Experience and Prospects of WWER-1000 Reactor Spent Fuel Transport

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ABSTRACT

The paper deals with the USSR experience in shipping the commercial WWER-1000 reactor spent fuel in TK-10 and TK-13 casks. The cask designs, their basic characteristics and the WWER-1000 spent fuel features are described. An example of calculational/experimental approach in the design of a basket (one of the most important components) for spent fuel assembly (SFA) accommodation in a cask is given. The main problems of future development works are presented in brief.

A concept of development of nuclear power industry with the closed fuel cycle is assumed in the Soviet Union, hence the spent nuclear fuel is to be transported from NPPs to reprocessing plants.

Construction of NPPs in the USSR for the nearest decades is based on the use of commercial pressure-water reactors of WWER-1000 type. The same reactor type is used and is planned to be used in the future in some CMEA-Countries, the spent fuel from which is to be transported into the USSR. So, the WWER-1000 spent fuel transportation is one of the main transport problems in the USSR nuclear power industry.

The WWER-1000 spent fuel is transported after 3-5 year cooling in at-reactor or in away-from-reactor storages. The spent fuel characteristics taken as the initial ones in shipping cask design are given in Table 1. The general view of a WWER-1000 spent fuel assembly is shown in Figure 1. Transportation is performed during the whole year through the regions with considerable variations of the environmental temperature. So, the casks are designed for the environmental temperature range of -50°C - +38°C.

Transportation is performed by special trains made-up of seven cask-cars, an escort car and buffer cars.

According to the safety conditions of operation of NPP with WWER-1000 reactors, spent fuel unloading from the at-reactor storage is possible only with the reactor shut-down. The reactor shut-down for fuel reloading is made in summer as a rule. On the other hand, from technical and economical viewpoints, regular shipping of spent fuel during the whole year is desirable. Therefore, as a commercial alternative for intermediate storage during a year before shipping, at NPPs with WWER-1000 reactors the accumulating stores are being built in the USSR, the fuel in which should be stored in the same casks in which the fuel is transported. Empty casks are delivered to NPP, unloaded from the cask-cars which are loaded then with the casks filled with fuel and prepared to dispatch beforehand.

To transport WWER-1000 spent fuel, the casks of two types were developed. These are:

- a pilot TK-10 cask of 3t capacity in fuel;
- a commercial TK-13 cask of ~6t capacity in fuel.

The pilot TK-10 cask is thick-walled (360mm) cylindrical vessel manufactured of steel shells and a bottom welded to each other. The material of the body is carbon steel. There is a steel jacket on the outer side of the cask body and at 120 mm distance off the bottom. On its cylindrical part between the jacket and the body there are T-shaped circular ribs acting as shock-absorbers. The space between the jacket and the body is filled with ethylene glycol solution of 65°C crystallization temperature, which functions as a neutron shielding.

The TK-10 cask coolant is water or air (nitrogen) at minor excess pressure resulted from FA heatup after the cask sealing.

SFAs are placed in a cask basket in which the tubes filled with boron carbide powder are used to provide nuclear safety. Each FA is surrounded by 18 tubes.

For the coolant temperature and pressure control, the appropriate gauges are placed in the cask, which may be connected to secondary instruments in the escort car or on the portable board.

According to the specified procedure, the acceptance tests of an available prototype of TK-10 cask loaded with SFAs were carried out. Heat conditions, neutron shielding efficiency and a sealing system of the cask were investigated during the tests. The test results allowed to confirm the possibility to increase twice the cask capacity with the same basic design approaches, and in this case to refuse from water use as a coolant.

The characteristics of the TK-10 cask and those of a new transport packaging, TYK-13, for WWER-1000 spent fuel shipping are given in Table 2.

The TYK-13 transport packaging comprises a protective TK-13 cask and a "37" - type basket of hexahedral boron pipes for FAs accommodation.

The inner cavity of the cask is filled with air or noble gas.

The TYK-13 design and its basic dimensions are given in Figure 2. The appearance of the TK-13 cask-car is shown in Figure 3.

The main components of the TK-13 cask are a body (1) and a lid (2).

The cask body is a cylindrical vessel made of a steel shell and a bottom welded to each other. The body material is corrosion-resistant steel, O8X18H10T, or low-carbon steel, 06H2M. When the low-carbon steel is used, the inner surface of the body is lined with corrosion-resistant steel, 08X18H10T.

On the outer side of the cask there is a neutron shielding enclosure (3). The space between the body and the neutron shielding enclosure is filled with ethylene glycol to provide neutron shielding. On its cylindrical part between the neutron shielding enclosure and the body there are T-shaped circular ribs (transverse frames) acting as shock-absorbers. The circular and radial shock-absorbing ribs are located also between the body bottom and the neutron shielding enclosure end face.

To provide free flow of ethylene glycol through the whole neutron shielding space, there are openings in the ribs. The neutron shielding enclosure has two holes: one in the lower part for filling in (draining) and the other in the upper part for checking ethylene glycol presence.

There are two valves in the cask to supply gas coolant into the inner cavity, to make leak-tests, to supply and to discharge the coolant when the cask is cooled. One valve (8) is mounted in the lower part of the cask body and the other one (9) is in the lid. In the transport position of the packaging the valves are plugged with additional sealing by lids.

The cask has two freight trunnions (10) to be gripped with a special traverse during reloading operations, two trunnions (11) to fix the cask to supports of a car and to manipulate the cask, two securing trunnions (12) to attach the cask during reloading operations at NPP.

A flange (13) is intended for mounting a lug used at horizontal lifting of the cask by a special traverse.

The lower part of the cask is provided with a support ring (18) with claws (19). The claws are used to place the cask into the universal seat in the pool at NPP.

On the inner surface of the cask body there are guide pins (22) to position and to fix a basket in the cask.

The lid is attached to the cask body with pins (15). Leak-tightness of a joint between the lid and the body is provided by two elastic gaskets (16) of thermal-stable and radiation-resistant rubber. On the outer surface of the lid there are shock-absorbing ribs and a mechanism (17) for remote removal of the lid. On the inner surface of the lid there are spring pressing mechanisms (21) to limit longitudinal displacement of SFAs in transporting.

The basket is welded steelwork consisting of a base (23) and a central pipe (24) with a mechanism to grip hexahedral pipes (25).

The hexahedral pipes for SFAs accommodation are manufactured of corrosion-resistant boron steel. The boron content is 1.5%. Width across flats is 257mm, pipe wall thickness is 6mm.

In a package with SFAs the fulfillment of requirements on limiting the temperature of fuel element claddings up to 350°C is provided under the following conditions:

- air temperature in transporting is from -50°C to 38°C;
- air temperature in a special NPP storage is not higher than 35°C. In the day time 45°C is allowed.

The TYK-13 design satisfies the existing in the USSR "Basic Safety and Physical Protection Rules for Nuclear Material Shipment" (BSPR-83), based on IAEA recommendations. Provision of BSPR-83 requirements is verified by thermal and strength, radiation and nuclear safety calculations as well as by model tests and full-scale tests at NPP.

Taking into account a special importance of strength for hexahedral boron steel basket in nuclear safety assurance, a conclusion was made about the necessity to confirm the strength of the basket pipes experimentally using calculational estimates of parameters of impact loading of a standard cask design and a model designed specially for the experiment. The model is a full-scale basket fragment consisting of two spacing grids and three hexahedral boron steel pipes. Inside the pipes the FA simulators (metal rod arrays), the total mass of which is equal to the mass of a FA of the same length, are placed. The basket fragment is placed inside a steel jacket simulating the cask body. On the ends, the model body is closed with lids. On the outer surface of the cask body simulator, the ribs for shock absorbing, in the case of the model drop on the rigid base, are welded. For the model, a distance between supports of hexahedral pipes is assumed 1490 mm. This corresponds to the distance for the standard basket design. The model mass is 4090 kg. A general view of the full-scale basket fragment is shown in Fig. 4.

In the experimental study the task was to reproduce the loads on pipes similar by magnitude and character to those arising in case of a cask drop on the rigid base from 9m height.

The analysis has shown that from the viewpoint of hexahedral pipe strength the horizontal position of the cask while dropping is the most unfavourable. The analysis of impact loads is performed with time intervals. For each time interval, the retarding force and the energy absorption in case of distortion of components were calculated.

The analysis was being performed till the moment when the total energy absorbed reached the dropping energy value. The analysis results for the basket hexahedral pipe performance are given in Table 3.

The analysis of calculational results has shown that with the model ribbing chosen and while dropping from 2-2.5 m height, overloads arise at which the stressed state of the basket pipe is close to that occurring when the cask drops from 9m height. For tests the height of 2,5 was assumed. This makes the estimate more conservative.

Tests were carried out in a special area with the use of a travelling crane of 10t capacity and with an electromagnetic grip.

The model was dropped on a metal plate of 44t mass as the rigid base.

In experiments to confirm the validity of the height chosen for the model dropping, the measurements of accelerations and stresses in the basket pipes were made. Acceleration transducers are placed on a hexahedral pipe in the middle and at the edge of the span as well as on the model body. "Brüel and Kjaer" piesoelectric transducers were used as the primary transducers. Recording was made on a mirror-galvanometer oscillograph continuously during the impact loading. Resistance strain gauges were placed to define longitudinal bending stresses in the middle and at the edge of the span. The measurement of stresses was made with TA-5 four-channel strain-measuring system designed for dynamic tests and with the use of a mirror-galvanometer oscillograph. In test data processing the maximum values for accelerations and stresses were obtained. The maximum overload coefficient was Kmax=140. The maximum stress value was σ max=140MPa. Comparison of experimental results with calculated data shows that for maximum acceleration values the discrepancy doesn't exceed 5% and for maximum stress values it doesn't exceed 14%.

The visual inspection of the model after the test and the analysis of absorbers distortion character have shown that the initial data assumed in the design analysis concerning the character of distortion of the cask components reflect the real picture of distortion.

After the model drop, the hexahedral pipes including the points of pipe supporting, the spacing grids and other bearing components of the basket were inspected.

No failure of the basket components which could lead to the integrity loss of protective boron pipes was found. The residual plastic distortion of the basket bearing components was not found either.

Thus, the strength of the basket for spent fuel assemblies under impact loading was experimentally confirmed. With the approach assumed for calculational and experimental investigation and with relatively small expenditures it was possible to substantiate the basket strength and to confirm safety provision in accident conditions with the cask drop onto a rigid base.

The first shipment of WWER-1000 spent fuel was made from the Unit-5 of Novo-Voronezh NPP in 1985 in TK-10 cask-cars. Since 1988 transportation is carried out in TK-13 cask-cars.

By February 1, 1989, 12 spent fuel trips were made including:

from Novo-Voronezh NPP - 7 trips (TK-10)
from South-Ukrainian NPP - 3 trips (2-TK-10, 1-TK-13)
from Kalinin NPP - 2 trips (1-TK-10, 1-TK-13)

Control of the coolant parameters (pressure, temperature) inside the TK-10 casks is made according to readings of the instruments placed in the escort car or with the help of a portable instrument located directly in the cask-car.

As the values of the coolant parameters are sufficiently below the permissible ones and are in agreement with the calculated data, the decision was made tc cancel the above control and to eliminate the penetrations for instruments in the cask.

Besides, during transportation of spent nuclear fuel assemblies, heat conditions in freight compartments of TK-10 cask-cars and the environmental temperature were controlled from the escort car and directly in situ (in freight compartments of cask cars). During transportation the radiation control was done inside and outside the cask-cars, and fastening of shipping casks was checked up.

The operation experience with TK-10 cask-cars has shown that the ambient temperature inside the TK-10 freight compartments, in summer period with pivoted ventilation windows opened and in winter period with electric heaters operated, doesn't exceed the specified values (from +2°C up to 50°C). There were no criticisms relating to the fastening system of TK-10, TK-13 shipping casks. The radiation situation was within the norms.

Currently in the USSR the works are in progress on the improvement of the design of a packaging for WWER-1000 spent fuel shipping. This concerns the development of a new design of the basket for spent fuel assemblies in which the neutron absorbers are planned not to be used. The works on the use of the solid neutron shielding are under way. For this, the most promising and developed from the viewpoint of heat parameters, radiation stability and shielding efficiency are seemed to be the materials on silicon-organics base. At the same time it should be noted that there is no single opinion concerning the need of the solid neutron shielding use.

One of the most important matters in the development of new designs is investigation and choice of steel grades for the cask body, therefore the criteria for choice and control methods during manufacturing should be specified.

The analysis of WWER-1000 spent nuclear fuel shipping experience as well as the experience of shipping of spent fuel from reactors of other types in the USSR from home and foreign NPPs allow to plan the use of special trains for spent nuclear fuel shipping in future. For WWER-1000 spent fuel this is also justified by the technology assumed for reactor reloading and by the possibility to load the casks with spent fuel once a year during a very short time. At the same time it is obviously possible to reduce the number of accompanying personnel in such trips considering that control of the cask parameters in a trip is not needed.

For spent fuel shipping from some foreign NPPs with WWER-1000 reactors beside the railway, the truck and water types of transport will be required. Currently the scheme for fuel shipping from "Kozloduy" NPP (Bulgaria) is being developed. The estimates made have shown that safety in this case will not be worse than in the railway trips.

WWER-1000 FUEL ASSEMBLY (COMMERCIAL)

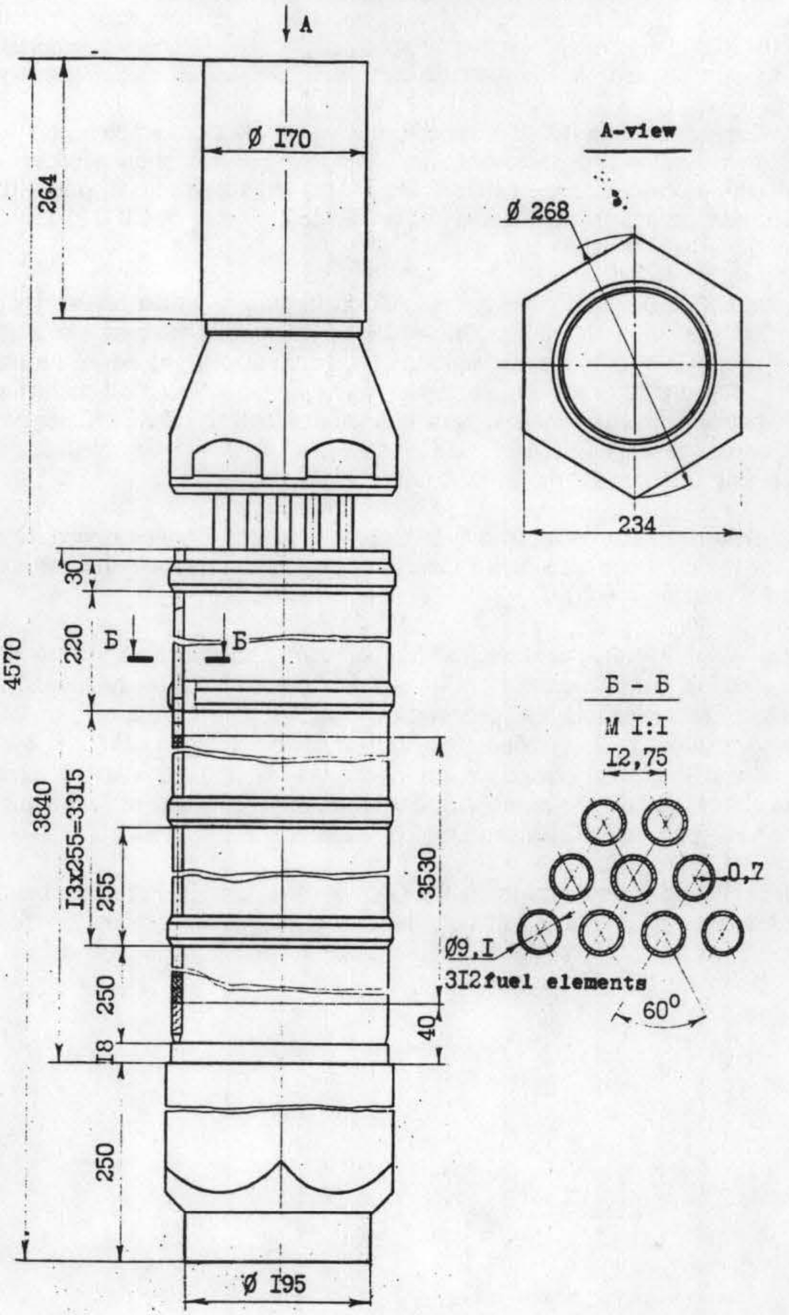
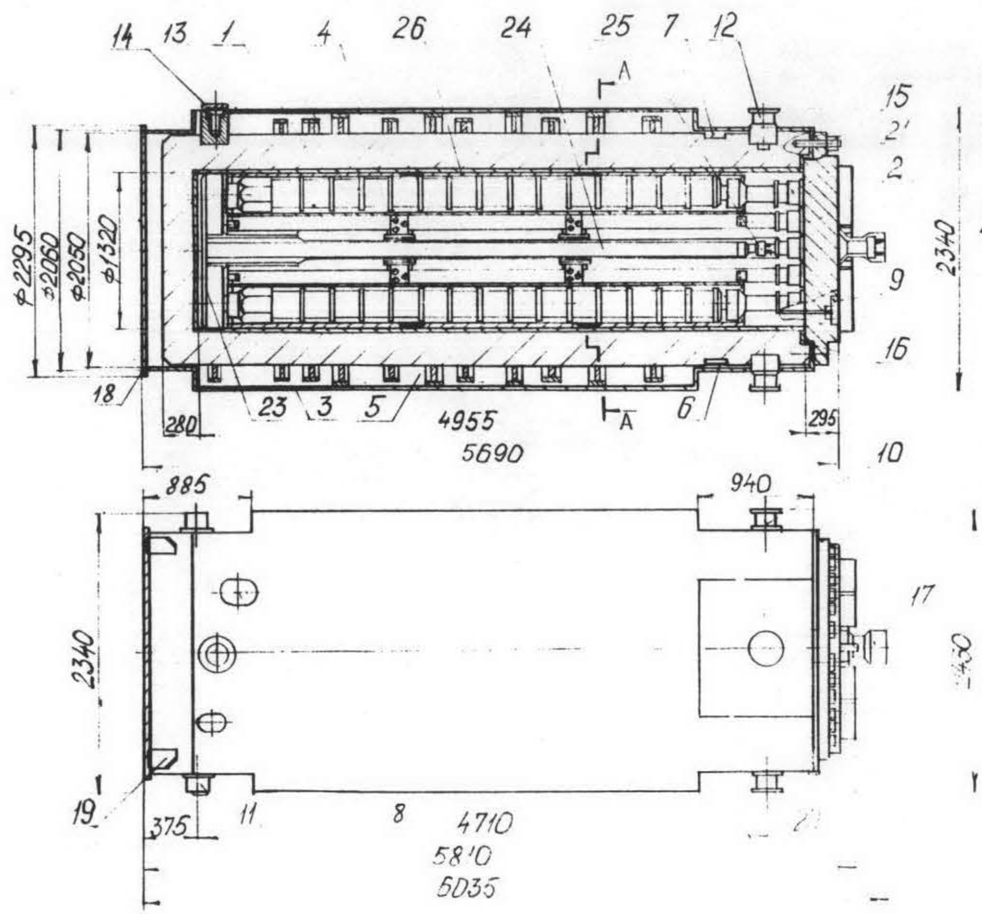
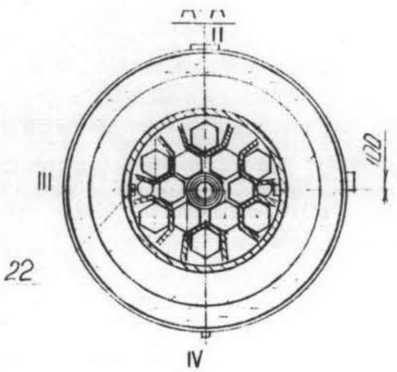


Figure 1.





1 - a body
2 - a lid
3 - a neutron shielding enclosure
4 - a fuel assembly (Without a basket)
5 - a neutron shielding
6 - a compensating tank
7 - a circular groove
8 - a discharging device valve
9 - a flowing device valve
10 - a freight trunnion
11 - a cask manipulating trunnion
12 - a securing trunnion
13 - a flange for a lug
14 - a plug
15 - a pin
16 - a gasket
17 - a mechanism to remove a lid
18 - a support ring
19 - a fixing claw
20 - a wedge-shaped stop
21 - a pressing mechanism
22 - a guide key
23 - a basket base
24 - a central pipe
25 - a mechanism to grip a basket
26 - a hexahedral boron steel pipe

Figure 2.

A TK-13 CASK - CAR

DESIGNED FOR TK-13 CASK TRANSPORT

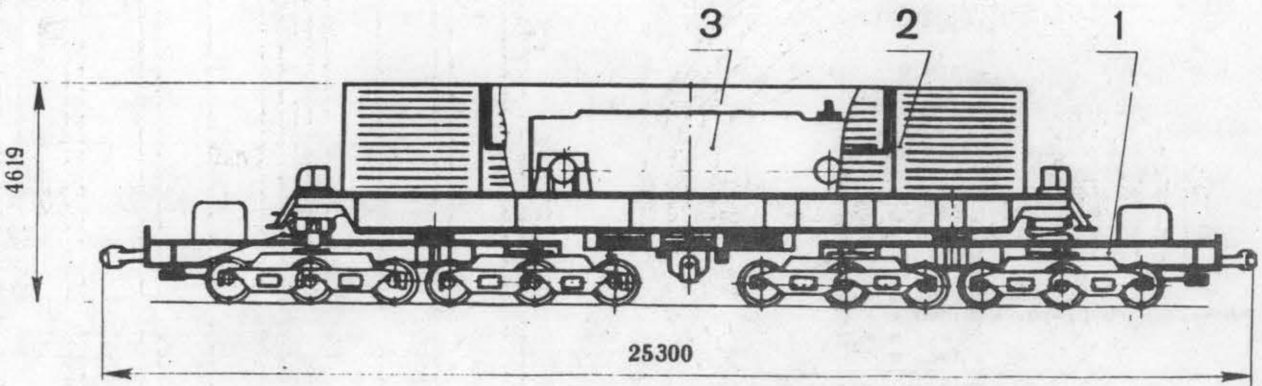


Figure 3.

1 - a conveyer

2 -- a car

3 - a TK-13 cask

Overall dimensions of a car - 02 - BM (international)

A number of axes - 12 pcs.

A mass of the car with a cask is 188t

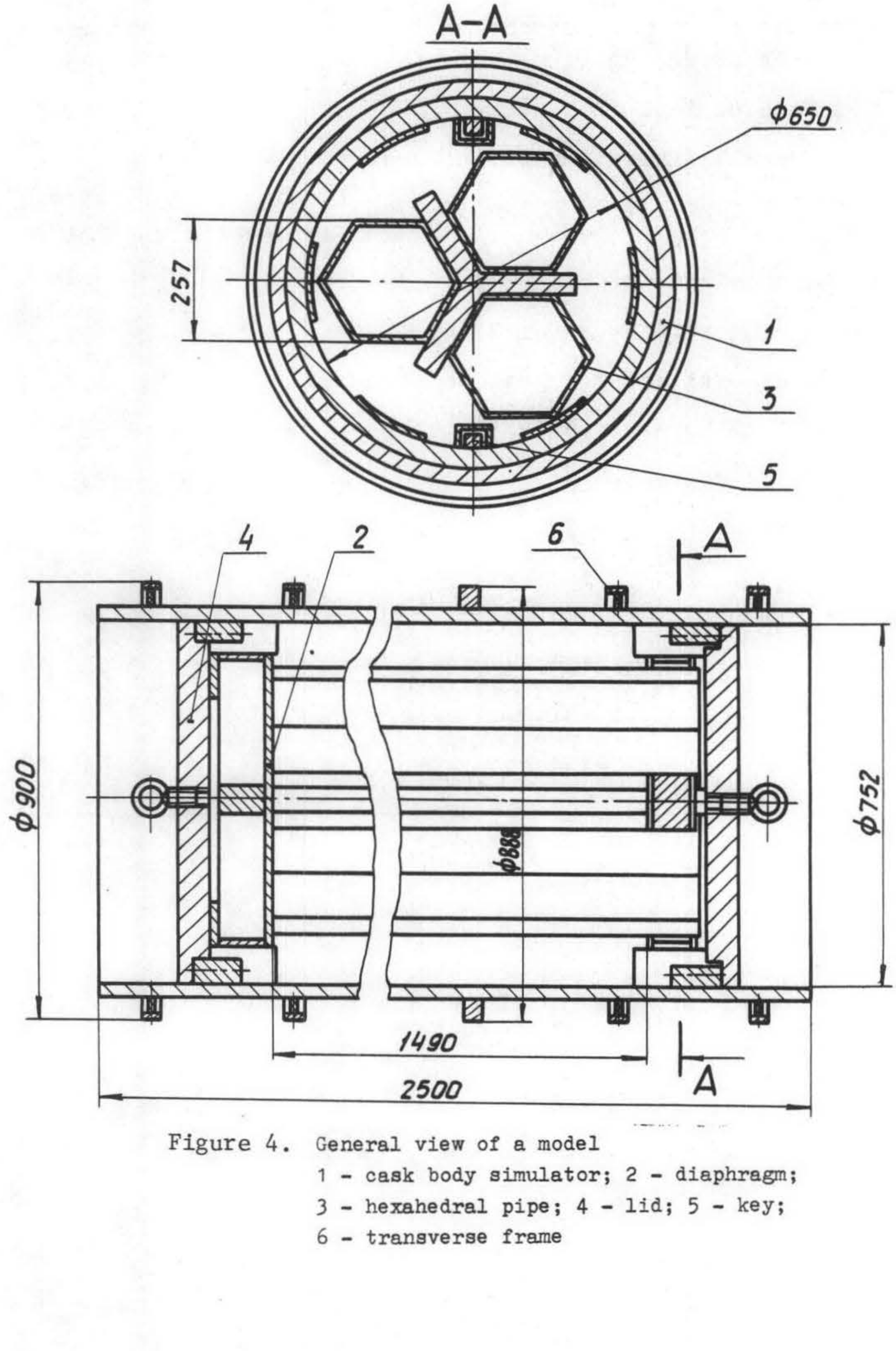


Figure 4. General view of a model
1 - cask body simulator; 2 - diaphragm;
3 - hexahedral pipe; 4 - lid; 5 - key;
6 - transverse frame

Table 1. WWER-1000 spent fuel characteristics

Item		Value
1. Mass of FA, kg		735
2. Mass of fuel in UO_2, kg		490±5
3. Overall dimensions of FA, mm:		
	lenght	4570
	width across flats	234
4. Core height, mm		3530
5. Initial enrichment in 235U, %		4,4
6. Decay heat after 3 year cooling, kW		1,7
7. Maximum burn-up, 6 Wd/t		50
8. 244 Cm content, g/t		94
9. Content of the main gamma-radiators, Bq/t:		
	144 Pr	$4 \cdot 10^{15}$
	106 Rn	$3.72 \cdot 10^{15}$
	134 Cs	$3.86 \cdot 10^{15}$
	137 Ba	$5.38 \cdot 10^{15}$
	154 Eu	$3.54 \cdot 10^{14}$

Table 2. Characteristics of TK-10 and TK-13 casks

	Item		TK-10	TK-13
1.	Cask mass, kg		80750	95000
2.	Mass in loaded state, kg		94400	120000
3.	Overall dimensions, mm			
		height	6130	6035
		outer diameter	2000	2295
		diameter of inner cavity	1000	1320
		height of inner cavity	5040	4955
4.	Number of FAs		6	12
5.	Coolant		water, gas	gas
6.	Type of a package		B(M)	B(U)

Table 3. Maximum displacements and stresses in a hexahedral pipe of the "37" basket

	Loading parameters	Cask drop H=9m	Model drop H=2m	Model drop H=2.5m
1.	Maximum displacement, mm	0,37	0.44	0.46
2.	Maximum stress, MPa	130	150	160
3.	Maximum overloading coefficient	119	123	133

Poster Session VIII

Package Design and Risk Assessment