TRAVELING WAVE REACTOR

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The traveling wave reactor (TWR) is a nuclear reactor concept that uses breeding to reduce the need for enriched uranium production. It is based on a concept of traveling of the breed-burn wave. This reactor is inherently safe since in any given time it does not have enough fissile fuel to become super critical. It would also greatly reduce nuclear waste volume and prolong uranium supply since it can burn used light water reactor (LWR) fuel and depleted uranium. Overall thermodynamic efficiency is also predicted to be better than LWRs since it uses sodium as coolant and can reach higher temperatures.

VALOVNI REAKTOR

Valovni reaktor je koncept jedrskega reaktorja, ki uporablja oplojevanje da zmanjša potrebe po proizvodnji obogatenega urana. Temelji na konceptu potujočega vala oplojevanja in fisije. Ta reaktor je inherentno varen, saj v nobenem trenutku v njem ni dovolj fisijskega materiala da bi postal nadkritičen. Takšen reaktor bi občutno zmanjšal volumen izrabljenega jedrskega goriva in podaljšal življensko dobo zalog urana, saj lahko za gorivo v njem uporabljamo izrabljeno gorivo iz lahkovodnih reaktorjev (LWR) in osiromašen uran. Pričakovano je, da bo termodinamski izkoristek takšnega reaktorja višji od trenutnih lahkovodnih reaktorjev, saj za hladilo uporablja natrij, ki ga lahko segrejemo da višjih temperatur kot vodo.

1. Introduction

Production of clean, renewable, reliable and safe energy for base load is a major goal of our society as we try to move forward from fossil fuels. Baseload plants are production facilities that are used to meet some of the given region's continuous energy demand and produce electricity at a constant rate [1]. Currently, one of the best means of clean energy production are nuclear reactors. But there is still room for improvement. Safety, waste production, efficiency, economics, weapons-proliferation resistance and overall social acceptance are some areas where improvements on existing nuclear reactors can be made. A company called TerraPower made an analysis in 2007 on how to provide humanity with the best source of energy. They concluded that the Traveling Wave Reactor (hereon referred to as TWR) offered improvements in all the above-mentioned areas [2]. TWR is a nuclear reactor concept that is based on converting ^{238}U into ^{239}Pu. The conversion happens in a form of a wave which is then followed by a wave of fission reactions. Energy released during this reactions is used to heat the sodium coolant which heats the water to produce steam which drives a turbine.

In this paper the proposed design and the underlying nuclear physics of the TWR concept are presented. The advantages of TWRs over currently most widely used nuclear reactors (Light Water Reactors - LWRs) will be outlined along with their potential importance in future energy production.

2. Fundamental physics of TWRs

In order to understand how TWRs work the knowledge of the basics behind physical principles that govern the behavior of TWRs is required. In this section, the fundamental physics of nuclear breeding and propagation of breeding and burning waves throughout the reactor will be discussed.

2.1 Nuclear breeding

Let us start with definition of fertile material. This is a material, which is not itself fissile but can be converted into a fissile material by irradiation with neutrons, capture of neutron and usually some number of beta decays.

Fissile material is such material which can undergo fission with thermal neutrons. Its potential barrier is lower than the binding energy that is introduced by capturing a thermal neutron.

Breeder reactor is a type of nuclear reactor that produces more fissile material than it consumes by converting fertile material into fissile material.

Nuclear transmutation is a process in which a nucleus in converted into another nucleus. Some of the most important neutron interactions are those, where fertile nuclides, like ^{238}U or ^{232}Th, are transmuted into nuclides, that can be fissioned by thermal neutrons, like ^{239}Pu or ^{233}U.

In figure 1 the chain of two breeding reactions is presented. Unstable nuclides have a certain half-life which is also denoted in the figure. This means that the fissile material is not produced instantaneously. In the upcoming sections the importance of this time for stability and safety of TWRs will be described. From now on the focus will only be on $^{238}\mathrm{U} - {}^{239}\mathrm{Pu}$ cycle.

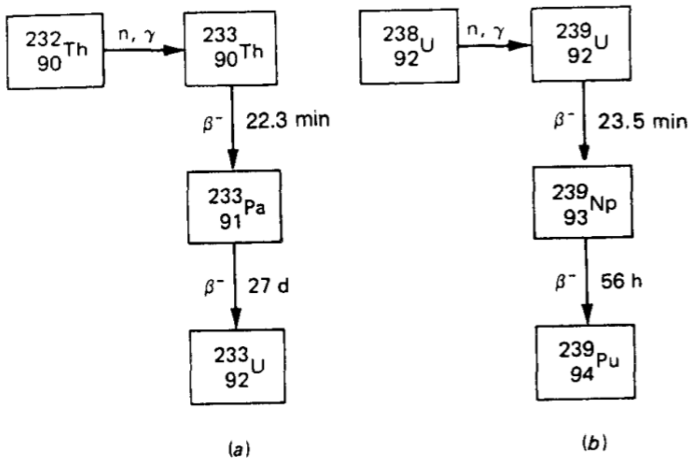

Figure 1. Transmutation process of a) ^{232}Th and b) ^{238}U into a) ^{233}U and b) ^{239}Pu. Reproduced from [3].

The relative amount of new fissile material that is produced is dependant on the number of excess neutrons; these are neutrons which are not needed to sustain the chain reaction. Let us define the average number of neutrons produced per neutrons absorbed in fuel η as

$$\eta = \frac{\int_{E_1}^{E_2} \Phi(E) \cdot \sigma_f(E) \cdot \nu(E) \mathrm{d}E}{\int_{E_1}^{E_2} \Phi(E) \cdot \sigma_f(E) \mathrm{d}E} \frac{\int_{E_1}^{E_2} \Phi(E) \cdot \sigma_f(E) \mathrm{d}E}{\int_{E_1}^{E_2} \Phi(E) \mathrm{d}E} \left(\frac{\int_{E_1}^{E_2} \Phi(E) \cdot \sigma_a(E) \mathrm{d}E}{\int_{E_1}^{E_2} \Phi(E) \mathrm{d}E} \right)^{-1} = \nu \frac{\sigma_f}{\sigma_a},$$

where E_1 and E_2 are the minimum and the maximum energies of neutrons inside the core. ν is the energy average and flux weighted number of produced neutrons per fission. Its dependance is shown in figure 2.

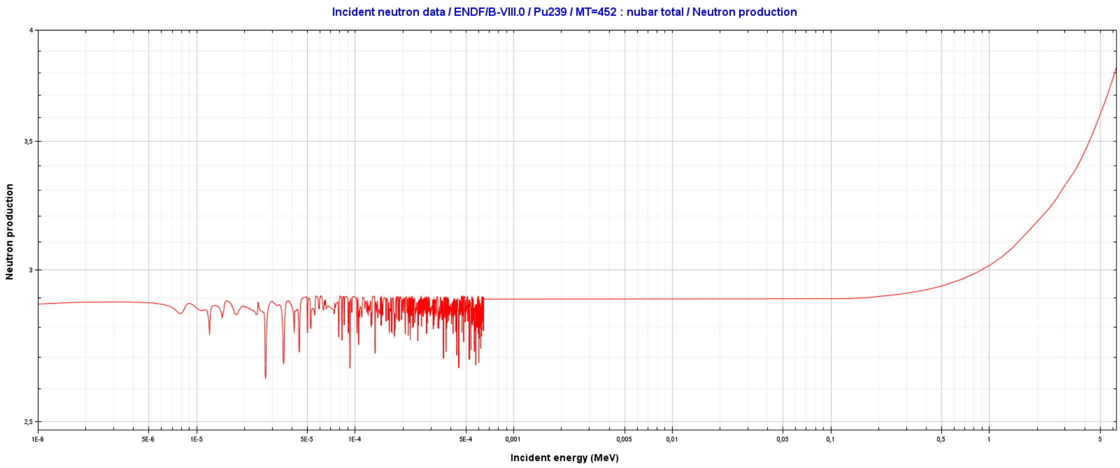

Figure 2. Number of neutrons produced per fission $\nu(E)$ for ^{239}Pu. Reproduced from [4].

σ_f and σ_a are energy averaged flux weighted microscopic cross section for fission and absorption respectively. Microscopic cross sections are energy dependant as can be seen in figure 3. Red line presents fission cross section σ_f and blue line presents cross section for radiative capture of neutron σ_γ. These two cross sections are the biggest contributors to the total absorption cross section for ^{239}Pu, therefor it will be assumed $\sigma_a = \sigma_f + \sigma_\gamma$.

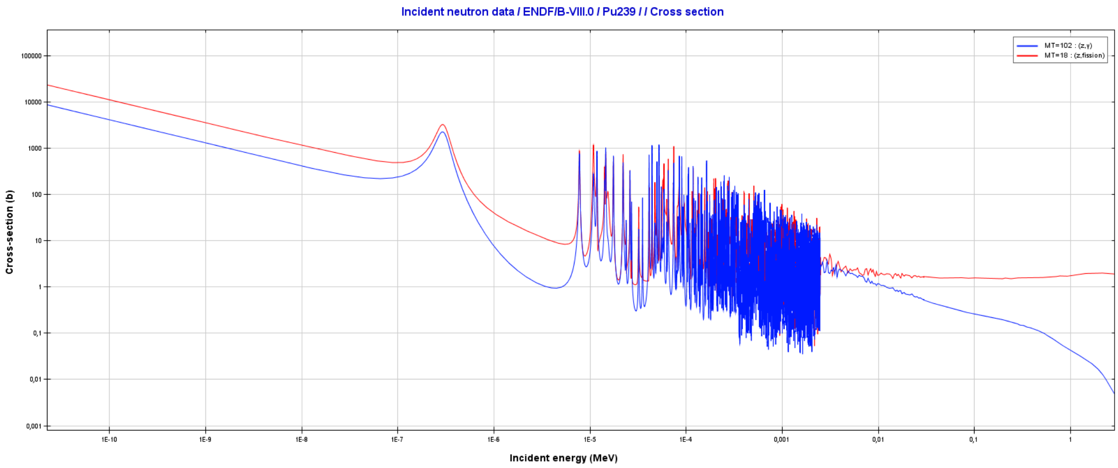

Figure 3. Fission (σ_f, red line) and radiative capture (σ_γ blue line) cross sections for ^{239}Pu. Reproduced from [4].

Ratio $\frac{\sigma_f}{\sigma_a}$ presents the fraction of absorptions that produce fission. It is depicted in figure 4.

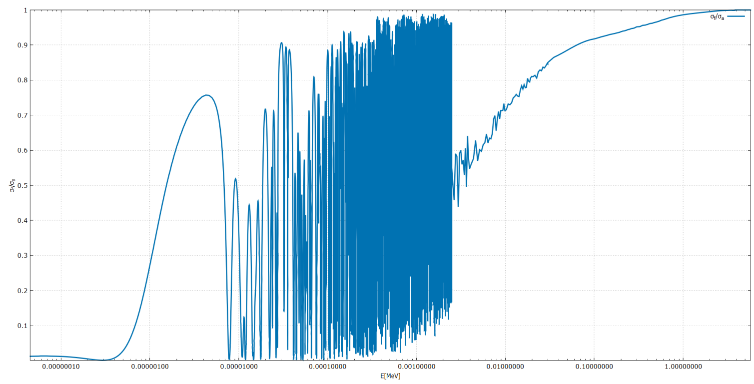

Figure 4. Figure presents ratio of $\frac{\sigma_f}{\sigma_a}$ for ^{239}Pu . Data for plot was obtained from [4].

To simplify η, definition σ_f, σ_a and ν have been integrated over all energies of neutrons in the core. They are weighted with flux of neutrons Φ which is also energy dependant. This flux is reactor specific. Since one neutron needs to be captured in ^{238}U and one to induce fission in ^{239}Pu the condition for breeding $\eta > 2$ is obtained.

η is dependant on energy of incoming neutrons and the type of fissile nucleus since both cross sections and ν depends on neutron energy and on the type of nuclide that the neutron interacts with. In figure 5 the dependance $\eta(E)$ is depicted for different nuclides. For fast neutrons with energies around 1 MeV ^{239}Pu has the highest η.

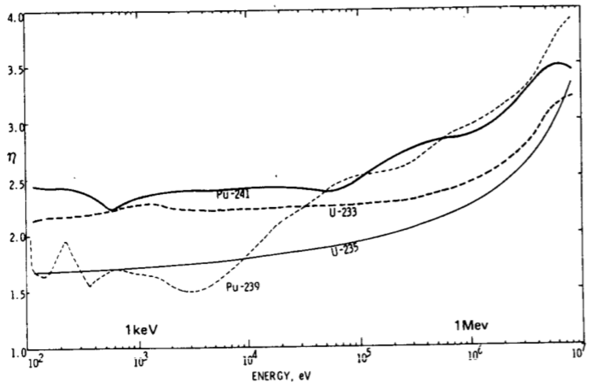

Figure 5. Relation $\eta(E)$ for different U and Pu isotopes. Reproduced from [3].

From the figure 5 it is apparent that η for ^{239}Pu starts to decrease when neutron energies are reduced i.e. when neutrons are moderated. Because of neutrons escaping and their absorption in non-fertile and fissile nuclides, it is desired to have η as high as possible. Neutrons that are born during fission are born mostly in fast spectrum with energies in the interval [1 MeV, 20 MeV]. When neutrons scatter on nuclei their energy decreases. This process is called moderation. One of the reasons why liquid sodium is used as a coolant in fast reactors, i.e. reactors where fission is induced by fast neutrons, is that it does not moderate neutrons very well so the spectrum stays mostly fast. In spite of that, the amount of sodium in the reactor core needs to be minimised to reduce moderation as much a s possible [3].

2.2 Inherent fuel safety

One of the major inherent safety concerns with LWRs is that there is almost always enough fissile material in the reactor that a run away reaction could at least theoretically happen. In case of emergency fuel cannot be removed from the place where the nuclear reactions are happening. A good analogy for this would be an internal combustion engine that is submerged in a pool of fuel. If it needs to be stopped, the fuel cannot be removed.

From here stems the idea for a reactor with internal safety. Fissile fuel must be produced in the core during reactor operation and its amount should not increase uncontrollably even if all safety mechanisms fail.

Very useful property of fission reactions is that not all neutrons are emitted instantaniously. A fraction of them is emitted when the fission products decay into more stable nuclei. These are called delayed neutrons. Since there are a lot of different fission products with different half-lives the delayed neutrons are usually split into groups with similar half-lives to simplify calculations. Example of this groups for ^{239}Pu is shown in table 1.

If the fuel is chosen in such a way, that the characteristic time of fissile component of fuel τ_β is significantly larger than the time of appearance of delayed neutrons, then the reactor will be

Group	Half-life [s]	fraction
1	54,28	0,000073
2	23,04	0,000626
3	5,60	0,000443
4	2,12	0,000685
5	0,62	0,000181
6	0,26	0,000092

Table 1. Table presents fraction and half-live of six delayed neutron groups for ^{239}Pu. Data was obtained from [5].

inherently safe. Let us try to define τ_β for $^{238}\mathrm{U} - {}^{239}\mathrm{Pu}$ chain

$$^{238}\mathrm{U}(n,\gamma) \rightarrow {}^{239}\mathrm{U}(\beta^-) \rightarrow {}^{239}\mathrm{Np}(\beta^-) \rightarrow {}^{239}\mathrm{Pu}(\mathrm{n,\ fission}). \tag{1}$$

Time of generation τ_β for fissionable isotope ^{239}Pu corresponds to half-life of its predecessors. Since $t_{1/2,{}^{239}\mathrm{U}} \approx 23$ min $\ll t_{1/2,{}^{239}\mathrm{Np}} \approx 2.3$ days [4] it can be estimated that $\tau_\beta \approx \frac{2.3\ \mathrm{days}}{\ln 2} \approx 3.3$ days which is significantly larger than the longest half-life of delayed neutrons which is around 55 s [3].

It must also be made sure that all self-regulation conditions are sustained in operation mode. This means that the equilibrium concentration of fissile fuel $\tilde{n}_{\mathrm{fiss}}$ must be greater than critical concentration n_{crit}. This condition is further described in the following section.

2.3 Neutron-fission wave

Idea of neutron-fission wave was first proposed by the Soviet scientist L. P. Feoktistov as he was trying to come up with self-sustaining and self-regulating nuclear reactor after the Chernobyl incident. He considered propagating nuclear chain reaction through fertile material ^{238}U in a form of traveling wave. Reactor core can be split into multiple sections as illustrated in figure 6.

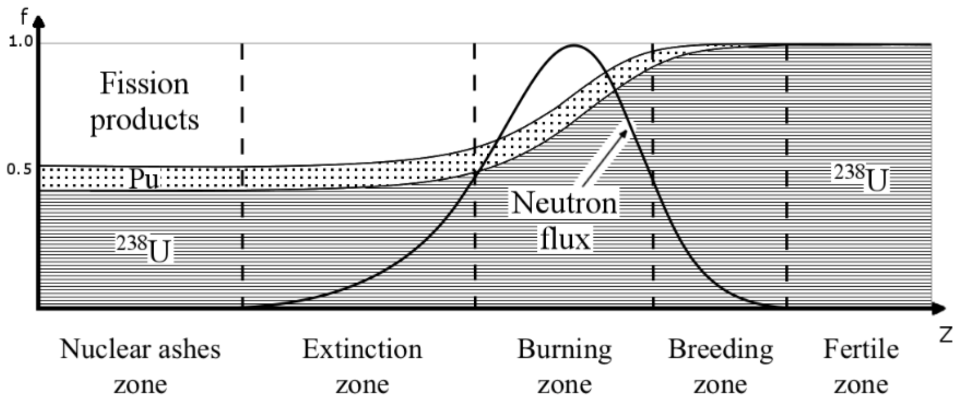

Figure 6. Nuclear burning wave propagating in ^{238}U medium. f denotes volume fraction, area filled with lines represents ^{238}U, with dots ^{239}Pu and white area presents other fission products. Reproduced from [6].

In the phenomenon of nuclear burning wave the active part of the core i.e. burning zone is propagating with time from area with fission products to area with fresh fuel. Next to the burning zone is the breeding zone in which new ^{239}Pu fuel is being created. When the concentration of plutonium n_{Pu} reaches critical concentration n_c, the burning starts in that region. A visualization can be seen in figure 7 [6].

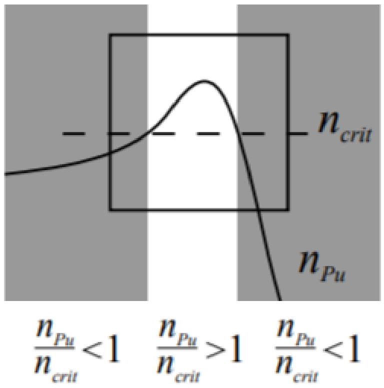

Figure 7. Area shaded grey represents the geometric region where the plutonium concentration n_{Pu} is below the critical concentration n_c. The white area is the burning zone. It is worth emphasizing that the calculation of n_{crit} was made only by considering ^{239}Pu, ^{238}U and ^{239}U. Consideration of fission product may change values for n_{crit} in the left grey region. Reproduced from [7].

As the breeding zone moves into burning zone a burning zone moves into extinction zone due to the burnup off fissile material and build up of fission products which absorb neutrons thus lowering η and making breeding impossible.

Although it is commonly referred to as traveling wave it is in practice more convenient to shuffle the fuel in the reactor instead to keep the burning wave stationary. This reduces the radiation stress outside of the core and keeps the reaction easier to regulate. The physics of the traveling and the stationary wave is the same.

2.3.1 Theoretical description

Let us now try to quantitatively describe the critical and equilibrium concentration of plutonium. Some simplifications will be made. One dimensional geometry will be assumed, the neutrons will also be grouped in a single energy interval. Further simplification will be made by assuming that ^{238}U is converted instantaneously into ^{239}Pu. This assumption gives valid results if reactor is operating for very long time, i.e. for calculation of equilibrium concentrations [7].

The main reaction is written in equation 1. From it the change of concentration of ^{239}Pu N_{Pu} can be derived as

$$\frac{\mathrm{d}N_{\mathrm{Pu}}}{\mathrm{d}t} = \phi(\sigma_{a8}N_8 - (\sigma_a + \sigma_f)_{\mathrm{Pu}}N_{\mathrm{Pu}}),$$

where ϕ is the energy integrated flux of neutrons, σ_{a8} is the energy-averaged neutron absorption cross section for ^{238}U, N_8 is concentration of ^{238}U, $\sigma_{a,f}$ are energy-average absorption and fission cross sections for ^{239}Pu and N_{Pu} is concentration of ^{239}Pu. Lets introduce equilibrium plutonium concentration $\tilde{N}_{\mathrm{Pu}}$. It can be expressed assuming $\frac{\mathrm{d}N_{\mathrm{Pu}}}{\mathrm{d}t} = 0$. The equilibrium plutonium concentration is

$$\tilde{N}_{\mathrm{Pu}} = \frac{\sigma_{a8}}{(\sigma_a + \sigma_f)_{\mathrm{Pu}}}N_8.$$

If the system is to be left alone under persistent neutron irradiation this is the concentration of ^{239}Pu it would achieve.

Let us define multiplication factor $k_{\mathrm{eff}} = \frac{N_t}{N_{t-1}}$ so that it tells us the ration of the number of neutrons in the current generation N_t and in the previous generation N_{t-1}.

Now let us also calculate critical concentration of ^{239}Pu N_c. At this concentration the multiplication factor equals $k_{\mathrm{eff}} = 1$. The number of neutrons in the system does not change. The N_c can be obtained from neutron balance equation

$$\frac{\mathrm{d}n}{\mathrm{d}t} = \phi((\nu - 1)\sigma_{f,\mathrm{Pu}}N_{\mathrm{Pu}} - \sum_i \sigma_{ai}N_i),$$

if $\frac{\mathrm{d}n}{\mathrm{d}t}$ is equated to 0. ν is the number of neutrons per fission event and i counts all the nuclei which absorb neutrons. N_c can then be expressed as

$$N_c = \frac{\sum_i \sigma_{ai} N_i}{(\nu - 1)\sigma_{f,\mathrm{Pu}}}.$$

There are three possible scenarios. If $N_{\mathrm{Pu}} = N_c$ our system is critical and energy production is constant. If $N_{\mathrm{Pu}} < N_c$ the reaction will come to an end without external source. If $N_{\mathrm{Pu}} > N_c$ reactor will be super critical (k $>$ 1). One might think that this last scenario is dangerous since if this happens the reaction will go out of control. But this is not the case. Let us recall that ^{239}Pu is produced on a time scale roughly similar to the longest half-life of nuclides in its production chain. That is above two days. Delayed neutrons appear in reactor with a characteristic delay of less than one minute. This means, that by the time that all delayed neutrons have appeared the concentration of ^{239}Pu has been reduced to very low value since ^{239}Np has not yet decayed into new ^{239}Pu and further increase in fission cannot occur. Reduction of fission reactions reduces neutron population thus giving opportunity for ^{239}Pu concentration to increase. To recap; increase of ^{239}Pu concentration leads to increase in fission events, leads to increase in neutron population, leads to faster burnup of ^{239}Pu nuclei, leads to reduction of fission events, leads to reduction of neutron population, ^{239}Np beta decay leds to increase of ^{239}Pu concentration, etc.

3. Design of TWRs

3.1 Plant design

TWR is a sodium-cooled fast reactor. The majority of neutrons that induce fission have energies in the range of [100 keV, 2 MeV]. It would be used to provide large quantities of base load electricity.

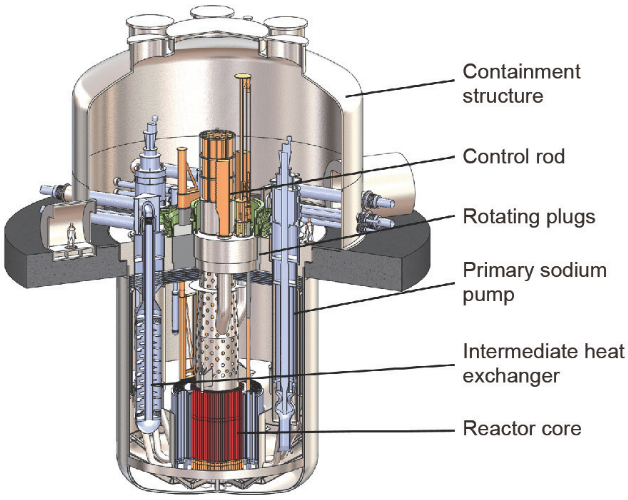

Figure 8. Illustration of TWR components inside the containment. Reproduced from [2].

TWR consists of three loops. Primary sodium coolant loop, secondary sodium intermediate loop and steam power conversion loop. Generated fission energy is transferred through both sodium loops to the steam generators which produce superheated steam that drives turbines.

The intermediate loop is there to provide integrity of the core and primary sodium loop. In case of leakage of fuel or a break in primary loop the radioactivity is contained inside the containment building. In figure 8 the containment building of TWR is illustrated. Reactor core, pumps and intermediate heat exchangers are submerged in a pool of molten sodium at atmospheric pressure, i.e. a pool-type configuration is used. The benefit of using a pool-type configuration is that it greatly reduces the risk and consequence of coolant leak accident [2]. Similar configurations have already been used in multiple fast sodium cooled reactors such as Experimental Breeder Reactor-II, SuperPhénix and BN-800.

Designs for commercial TWRs have electric power rating from 600 MW to 1200 MW. Core inlet and outlet temperatures are 360°C and 510°C [2], which are significantly higher that those of LWRs. For example, in Krško nuclear power plant the inlet and outlet temperatures are 287°C and 324°C [8]. Achieving higher temperatures is possible because of higher boiling temperature of sodium. In LWR coolant must be kept in liquid state to limit fuel degradation and increase heat transfer from fuel elements. In order to increase temperature even more the coolant pressure needs to be increased which is hard from engineering point of view. Since the boiling temperature of sodium at atmospheric pressure is 880°C the steam can be heated to higher temperatures. This in turn means greater thermodynamic efficiency on the turbine. TWRs are expected to have an efficiency of around 41 % [2], which is significantly higher than 35 % of LWRs [8].

3.2 Core design

One of the main differences between TWRs and sodium fast breeder reactors (SFRs) is fuel composition. SFRs require relatively high enrichment of fuel to achieve criticality. Usually more than 20 % of ^{235}U. They also have burnup typically significantly under 50 % of initial fissile atoms. This mean that a process of fuel reprocessing is needed to reuse fuel [2].

TWR cores improves fuel performance and reactivity. This allows us to use fuel with near-zero amount of fissile nuclides like ^{235}U or ^{239}Pu. TWRs could burn materials such as depleted uranium, natural uranium, low-enriched uranium fuel and also spent LWR fuel. TWRs would not rely on separate reprocessing and transuranic fuel fabrication infrastructure since the fissile fuel is bred in the core from breedable ^{238}U.

It is thought that TWRs could achieve burnup of up to 170 $\frac{\mathrm{GW\cdot days}}{t_{\mathrm{heavy\ metal}}}$ [2] which is significant improvement of 50 $\frac{\mathrm{GW\cdot days}}{t}$ that current LWRs achieve [9]. This increase in fuel utilization corresponds to waste reduction of 80 % [2] by weight of heavy metals over LWRs if its assumed once-through scheme (i.e. no recycling of the fuel) in LWR operation.

Since the fuel would stay longer in TWRs than in current LWRs it needs to be made resistant to damages that can be caused because of high neutron fluences and build up of fission products.

The clad material used in TWRs is a ferritic-martensitic steel HT9 which is optimized to resist swelling due to irradiation dose. It is very important that the fuel pins swell as little as possible when receiving high fluence since this improves the heat transfer and reduces chances for leaking of fuel into the primary loop. In figure 9 the difference in swelling of fuel pins that use two different types of cladding material is shown; stainless steel and HT9 which is currently the best candidate to be used in possible future TWRs.

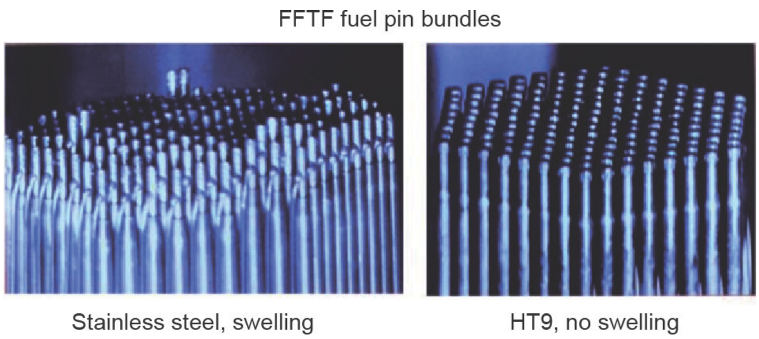

Figure 9. Irradiation-induced swelling of stainless steel and HT9 pins from Fast Flux Test Facility. Reproduced from [2].

Leakage is reduced by making the core bigger. By adding new rows of fuel to the periphery of the core a low power region is established which reduces leakage and increases reactivity of the core [2].

4. Conclusion

Traveling wave reactors offer great improvements over main disadvantages of current light water reactors. Reducing waste and providing greater safety are just two of them. They have great potential to replace or even work in tandem with LWRs. Spent fuel from LWRs could be used in TWRs since the fraction of ^{238}U is still very high. This will reduce the problem of nuclear waste even further. Despite all the work that has been done, working reactor is still relatively distant. New materials that can sustain high fluences need to be tested and worked on. There were plans between China and TerraPower to build such a reactor in the early 2020s but since 2019 this plans were abandoned due to political reasons. Fear of nuclear energy is still a big obstacle to overcome and progress in a world with sustainable and better nuclear energy.

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