ASSESSMENT OF THE HIGH PERFORMANCE LIGHT WATER REACTOR CONCEPT

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Abstract

From 2006-2010, the High Performance Light Water Reactor (HPLWR) was investigated within a European Funded project called HPLWR Phase 2. Operated at 25MPa with a heat-up rate in the core from 280°C to 500°C, this reactor concept provides a technological challenge in the fields of design, neutronics, thermal-hydraulics and heat transfer, materials, and safety. The assessment of the concept with respect to the goals of the technology roadmap for Generation IV Nuclear Reactors of the Generation IV International Forum shows that the HPLWR has a potential to fulfil the goals of economics, safety and proliferation resistance and physical protection. In terms of sustainability, the HPLWR with a thermal neutron spectrum investigated within this project, does not differ from existing Light Water Reactors in terms of usage of fuel and waste production.

1. Introduction

The High Performance Light Water Reactor (HPLWR) is a Light Water Reactor operated at 25MPa with a heat up of the coolant inside the core from 280°C to 500°C. In Europe, the research of this innovative reactor concept was investigated in a project, called High Performance Light Water Reactor Phase 2, described by Starflinger et al. [1]. Ten partners from eight European countries and three Active supporters worked on critical technological and scientific issues to determine the future potential of this innovative concept for the electricity market. This project is part of the European contribution to the research on Supercritical Water-Cooled Reactors (SCWR) within the Generation IV International Forum (GIF). The GIF roadmap for SCWR [2] describes specific goals which all future nuclear reactor concepts shall fulfil:

> ***Sustainability–1*** *Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.*
>
> ***Sustainability–2*** *Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment*

Economics–1 *Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.*

Economics–2 *Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.*

Safety and Reliability–1 *Generation IV nuclear energy systems operations will excel in safety and reliability.*

Safety and Reliability–2 *Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.*

Safety and Reliability–3 *Generation IV nuclear energy systems will eliminate the need for offsite emergency response.*

Proliferation Resistance and Physical Protection–1 *Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.*

Those goals should be in mind right from the beginning of the preliminary design stage of Generation IV Nuclear energy systems. Since the HPLWR project has finished in February 2010, the results have been assessed regarding the above-mentioned goals.

2. Assessment of the HPLWR Concept

The documents covering several aspects of the assessment of the HPLWR are provided by working groups of the Generation IV International Forum. For this assessment in particular, the "Cost Estimating Guidelines for Generation IV Nuclear Energy Systems" [3], the IAEA Technical Report 392 "Design Measures to Facilitate Implementation of Safeguards at Future Nuclear Power Plants" [4] and own calculations have been applied. There are two other guidelines from GIF working groups available which are considered to be used in a later stage of the concept development when a more mature knowledge of the HPLWR will be available: "Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems" [5] and "Safety Approach for Design & Assessment of Generation IV Nuclear Systems" [6].

2.1 Sustainability

As described by Schulenberg et al.[7], the core of the HPLWR has been designed in Europe with a thermal neutron spectrum, whereas the fast neutron spectrum core was investigated by Japanese Scientists, see Ishiwatari et al. [8], using the synergies offered working within GIF. The HPLWR designed with a thermal core can use UO_2 fuel or MOX fuel with recycled Pu. In any case, however, it will fission more nuclear fuel than it is producing. Thus, the goal "Sustainability-1", expecting an efficient use of fuel, which fast breeders do much better, can hardly be met with a thermal core design.

However, there is a chance for designing a fast core for a Supercritical Water Cooled Reactor with a negative void coefficient, which is a key requirement for safe operation. According to Ishiwatari et al [8] it will not serve as a breeder of fissile material, but rather as a transmuter or burner of minor actinides. Reactor design, containment design and safety systems, as well as the balance of plant for such a fast reactor could be almost identical with the HPLWR designed with a thermal core.

In the following looking at goal “Sustainability-2”, referring to radioactive waste production, we will refer to a once through cycle only. Radioactive waste is characterized by means of several attributes, which are radiotoxicity, i.e. activity, deposited energy, and quality factor for different kinds of radiation (neutrons, gamma), solubility in water and volatility. Usually, different scenarios, like pollution of water reservoirs, drinking or drilling into the deep geological repository, are defined, which requires modelling of the final repository which is clearly beyond the scope of the HPLWR Phase 2 project.

Therefore, a simplified approach has been applied to assess the waste management taking only the radioactivity and the heat production of waste into account. These two data are system specific (fuel used, burn-up, equilibrium cycle length) and can serve later as input parameters for detailed studies. In order to get both qualitative and quantitative results of the expected nuclear waste in a once through fuel cycle, spent fuel from a VVER-440 has been selected as reference fuel to be stored in a underground geological disposal site. The simulation results are compared with those for spent fuel of the HPLWR. The amount of radioactive waste was estimated by means of simulations by Keresturi et al [9] using the KARATE code system. The codes MULTICELL and ORIGEN have been used for calculating the amount of radionuclides, their activity and their heat production inside of a deep geological repository. The following assumptions have been made:

- Equilibrium cycle, which contains assemblies with Gd integrated poison.
- 3 year irradiation inside the reactor core

Figure 1 shows the specific activity of spent HPLWR fuel (red) the comparison to spent VVER-440 fuel (green). Both curves practically show the same behaviour. The heat generation curves (Figure 2) also show a similar general trend, but the HPWLR fuel produces slightly less heat within the first 10000 years residence time in the final repository. The reason for this behaviour is the lower content of actinides in the fuel, which is caused by the low discharge burn-up of 32.8 MWd/kg HM of the equilibrium cycle [10].

As a conclusion, it can be stated that the specific activity of spent HPLWR fuel is comparable to VVER-440. The heat generation in the time period of a geological repository is slightly lower due to the lower actinide content. It is important to mention that the spent HPLWR fuel still contains a high enrichment of U-235 and a low discharge burn-up, which provides valuable fissile material for reprocessing. Therefore, the HPLWR is rather suited for a closed fuel cycle. High enrichment and a low discharge burn-up, on the other hand, cause a cost penalty.

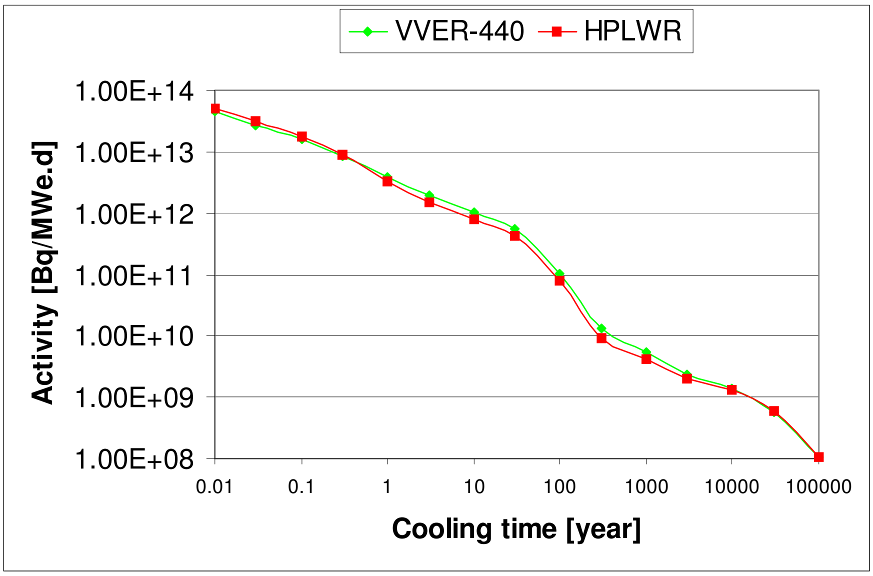

Figure 1 Specific activity of spent HPLWR fuel and spent VVER-440 fuel.

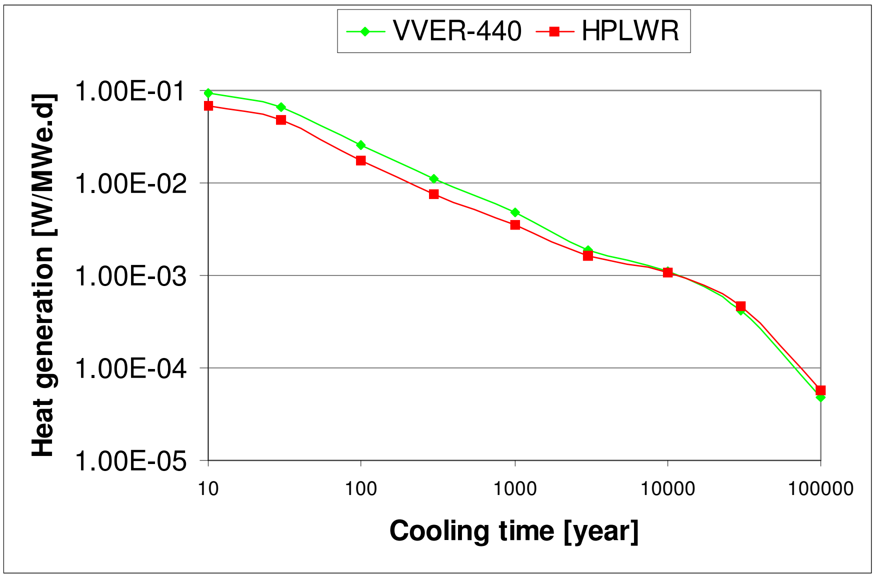

Figure 2 Heat generation of spent HPLWR fuel and spent VVER-440 fuel.

With respect to the Gen IV goals of sustainability, the HPLWR with a thermal neutron spectrum does not show any significant advantage compared to other Gen III systems of Light Water Reactors. Regarding waste production, the HPLWR is very similar to existing LWRs and shows slight advantages in terms of less heat generation. It should be noted that integrating the HPLWR into a fleet of LWRs would not create any new concern for waste management. Once the general waste issue of existing LWR waste will be solved this solution can be easily applied to the HPLWR.

2.2 Economics

On basis of the design work performed during the project period, cost estimation and an economic assessment were performed. In order to compare the HPLWR with existing LWRs, qualitative cost indicators have analyzed. Table 1 displays qualitative cost indicators like volumes of containments and mass of components in the primary system. Two modern nuclear power plants in Germany, the BWR Gundremmingen and the PWR in Neckarwestheim GKN2 [11, 12] are selected here for a coarse comparison with the HPLWR. The first indicator discussed here is the steel mass on the nuclear island. For the reference PWR, the main components, RPV and its closure head, the four steam generators and the four main circulation pumps have been selected. Summing up the weights, a specific indicator of 2.03 t steel/MWe can be obtained for these components. For the reference BWR, a value of 0.6 t steel/MWe has been calculated. Steam separators and dryers are included in the RPV value and the internal recirculation pumps are light weighted compared to the PWR. For the HPLWR, a value of 0.78 t steel/MWe has been computed. It has neither a steam generator, nor recirculation pumps, but the 25MPa pressure require a certain wall thickness resulting in a total mass of the RPV and closure head of 778t. In this comparison, the BWR has some advantages compared to the HPLWR.

		PWR	BWR	HPLWR
Net electric power	MWe	1400	1344	1000
Steel masses				
- RPV	t	370	785	656
- Closure head	t	116	incl.	122
- Steam generator (SG)	t	490	0	0
- No of SG		4	0	0
- Recirculation Pumps (RP)	t	100	3	0
- No of RP		4	8	0
Total steel mass	t	2846	809	778
	t/MWe	**2.03**	**0.60**	**0.78**
Total volume of the containment	m^3	65450	22931	9051
	m^3/MWe	**46.75**	**17.06**	**9.05**
Mass of turbine train	t	2860	2860	1430
	t/MWe	**2.04**	**2.13**	**1.43**

Table 1 Qualitative cost indicators comparing the HPLWR and existing Gen II plants.

The second cost indicator is the volume of the containment. The volumes are taken from drawings and provide a maximum value of the total inner volume. The reference PWR has a ratio of 46.75 m^3/MWe, whereas the reference BWR with 17.06 m^3/MWe and the HPLWR with 9.05 m^3/MWe provide smaller values. It must be mentioned here that the comparison of a pressure suppression containment (BWR) with a containment which can be pressurized (PWR) is not really fair, but is shows that a cost reduction already took place regarding containments (less concrete) with the development of BWR containments. The HPLWR specific containment volume is even smaller than the BWR one which shows one great advantage of this concept. Smaller containment requires less concrete and steel, which has a positive effect on cost savings. The third indicator is the ratio of the turbine mass and the electric power. According to Herbell et al. [13], the mass of the HPLWR turbine is about half of the mass of existing referents plants. The resulting cost indicators show also an advantage of the HPLWR turbine (1.43 t/MWe), which is mainly caused by using a full speed turbine for the HPLWR instead of half speed turbines (being larger) for the reference power plants (PWR: 2.04 t/MWe; BWR: 2.13 t/MWe).

This qualitative assessment confirms that a certain potential can be expected for cost savings for a HPLWR compared to a conventional LWR. This assessment must be continued through the entire design process of the HPLWR concept.

For the estimation of the capital cost, the guidelines of the GIF Economics Working Group [3] recommend to use a top-down model for cost estimation for Generation IV plants, which are in a development state like the HPLWR. In this model, a reference plant has to be defined and the cost differences of the HPLWR to the reference are estimated using available information and data or engineering judgment.

AREVA made an assessment of plant construction and the electricity generation costs of a HPLWR in comparison with a typical LWR. As reference value for the LWR capital costs a value of 3000 $/kWe was taken from actual literature [14]. This value was converted to a reference Euro value of 2200 €/kWe. According to the Cost Estimating Guidelines for Generation IV Nuclear Energy Systems [3], a specific break down of costs has been executed for both the 1000MW reference plant and the HPLWR. The cost break-down of the reference plant (see Table 2) was taken from a description of the ABWR available on the web [15]. For this analysis it is assumed that the breakdown of costs can be applied, as a first guess, for the scaled reference plant, too. With the specific costs, the electrical power and the available cost breakdown, the costs within main cost categories like “structures and improvements”, “reactor equipment” etc were calculated. For each category, a more detailed cost breakdown was then derived considering the results gained within the project.

With the available results for the HPLWR, each category has been evaluated regarding possible cost reductions. According to the assumptions made in all major cost categories, cost savings can be expected in the order of 20%. For example, the size reduction of the reactor building and containment are considered to reduce the construction costs of about 41% (equivalent to about M€ 80). In the “structures and improvements”, the construction costs of M€ 430 could be reduced to M€ 334, which equals a saving of 22.4% (M€ 96) compared to the reference value.

Cost Item	% of capital costs	Reference Plant [M€]	HPLWR [M€]
Direct Costs			
Structures and improvements	21	430	334
Reactor plant equipment	22	520	424
Turbine plant equipment	12	230	168
Electric plant equipment	5	150	134
Heat rejection equipment	3.5	45	39
Miscellaneous Equipment	2.5	35	31
Direct Costs Total	**66**	1,420	1,130
Indirect Costs			
Construction			
Design and Engineering			
Project management			
Commissioning			
Indirect Costs Total	**34**	835	665
Total overnight costs		**2,255**	**1,795**

Table 2: Overall reference plant cost breakdown

Adding all direct costs, a saving of M€ 290 (20.4%) could be expected compared to the reference power plant. For the indirect costs, a proportional reduction to the indirect costs (20.4%) was assumed. Finally, the total overnight costs of the HPLWR power plant was calculated to M€ 1,795, 20.4% (M€ 460) less compared to the reference plant which costs M€ 2,255 in this example. The specific plant construction costs amount to 1,795 €/kWe for the HPLWR and 2,255 €/kWe for the reference plant. These values calculated with a high uncertainty having the limited data base in mind. However, once more information about the design of the HPLWR plant is available, these numbers shall be re-evaluated.

The reduction of the containment size and the higher plant efficiency don’t play a dominating role in determining the construction costs. Therefore, it is necessary to continuously assess all accounts, i.e. assess each system and component for possible cost reductions.

It should be mentioned here, that the absolute values in Euro are expected to change within time and just provide an adequate, but indicative value for cost saving. Therefore, a parametric study has been carried out to investigate the influence of e.g. construction costs on the electricity generation costs. The following parameters were varied:

- Specific capital costs (10 and 20% less than LWR, and equal to LWR)
- Sensitivity of fuel cycle cost in case of a HPLWR variant with 10 less capital costs than a LWR.

Tables 3 and 4 show the electricity generation costs at certain stages of operation. Ten and twenty years of operation are located within the depreciation period (25 years), whereas after thirty and forty years of operation, capital costs do not contribute to the electricity generation costs anymore.

			Reference case	Optimistic	Best estimate	Pessimistic
Plant erection costs		€ / kWe	2200	1760	1980	2200
Fuel costs		€cent / kWh	0.79	0.79	0.79	0.79
Electricity generation costs after	10a	€cent / kWh	4.86	4.32	4.59	4.86
	20a	€cent / kWh	3.51	3.19	3.35	3.51
	30a	€cent / kWh	1.78	1.78	1.78	1.78
	40a	€cent / kWh	1.84	1.84	1.84	1.84

Table 3 Electricity generation costs after years of operation. Specific fuel costs are constant. Specific capital costs are variable (in blue).

Table 3 depicts the sensitivity analyses varying the specific plant erection costs within 2200 – 1760 €/kWe. The fuel costs are selected constant to 0.79 €cents/kWh. Within the depreciation period, the capital costs have a certain influence on the costs of electricity (difference optimistic – pessimistic: 0.54 €cent/kWh). Afterwards, the constant fuel price leads to equal electricity generation costs for all different plant erection costs. The electricity generation costs are increasing a little between 30 and 40 years due to the price increase rate assumed (3%).

In Table 4, the plant erection costs are held constant to -10% of the reference value and the fuel costs are varied. A high value of 1.04 €cent / kWh and a low value of 0.63 €cent / kWh were selected to investigate raising and falling fuel prices on electricity generation costs. As seen in Table 4, the electricity generation costs are lower than the reference case and the spreading for the optimistic and pessimistic fuel costs are 0.38 €cent / kWh after ten years of operation. After twenty years, the spreading is 0.33 €cent / kWh. It should be noted that in this particular case, the HPLWR electricity generation costs with the pessimistic fuel costs (3.57 €cent / kWh) are higher than the costs for the reference case (3.51 €cent / kWh). The reason for this is that the reference fuel price of the reference plant is lower than the pessimistic one of the HPLWR. Five years before the end of the depreciation period, the capital cost still have an influence on the electricity generation costs, but not as decisive as in the beginning. This trend can also be seen after 30 and 40 years of operation in which the electricity generation costs do not change over time and are clearly determined by the fuel costs.

			Reference case	Optimistic	Best estimate	Pessimistic
Plant erection costs		€ / kWe	2200	1980	1980	1980
Fuel costs		€cent / kWh	0.79	0.63	0.79	1.04
Electricity generation costs after	10a	€cent / kWh	4.86	4.48	4.59	4.76
	20a	€cent / kWh	3.51	3.24	3.35	3.57
	30a	€cent / kWh	1.78	1.67	1.78	2.00
	40a	€cent / kWh	1.78	1.67	1.78	2.00

Table 4 Electricity generation costs after years of operation. Specific capital costs are constant at -10% of reference value. Specific fuel costs are variable (in blue).

A comparison of nuclear energy and energy sources has been carried out by VTT (see Table 5). It turned out that nuclear power will be a strong contender for the future and, assuming a penalty for carbon dioxide emissions, be very competitive against fossil fuel condensing power solutions. The competition for HPLWR will mainly be from other nuclear power plants.

		State of the art 2007	Projection for 2020	Projection for 2030
Nuclear	€cent / kWh	5.0 – 8.5	4.5 – 8.0	4.5 – 8.0
Combined Cycle Gas Turbine	€cent / kWh	5.0 – 6.0	6.5 – 7.5	7.0 – 8.0
Coal	€cent / kWh	4.0 – 5.0	6.5 – 8.0	6.5 – 8.0

Table 5 Projection of electricity generation costs for different power conversion systems

W***ith respect to the Gen IV goals of economics*****,** the HPLWR is expected to have less life cycle costs than a Gen III light water reactor and thus a clear life-cycle cost advantage over other energy sources. Due to the reduction of capital costs, the financial risk is definitely reduced compared to the reference LWR plant, and such expected fulfilling both goals of economics.

2.3 Safety

The safety system of the HPLWR was designed and analyzed. Several transients and accidents have been simulated by means of thermal hydraulic system codes from different organizations. The transient analyses performed, addressed a variety of initiating events, including anticipated transients (e.g. spurious scram, partial loss of feedwater, spurious closure of one main steamline isolation valve, etc.) as well as accidents (Loss of Coolant Accident, Reactivity Induced Accidents and Anticipated Transients without SCRAM).

Due to the scope of the project, the information was not mature enough to perform a complete assessment according to the GIF methodology [5]. Therefore, detailed conclusions about likelihood of core damage frequencies as mentioned in Safety-2 and elimination of the need for offsite emergency response in Safety-3 shall be left to a future assessment of the concept. However, a qualitative summary shall serve here as a first approach. Quantitative results of accident and transient analyses are summarized by Andreani et al. [17].

- The Automatic Depressurization System (ADS) proposed on the base of the design calculations performed with a coarse model of the core is adequate to limit pressure excursions to much below design limits. It has also been shown that the system with the chosen parameters enables the water introduced in the vessel to provide sufficient flow in the core and effective cooling of the fuel for all anticipated transients and accidents investigated.
- In case of loss of feedwater (LOFW) events with failure of one or two pumps, the temperature excursion is lower than 60 K, even under assumption of a very small pump-motor inertia. Considering this small excursion, the initial temperature of the cladding (and therefore the core design) has a stronger impact on the fulfilling the acceptance criteria than the temperature excursion during this type of transients. Therefore, the pump inertia is considered to be not a critical parameter.
- For low values of the core flow rate (below 40% of the nominal value), flow reversal could occur in the gap and moderator channels. Modifications in the core thermal and hydraulic design are recommended to avoid this condition. In particular, it has been shown that the heat transfer from the fuel to the moderator channel boxes plays an important role, and a better insulating material for the moderator boxes would be beneficial.
- The core coolability by means of the low pressure coolant injection system (LPCI) has been demonstrated for large break loss of coolant accidents in both the steam and feedwater lines. The shortcoming of this system is the high power required to operate the pumps.
- In order to reduce the power demand for emergency cooling water injection systems, an active high pressure coolant injection system (HPCI) has also been investigated. Design calculations showed that this system should be capable to provide core cooling in the case of an event with depressurization. As it cannot be operated for a long time, an option would be to start the LPCI system at low pressure and close the HPCI system. This strategy, however, needs to be further investigated in future safety analyses.
- The limited analysis for a small break LOCA showed that the intervention of an auxiliary feedwater supply system (starting at nearly full pressure) would be sufficient to maintain the reactor in a safe state. Whether this system will be available or ADS should be actuated to permit the intervention of other systems will be a design choice.
- In case of accidents initiated by reactivity insertions, fuel centreline temperatures arrive at values very close to acceptability limits. The core design has to be optimized to avoid this condition.

- In one case, namely the uncontrolled withdrawal of an absorber from the bottom position without SCRAM, fuel melting is calculated to occur. This can be avoided by limiting the allowed position of control rods or by applying lower worth control rods compared to shutdown rods. Some further study is needed to introduce appropriate preventing measures.

Within the limitations imposed by this methodology, by uncertainties in the validity of certain models and by uncertainties of analyses with point kinetics, the main conclusion of the safety analyses is that the preliminary **safety concept is likely adequate to match the requirements,** although a number of open issues remain to be addressed in future projects.

In relation to the fulfilment of the European Utility Requirements (EUR) [16], the preliminary analyses performed do not give any indication that the core melting frequency could be higher than in current LWRs due to its intrinsic characteristics. For instance, the smaller heat storage capacity and the impossibility to rely on natural circulation for cooling the core do not result in specially challenging conditions that require economically unbearable counter-measures. Therefore, it can still be expected that the EUR can be fulfilled.

With respect to the Gen IV goals of safety and reliability**,** the HPLWR shows a good performance regarding safety issues. No case has been found which prevents the expectation that the European Utility Requirements will be fulfilled later. From this, it can be concluded that the HPLWR concept provides a very high level of safety. Since known and reliable systems (e.g. low pressure coolant injection system) and components (e.g. safety relief valves) are foreseen for the HPLWR, the reliability of them can be expected to be in the same order like for existing LWRs. The issue to exclude the need of evacuation , Safety-3, was implicitly considered by designing the containment and the related safety systems following accepted design rules of light water reactors, which already take this goal into account. This goal is expected to be met, having in mind that many more analyses are required to confirm this statement.

2.4 Proliferation Resistance and Physical Protection

The base for the assessment of the HPLWR concept against proliferation resistance and physical protection is the IAEA Technical Report 392 “Design Measures to Facilitate Implementation of Safeguards at Future Nuclear Power Plants” [4]. Chapter 7 of this report provides guidelines for design provisions for future water cooled reactors to facilitate implementation of safeguards. As a first approach, these guidelines shall be applied to the HPLWR because of its LWR nature.

Regarding proliferation resistance, the diversion of fissile material must be detected. With respect to the enrichment of about 7% U-235 in maximum, for HPLWR a diversion of 670 fuel rods (equivalent to 75kg of U-235 [4]) of fresh fuel must be detected within 12 months period. For discharged fuel, about 564 rods for 32300 MWd/kg burn-up and 428 rods for 50400 MWd/kg burn-up must be diverted to reach the IAEA limit for Pu of 8 kg. As shown by Schulenberg et al. [7], 40 fuel rods form an assembly and nine assemblies are grouped to a cluster. This means that more than one fuel assembly cluster (about 5.5m length) must be diversified and reprocessed in order to reach the detection limit of the IAEA.

In order to prevent the diversion of fissile material, specific counter measures are applied. For water cooled reactors, the following countermeasures are foreseen by the IAEA (see Figure 5):

- **Seals:** To be applied to close pathways from one location inside the containment to another. Seals are usually installed on the concrete blocks covering the reactor pit or on the canal gate (red squares).
- **Cameras:** The optical surveillance is important in a nuclear power plant. The view angle of the camera should not be obstructed by large components or obstacles (yellow).
- **Access areas:** The access areas to fuel shall be clearly defined. In the containment, the fuel loading machine provides the access area to the fuel (green).
- **Paths:** The paths of the fuel inside the containment shall be clearly defined through design. Having the size of fuel assemblies in mind, the size of hatches shall be designed such that the assembly clusters only fit through the equipment lock (which is monitored) and not though other smaller openings (blue).
- **Data collection area:** It is very important to know the amount of nuclear material in the core and in the storage areas adjacent to it. Therefore, electronic equipment is being used to collect and store data continuously for verification (brown).

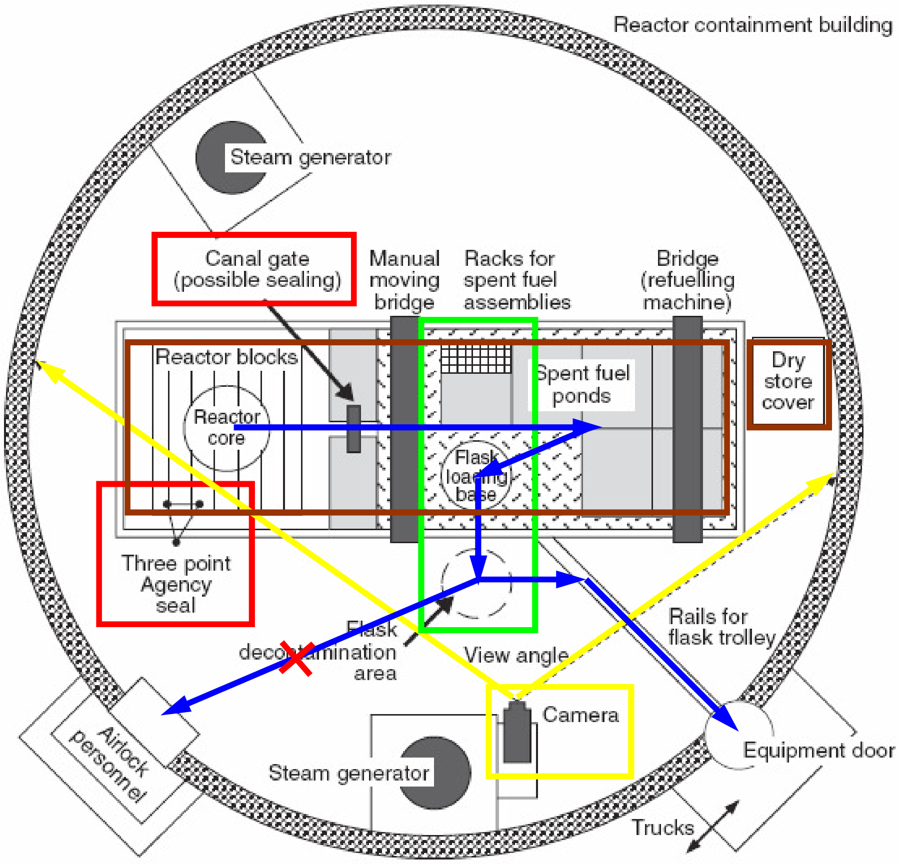

Figure 5 Countermeasures to be applied to water cooled reactors [4].

With regard to the HPLWR design, all principles can be applied here without modification. It is not necessary to derive a new procedure.

2.4.1 Application of design guidelines to HPLWR and assessment

According to the IAEA report [4], chapter 7, boundaries must be selected for which the guidelines shall be applied. In general, such boundaries can be entire facilities, parts of them, transportation between them, etc. on coarse or fine level. For the HPLWR as a first approach taking the level of design detail into account, the boundary chosen is the reactor containment, including reactor pressure vessel, spent fuel storage pool, fresh fuel storage room/pool. Not considered, because not HPLWR specific, are the enrichment plant, fuel fabrication and transport, spent fuel transport and interim / final disposal site.

The IAEA report provides ***seven specific design measures / requirements*** to be applied. As follows, the design measures are being explained and a first comparison with other Gen IV systems is given:

1. **Data and information collection and transmission**

   A break in information flow must be treated as a potentially suspicious event which could lead to a process of re-verification, which in turn is very time-demanding and costly. Data collection can be performed through images from optical surveillance inside the containment, results from Cerenkov inspection, seal and confinement integrity and nuclear data from gross gamma single measurement or scan, neutron counting, gamma spectroscopy, etc. Compared with other Gen IV Systems, in this aspect the HPLWR is **comparable or slightly better,** because Cerenkov radiation easier to detect in water compared to e.g. gas cooled or liquid metal cooled reactors, and there is a well defined number of fuel assemblies in HPLWR e.g. compared to pebble bed reactors.

2. **Identification for fuel assemblies and fuel rods**

   An identification must be readable from above in fresh fuel storage area, in spent fuel pool and inside reactor pressure vessel during refueling (e.g. with small diving cameras). In the current design labeling of the cluster head plate, impossible to remove, and space for an individual serial number on all fuel rods required are foreseen. Additionally, impeding opening of screws in fuel assembly piece, e.g. with small weld spot is a specific measure to fulfill this requirement. Compared with other Gen IV Systems, in this aspect the HPLWR shows a **strong advantage**, because sodium and lead are opaque and individual fuel assemblies are difficult to identify. For pebble bed reactors it is almost impossible to identify individual spheres and for molten salt reactors the question arises, how precisely inventory of liquid fuel can be measured.

3. **Containment (=confinement) and surveillance**

   Confinement of fissile material is provided by seals. Such sealing systems are required for the spent fuel inventories stored in ponds, spent fuel casks, the reactor core (here the concrete plate covering reactor pit) and for transfer canal gates. Optical surveillance is maintained through cameras mounted in the containment for the spent fuel pool, the reactor closure and for exit doors and hatches. Compared with other Gen IV Systems, in this aspect the HPLWR the requirements and measures are **comparable**.

4. **Fresh fuel receiving and storage area**

   The requirements for fresh fuel receiving and storage area are a minimum number of openings, through which the fuel can enter and leave such a storage area, a layout to be able to seal groups of fuel assemblies. Provision of adequate space and illumination must be provided and a minimization of fuel moving in general. Compared with other Gen IV Systems, in this aspect the HPLWR shows **advantages**, because low enriched uranium (LEU) is foreseen for the HPLWR, which can be stored a so-called dry storage enabling all measures mentioned above. For fast spectrum reactors, high enriched uranium (HEU) fuel is foreseen which prevents the use of a dry storage because of radiation. Grouping of fuel assemblies can only be handled by means of roboters.

5. **Fuel loading and unloading**

   The requirements for fuel unloading and loading are a suitable mounting for surveillance equipment in containment, by an indexing mechanism on refuelling machine to identify the FA position and by provisions for sealing the canal gate. Compared with other Gen IV Systems, in this aspect the HPLWR shows **advantages**, because a simple optical observation in water compared to e.g. liquid metal coolant.

6. **Reactor core**

   The requirements for the HPLWR core are a suitable arrangement for surveillance and sealing on concrete slabs, a suitable arrangement for surveillance equipment to view the reactor vessel operations when vessel is open and underwater illumination and sufficient water clarity. Compared with other Gen IV Systems, in this aspect the HPLWR shows **advantages**, because clear water is the excellent medium for optical observation of the reactor core.

7. **Spent fuel storage and shipping area**

   For spent fuel storage and shipping area, the requirements are suitable arrangements for surveillance equipment, storage racks preferably arranged in a single layer, an indexing system for identification of specific fuel assembly locations, a minimum number of openings through which the spent fuel can be moved, water clarity and provisions to facilitate annual Physical Inventory Verification, i.e. counting, verifying spent fuel attributes by irradiation measurement. Compared with other Gen IV Systems, in this aspect the HPLWR shows **advantages**, because there is a low numbers of fuel assemblies for the HPLWR to be observed compared to e.g. with pebble bed reactors, and the physical inventory is easier to verify, especially under clear water compared with liquid metal cooled reactors.

With respect to the Gen IV goals of proliferation resistance and physical protection**,** the HPLWR with thermal neutron spectrum shows comparable up to strong advantages regarding proliferation resistance, caused by highly unattractive content of Pu and U-235, a low number of fuel assemblies to be monitored, water as clear medium providing an additional verification: It is important to mention the proved IAEA principles can be applied and no new procedures must be invented for the HPLWR.

Specific design measures for the HPLWR fuel (e.g. labelling of fuel assemblies) have already been taken into account. Compared to other Gen IV systems, HPLWR with thermal neutron spectrum is among the most proliferation save reactors. The physical protection is implicitly fulfilled by designing according to the latest design rules, e.g. protection against external events or aircraft crashes. This goal is very likely to be fulfilled.

3. Conclusion

The assessment of the concept with respect to the goals of the technology roadmap for Generation IV Nuclear Reactors of the Generation IV International Forum shows that the HPLWR leads to fulfil the goals of economics, safety and proliferation resistance and physical protection very well. In terms of sustainability, the HPLWR with a thermal neutron spectrum investigated within this project, does not differ from existing Light Water Reactor in terms of usage of fuel and waste production. Consequently, future activities should address this topic in more detail, i.e. investigating a core with an epithermal neutron spectrum or the use of Thorium to investigate the breeding capabilities using supercritical water reactor technology.

As a result of the technical assessment, exemplarily described by Andreani et al. [17] and Schulenberg et al. [18], several research topics have been identified. The highest priority shall have materials investigations to find a suitable cladding material including development, water chemistry, in-pile and out of pile testing. Additionally, the codes used in the HPLWR project have not been assessed against experiments because of limited data. Those data (thermal-hydraulics, neutronics, etc.) are to be provided by means of suitable experiments. These findings and the resulting implementation of such future activities are in accordance with the GIF roadmap [2] and the HPLWR roadmap [19]. For further cost reductions, the HPLWR plant should be designed in detail down to each system and component which is, however, more task of the industry and not of research organisations or universities.

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