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NUCLEAR HIGH-RADIOACTIVE RESIDUES: A NEW ECONOMIC SOLUTION BASED ON THE EMERGENCE OF A GLOBAL COMPETITIVE MARKET

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NUCLEAR HIGH-RADIOACTIVE RESIDUES: A NEW ECONOMIC SOLUTION BASED ON THE EMERGENCE OF A GLOBAL COMPETITIVE MARKET

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Abstract: Nuclear energy is economic and does not emit CO2 but has two central setbacks. First, it has not been yet implemented an efficient method of disposing the spent fuel. Second, the reactors' complexity is expensive and turns possible the occurrence of accidents. In this paper, first I propose a very simple, economic and safe boiling heavy-water reactor that may constitute a way of mitigating these setbacks. The reactor is a container filled with a hydraulic suspension of non clad fuel that is crossed-over by two fluxes: by one side, the fuel suspension that remains 250 days in the reactor and, by another side, the cooler that remains 50 seconds in the reactor. Second, I discuss that the solution of nuclear high-radioactive residues problem passes by the emergence of a global competitive market.

Keywords: Nuclear reactor; Heavy water; Boiling water; Continuous fuel feeding; IV generation; Nuclear residues pricing and trading

JEL codes: D41; D45; L72; Q48

1. INTRODUCTION

In physics' theory, a nuclear reactor is a simple system that arises from the interconnection of tree sub-systems: the fuel, the moderator and the heat transport sub-systems. Typically, the moderator and the heat transport sub-systems overlap.

When a fuel's nucleon captures neutrons, fission occurs with release of energy and h high-velocity neutrons (per absorbed neutron).

As neutron-capture decreases with its velocity, it is necessary to moderate neutrons velocity.

Those neutrons that are captured by new fuel's nucleon induce new fissions (they are useful). But not all of the produced neutrons are useful. That is because the moderator, the cooler that removes thermal energy and fuel cladding (plus fuel's non-fissile part) absorb some of the produced neutrons while some other are loss to the reactor exterior.

The number of new fissions per previous fission, $k < h$, is crucial in the reactor dynamics because when $k < 1$ the reactor stops and when $k > 1$ the reactor 'explodes'.

Because Earth materials with $h > 1$ are rare, reactors must be efficient in the management of neutrons, i.e., $k \approx h$. To have an efficient reactor, the moderator/coolant has to be Deuterium (heavy water), the fuel has to be 'pure' and the reactor has to be compact and large size.

Adding Deuterium's high cost with the fact that nuclear fuel is a small fraction of total cost, merely 10% of nuclear reactors use Deuterium as moderator/coolant, HWR. The others 90% use Protium (light water) as moderator/coolant, LWR, (see, WNA, 2006)

Although seeming cost-effective, the use of light water imposes complexity in reactors design and control difficulties that overpass the gain from using a low cost moderator/coolant. It adds that the risk of occurrence of a catastrophic nucleus 'meltdown' is a direct consequence of using light water as moderator/coolant. CANDU-AECL has been preaching this truth for decades without results.

In this paper I suggest a boiling heavy water reactor design, BHWR, which is simple, economical and safe. Due to its dissimilarity with state-of-the-art nuclear reactors, I suggest that this design be classified as new IV generation type.

The reactor is simple because it is continuously fuel feed with non-clad powdered fuel. This characteristic makes it possible to control reactor's power with a simple feedback loop that decreases the fuel intake when steam pressure increases.

It is economical because there is no need for redundant and expensive 'fault free' control systems or cladding of the fuel. Adds that, being fuel a suspension, reactor is compact because burning rate will be very high (up to 100 Kw/kg) and LWRs' "spent fuel" may be used without any treatment or cladding (that would costs at least 300 us$/kg).

It is intrinsically safe because the reactor becomes instantaneously sub-critical when there is i) interruption on fuel feeding, ii) fuel compacts at the bottom of the reactor or there is iii) a major moderator loss.

2. IT IS NEEDED A GLOBAL MARKET FOR SPENT FUEL

Nuclear reactors use scarce resources (fuel, capital and know-how) in the production of electricity for which there are market prices. It is acknowledged that the existence of a market price induces an efficient allocation of those resources: economic agents pursue ways of saving high-priced resources while increasing output. This market dynamics directs into efficiency.

But, it is well known that the principal obstacle for the development of nuclear industry is the non-existence of an effective way of disposing spent fuel (that is highly radioactive). Although nuclear promoters are ready to pay a price for disposing that highly radioactive waste, nobody knows what should be the right price. From Mahrenholz (1982) it results an average cost of 1000 us$/kg for transporting, monitoring and stocking the spent fuel 'for ever' (1.15 us$/Mwh, 2003 prices, for a burning rate of 36 Gwd/t). This represents 2/3 of nuclear fuel's price.

Being the cost of dry spent-fuel storage estimated as $3/kg per year (Bunn et al., 2001), 1000 us$ would represent a $3 per year perpetual yield with implicit average real interest rate of 0.3% a year that would be an inexpensive way of underdevelopment countries obtain funding (Siegel, 1989, estimates that, in the last 200 years, average bounds real return rate has been twelve times that value, i.e. 3.5% a year).

Do to safety reasons, it is assumed by governs that market is unable to resolve this issue, assuming each country that all the others are non-trustable. This is a long discussion that overpasses this work but this is completely erroneous: Governments are unable to promote efficient allocation resources: e.g., nuclear plants have been paying the 'disposing fee' for decades and no government has implemented a solution for this problem.

The only way of finding solutions for this problem is the creation of a spent fuel market.

First, spent fuel market should discriminate i) FP (fission products) and AI (actinides isotopes) from ii) residues without FP or AI. For example, the price of residues could be 250 us$/kg and the price of FP and AI could be 20000 us$/kg.

Second, FP and AI price could be divided in iii) LLFP - long-lived FP (Zr93, Tc99, I129, Cs135) weight; iv) LLNFAI - LL non-fissile AI (Palladium, Plutonium 238, 240 and 242, Americium and Curium) weight; and v) LLF AI - LL fissile AI (Plutonium 239 and 241) weight. For *LWR*s' spent fuel it would result a market price higher than for *CANDU*s' spent fuel.

Third, this market should be global (it should be allowed the import and export of nuclear residues). It seems natural that at least those countries that produce significant quantity of nuclear residues would be trustable to trade in this 'nuclear residues' market. Those trustable countries would license companies, with IAEA supervision, to promote nuclear facilities and trade in that marker.

Being the global production of spent fuel 10000 t a year (e.g., Greenwald *et al.*, 2005), that market would trade approximately 10 thousand million us$ a year.

With this market trading, high-development regions or countries could license new nuclear facilities even maintaining a zero high-radioactive residues inventory policy while other regions or countries keen to develop could build nuclear facilities to process and dispose safely those residues.

With this market trading and setting prices, technologies that minimize the production of long-lived radioactive isotopes would be encourage. It would also become profitable to develop better and better technical solutions to remove high-radioactive isotopes from spent-fuel and new nuclear facilities dedicated to the burning of long-lived radioactive isotopes.

A 1000 Mwe nuclear reactor produces 30 t of spent fuel a year, being its promoters willing to pay 30 million dollars to some one that process and store safely it. Foreseeing that with market prices it would become economical to burn all the plutonium and concentrate all high-radioactive isotopes, it would result in just 150 kg of long-lived radioactive isotopes stocked ‘for ever’.

3. LIGHT WATER VS. HEAVY WATER

Although light water is a good moderator because it removes neutrons’ energy in just a few collisions (it needs 16 collisions to moderate 1 MeV neutrons) and is inexpensive, it absorbs too much neutrons (Protium absorbs 640 times more neutrons than Deuterium). Being so, the LWR’s fuel must have an average h much higher than 1, i.e., fuel must have a high grade in fissile isotopes. But this turns reactors intrinsically unsafe: when fuel compacts at the bottom of the reactor it becomes supercritical and meltdown. To avoid this type of catastrophic accident, fuel cladding is unavoidable.

Being light water low-cost, little effort is made in designing ‘primary circuit’ strictly tight. Being so, fuel must be in insoluble form, i.e. ceramics, to prevent that, when clad cracks, radioactive material escapes to the exterior jointly with the moderator/coolant. As ceramics are bad heat transporters, LWRs’ fuel-burning rates must be low, i.e., smaller than 35 kw/kg.

Finally, to maintain at all times a h much higher than 1, LWRs’ spent fuel is very radioactivity because it maintains a grade on fissile material higher than 1%.

Although light water is a good moderator and has low-cost, it introduces extreme complexity in reactors design. This results from the fact that in a out-of-control situations, LWRs drift rapidly to meltdown state. Being so, as there is no such thing as ‘fault free’, controls systems must be as accurate as the-state-of-the-art allow and must be several times redundant. Even though control systems complexity, meltdown risk remains high (estimated as 10^{-7} per year level) (see, Vesely and Rasmuson, 1984).

Being impossible to overpass light water limitations, I propose going back to nuclear concepts and redesign a new type of reactor from the scratch.

The first step is to focus again in Deuterium as a moderator and cooler that has idiosyncrasies that must be addressed.

A) Heavy water is expensive (300 us$/kg) (see, Miller, 2001).

B) Heavy water is 45% less able to remove neutrons' energy (it needs 29 collisions to moderate 1 MeV neutrons) than light water.

C) Heavy water allows the use of low-grade fuel that maintains sub-critical when it compacts at the bottom of the reactor.

4. SOLUTION PROPOSED

To address the heavy water high cost and low ability to remove neutrons' energy, it is necessary to i) build a 'primary circuit' strictly tight, to ii) increase fuel-burning rates and to iii) reduce the 'out of reactor' quantity of coolant.

Being that turning 'primary circuit' strictly tight has a cost is has a major benefit: as fuel is sub-critical when compacts, it becomes possible to use unclad powdered fuel in hydraulic suspension.

The use of a fuel hydraulic suspension as several advantages:

As powered fuel is in intimate contact with water, it is possible to boost up fuel burning rates to 100 kw/kg.

As powered fuel may be continuously feed to the reactor, its power control becomes very simples: a feedback loop that decreases the fuel intake when steam pressure increases with a continuous exhaustion of 'average fuel' as spent fuel.

But, being burning rates so high, the only way to extract heat is by considering a boiling water reactor. This adds the advantage of decreasing the quantity of heavy water and radioactive material out of the reactor and decreasing the probability of heavy water loss in the heat-permuter (and increases thermodynamics' efficiency).

It adds that the use of unclad fuel decreases the percentage of lost neutrons.

Finally, it is important to notice that, at least theoretically, the reactor works with no breaks, 365 days a year.

Do to its simple design, it is not demanding to maintain the 'primary circuit' strictly tight. That is easy to accomplish because the reactors does not have control rods, there is only high diameter pipes and there is only two rotating axis (the steam turbine and the returning pump) that are easily made tight.

5. DIMENSIONING

Assuming that reactor powers 3500 MWt - 1100 MWe and that burning-rate is 100 kw/kg, reactor will contain 35t of fuel in suspension. For a fuel weight proportion of 33%, it will be necessary a spherical container with 6 m in diameter filled with 70 t of heavy water with a 0.7 density (that costs 20 million us$). That represents just 1% of total cost of a LWR.

With this weight proportion, there will be 70 Deuterium atoms per each Uranium atom. From this atomic proportion, 2/3 of neutrons, prior to collide with an Uranium atom, it collides with 29 or more Deuterium atoms.

Assuming the reactor outtakes steam at 90 bars (303 ºC and 2744.64 kj/kg enthalpy) and it intakes liquid water at 70ºC (293.03 kj/kg enthalpy), it is necessary a steam flux of 30 m3/s, i.e. 1428 kg/s, to exhaust the produced heat. For a steam velocity of 30 m/, the steam pipe must have 1.25 m diameter. From this figures, on average heavy water recycles between the reactor and turbines each 50 seconds.

It is not possible to have higher proportion of fuel in suspension because the suspension would become too viscose and heavy water would boil too violently.

The heavy water outside the reactor will be just 10% of the total (in pipes, turbines and pumps). That results from steam low density (50 kg/m^3).

The fuel feeding will be done with a high-pressure pump. The residues extraction will be done by the removal from the reactor of a portion of fuel suspension and the evaporation of heavy water that is re-used in the fuel feeding procedure. From point 7-simulations, the fluid flow extracted from the reactor (and re-injected with fuel) is smaller than 10 litres an hour.

6. NEUTRONICS

There will be a continuous intake of fresh fuel and outtake of spent fuel. Inside the reactor there will be a fuel composition with k = 1 (critic state). The spent fuel will have the same composition as the average fuel inside reactor.

Lets assume the neutronics' constants of table 1 (from Munter, 1992).

Substance	Absorption Cross-section	Fission Probability	Neutron Yield	Belated Neutrons
Heavy water 97%	0.0071			
U235	680.9	85%	2.08	0.64%
U238	2.68			
Pu239	1017.3	73%	2.08	0.20%
Pu240	289.6			
Pu241	1400	73%	2.17	0.54%
Residues	10			

Table 1- Assumed neutronics' constants

7. SIMULATIONS

In this point it will be simulated two situations. In the first it is used as fuel the typical LWR spent fuel (0.8% U235, 1% Pu and 3.6% fission residues) in 'open circuited'. In the second simulation it is used the same fuel in 'close circuited': the plutonium is extracted and recycled.

Loss neutrons to the exterior has been computed by assuming that an neutron emitted at a distance $D < 0.25$ m from the reactor walls will have the probability $0.5 - 2D$ of escaping to reactor exterior. Under these assumptions, spherical reactors with 6 m diameter will loss 5.91% of produced neutrons.

It is assume that residues and heavy water atoms weight 0.50 and 0.075 of actinides atoms, respectively.

7.1. Fuel in open circuit

Assuming that fuel is in suspension in 70t of heavy water, in equilibrium, reactor will be feed with 1.928 g/s (=6.942 kg/h) of fuel being the reactor composition that shown in table 2. Do to re-burning, the fissile grade decreases from 1.33% to 0.55% and the plutonium grade decreases from 1.06% to 0.43%.

Substance	Fuel Composition		Neutrons Absorption	Irradiation
	Intake	Average		21.0 GW/t
Heavy water			1.89%	
U235	0.80	0.16	11.23%	26.1%
U238	94.75	92.86	24.93%	
Pu239	0.37	0.26	26.81%	54,4%
Pu240	0.32	0.28	7.99%	
Pu241	0.16	0.07	9.62%	19,5%
Residues*	7.20	11,56	11.54%	
Losses to exterior			6.0%	
b		0.38%		
* Residues weight is half this value				

Table 2- Open circuit reactor steady state

7.2. Fuel in close circuit

Assuming that plutonium is recover from spent fuel and added to fuel, in equilibrium, reactor will be feed with 1.364 g/s (= 4.910 kg/hour) of fuel plus 0.014 g/s (=50 g/hour) of recycled plutonium (Pu238, Pu239, Pu240, Pu241 and Pu242) with grades shown in table 2. That represents a 40% increase in irradiated energy per kg.

Substance	Fuel Composition		Neutrons Absorption	Irradiation
	Intake	Average		29.7 GW/t
Heavy water			1.67%	
U235	0.80	0.13	8.16%	19.2%
U238	94.75	92.61	21.97%	
Pu239	0.37 + 0.29	0.29	26.44%	54.3%
Pu240	0.32 + 0.43	0.43	10.96%	
Pu241	0.16 + 0.10	0.10	12.92%	26.5%
Residues*	7.20 + 0.20	13.46	11.88%	
Losses to exterior			6.0%	
b		0.37%		
* Residues weight is half this value				

Table 3- Closed circuit reactor steady state

The reactor discharges 0.66 g/s (=2.375 kg/hour) of residues with 6% of long-lived radioactive isotopes, LLRI, (Tc99, I129, Cs135, Np237, Am and Cm). Comparing with LWRs' spent fuel, its re-burning in the BHWR decreases 60% the total quantity of LLRI.

Recalling that, on average, a LWR irradiates 36 GW/t, re-burning its spent fuel in close circuit increases energy output by 80%. This means that actual LWRs discharge spent fuel is sufficient to feed 300 BHWR-1100 MWe.

7.3. Reactor control - fuel feeding halt

Assuming that Plutonium is recycled, that belated neutrons are 0.39% of total and that they lag 8 s behind, that reactor is in a situation of full power and that fuel feeding is cut-short. Then, reactor becomes immediately sub-critical and slowly starts decreasing power, taking 30 minutes to decrease power 3%. After 5 hours, the reactor power decreases to 5% of its previous full power level (fig. 1).

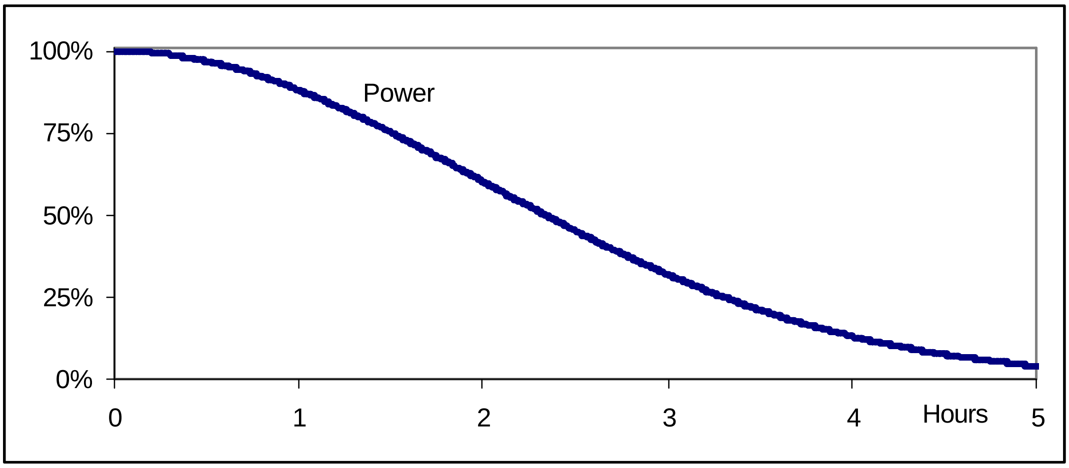

Fig. 2 – Evolution of power after fuel cut-off

This simulation illustrates that the fuel feeding control is adequate both to manage the reactor power on a meticulous scale and to shut down it. The decreasing of power occurs with no complex control system but just by fuel feeding variation.

7.4. A reactor prototype

Engineering achievements would be impossible without the building of prototypes. Here I will simulate a 1/200 prototype. The reactors dimension will be scale down to 1 m diameter sphere filled with 350 kg of fuel, 700 kg of heavy water, 35 MWt. As neutrons losses to reactor’s exterior increase to 36%, fuel grade will be scaled up to 4.2% U235. Being the reprocessing of fuel a well-established industrial process, it is unimportant to include at the prototype scale. Being so, the fuel will be in open circuit. Being steam turbines will known, it would be excluded from the prototype.

Substance	Fuel Composition		Neutrons Absorption	Irradiation
	Intake	Average		27.0 GW/t
Heavy water			0.74%	
U235	4.20	1.502	40.20%	84.5%
U238	95.0	94.779	9.92%	
Pu239	0.00	0.182	7.19%	14.4%
Pu240	0.00	0.074	0.84%	
Pu241	0.00	0.012	0.66%	0.1%
Residues*	0.00	1.502	4.46%	
Losses to exterior			36.0%	
b		0,58%		
* Residues weight is half this value				

Table 3- Open circuit reactor’s 1/200 prototype steady state

8. RADIATION SHIELDING

Contrary to actual nuclear reactors design, there is no water shielding between the fuel and the walls of the reactor. This means that significant neutron radiation goes across the reactor walls to its exterior. Being so, it is necessary to have an exterior shielding. As the reactor has no moving parts, one inexpensive solution is to encircle it with anhydrous sodium chlorite and to embed it near surface. The anhydrous sodium chlorite is inexpensive (25 us$/t), it is a good heat insulate and Chlorine has a reasonable absorption cross-section (33.5)

The primary circuit, including the steam turbines, is enclosed in a contention sphere that strengths the tightness of the primary circuit and prevents any accidental loss of radiation to environment.

The shielding and embedding of the reactor would create a free space inside the contention sphere that would easy the maintenance of equipment located there (steam turbines, pipes and fuel feeding and removing system) without emptying the reactor.

In figure 2 it is presented a sketch of the proposed BHWR.

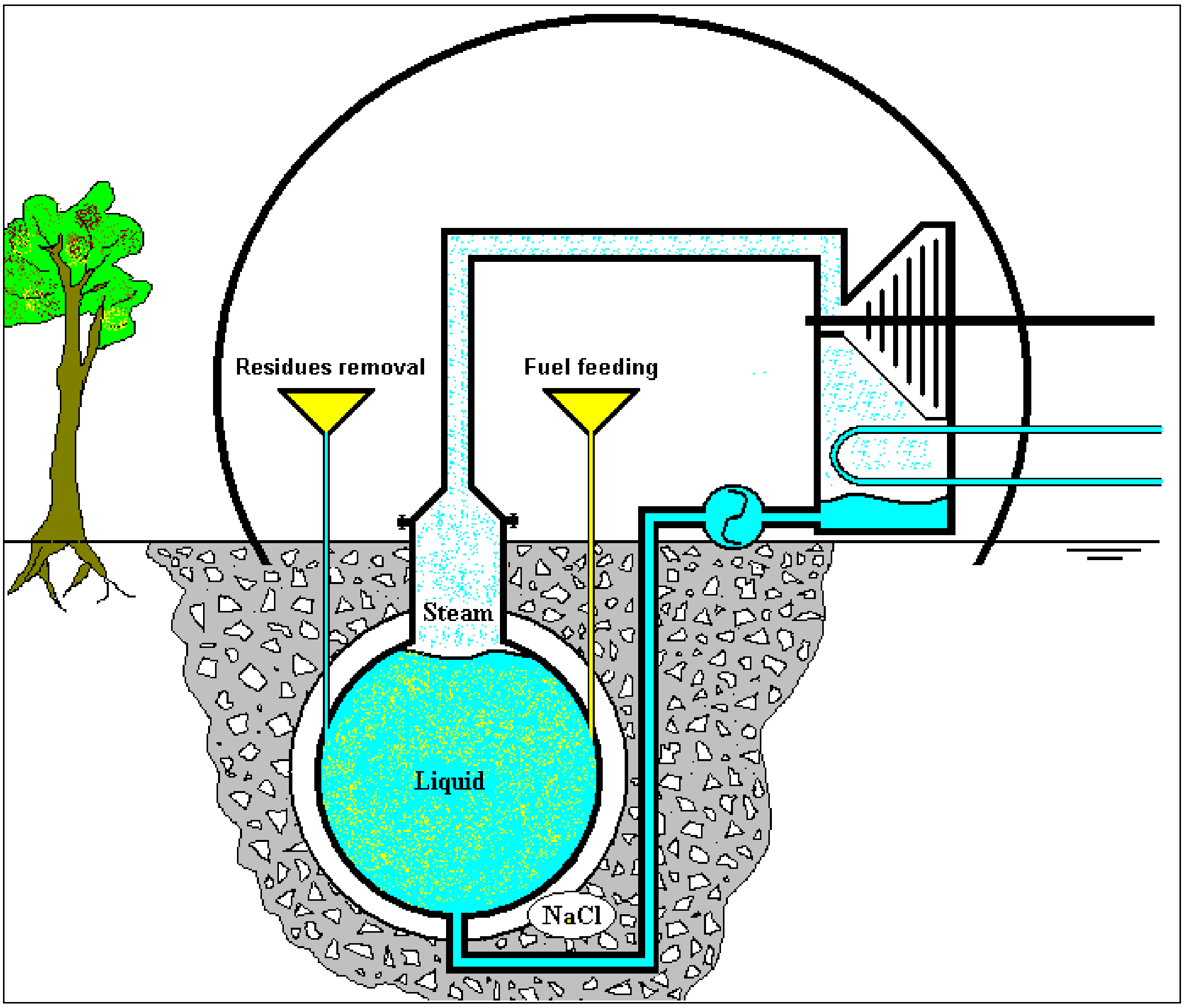

Fig. 2 – Sketch of the reactor primary circuit

9. CONCLUSION

In this work it is proposed a new type of nuclear reactor: the boiling heavy water reactor, BHWR. This new design is simple, economical, safe and it uses LWRs' spent fuel in closed circuit (plutonium is recycled).

The reactor is a spherical container build underground and filled with powdered fuel in suspension in heavy water. Burning rate is up to 100 kw/kg.

The use of heavy water makes the reactor intrinsically safe because it is impossible the occurrence of reactor's meltdown. The use of continuous fuel feeding makes the reactor easily controllable with just a feedback loop that decreases fuel intake when steam pressure increases and vice-versa.

In a simulation, a 3500 MWt-1100 MWe reactor would be a 6 m diameter spherical container filled with 35t of powdered fuel in suspension in 70 t of liquid heavy water.

The reactor would be continuously feeding with 1.364 g/s of fuel plus 0,014 g/s of recycled plutonium.

Using feeding mechanism, The BHWR reactivity will be set between $k =$ 0,999999 and k = 1,000001 that turns unnecessary the existence of control rods or any other control system besides a feedback loop that decreases fuel feeding flows when steam pressure increases and vice-versa. It is shown by simulation that, when fuel feeding is halted, the reactor stops in 5 hours.

Recalling that, on average, a LWR irradiates 36 GW/t, by re-burning the spent fuel in close circuit in a BHWR there is and 80% increase in energy output per kg of fuel. This means that actual produced residues would be sufficient to increase the number of actual reactor by 300 new BHWR-1100 Mwe without increasing the demand for nuclear fuel or Zirconium alloy. That is important because nowadays Zirconium market supply is short and unable to respond to a significant increase in demand.

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