage, transportation and disposal of SNF, using depleted uranium as a material, which provides the most effective gamma shield and maximum safety in case of beyond-design-basis accidents and acts of terrorism.

The works on the study of a new double-purpose TC creation possibility, aimed at transportation and storage of SNF of WWER reactors on the base of metallic DU were started at RFNC-VNIIEF and VNIINM in the beginning of 90-s in accordance with Minister's and are being carried out now.

During this period of time at the expense of ISTC there has been carried out a great amount of engineering and design, research and design-theoretical works, which resulted in the following:

- a special uranium alloy BZ-2 has been developed. This alloy meets the requirements of being a component of TC with SNF. There have been studied the running ability of the alloy under conditions of its operation as a part of TC gamma shield and serviceability of 50 years operation under such conditions has been substantiated. According to VNIINM evaluation the amount of the accumulated metallic uranium in the form of wastes is sufficient enough for manufacturing of several hundreds of TC gamma shield blocks.
- there has been developed and tested a fundamentally new technology of manufacturing of TC gamma shield blocks by means of uranium alloy cast molding into a leakproof shell made of stainless steel with further argon-arc welding of elements into a single gamma shield block, which serves as a load-carrying TC block, which can react loads (patent №2089341). To prevent the interaction of stainless steel and melted uranium, a special coating has been developed, which protects the steel at melting temperature (~ 1400°C).
- there has been developed the technical project for TC-117, intended for transportation and storage of WWER-1000 SFA with 36 SFA volume capacity, and the design-technical substantiation of safety has been fulfilled in compliance with the requirements of Rules PBTRM-2002 and IAEA-96 (NS-R-1). Moreover, the safety of TC with WWER-1000 SFA has been studied computationally for beyond-design-basis accidents at power engineering stations, places of storage and on SNF recycling plants, as well as for acts of terrorism.

Along with works on TC-117 with gamma shield, made of metallic DU, RFNC-VNIIEF together with VNIIKhT and VNIINM and Oak Ridge National Laboratory (ORNL, USA) has conducted works within the frames of ISTC project on creation of a new slip-cast material, based on stainless or carbon steel and DU dioxide (slip-cast uranium cermet), which is supposed to be used for manufacturing of multi-purpose universal TCs for transportation, storage and disposal of power reactors' spent nuclear fuel.

Uranium cermet has a number of advantages if compared to other materials, currently used in protective containers for SNF, namely:

- due to greater density of DUO_2 (~ 30-50% greater than in steel and metallic concrete) uranium cermet has better gamma shield and due to high level of oxygen in DUO_2 (1,3r/cm^3) it will provide even a neutron shield. This will enable to increase the specific load of SNF in cermet containers in comparison with steel and metal-concrete containers;
- in contrast to metallic DU, cermet, made of stainless or carbon steel and DUO_2 is more tolerable to the effect of aggressive medias. This enables the use of cermet containers for long-term (in geological time scales) storage of SNF and its disposal in underground storage facilities.
- due to the content of DUO_2 , uranium cermet is an indispensable material for providing nuclear safety of underground storage facilities of SNF, as well as for slowing down of SNF degradation and reduction of radionuclides leakage from the storage facility;

Thus, according to the combination of its properties, uranium cermet is a perspective material from the point of view of its use in the design of protective containers for SNF and, moreover, the mass production of cermet containers may serve as economically sound mean of utilization (disposal) of DU excess and secondary stainless steel for the sake of ecology.

2. TC design description.

TC-117, developed in frames of technical project as a transport package, meets the requirements to B (U) type package, containing fissile material according to IAEA classification.

The package design guarantees meeting the safety requirements, regulated by normative documents for transport containers and SNF storage facilities.

TC-117 design includes a protective container and a basket for ordered distribution of SNF (figure 1, 2).

The protective container is a thick-walled, multilayered cylindrical casing closed by two covers. They are the internal cover for tight sealing, and the external cover for protection. The sealing cover of the protective container is made of steel 12X18H10T, it includes two gaskets for sealing. One of them is made of rubber of the type 51-11r-99op, the other is a spirally coiled gasket. The protective cover is made of steel 09G2S. It is lined by a sheet of steel 12X18H10T, it is also sealed by two gaskets, but they are made of rubber of the type 51-11r-99op.

The casing of the protective container has an internal load-bearing shell. Coaming and bottom are welded to it. The coaming is made of steel 12X18H10T, and the bottom is made of steel 09G2S. It is lined by a sheet of steel 12X18H10T from within. The load-bearing shell of TC-117 is a set of rings made of uranium alloy BZ-2 and covered by stainless steel of the type 12X18H10T. Internal covering of a uranium ring has thickness of 40mm, and external covering of a uranium ring has thickness of 30mm. The rings made of alloy BZ-2 are welded among themselves by ring seams on material of the internal and external coverings of the rings.

The bottom and internal sealing cover play the role of the anti-radiation protection at end faces of the container.

Solid neutron protection made of siloxane rubber of the type KL-1505 is placed directly behind the external covering of the gamma-protection. From the outside, the side neutron protection is covered with a thin-walled shell made of steel 12X18H10T. The solid neutron protection is also placed in the bottom part of the TC-117 casing and on the protective cover. From the outside, it is covered with a thin-walled sheet of steel 12X18H10T. Removal of residual heat release of SNF is performed by vertically arranged thermal bridges made of steel 09G2S located through the neutron protection and ribbing of the external surface of the casing of the protective container made of steel 12X18H10T, which serves simultaneously for side amortization.

The role of axial and angular amortization is played by ribs having various rigidities, and the supporting ring connecting them. They are welded to the bottom and the protective cover of the container. The ribs and ring are made of steel 12X18H10T.

The original design of a basket is used for the ordered location of SFA of WWER-1000 in the internal cavity of TC-117. The basket is a set from 36 hexahedral aluminum pipes (alloy AMG-6), which are connected among themselves by welding (fig.2).

The basket design provides nuclear safety in normal conditions of operation and in abnormal environments, the allowable level of the maximal temperatures on shells of fuel rods due to good transfer of heat from assemblies to the casing of the container, fixing of the basket in the container, possibility of its placement in the container and motion of it outside the container by the device to a standard capture of the reloading machine.

Weight and overall characteristics of TC-117 provide realization of the required operations with the container and the basket in corresponding premises of nuclear power station, in containers storage facility and in SNF stationary storage facility, as well as transportation of TC-117 in horizontal position by truck-railways of general use in 02-BM container cars. Moreover, TC-117 design guarantees the possibility of transportation by means of water transport and tolerates transportation by special motor transport.

TC-117 includes original shock absorption system, which provides a high level of mechanical loads reduction during accidents and unregulated effects on TC. The shock absorption system reduces the loads, which realize in the container when TC-117 with WWER-1000 36 SFA is dropped down on a rigid surface from 9 meters height. This system excludes fissile elements destruction and fuel pouring out. Based on modern safety requirements during SNF handling, the joint (fixed) with the container shock absorption system is more preferable if compared to removable absorbers, which are installed only during transportation, as it makes possible to increase the safety level during TC with SNF handling at power stations and in storage facilities in case of design and beyond-design-basis accidents, including acts of terrorism. Furthermore, TC-117 with joint shock absorption system allows meeting the old 02-BM standard, according to which the existing fleet of cars-containers was manufactures. Also, this system is in compliance with Russian requirements to rail transportation and the requirements of all European and Asian countries, from where Russia will bring SNF by railroads.

Thus, the suggested original design of the container, the basket and engineering and design solutions made it possible to create a dual-purpose TC, aimed at transportation and dry storage of SNF of WWER reactor with advanced safety level, maximum volume capacity and relatively low price.

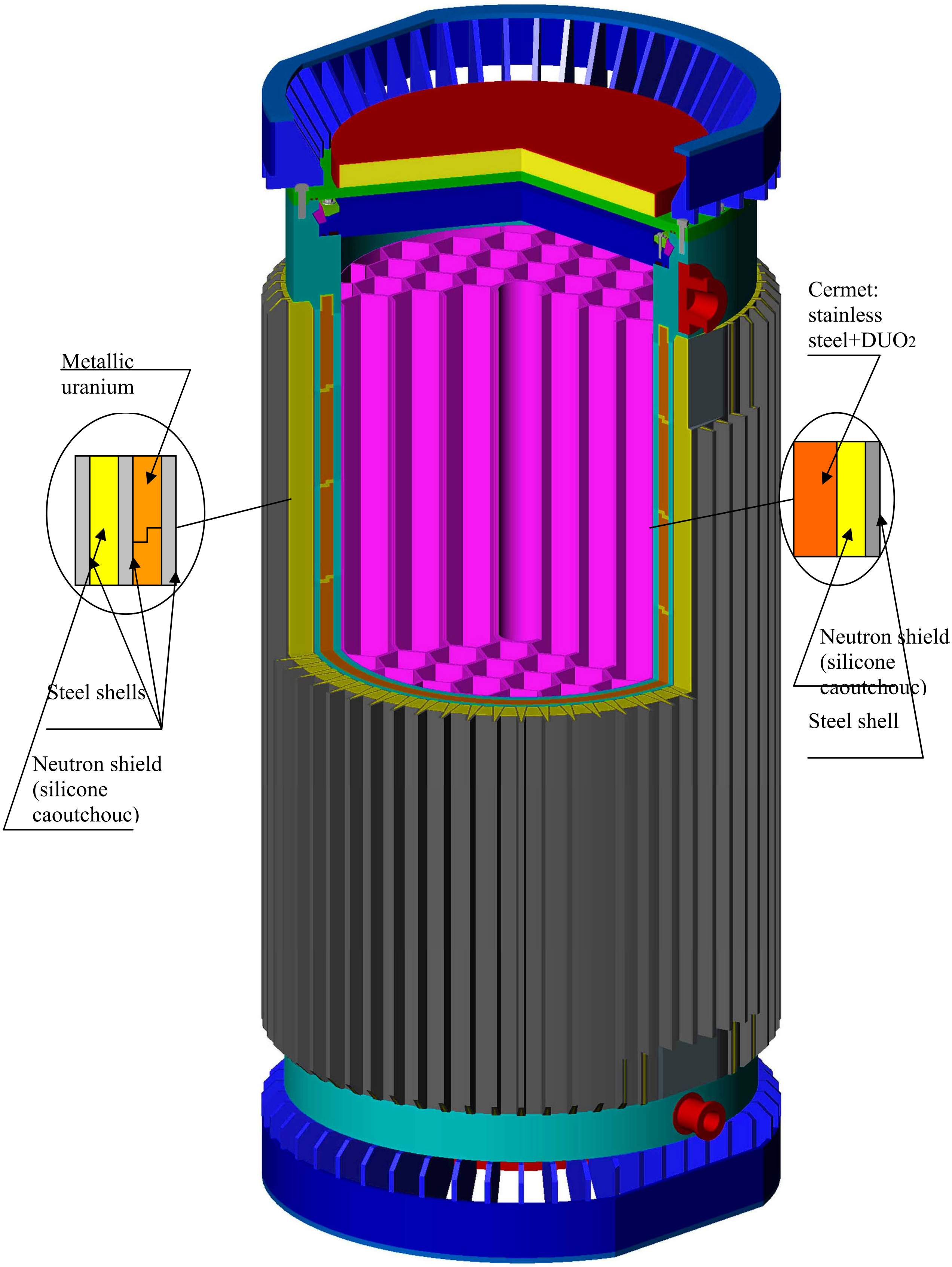

Fig. 1. Lay-out diagram of TC-117 protective container.

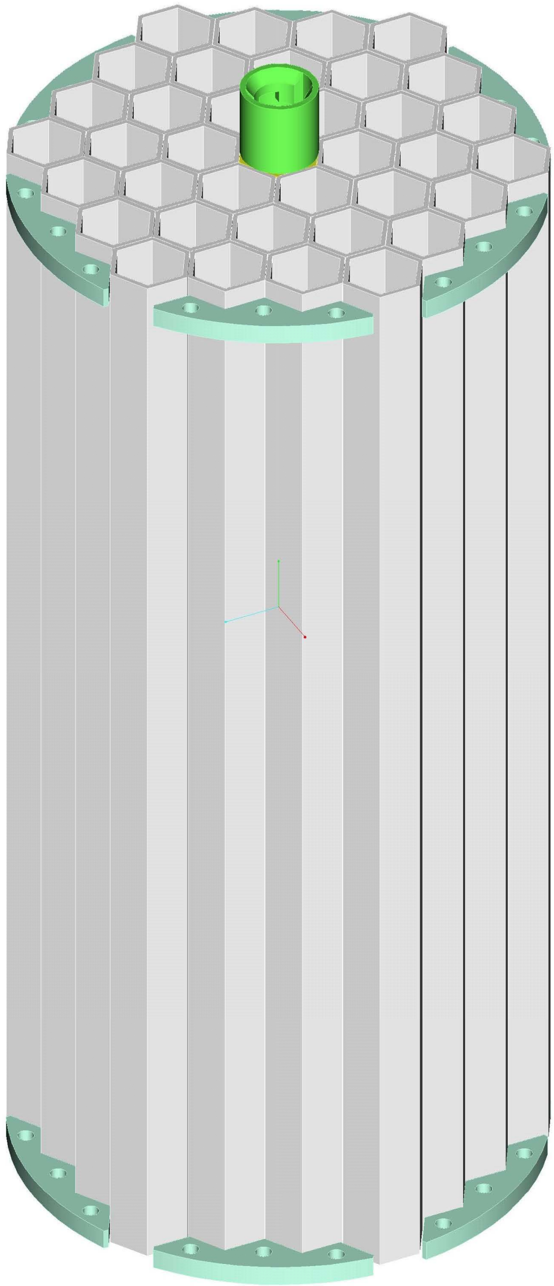

Fig. 2. Lay-out of the basket for ordered arrangement of WWER-1000 SFA in inner cavity of TC-117

3. TC-117 main specifications.

- mass of empty TC is 102500 kg;
- mass of TC, loaded with WWER-1000 SNF is 144500 kg;
- height of TC (overall dimension) is 6000 mm;
- outside diameter of the container is 2700 mm.

30 SFA of WWER-1000 with not less than 3 years of exposure in the reservoir or 36 SFA of WWER-1000 with not less than 5 years of exposure in the reservoir and burnup of 50 GW(d)/ton can be located in TC-117 for transportation and storage. Moreover, TC-117 provides safe transportation of 12 SFA with 1 year of exposure in the reservoir and 18 SNF of WWER-1000 from mixed uranium-plutonium fuel (MOX fuel) with exposure in the reservoir not less than 3 years.

On the base of TC-117, which is supported by a great number of engineering and design, research, theoretical and calculation data, RFNC-VNIIEF together with VNIINM have developed the concept of dual-purpose universal TC, which is characterized by maximum degree of universality and practically completely meets all technical requirements.

Double-purpose universal TC includes:

- unified (joint) protective container with fuel volume capacity up to 14 tons. It is based on the design of the container, developed in frames of TC-117 technical project and has been optimized subject to the load of SFA of RBMK-1000, RWR and BWR reactors;
- several modifications of the baskets for provision of ordered loading of all types of SFA (WWER-1000, RBMK-1000, PWR, BWR) stipulated by technical requirements.

Thus, double-purpose universal TC will consist of:

- TC-1 for storage and transportation of SFA of WWER-1000 (both uranium and MOX fuel);
- TC-2 for storage and transportation of SFA of WWER-1000;
- TC-3 and TC-4 for storage and transportation of SFA of PWR and BWR.

Due to small need in new generation of TC for WWER-440 SFA as well as subject to considerably lower height of SFA of WWER-440 in comparison with other types of SNF, two variants can be realized within the frames of the conception:

- use of this universal TC with a basket for SFA of WWER-440 (TC-5), with maximum volume capacity equal to 92 SFA of WWER-440;
- development of container modification for SFA of WWER-440, which will differ from the universal TC just in height, while the used materials are absolutely the same, as well as all design and technological solutions.

Table 1. Comparative data of double-purpose universal TC with DU shield and its best foreign analogues.

Characteristics	TC, being developed	Analogue 1	Analogue 2
Title	Double-purpose universal TC for transportation and storage of SFA	Double-purpose container for transportation and storage of SFA	Double-purpose container for transportation and storage of SFA
Container brand mark	UTUK	NAC-STC	Castor V/21
Manufacturer (country)	Izhorskiye plants, ChMZ (Russia)	"NAC International", USA	GNB, Germany
Item price		Russian TC will be cost competitive than those in Germany and USA	
Height, mm	6000	4900	4886
Outside diameter (overall dimension), mm	2700 (2750)	2515	2400
Gamma radiation protection	Stainless steel, metallic DU/ slip-cast uranium cermet	Stainless steel, lead	Cast iron with spheroidal graphite
Neutron shield	Siloxane rubber	Resin	Rods made of polyethylene
Mass of the container with SNF, t	144,5	116	106
Volume of container loading (items, SNF)	36 SFA of WWER-1000 or 92 SFA of WWER-440 (14t U)	26 PWR or 57 BWR (10 t U)	21 PWR (8,4 t U)
Specific cost of TC for 1 t of U	57 thousand dollars (USA)	81 thousand dollars (USA)	59 thousand dollars (USA)
Requirements to SNF preliminary burnup, GW(d)/ton	50	<50	<50
Requirements to thermal load, KW	50,0	22,1	20,0

4. Safety computational substantiation.

Safety computational substantiation of double-purpose universal TC has been carried out in the following directions:

a) substantiation of radiation protection;
b) substantiation of nuclear safety;
c) substantiation of thermal regimes;
d) substantiation of strength and tightness of container design;
e) substantiation of container resistance to the effects of beyond-design-basis accident, including acts of terrorism.

a). <u>Radiation and nuclear safety.</u>

The calculations proved that the requirements to radiation and nuclear safety are being executed both under normal service conditions and in all emergency situations.

b). <u>Thermal regimes.</u>

Substantiation of thermal regimes was executed for the following cases:

b.1. Determination of TC thermal state under the influence of internal heat source;

b.2. Determination of TC thermal state in case of fire with T=800^{0}C, t=30 min, as well as with T=800^{0}C, t=60 min and further cooling at T=38^{0}C (~24 hours), taking into account the internal heat source;

b.3. Determination of TC thermal state under conditions of total failure of heat sink from the external surface of the container (~24 hours), taking into account the stationary heat source;

b.4. Determination of TC thermal state under conditions of heat carrier loss from the container inner surface.

The calculations showed that the maximum temperature of fuel elements, neutron shield and inner seals does not exceed the accepted value.

c). <u>Strength substantiation.</u>

Strength substantiation of TC has been executed for the following cases:

- effect of internal pressure in container cavity;
- quick lifting of TC by means of hooks;
- quick lowering of TC onto canting journals;
- TC strength during transportation by means of railway transport;
- TC drop from 0.3 m height onto a rigid surface;
- TC drop from 9 m height onto a rigid surface;
- TC drop from 1 m height onto a pin;
- TC sinking into water, 200 meters deep.

The results of calculations prove that the design of dual-purpose universal TC satisfies the requirements to strength and tightness during all types of external effects, considered above.

d). <u>Substantiation of container resistance to the effects of beyond-design-basis accident, including acts of terrorism.</u>

During computational estimations of container resistance to the effects of beyond-design-basis accidents, including acts of terrorism, the following events have been considered:

- fall of a slab having weight of 120 tons from height of 12 m against a vertically staying cask;
- drop of the airplane onto a vertically placed container with velocity V=100m/s and collision angle ~ 10^0;
- shooting of vertically placed container from sniper rifle by armor-piercing fire bullet B-32, (caliber 12,7 mm);
- shooting of container, loaded with TC from hand antitank grenade cup discharge by cumulative grenade, (caliber 90 mm);
- detonation by means of 50 kg of explosive, placed on the upper surface of vertically placed container;

The results of computations showed that:

- during the drop of 120 t plate onto the container casing, the lids and holdfasts deform elastically. Container keeps its strength and tightness;
- during collision of the airplane and container (velocity equal to 100 m/s) the container casing in the area of hit (coaming) deforms elasto-plastically. Out of the area of hit the casing deforms elastically. Lids and elements of their fastening preserve their strength. The cask does not lose its tightness;
- armor-piercing fire bullet B-32 (caliber 12,7 mm) does not punch TC, the cask remains tight;
- cumulative grenade having caliber of 90 mm punches a hole with diameter of about 15 mm in the cask casing. After punching through the casing, residual velocity of shaped jet is equal to 3.2 km/s that is about 15.8 % of the initial energy;
- at detonation of HE having weight of 50 kg, elements of the cask and its lid, elements of their fastening are deformed in elastic-plastic way. However, the load-bearing elements of the cask are not destroyed. The cask keeps its tightness, and there is no release of its radioactive content.

Conclusion

1. The considered within the frames of the suggested conception of double-purpose universal TC design with DU shield meets all the requirements, conformed to the containers, aimed at transportation and storage of SNF of power reactors both under normal service conditions and emergency states. Double-purpose universal TC possesses increased resistance to the effect of beyond-design-basis accidents and acts of terrorism. It can be used for transportation and storage of SNF of power reactors of Russian and international atomic power plants.
2. Works, directed towards the creation of dual-purpose universal TC with metallic DU or slip-cast uranium cermet gamma shield, which has maximum load in terms of SNF, provide the solution of the following tasks:

- TC quality improvement due to fuel volume capacity increase;
- creation of mini storage facility for SNF on the base of dual-purpose universal TC, which will correspond to all safety requirements during storage;
- increase of TC protection level during the effect of beyond-design-basis accidents and acts of terrorism;
- utilization of the accumulated wastes of DU in form of metal devices and isotope separation production wastes, which find no use and are stored, representing danger for the environment. During manufacturing of one container lot less than 50 tons of DU will be required.