DESIGN AND INSTALLATION OF A HOT WATER LAYER SYSTEM AT THE TEHRAN RESEARCH REACTOR

by

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A hot water layer system (HWLS) is a novel system for reducing radioactivity under research reactor containment. This system is particularly useful in pool-type research reactors or other light water reactors with an open pool surface. The main purpose of a HWLS is to provide more protection for operators and reactor personnel against undesired doses due to the radioactivity of the primary loop. This radioactivity originates mainly from the induced radioactivity contained within the cooling water or probable minute leaks of fuel elements. More importantly, the bothersome radioactivity is progressively proportional to reactor power and, thus, the HWLS is a partial solution for mitigating such problems when power upgrading is planned. Following a series of tests and checks for different parameters, a HWLS has been built and put into operation at the Tehran research reactor in 2009. It underwent a series of comprehensive tests for a period of 6 months. Within this time-frame, it was realized that the HWLS could provide a better protection for reactor personnel against prevailing radiation under containment. The system is especially suitable in cases of abnormality, *e.g.* the spread of fission products due to fuel failure, because it prevents the mixing of pollutants developed deep in the pool with the upper layer and thus mitigates widespread leakage of radioactivity.

Key words: hot water layer system, Tehran Research Reactor, pool-type reactor, radiation level, containment

INTRODUCTION

In many research reactors, a hot water layer system (HWLS) is used to minimize the pool-top radiation level. The pool is divided into a hot water layer at the upper part of the reactor pool and a cold part below it, with a lower temperature during normal operation. The mixing of water between these two layers is minimized because the hot water layer is formed above the cold water, suppressing the floatation of cold water, thus reducing the pool-top radiation level [1, 2].

The Tehran Research Reactor (TRR) is a 5 MW pool-type research reactor in which, similarly to most research reactors, water acts as radiation shielding, as well as a moderator and a coolant. Historically, the first HWLS was put into operation in the HANARO reactor [3-7]. It all began when it was decided to upgrade the reactor from 20 MW to 30 MW. It turned out that the background radiation under HANARO containment surged beyond safety limits. It is believed that the fission products leaking into the pool water were the main contributors [8]. As a remedy, so as to reduce the level of radioactivity under containment, a HWLS was devised and established for the first time. A hot water pool layer with a depth of two meters and a temperature difference of about 5 °C in relation to the rest of the pool water kept the bulk of the water confined underneath it. After the introduction of the HWLS, the radiation level under HANARO containment decreased as much as 90% in comparison to its previous status [3] and [9]. Evidently, this simple system works by preventing aerosol propagation out of the pool surface water. Upon its first successful application at the HANARO reactor, the IAEA proposed the installation of the same system to other research reactors in order to further enhance the health and safety level in open-pool reactors. Following this recommendation, countries such as Australia, Egypt, and Argentina have devised and commissioned similar concepts [1, 10-12]. As a result of discussions with the IAEA and follow-up consultations, it was decided to design and commission a similar HWLS at the TRR. Some useful data pertaining to the TRR are summarized in tab. 1. At present, the maximum power level of the TRR is 5 MW. In case of any further power up-

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Table 1. Summary of some useful data pertaining to TRR

Power	5 MW	
Fuel composition	^{235}U-12.44%	
	^{238}U-49.78%	
	O-11.17%	
	Al-26.5%	
Pool	Area	57.24 m^2
	Depth of water over core	7.4 m
	Volume	477.8 m^3
Moderator	Light water (H_2O)	
Control element	5, Fork type	
Shield	H_2O, Pb, concrete	
Number of fuel elements	22	
Coolant	Light water (H_2O)	
Coolant mass flow	500 m^3/h	
Purification system	Ion exchange	
Inlet mass flow to demineralizer system	76 L/min	
Reactor containment	Inner diameter	30 m
	Height	13.7 m

grading, a HWLS would be very useful in maintaining the radiation level below the safety limit. Nevertheless, HWLS shows its true merit in cases of accidents followed by the release of radioactivity. It is quite important to note that the shear existence of the HWLS in the TRR reactor at its present status, even without upgrading, helps to reduce radiation background and thus improves the safety level and protection of the personnel.

BASIC THEORY OF HWLS

The hot water layer system is based on the fundamental relation between mass (M) and volume (V); *i. e.* $\rho = M/V$. Basically, particle kinetic energy increases as the temperature is increased. As a result, thermal agitation makes particles more energetic, causing volume expansion and, consequently, density (ρ) reduction. Dimensional increase depends on the state of the matter, so that gases experience more expansion than liquids and liquids more expansion than solids. The reactor pool water is no exception to this rule, so that as the pool upper layer gets hotter, it expands more. An increasing volume means lower density and this, in turn, leads to a reduction in weight. On this basis, the hot water gets lighter in weight and has a tendency to move upwards and stay on the top surface, while the cooler and denser water remains deep down. This means that if we constitute two separate layers of water with two different temperatures, with the upper one kept at a higher temperature, the two layers should show a tendency not to mix. This allows keeping all pollutants present in the deep water confined underneath the warmer layer. In this manner, the hot water layer acts as a sort of a shield, confining the bulk of water underneath it carrying pollutants. Therefore, one can utilize the said property in a manner to have the top layer of the pool water kept at a slightly higher temperature, while the rest remains in the same status as it normally should. In case of an abnormality resulting in higher activity due to core malfunction, the hot upper layer prevents pollutants originating from the core to rise to the surface, thus repressing an increase in radiation.

DESIGN AND ESTABLISHING HWLS IN TRR

The TRR is a 5 MW pool-type research reactor commissioned in 1967. It is a multipurpose reactor for basic research in science and technology, and of lately, a wide range of other applications, especially in the production of radioisotopes for medical and industrial use. For pool-type reactors, easy access to the reactor core is the key factor for easing operation and experimentation. Thus, the openness of a pool is the prime advantage of pool-type reactors. At the same time, this may also be regarded as a disadvantage, as there is no physical barrier between the pool surface and the environment, preventing the radionuclides contained in the pool from leaving the water and thus contributing to the total dose under containment. This is of particular importance since the TTR plays a major role as a radiopharmaceutical provider in the country. As the demand for radiopharmaceuticals increases, the possibility of upgrading the power of the reactor beyond the present 5 MW level is under consideration. The problem of aerosol contamination is more salient at an elevated power. In any case, regardless of whether or not the power is upgraded, it is always prudent to approach the issue of reducing the level of air contamination during normal operation according to the ALARA criteria.

TRR heat removal system and its connection to HWLS

Similarly to most pool-type reactors, the TRR core is submerged at a depth of 8 meters in a pool of water10 meters deep. Water plays a threefold purpose: as a moderator, a coolant, and radiation shield. The pool is divided into two sections, numbered 1 and 2, with the core normally being situated in pool 1 (also known as the stall position). Figure1 shows the schematic diagram of the general layout of the cooling system. The HWLS is supposed to piggyback on the ex-

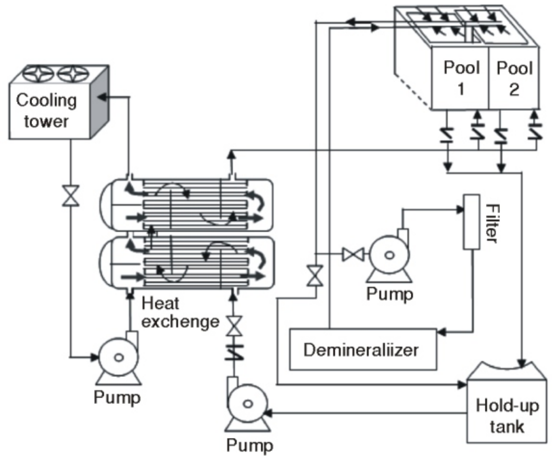

Figure 1. A simple schematic diagram of the TRR cooling system

isting cooling system and a lot of consideration was put into taking advantage of the majority of features of the existing facilities. It is obvious that the HWLS is to be installed on the primary circuit so as to help raise the temperature of the upper pool layer. Among the many alternatives initially considered to do the job, one was that of somehow using the option of pool overflow and making necessary modifications on the demineralizer circuit, fitting it to accept the HWLS module. The idea was soon discarded because of the complexity of its execution, as well as the distance of the pool to the pump room, *i. e.* access to the demineralizer circuit. At the end, it was decided to consider an independent system with a minimal piping length and minimal changes imposed on the existing system. Moreover, it was decided to make use of available facilities at the mezzanine floor where the heat and ventilation system already existed. Figure 2 shows a simple diagram of the HWLS system, as well as the existing system upon which the new system was installed. From a depth of approx. 70 cm in pool 1, the surface water is pumped into a small heat exchanger installed at the ventilation

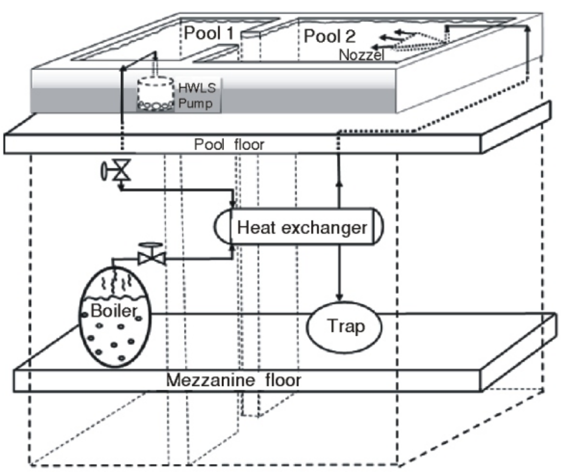

Figure 2. A schematic diagram of the HWLS and its connection to the pool and HVAC system in TRR; boiler and trap are parts of the existing system

room and, upon receiving heat, returned to the very top layer of pool 2. It is worth mentioning that the way hot water enters pool 2 is crucial, in the sense that if it flows in the usual manner, the intended hot layer will not form in a manner as stable as desired. Therefore, a stratified nozzle was designed to guide the discharge water into pool 2 at a grazing angle facilitating the formation of a stable hot layer on the very top. Here, the heat source is a 120 °C hot vapor diverted from the existing main line in the ventilation room. This, in fact, is the main reason why the ventilation room was chosen for the HWLS system. It is the best of all options because of an already existing heat source and, additionally, because of the minimal piping required to fulfill the task.

General HWLS specifications

The present system functions as follows. Water from pool 1 is pumped into the heat exchanger from a depth of 70 cm and, upon receiving heat, redirected to pool 2 by a laminar flow, as mentioned. The high pressure, 120 °C vapor from the existing heat, ventilation and air conditioning (HVAC), provides the heat source. After a while, a hot water layer gradually develops over the entire top surface of the pool, up to a meter thick. Taking into account all other options, the current arrangement is the most feasible and most simple solution for achieving the set goal. Let us take T_1 and T_2 as the inlet and outlet temperatures of the HWLS's heat exchanger at the pool side. T_1 is designated as the temperature of the water at a depth of approximately 70 cm below the pool surface, T_2 as the temperature of the top surface warm water entering pool 2. The aim is to keep the HWLS working as long as needed in order to bring the average temperature of the hot layer to a preset level, let us designate it as T . Therefore, of the several constraints on the HWLS, the first is to monitor $T'' – T_1$ while keeping the hot layer system working as long as needed to maintain this difference within the designated narrow range. The second concerns the constraint imposed on T and T so that they do not exceed 70 °C as, otherwise, the pool surface evaporation is likely to exceed the desired level. Experiments have also shown that excessive humidity on the part of T' can damage the containment outlet air filter requiring its frequent replacement. It has also been established that there is no need to maintain the temperature difference between T' and the bulk of the pool water above 10 °C. Figure 3 shows a typical status of all cited temperatures of the HWLS monitoring system during workdays. As a typical number, it is shown as T_1 = 38.5 °C, the upper layer pool temperature almost equaling the bulk pool temperature prior to the application of the HWLS. T_2 = 57.2 °C is the hot water temperature leaving the heat exchanger and entering the pool surface. T' = 49.0 °C is the set point for the hot layer average temperature to be main-

Figure 3. A typical temperature over a working session of the TRR, showing real values and set points

Figure 4. HWLS, as installed in the HVAC room and connecting pipes

tained over the course of reactor operation. T = 50.0 °C is another set point temperature imposed by the operator at which the hot vapor valve shuts itself off automatically. This means that as soon as T_1 is greater than T, the heating process automatically shuts off under this constraint, thus preventing unnecessary heating beyond the optimal value and avoiding the loss of energy. Figure 4 shows HWLS as installed in the HVAC room, with its piping, vapor controller valve (at the top) and temperature sensors.

DISCUSSION

Our HWLS was subjected to continuous testing over a period of approximately 6 months upon the completion of the system and the beginning of its operation. During this stage, various depths and temperatures were examined in an attempt to find the combinations which would yield the best possible results. Aside from many operational advantages, there is one other salient achievement of installing the HWLS – the remarkable activity reduction over the pool area. This has been verified through two parallel routes of which the first is the daily analysis of the pool water to reveal the radioactivity content of the primary loop. This is achieved by taking two 450 cm^3 standard samples, one from the surface and the other from the bulk of the water, up to a depth of 2 meters. The second route comprises readings of radiation monitors located in various areas of the TRR so as to reveal the radioactivity content under containment.

In what follows, these analyses are investigated in more detail.

Daily analysis of reactor pool water

During the 6-month test phase, a standard sample of pool water is taken for detecting various major radionuclides. In fact, this has been a routine method of checking for radionuclide content in the water even before the installation of the HWLS. With the new HWLS installed, one can be sure that there is a systematic reduction of all radioisotopes in the top layer and, therefore, a lower contribution to overall radioactivity in the controlled areas. As an example, a continuous run dating to October 2009 is presented here. At least two simultaneous samples were taken per day, one from the top layer, the other from a depth of 2 meters or more (as samples of the bulk of the pool water). Table 2 shows the radioactivity of some of the major radionuclides in all parts of the pool over the course of reactor operation. Depths of 2 meters or deeper are indications of pool water quality on the whole, while depth values for the top layer are indications of how effective the HWLS is. It has been shown that there is a reduction in radioactivity of almost an entire order of magnitude in most elements at the top level of the water. Table 3 summarizes the conclusion on an average basis.

Radiation monitoring while HWLS is in operation

Several radiation monitors have been placed at important locations of the TRR. Checking these monitors may reveal how effective the HWLS is when in operation. Three gamma detectors at the bridge, beam hole floor (BHF)-North and the stack are chosen, as well as several others, to show how the HWLS would affect radiation levels at the chosen points. All of the detectors record the exposure rate in terms of mR/h ($1R = 2.58 \cdot 10^{-4}$ C/kg). The most salient difference is observed by the bridge detector situated right above the pool. Normally, during continuous reactor operation, radiation received by this detector reaches its saturation level within 30 hours. At 5 MW power, the saturation exposure rate recorded by the bridge detector is around 10 mR per hour. Figure 5 shows the effectiveness of HWLS in reducing radiation at the pool surface. The first curve in this figure shows a generic trend regarding radiation over a typical 1-week operation. The second one shows the effect of switching on the HWLS. As a result, the radiation at pool level

Table 2. Analysis of pool water activity over a weeklong operation of the TRR of October 2009; notice the reduction in the level of activity at the top layer while the HWLS is ON; all activities are in Bq/L

Date	10/10/2009	11/10/2009		12/10/2009		13/10/2009		14/10/2009		15/10/2009	
HWLS status	OFF	ON		OFF		ON		ON		ON	
Radio isotope	Activity in top water layer	Activity in top water layer	Activity in pool water at 2 m depth	Activity in top water layer	Activity in pool water at 2 m depth	Activity in top water layer	Activity in pool water at 2 m depth	Activity in top water layer	Activity in pool water at 2 m depth	Activity in top water layer	Activity in pool water at 2 m depth
Na-24	9.01E+3	1.94E+4	2.98E+4	3.56E+4	3.74E+4	9.93E+3	5.12E+4	1.16E+4	5.99E+4	1.22E+4	5.80E+4
Mn-56		3.19E+2	6.90E+2	6.90E+2	6.99E+2		5.98E+2				
Tc-99m	1.15E+2	9.30E+1	1.19E+2	1.34E+2	1.62E+2	3.18E+2	1.38E+2			4.66E+3	1.39E+4
Xe-135	1.96E+1	8.19E+1	8.09E+1	9.58E+1	1.03E+2	8.58E+1	7.75E+1				
Y-91m		2.63E+2	3.63E+2	6.70E+2	4.47E+2	5.56E+1	5.66E+2				
Ar-41		5.18E+2	1.38E+3	4.95E+2	4.19E+2		3.94E+2				
I-133	9.51E+1	1.52E+2	2.20E+2	2.88E+2	2.54E+2	9.84E+1	2.72E+2	1.28E+2	4.63E+2	9.75E+1	3.75E+2
I-131	6.88E+1	5.79E+1		8.26E+1	6.53E+1			2.64E+1	8.19E+1	2.70E+1	7.77E+1
Sb-124	8.74E+1	7.00E+1		1.33E+2	1.03E+2	5.71E+1	1.04E+2	2.38E+1	9.98E+1	3.26E+1	8.49E+1
Sb-122	1.13E+2		1.53E+2	1.31E+2	1.78E+2	7.33E+1	1.90E+2	5.24E+1	1.86E+2	6.14E+2	2.15E+2
Pt-197m	6.28E+2		1.28E+3	1.36E+3			2.26E+3				
Sr-92			3.84E+2	3.58E+2	4.33E+2		5.87E+2				
Ce-141	3.98E+1							1.07E+1	1.63E+1	1.18E+1	
Ba-139			2.79E+2		6.90E+2						
La-140	7.94E+1							1.16E+2	3.41E+2	9.19E+1	2.09E+2
Te-132	5.02E+1		5.96E+1					2.14E+1	7.58E+1	2.74E+1	7.68E+1
Cr-51	3.08E+2								1.96E+2	8.39E+1	1.35E+2
Ag-110m	2.79E+1			9.08E+1							

Table 3. Analysis of average pool water activity over a week-long operation on October 10, 2009; notice that there is a systematic reduction of all radionuclides in the top hot layer

Radioisotope	Average activity in top water layer [BqL^{-1}]	Average activity in pool water at 2-m depth and below [BqL^{-1}]	Percent of activity reduction due to HWLS present [%]
Na-24	1.64E+4	4.09E+4	59
Mn-56	5.04E+2	6.62E+2	24
Tc-99m	1.00E+3	2.86E+3	65
Xe-135	Very low activity		
Y-91m	3.29E+2	4.58E+2	28
Ar-41	5.06E+2	7.31E+2	30
I-133	1.43E+2	2.80E+2	49
I-131	5.25E+1	7.49E+1	30
Sb-124	6.37E+1	9.57E+1	33
Sb-122	8.61E+1	1.72E+2	49
Pt-197m	9.93E+2	2.08E+2	52
Sr-92	3.85E+2	4.68E+2	23
Ce-141	Very low activity		
Ba-139	Very low activity	1.61E+2	Almost 100
La-140	9.57E+1	2.75E+1	65
Te-132	3.3E+1	7.07E+1	53
Cr-51	1.95E+1	3.18E+2	38
Ag-110m	Very low activity		
W-187	Very low activity		

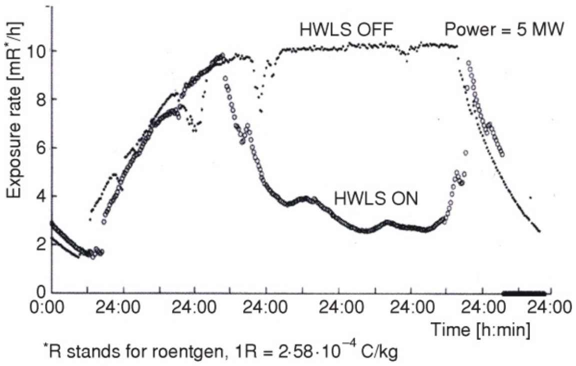

Figure 5. Radiation at the bridge detector for the two generic runs of the TRR over a week-long operation of the system; radiation decreases dramatically after the HWLS is switched ON

drops as much as fivefold. Radiation detectors at BHF-North and the stack are the ones showing certain differences when the HWLS is active. As is shown in figs. 6 and 7, if the values of all parameters are kept the same, there is a meaningful though not a prominent reduction when the HWLS is in function. The effect of the HWLS, however, may not be as dramatic on the part of the other two detectors. This may be due to the

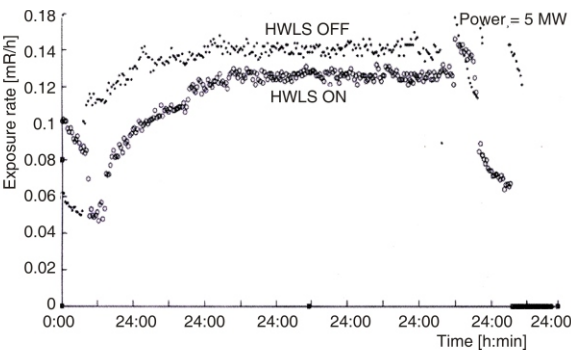

Figure 6. Radiation level at the BHF-North detector for two generic rund o the TRR over a week-long foperation; radiation decreases while the HWLS is ON, but not to an extent equaling the one at the bridge detector

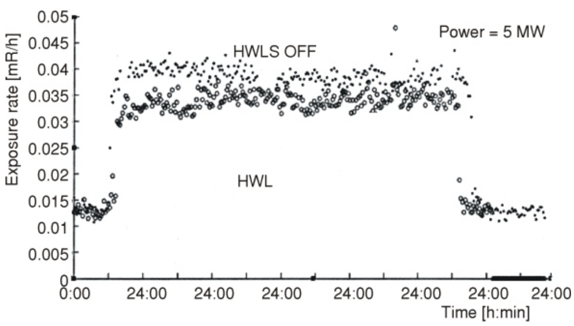

Figure 7. Radiation level at the stack detector for two generic runs of the TRR over a week-long operation. In one run, the HWLS is ON from start-up; it shows some reduction, but not to the extent registered by the bridge detector

fact that these detectors are not receiving a direct contribution from the pool surface radiation.

CONCLUSIONS

It has been shown that our HWLS could easily be annexed to a typical, already operational research reactor. In the case of the TRR, the best alternative was to make use of the available HVAC installation at the mezzanine floor, already under containment. The HWLS not only helps to reduce the radiation level, especially at pool level, but also plays a significant role in possible accidents. In emergency cases, when there is a fuel leakage or any sort of radioactivity contamination (*e. g*. radioactive sample rupture), the HWLS shows its true merit by helping to keep the contamination confined below the hot water layer at the pool surface.

AUTHOR CONTRIBUTION

The idea was set forward by M. Gharib, the installation carried out by the TRR staff of which S.Samanipoor and A.M.Turkzaban deserve special mention. Data taking was carried out by P.Ebrahimi, the analyses needed carried out by M. Gharib and S. L. Mirmohammadi, while the authorship of the manuscript belongs to S. L. Mirmohammadi and M. Gharib. The final version of the paper was reviewed by S. L. Mirmohammadi and R. Amrollahi.

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ПРОЈЕКТОВАЊЕ И ИНСТАЛАЦИЈА СИСТЕМА СА ВРЕЛИМ ВОДЕНИМ СЛОЈЕМ НА ТЕХЕРАНСКОМ ИСТРАЖИВАЧКОМ РЕАКТОРУ

Систем са врелим воденим слојем (HWLS) представља нови систем за смањење радиоактивности испод контејнмента истраживачког реактора. Систем је посебно користан у истраживачким реакторима базенског типа, или другим лаководним реакторима са отвореном површином базена. Основна намена овог система је да боље заштити операторе и реакторско особље од нежељених доза услед радиоактивности примарне петље. Ова радиоактивност потиче углавном од индуковане радиоактивности у воденом хладиоцу, или могућег малог цурења горивних елемената. Како нежељена радиоактивност расте пропорционално реакторској снази, то је HWLS делимично решење за ублажавање ових тешкоћа када се планира повећање снаге реактора. По извршеној серији тестова и провера различитих параметара, HWLS је био изграђен на Техеранском истраживачком реактору и стављен у рад 2009. године. Подвргнут је серији обимних тестова у периоду од шест месеци и установљено је да би HWLS могао да обезбеди бољу заштиту реакторског особља од преовлађујућег зрачења испод контејнмента. Систем је посебно погодан у случајевима абнормалних појава, на пример, ширење фисионих продуката услед отказа горива, јер спречава мешање загађивача који се развијају дубље у базену са горњим слојем, и тако ублажава распростирање цурења радиоактивности.

Кључне речи: систем са врелим воденим слојем, Техерански истраживачки реактор, реактор базенског типа, ниво зрачења, контејнмент