

The Dual Fluid Reactor - A novel concept for a fast nuclear reactor of high efficiency

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Abstract

The Dual Fluid Reactor, DFR, is a novel concept of a fast heterogeneous nuclear reactor. Its key feature is the employment of two separate liquid cycles, one for fuel and one for the coolant. As opposed to other liquid-fuel concepts like the Molten-Salt Fast Reactor (MSFR), both cycles in the DFR can be separately optimized for their respective purpose, leading to advantageous consequences: A very high power density resulting in remarkable cost savings, and a highly negative temperature feedback coefficient, enabling a self-regulation without any control rods or mechanical parts in the core.

In the current reference design the fuel liquid is an undiluted actinide trichloride based on isotope-purified Cl-37, circulating at an operating temperature of 1000 °C. It can be processed on-line in a small internal processing unit utilizing fractional distillation or electro refining. Medical radioisotopes like Mo-99/Tc-99m are by-products and can be provided right away. In a more advanced design, an actinide metal alloy melt with an appropriately low solidus temperature is also possible which enables a reduction of the core size and allows a further increase in the operating temperature due to its high heat conductivity.

For the reference design, pure Lead as coolant is the best choice. It yields a very hard neutron spectrum, fostering a very good neutron economy and therefore making the DFR a preferred thorium breeder but also a very effective waste incinerator and transmuter. With its high coolant temperature the DFR achieves the same ambitions as the Generation IV concept of the very high temperature reactor (VHTR), with all its advantages like electricity production with high efficiency and the synthesis of carbon-free fuels, but with overall production costs competitive with today's refined oil.

The specific combination of the liquids in the very high temperature regime requires structural materials withstanding corrosive attacks. Because of the small size of the reactor core the utilization of these expensive materials would have no significant impact on the overall energy (and also economic) efficiency, measured by the EROI (Energy Return on Investment), which is more than 20 times higher than for a light-water reactor (LWR).

The DFR inherits the positive properties of the lead-cooled reactor (LFR) and of the MSFR, especially its outstanding passive safety features.

Keywords:

Fast breeder reactor, Molten-salt reactor, Lead-cooled reactor, High temperature reactor, Partitioning and Transmutation, Pyrochemical processing

1. Introduction

In the early decades of nuclear fission power technology development, most of the possible implementations were at least considered in studies and many were tested in experimental facilities as most of the types of the Generation IV canon. Uranium enrichment and fuel reprocessing with the wet chemical PUREX process for today's reactors originated from the Manhattan project in order to gain weapons-grade fissile material. The use of fuel elements in light water reactors originated from the propulsion systems of naval vessels like submarines and carriers.

A sound measure for the overall efficiency and economy of a power plant is the EROI (Energy Return on Investment, [1]). The known problem of solid fuel elements in power reactors that fission products accumulate during operation requires heavy safety measures to avoid a core meltdown. These measures reduce the EROI for today's pressurized water reactors

(PWRs) to values of about 75 (see [1] and Sec. 9) which is only a factor of 2 higher than for fossil-fired power plants. This is in fact surprisingly low compared with the possible maximum EROI for nuclear energy of 10,000 (see Sec. 9).

Unfortunately, most Generation IV reactor concepts except the Molten Salt Fast Reactor (MSFR, see below) are again based on solid fuel technology. For the probably most intensively developed breeder technology, the Sodium-Cooled Fast Reactor SFR (or the Traveling-wave variant, Terrapower's TP-1 [2]), sodium has been chosen as the coolant. It has aggressive chemical reactivity with air, water and structural materials as well as a high neutron reaction cross section with the possibility of a temporary positive void coefficient. These properties require a reactor pressure vessel, double-walled piping, and an intermediary cooling cycle. In effect all this sums up to expenses which double the electricity production costs of the SFR relative to a PWR as calculated for the Superphénix class [3]

(p. 24). Hence Generation III and most of Generation IV nuclear power plants are in danger of losing competition against fossil fired power plants, especially in the advent of the shale gas exploitation.

The Dual Fluid Reactor (DFR) concept presented here is designed with respect to the EROI measure and passive safety standards according to the KISS (keep-it-simple-and-safe) principle and with attention to the state of technology in mechanical, plant and chemical engineering for a speedy implementation. It was a gap in the reactor concepts of the past with a high development potential. A DFR power plant could exploit the potential of nuclear fission power with an EROI two orders of magnitude higher than fossil fired power plants.

2. Basic principle

The Dual Fluid Reactor (DFR) is a heterogeneous fast reactor with a liquid coolant and a liquid fuel whereby both flow through the reactor core. The separation of the cooling and fuel supply function is achieved by an interconnected array of fuel conduits immersed in the coolant liquid. Both cycles can now be optimized for their respective purpose. This has many advantageous properties in comparison to the MSFR, where both functions must be satisfied by one material in a trade-off between high-temperature fuel, low-temperature cooling, and an acceptable heat capacity.

The coolant liquid is required to have the highest possible heat transportation capability and best neutronic properties. Pure molten Lead has low neutron capture cross-sections, a low moderation capability, and a very suitable liquid phase temperature range. For the fuel it is possible to employ undiluted fissionable material as opposed to the MSFR that works with less than 20% actinide fluoride, see Sec. 4 for details. Consequently, a DFR has increased power density, small core volume and very hard neutron spectrum that further improves the neutron economy. Additional benefits of liquid metal coolant comprise the application of magneto hydrodynamic techniques both for pumping and, possibly in the future, direct electricity generation because of the high concentration of charge carriers. Furthermore, the reactor core and primary coolant loop can operate at normal pressure which allows for simple and cost regressive size scaling.

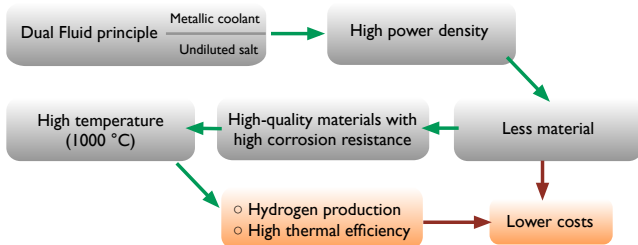


Figure 1: The flow chart shows the advantages of the Dual Fluid principle partially depending on each other. It is essential for the understanding of the synergetic effects.

Fig. 1 explains the synergetic effects. The Dual Fluid principle opens the possibility of a liquid fuel with high actinide

concentration in combination with a coolant with high heat transfer capability, which leads to a high power density. Liquid fuel like in the MSR already reduces the consumption of structural materials compared with solid fuel reactors, but the power density is limited. In the DFR, both positive properties can be combined which leads to a massive reduction of structural materials. At high operating temperatures (needed when using an undiluted salt, see Sec. 7), corrosion of core structural materials limits the choices of such materials. However, corrosion resistant materials at high temperatures do exist, but they are quite expensive. Using such materials in a DFR design has little effect on its economy due to its small size, low material inventory, and the absence of any parts that need be to replaced periodically. On the other hand, the use of such expensive corrosion resistant materials in an MSR has adverse economic effects due to its high inventory of structural material. This limits the temperature of the MSR and focused the MSR research in the past years on finding suitable eutectic salt mixtures, also complicating the production and reprocessing techniques. For the DFR, very simple state-of-art techniques can be applied, see Sec. 4.2.

Another comparison can be made with the Generation IV concept of the Lead-cooled fast reactor, LFR. Again, due to economic reasons, the wall material of the exchangeable fuel rods must be cheap, which focused the research on finding suitable steel alloys. They yet have a higher Lead corrosion susceptibility than the expensive materials intended for the DFR design, therefore also limiting the operating temperature. Due to the these material restrictions, both, the LFR and the MSR, are not able to achieve operating temperatures suitable for economic hydrogen production from water. These restrictions do not exist for the DFR.

Contrary to the MSFR, DFR's liquid fuel is not limited to actinide salts, even though it is the current reference design. However, an alternative could be a solder-like melt of a metal alloy made up of actinides and, if necessary, metals with low melting points in order to reduce the solidus temperature of the alloy and gain a pumpable fluid. The advantage would be an even higher power density due to better heat transportation capability, and a possible higher operating temperature due to the lower corrosive potential of the metal alloy. The basic design, then, allows for a high degree of possibilities which can be trimmed to a specific purpose. These concepts, will be discussed briefly in Sec. 4.2.

As a result, a new concept not fitting into one of the Generation-IV reactor developments has been invented, that foresees a compact core with a very high power density, an operating temperature of about 1000 °C, inherits MSFR's passive safety features, and has hard neutron spectrum. The abundant neutron excess can be used for multiple transmutation purposes, like nuclear waste incineration, and breeding for ^{238}U and ^{232}Th cycles. All this produces a nuclear power plant with a outstanding economic competitiveness.

3. System overview

Fig. 2 shows how a DFR reference power plant might look like. The reference design has power output of 3 GWth and an

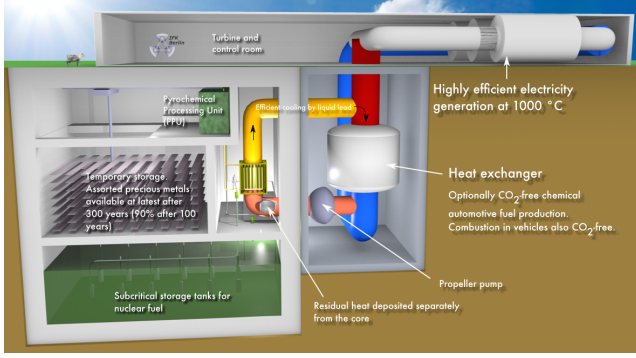


Figure 2: Possible power plant based on the DFR, with the nuclear part including the core, the pyro-processing unit (PPU), disposal and decay heat dump (left hand side) and the conventional part with the heat exchanger and turbines (right hand side). The compactness allows for a subterranean installation.

electric output of $\sim 1.5 \text{ GW}_e$ which is currently the typical nuclear plant size for the electric grid of industrialized countries [4]. Due to its compact size, the nuclear part can reside in a subterranean bunker that can withstand high magnitude earthquakes, direct aircraft impacts and non-concentrated conventional military attacks. The conventional part can utilize supercritical water or supercritical CO_2 (see Sec. 8.1) and is not fortified for economical reasons, but fortification to any desired degree can easily be achieved.

3.1. Fuel and coolant loop

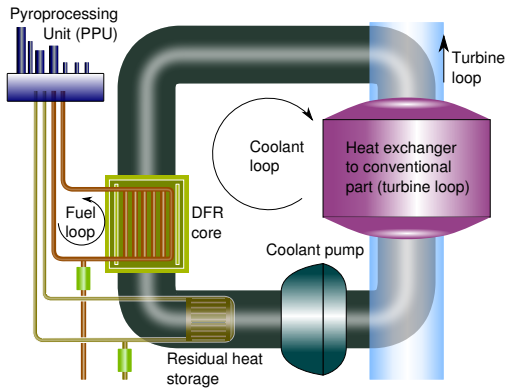


Figure 3: DFR fuel and cooling loop. The fuel circulates between the PPU (which is also connected to the fission product storage) and the core whereas the coolant loop connects the fissile zone to the conventional part, also cooling the fission product storage. PPU, core and fission product storage are equipped with a fuse plug.

Since the cooling function is separated from the liquid fuel, the circulation of the fuel's can be adjusted to nuclear purposes like maximum burn-up, transuranic incineration, isotope production, fertile material conversion (breeding), specific deactivation of fission products, etc. Fig. 3 depicts the reactor core as well as the fuel loop and the primary coolant loop. The liquid fuel enters the core vessel at the bottom, spreads over a system of vertical tubes where it becomes critical, and leaves the reactor on top towards the Pyrochemical Processing Unit (PPU).

The Lead coolant supply pipes have a large cross section in order to reduce the circulation speed and therefore reducing the abrasion at the surface materials. It circulates with a rate of 90 tons/s ($10 \text{ m}^3/\text{s}$). When it enters the core vessel from the bottom it takes the heat from the fuel duct by conduction and leaves the vessel on top towards the heat exchanger. Depending on the power needed, part of the Lead's heat is taken for electricity production or as process heat. The Lead leaves the exchanger at a lower temperature and is pumped back to the reactor vessel. This can be accomplished by a propeller pump which produces a steady stream without generating sonic shock oscillations in the liquid metal. For maintenance the Lead coolant can also be drained at the bottom of the reactor vessel into a temporary coolant storage where it can be pumped back into the reactor vessel.

3.2. DFR core

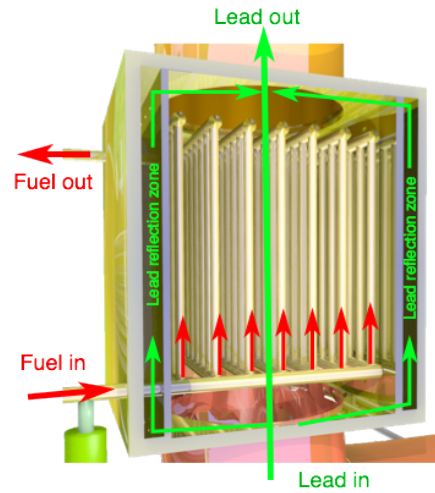


Figure 4: DFR core details. The cubic core (without blanket here) includes a pipe system filled with fuel salt which is connected to the fuel loop (with fuse plugs) and immersed in flowing Lead (coolant loop).

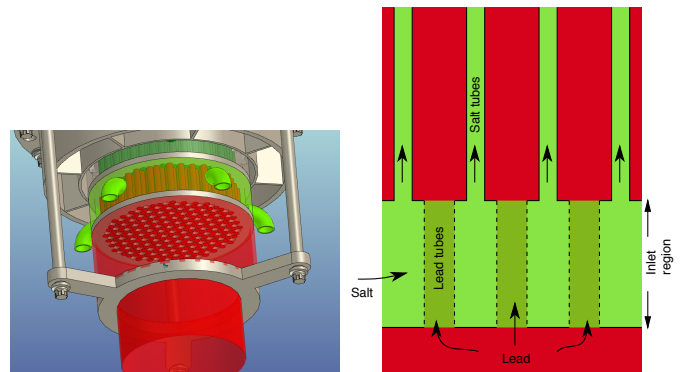


Figure 5: **Left:** DFR core inlet region, cylindrical design. The reflector region is located directly below the lateral salt feed tubes, surrounded by the blanket region. **Right:** Schematics of the inlet. In the inlet region, the salt surrounds the Lead tubes and enters the salt tubes in the core. This ensures equal pressure on all salt tubes.

The reference plant uses mixture of actinide salts as fuel. It has a cubical core with a width of about 3 m for the critical zone that contains ~10,000 vertical ducts (the number is reduced in Fig. 4 and 5 for illustration reasons). Fig. 4 is a simplified draft of the core in order to elucidate the principal. An actual core CAD model is depicted in Fig. 5.

The parallel arrangement of the fuel tubes guarantees a quick drainage of the fuel liquid within minutes while the high number of tubes provides sufficient surface for the heat transfer to the surrounding coolant. An equal flow velocity through all vertical rods is desirable and is achieved by a horizontal-flow inlet zone with baffle plates providing equal pressure differences at the vertical junctions.

An additional outer volume filled with Lead serves as a neutron reflector reducing the loss of neutrons and contributing to the reactivity regulation. The separation walls have small vents at the top and bottom in order to correspond with the Lead loop. A further fertile blanket, with simple structure, can increase the conversion ratio remarkably.

While passing the core region through the conduit array more and more actinides are fissioned and transmuted and the fuel changes its chemical composition. The fuel volume of the reference plant is only a few cubic meters, which further simplifies its handling and processing.

3.3. Heat transfer

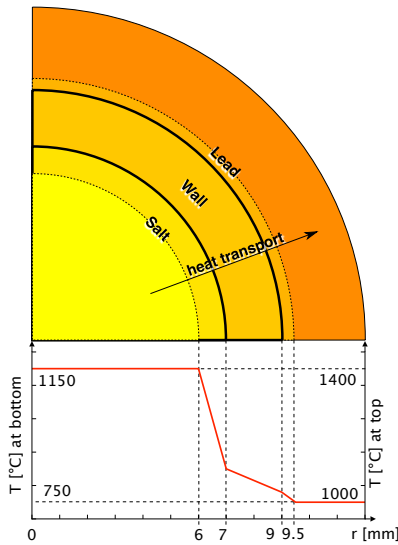


Figure 6: Heat transfer from inside of a single fuel pipe to the coolant. The temperature gradient can be divided in three zones: The turbulence layer of the fuel liquid (salt → inner pipe wall), the tube wall itself and the turbulence layer of the liquid Lead (outer pipe wall → Lead). Values are for high salt velocities and MHC pipes. For SiC, see text.

Fig. 6 shows the heat transport. Inside the fuel tubes where the heat is generated the temperature has its maximum. In a region of only 1 mm towards the tube wall the temperature drops by 270 °C, inside the wall by up to 85 °C, and up to 0.5 mm outside the wall another 50 °C, so the total radial temperature drop is roughly 400 °C. The Lead coolant moves from the bottom to the top which defines the Lead temperatures at those points to

750 °C and 1000 °C, respectively. Consequently, the temperature inside the fuel (tube center, not at the walls) is 1150 °C at the bottom and 1400 °C at the top which defines the highest absolute temperature in the reactor core. Since the bottom salt temperature at the tube wall is by at least the wall temperature gradient (85 °C) higher than the bottom Lead temperature, the salt would not freeze out there. These tube wall salt temperatures are 840 °C and 1090 °C for the bottom and top region, respectively, compared to the salt melting point of about 800 °C.

3.4. Tank for short-lived fission products

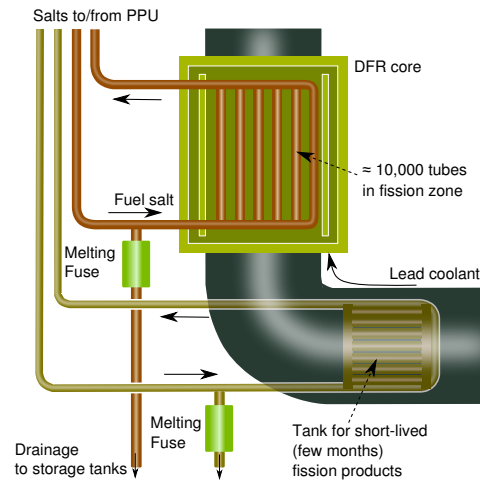


Figure 7: Close-up of the DFR core region with part of the coolant cycle and the short lived fission products storage inside the coolant conduit ahead of the core.

Highly radioactive and heat generating fission products with half-lives of weeks to months pose the main problem for reactors with solid fuel rods and cause core meltdown unless sufficiently cooled. In the DFR like the MSFR these fission products are regularly separated from the fuel liquid so that the core contains only few quantities of fission products and its handling in case of an emergency is unproblematic. However, the problem is then transferred to the storage of the fission products. In the DFR, this problem is solved by storing the short lived fission product salts, roughly 1 m³, in the pipes of a special coolant duct segment shown at the bottom part of Fig. 7, just before the Lead reaches the core, where they are cooled by the liquid Lead stream during normal operation of the plant. The molten salts of the short lived products slowly revolve through this tank as well as the PPU. In case of an emergency or maintenance shut-down, they can be drained through a melting fuse plug, similar to the fuse plug used for the reactor core, see next chapter.

3.5. Melting fuse and the subcritical heat storage

Melting fuse plugs, already proven and tested in the Oak Ridge molten salt reactor experiment, are used in the DFR for the short-lived fission products tank and for the reactor core (green plug below the core and the tank). It is essentially a pipe

segment which is actively cooled with a constant heat transportation such that the fuel inside this segment just freezes out. The cooling power of the fuse is fixed, so that the plug does not yet melt at 1000 °C. In case of an emergency, i.e. higher core temperatures or power outage, or for an intended fuse plug cooling power-off in a regular shutdown, the fuel heat power will melt the plug which opens, and the fuel is drained gravitationally to the subcritical tanks.

The subcritical tanks (see Fig. 2) are used for fuel inventory and the concentrated highly radioactive short-lived fission products from the storage in the main coolant loop. Each of the tanks has a capacity for a subcritical mass of the liquid fuel. They are embedded in a volume filled with salt or metal (e.g. iron, assembled from ‘Lego’-like bricks, establishing full heat contact by temperature expansion) which transduces the quickly fading heat energy passively through the outer walls to the surrounding. The heat production lowers from 200 MW (emitted from the core) immediately after shutdown to some 5 MW (from the coolant duct segment) after 12 days. The salt remains liquid for several days and can be pumped up, entering the fuel loop again. After longer storage, a preheating system is required.

3.6. Fission product treatment

The PPU removes the fission products from the liquid fuel and replenishes it with fresh actinides that may come from natural/depleted uranium, burned fuel elements, and thorium at a consumption rate of 1200 kg/year. Fission products are sorted by chemical elements and the longer living (half-lives of years to decades) are cast into small globes which are packed and hermetically sealed in ripple tubes. The tubes are transferred to a decay storage bunker below by a manipulator arm (also indicated in Fig. 2). The bunker can store all fission products, 500 kg/year, produced during whole life-time of the reactor. The sorted fission products can be removed according to their half-life. 90% of all fission products can be removed after 100 years, providing valuable and rare metals. The medium-lived fission products decay within 300 years and may remain in the storage for that time. The ripple tubes inside the storage are passively cooled by ambient air utilizing the stack effect.

4. Liquid fuel and its processing

The employment of a liquid fuel eliminates the need for the costly fuel element infrastructure industry and replaces it with online processing of the fuel. In principal, it is possible to consider all chemical separation methods in the reprocessing of nuclear fuel, since the radioactivity is a subordinated problem. This, however, is not true for the presently applied PUREX process, as shown in the following.

4.1. Present reprocessing techniques

Originating from the weapon production, the usual aqueous organic reprocessing techniques like PUREX are performed off-site. As the chemical processes proceed slowly at normal temperatures large volumes of consumed auxiliary chemicals with medium and low radioactivity are required and have to be

dumped. In order to limit this additional nuclear waste, spent fuel elements need to be stored for at least 1 year, in practice rather 5–10 years, before starting the PUREX processing, otherwise the expensive organic solvents are destroyed by the intense radiolysis and therefore have to be replaced very often. Hence, the radioactivity of the fuel has an eminent relevance here. The class of aqueous organic reprocessing techniques is inappropriate for online fuel processing.

A real progress was made by implementation of the reprocessing inside the Integral Fast Reactor (IFR). It uses electrorefining, a long known method in metallurgy, for the separation of the fission products: The metallic fuel is converted to a salt which in turn is used for the electrolysis wherein the actinides deposit at the electrode and the fission products mainly remain in the molten salt. This manageable reprocessing unit was used on-site of an IFR plant [5]. After the IFR program was canceled its successor, the S-PRISM reactor, inherited the process, though in a central off-site processing facility.

A possible online reprocessing technique was tested for the MSFR – a dry method with a vapor-phase fluoride-salt distillation system as the main component where the metal salts are separated by boiling points. However, many fluorides have very high boiling points so that additional fluorination is required and yet metal fluorides remain in a slurry needing further treatment steps. In an MSR, a real online fuel reprocessing conflicts with the cooling requirements, therefore the reactor must be shut down to branch the fuel into the reprocessing facility which needs a high capacity in order to keep the outage time of the reactor short. Nevertheless, such pyrochemical processing facilities are still small in comparison to PUREX-like methods.

The distillation techniques, and in particular, the electrorefining techniques are subject to ongoing development activities for the Generation IV reactors as well as a substitute for the complex wet chemical PUREX reprocessing plants [6] [7].

However, online does not necessarily mean continuous. Batch techniques may be used as well, provided the continuously pumped fuel fluid is intermittently stored in a small buffer while the previous batch from the buffer is processed.

None of the present reactor concepts of the Generation IV provides a real online fuel reprocessing. This means that none of these concepts has all the advantages of a liquid fuel that could be achieved with a true online fuel reprocessing like very low criticality reserves which are a control issue in solid-fueled reactors, especially ADS, or MSRs with long fuel processing periods.

4.2. Fuel processing in the DFR

As pointed out, for online fuel processing the employed technique must be congruously fast so only dry high temperature methods can be considered. Moreover, the fuel must be impervious to radiolysis within the process. The liquid fuel of the DFR for the reference design is a molten salt, but could be also a metallic melt as a future option. Therefore, the DFR concept is *not an MSR variant*, and the reprocessing techniques are different because of the very different salts. Due to the ionic nature of the bond in the case of the salt and the metallic bond

in the case of the metallic melt, the liquid is impervious to radiolysis which makes it suitable for *physico-chemical* separation methods at high temperatures. These methods will be used in the PPU of the DFR.

For the possible future concept of a metallic fuel melt there are several options ranging from a more heterogeneous system with liquid plutonium over a solution of actinides in Pb/Bi/Sn to a dispersion of solid actinides and/or actinide compounds in Pb/Bi/Sn. The prospects of metallic fuels were already investigated in the 1950s [8]. More precisely, the last option would be made up of actinides which are suspended in a melt of metals with low melting points with a fraction of up to 75 mol.% which reduce the solidus temperature of the alloy below the operating temperature, because some of the involved actinides have too high melting points. Suitable metals with sufficient neutronic properties are Lead, Bismuth and Tin. The accrued multi component alloy does not necessarily need to be an eutectic – if the liquidus temperature is above the operating temperature the mixture is sufficiently pumpable in this pasty phase. The processing of the metallic melt can be performed with a first fractionated distillation step where the metals with low boiling points compared with actinides like Lead, Bismuth and some of the fission products can be separated and the remaining slurry is converted to salts and then distilled as before. Then, the resulting salt fractions need to be converted to metals back again by electrolysis before re-insertion into the reactor fuel loop.

For the reference concept we use molten salts because of their lower melting points and wider range of experience. Unlike MSR we adopt chlorides since fluoride salts have considerable moderating quality thus softening the neutron spectrum and deteriorating the neutron economy. This together with the high boiling points of many of the involved metal fluorides render fluorine inapplicable. Higher halogens are more practical with respect to both properties. For the metals in the fuel mixture chlorine salts have sufficiently low boiling points so that a separation by boiling points in a fractionated distillation facility alone becomes feasible.

Hence, the fuel is a binary combination of only a fertile and a fissile actinide chlorides which can be $^{238}\text{U}/^{239}\text{Pu}$ or $^{232}\text{Th}/^{233}\text{U}$ [9]. **It should be clearly noticed that no carrier salt is needed or desired, as opposed to current MSR concepts – this is the advantage of the Dual Fluid principle.** The fraction of the initial load of reactor-grade Pu or enriched U depends on the size of the reactor core because of neutron losses through the surface. For the reference plant it is 23% (reactor-grade Pu) or 19% (^{235}U) mass fraction according to first static SERPENT calculations. The maximum ^{239}Pu fraction required for the smallest useful set-up can be very high and is not limited by the reactivity coefficient of the Doppler-broadening effect of ^{238}U while larger cores can manage smaller fractions. The rest of the fuel is fertile material like ^{238}U or ^{232}Th . Here, the fuel salt would consist of the trichlorides of the actinides, i.e. UCl_3 and PuCl_3 , which have a suitable temperature range of the liquid state. Purified ^{37}Cl should be used in order to avoid neutron losses due to their capture by ^{35}Cl and production of the long-lived radioactive isotope ^{36}Cl .

Both previously developed and tested reprocessing methods

of the Generation IV reactors, fractional distillation and electrorefining, can also be employed by the DFR. The capacity of the PPU can be designed even much smaller because of the low fuel volume [10]. In a simple version, the electrorefining method can be used in order to purify the fuel salt by precipitation of a fission product mixture. For the purpose of specific transmutation, a more precise partitioning is required which can only be accomplished by fractionated distillation/rectification, which is beyond the MSFR principle.

Basically, whenever liquid fuels are used certain preprocessing steps have to be accomplished in order to deal with volatile and ‘noble’ fission products. In the case of a fuel salt and the fission of plutonium, significant quantities of metals are produced which can hardly form chloride compounds, notably Mo, Ru, and Rh. In the frame of the MSRE this issue was investigated in the view of the possible segregation problem of said fission products. It turned out that the segregation is not a progressive process but instead an equilibrium accrues between segregation and solvation [11]. This equilibrium level can be controlled by the overall chemical potential of the molten salt which may be adjusted by the quantity of chlorine ions and possibly certain minor additives. The chemical potential also determines the corrosive properties of the salt. In preprocessing steps the noble metals in the fuel coming from the reactor can be precipitated by bubbling noble gas (He, Ar) through the fuel salt. The metals precipitate as platelets at the phase boundary between the gas bubble and the salt liquid where they can be subsequently retrieved by a rake. This makes it possible to easily separate ^{99}Mo , which decays to the important medical isotope ^{99m}Tc , see also sec. 8. Concurrently to the gas bubbling the volatile fission products Kr, Xe, Cs and I_2 are expelled as well and can be removed easily.

Volatile iodine as well as cesium can be removed from the fuel loop/PPU and bound chemically stable. Since a permanent reprocessing of the molten salt fuel is possible, only very few fission products accumulate so that their integration in the fuel salt is unproblematic. The low fission product concentration in the core also reduces corrosion. The salt has to remain in the liquid state during operation which is assured in the core by the criticality condition and in the PPU by the residual heat. A frozen salt would not damage the reactor but has to be preheated, e.g. by induction heaters.

Small, possibly mobile, DFR systems could use a once through cycle, i.e. they are not connected to a PPU and use the fuel inventory once. It can then be exchanged by pumping and processed in a PPU at a different location. The fuel’s range can be extended with a centrifuge which precipitates some of the fission product compounds by density separation.

5. Reactor operation and regulation

5.1. Neutron absorption and negative temperature feedback

The PPU fabricates a fuel mixture that is critical inside the reactor at the desired operating temperature of 1000 °C. There are three main effects which provide negative feedback to the fission reaction rate by depression of the neutron flux when the temperature rises:

1. Doppler broadening of the resonances in the neutron capture cross sections increases the macroscopic neutron capture cross section.
2. Density decrease of the molten salt fuel which reduces the fissile nuclei concentration, the far dominant effect with $\frac{dk}{dT} \approx -\frac{0.0005}{K}$ [12] assuming the density decrease of UCl_3 for the whole salt, where k is the effective neutron multiplication factor and T the fuel temperature.
3. Density decrease of the molten Lead reduces the concentration of the neutron reflecting Lead nuclei.

The change in reactivity due to a temperature induced density change in the liquid fuel is by far dominant and almost instantaneous because it is determined by the speed of sound.

Lead has a high atomic mass and 4 stable isotopes due to nuclear shell closure. Therefore, it is an excellent neutron reflector with low moderation qualities and low isotope-weighted neutron capture cross section.

These effects together with the density change cause a strong negative temperature coefficient in the fast neutron spectrum. This is in contrast to liquid Sodium as coolant which has a higher neutron capture cross section, higher neutron moderation and lower reflection quality which means an increase of the neutron flux with rising temperature, i.e. temporal positive temperature coefficient in several designs.

Furthermore, since the most abundant Lead isotopes are each at the end of a decay chain, prolonged exposure to neutrons can only induce low radioactivity. The highest stable Lead isotope, ^{208}Pb , has the lowest neutron capture cross section, which leads back to stable Lead via $^{208}Pb(n,\gamma)^{209}Pb(\beta)^{209}Bi(n,\gamma)^{210}Bi(\beta)^{210}Po(\alpha)^{206}Pb$. The stable ^{209}Bi accumulates slowly, so that only ^{209}Pb contributes remarkably to some activity, decaying with a half-life of only 3 h and, in contrast to Sodium, free from gamma radiation. For the only longer living nuclide, ^{210}Po (half-life 140 days), even 50 years of reactor operation and ^{209}Bi accumulation leads to an activity just comparable with natural Uranium. As a result the low and gamma-free radioactivity makes an intermediary cooling loop obsolete, which further reduces the expenses, see Sec. 8.1.

Due to its very strong overall negative temperature coefficient (five times that of a TRIGA reactor [13]) and limited fuel heat capacity, the usage of control rods in a DFR type reactor is not necessary.

5.2. Startup procedure

To start up the reactor the system is pre-heated until the coolant and the fuel salt liquify. Concurrently the cooling of the melting fuse plug is started. The fuel salt is pumped from the storage tanks to the reactor. At the tee connector just below the reactor some of the fuel fluid branches to the fuse where it freezes out and plugs it. As soon as the salt, preheated to 900 °C, slowly moves into the reactor core it becomes critical. Thanks to the very strong negative reactivity coefficient, dominated by the liquid fuel, an equilibrium temperature will be reached very fast, and it can not freeze out anymore (melting temperature at 800 °C).

Now the reactor is regulated by the described loops (see sec. 3). At the beginning the fission rate and correspondingly the power production is minimal. Then the coolant pump starts to accelerate the circulation of the Lead. The discharge of heat to the heat exchanger causes a temperature decrease in the reactor (of course the heat exchanger must be able to dump the heat energy). The control loops render the reactor supercritical until the nominal temperature is regained and well-balanced. This may continue until the nominal power output is reached. Conversely, if the Lead circulation speed is decelerated (also in case of a malfunction) the temperature in the reactor increases and it becomes subcritical until leveled off at the nominal temperature but with lower fission rate. In such a manner the fission rate in the reactor follows the power extraction. This can be done actively by the Lead pumping speed, or passively by feedback from the turbine's electricity generation. There is no need to control the fission rate directly in the reactor core (e.g. by control rods).

The equilibrium (nominal) temperature is determined by the fraction of the fissile material in the fuel salt. The PPU provides the appropriate fuel salt mixture.

5.3. Shutdown procedure

For a regular shut down the coolant circulation and the fuse cooling is stopped and the fuel salt empties to the storage tanks. The same happens if the power to the entire plant fails. Any other reason like malfunction and sabotage increasing the fraction of the fissile material raises the equilibrium temperature. For these incidents, again the melting fuse plug kicks in.

Consequently, the emergency shut down is the same as the regular shut down.

6. Neutron economy

With the U-Pu fuel cycle the fission of Pu produces a high neutron yield. Even after regeneration of the Pu fuel by conversion of fertile ^{238}U a large neutron surplus remains. Neutronics simulation calculations have been performed (Serpent, OpenMC); preliminary results, though with no conversion ratio calculations, are to be published [14]. If (besides fissile material) only ^{238}U is fed into the fuel this neutron surplus will end up as additional plutonium. In this case (or similar for ^{232}Th) the conversion rate is larger than one and the reactor works in the breeder mode.

The neutron surplus can also be used for other transmutation purposes, e.g. when long-lived fission products are specifically mixed in the fuel salt by the PPU. There is still a considerable neutron surplus when the reactor transmutes its own long-lived fission products which can be used to transmute fission products from waste fuel elements of other nuclear reactors. Only if this additional neutron surplus is consumed otherwise, but not for breeding, the reactor works as a self-burner, i.e. conversion rate equal one.

Alternatively the PPU can mix in Th or inert materials to even out the neutron surplus. The fission neutron yield of ^{233}U from the Th/U fuel cycle is considerably lower than for the plutonium fission. As other fast neutron breeders [15], the DFR

also can be operated in the Th/U cycle with a conversion ratio slightly larger than 1. The transmutation of its own long-lived fission products may be feasible. For that, the PPU needs to separate out and store the ^{233}Pa until it decays to ^{233}U . The PPU can handle the transition from the U/Pu to the Th/U fuel cycle continuously.

The fissile material in the fuel salt may also contain transuranium elements from waste nuclear fuel elements. As in the case of fission product transmutation the PPU would process chlorine salts made of the fuel pellets of waste fuel elements separating the chemical elements by boiling points. Then the PPU mixes the fuel salt from the desired actinides so that the criticality condition in the core is maintained. In this way the sources of fuel are natural uranium, depleted uranium, nuclear waste, and thorium. The reference plant can consume radiotoxic transuranium elements from burned LWR fuel up to 1200 kg per year.

One DFR using the U/Pu cycle can provide the initial fissile charge for another DFR, where the doubling time is comparable to the total construction time of a power plant and not the limiting factor for deployment. SFR's (like the French Superphénix and the Russian BN) together with PUREX-reprocessing plants have doubling times of 30–40 years. Utilizing the Th/U cycle in water cooled reactors with fuel elements would exceed even these long doubling times. The thorium MSFR (also known as liquid fluoride thorium reactor – LFTR or “lifter”) would have a doubling time of about 25 years.

7. Materials and fabrications

As mentioned in Sec. 4.2, for a compact nuclear core a high actinide fraction is necessary to obtain sufficient fissioning and breeding capabilities. Thus, the fuel salt should be undiluted which renders eutectic compositions dispensable. This results in elevated melting points of about 800 °C and demands high operating temperatures above 1000 °C. Therefore, the materials of the nuclear part must withstand high-temperature corrosion, a high neutron flux, and must have a very good high-temperature stability and creep strength.

These extremely resistant materials are known for many ten years but could not be treated in the past. This includes in particular alloys from the extended group of refractory metals, molybdenum- and tungsten-based alloys, as well as high-performance industrial ceramics. Meanwhile, however, fabrication methods are far advanced, so that such materials find applications over a widespread range in the industry [16], especially in the chemical industry, mechanical engineering as well as in the aviation (nozzles, jet vanes, balance weights). Their demand is still low but their technical feasibility has been proven in the past decades. For this reason they are expensive, and current material research for solid-fuel based reactors (LWRs, but also most of the Generation IV concepts) is focused on replacements like steel and Ni alloys.

This is in contrast to the DFR where higher material costs play only a minor role since the material demand is several times lower than for LWRs, as also pointed out in Sec. 2 (Fig. 1) and Sec. 9. The entire reactor needs only a few 100 tons of

refractory materials, with only 20 to 50 tons for the core, while the remaining 80–90 percent are in a simple geometry. The durability and creep resistance is a central point: it requires but at the same time enables a core that needs not to be exchanged. This point is often not seen by critics implicitly assuming a disposable material technique as required by the solid fuel rod technology involving a very restricted view on the material variety.

Tungsten and Tantalum show much less corrosion in NdCl_3 - NaCl-KCl or MgCl_2 - KCl salts compared to Hastelloy-X or Iron-/Chromium-based alloys [17] [18]. Molybdenum-based alloys show a high resistance against both molten fluorides [19] and, also Niobium alloys, against Lead [20] [21]. Chloride salts are significantly less corrosive than fluorides [22].

As a further option new ceramics may be considered, as coating and in the form of new fiber backed composite workpieces. Silicon carbide (SiC) is known for its low neutron capture cross-section and is therefore in the focus of today's nuclear material research. Especially CVD-like SiC, is very resistant against Lead corrosion at more than 1000 °C, even when Lithium is added (Pb-17Li), where pure Li would dissolve SiC at 500 °C [23]. Regarding molten salt corrosion, much less data is available for SiC. It was tested with NaCl which has a similar enthalpy [12] like UCl_3 and showed a good resistance up to 900 °C [24] even though it was a much less corrosion-resistant variant (reaction-bonded SiC with Si excess). Compared to that, CVD-SiC showed a much higher corrosion resistance [25]. Below 1200 °C, this material also shows a high irradiation resistance, whereas SiC/SiC fibre pieces are less resistant although the newest generation of these composites showed a higher resistance again [26]. Micro crystalline damages caused by the high neutron flux as well as thermal stress will be automatically healed at those high temperatures (annealing in metals) and ceramics are more resistant at elevated temperatures. In the PPU, there are even less restrictions as neutron embrittlement and heat conduction do not play a dominant role anymore.

Pieces from high-performance alloys, even from refractory ones, can be produced by new electron welding processes, high-pressure sintering and laser techniques. In particular the laser treatment cares for a high-purity crystal structure (smooth melting) – a factor very important for the corrosion resistance. Generally, refractory compounds are processed with the methods of the powder metallurgy, particularly because of their high melting temperatures and durability. The sintering process limits the size and shape of work-parts but new laser sintering methods might relieve many restrictions. Even though the fraction of voids for today's applications is still too high, sintering extruders are capable of producing monolithic pipes with smooth surfaces [27]. The whole array can be assembled with electron beam and/or laser welding in vacuum [28] [29]. For valves in molten-salt, contact-surface seals can be used since they will only be used hourly.

The high operating temperatures are well above the brittle-ductile region of refractory metals hindering strongly an embrittlement, best seen on Mo-based alloys [30]. Furthermore, highly-resistant coatings can be considered. Some refractory alloys are already ductile between 300 °C and 500 °C (or lower),

e.g. MHC (1Hf-0.1C-Mo) oder TZM (0.5Ti-0.08Zr-0.02C-Mo), maybe with some additions of Rhenium in the 1% region. All operating temperatures (inlet and outlet) are well between 850 °C and 1100 °C, 1400 °C occur only in the axial center of the fuel, not at the tube walls (see Sec. 3.3 and Fig. 6). The thermal expansion coefficients of refractory alloys are similar to the ones of ceramics not causing significant stress or tension, as also can be seen in turbine parts or high-temperature furnaces.

The entire core (total dead weight is a few ten tons) can be produced in a factory by the methods mentioned above and deployed on site exclusively by bolting and screwing or stacking/clamping in the case of SiC. Possibly the core must be segmented in order to ease the exchange of possibly damaged parts. For the coatings, corrosion resistant materials (SiC also as structural material, Si₃N₄, AlN in the core, possibly TiB₂, B₄C elsewhere) [31] exist, having a heat conductivity similar to Ni. For isolation, fan and fold sheets can be used but because of the high neutron flux the entire core has to be surrounded by a concrete shield anyway.

8. Applications

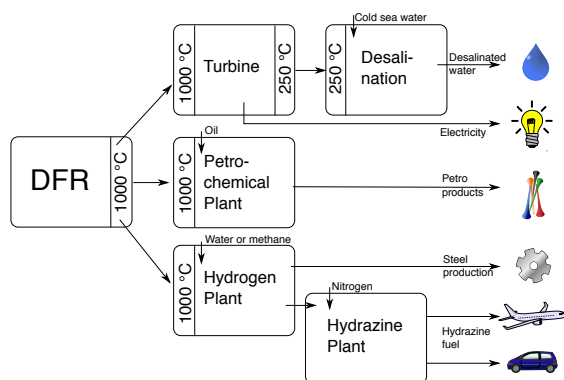


Figure 8: Possible applications for the DFR.

Fig. 8 depicts possible application. The high temperature opens the hydrogen-based chemistry with synthetic fuels suitable for today's vehicles. The low production costs make these applications competitive with fossil fuels like gasoline. Further applications are described in the following.

8.1. Conventional part

Due to the low and gamma-free radioactivity of liquid Lead (see Sec. 5.1) it is possible to extend the primary coolant loop directly into the conventional part of the plant. This translates into a considerable reduction of the reactor construction cost, as opposed to Sodium cooled reactors which require a secondary cooling circuit due to the high radioactive and gamma-emitting content of Sodium.

In the conventional part the heat energy needs to be transduced from the liquid metal, a medium with very high heat transport capacity, to a working medium with considerable lower heat transport capacity suitable for turbines. Without further development the most cost effective technique, nowadays, is

supercritical water (scH₂O) cycle. Albeit the newest coal fired plants work at 700 °C there is no principal problem to increase it to 1000 °C. Generally scH₂O turbines have more in common with gas turbines than with steam turbines since there is no phase change throughout the whole cycle; so operating parameters are quite similar. The reactivity of water with respect to its ability as oxidizer increases with temperature. However, modern gas turbines are made of very resilient materials and are capable to get along with sulphuric acid, dust particles, and hot steam at 1400 °C.

Another near future possibility is the usage of supercritical carbon dioxide (scCO₂) turbines, leading to more compact machine components with a slightly higher thermal efficiency and significantly reduced corrosion rates and pressures compared to scH₂O turbines. Although still in development [32] [33] [34], the experience and outlook is promising. The corrosion rates are monitored to be less than 1 mm per year at 1000 °C using industrial INCONEL MA 754 nickel-base alloy, decreasing with time [35]. The alloys used in the DFR are significantly more corrosion resistant so scCO₂ should be a minor problem.

8.2. Process heat and electricity

If the DFR is employed for process heat generation the conventional part may be modified. For process heat generation only a heat transducer to a secondary liquid coolant cycle or a direct heating of a chemical reactor in close vicinity with the primary coolant may be used. If a mixed process heat and electricity generation is desired, a first indirect heat exchanger which decouples heat energy at the high operating temperature may be followed by a subsequent heat exchanger which heats at a lower temperature water in a steam or supercritical water cycle with a connected turbine.

8.3. Future MHD option

A further possibility is the utilization of an MHD generator connected to the Lead coolant loop. Liquid metals are particularly eligible for that because of their high concentration of free charge carriers. The efficiency of the MHD generator is chiefly limited by the nozzle which converts the internal energy of the fluid into directed stream energy which is then converted to electricity. The still considerable residual heat after the MHD generator may be used in a subsequent heat exchanger with a water cycle as above. Such a system may be significantly less costly than multiple turbines.

8.4. Radiotomic chemical production

The short lived fission products storage may be designed in an alternative way in order to enable the utilization of the intensive radiation for radiotomic induction of chemical reactions requiring high doses (kGy/s). There is a constant power level of 30 MW of the short lived fission products in the reference plant which may induce a γ dose power of 0.1–1 MGy/s into compressed gases.

There is a small number of simple molecules that are the base for several process chains in industrial chemistry and result from strong endothermic reactions which are performed with

high expenses over several steps frequently employing costly catalyzers. Here a γ quantum can directly provide the required energy by multiple excitation/ionization of the educts resulting in a considerable simplification of the required equipment and reduction of costs all the more the radiation source exists anyway. This possibility was already revised in the past [36].

Such basic compounds are nitrogen oxides $\text{NO}_{(2)}$, ozone O_3 , hydrocyanic acid HCN , and carbon monoxide CO . Nitrogen oxide and ozone can be obtained by irradiation of compressed air. Hydrocyanic acid originates from methane and nitrogen. Carbon monoxide results from radiative dissociation of carbon dioxide. The DFR reference plant may produce 10^{4-5} tons/year of these chemicals.

8.5. Medical isotope production

The radiotracer ^{99m}Tc is a prime example of a medical application that would not be possible without a nuclear reactor. Seeking an alternative during the world-wide Molybdenum crisis 2009/2010 failed due to the high neutron flux required for the production of the ^{99m}Tc precursor ^{99}Mo [37]. A cost-effective production in commercial reactors seems not to be possible for several reasons, so it is mainly produced in research reactors. An expensive separation process follows, and a sophisticated logistic chain to finally deliver the technetium generators to hospitals is required due to the short half-life of ^{99}Mo of only 3 days.

The Nuclear Energy Agency (NEA) estimates the future ^{99}Mo world demand to be $4 \cdot 10^{16}$ 6-days-Bq (10^6 6-days-Ci) per year, corresponding to a demand of roughly 1 kg (assuming 10% separation efficiency) directly from the nuclear fission in LWRs providing ^{99}Mo . In contrast, one single DFR produces at least 30 kg ^{99}Mo per year but – more important – already provides it in a separated form, see also Sec. 4.2. This strongly reduces the handling so that a complete on-site medical-clean production of the technetium generators are feasible which further simplifies the logistics of the delivery to the hospitals. This could lead to a cost implosion for the ^{99m}Tc radiotracer and therefore to an inflation of applications.

9. EROI consideration

Energy Return on Investment is probably the most important factor to characterize the economical efficiency of an energy source. It is defined as the ratio of the total electricity output of a power plant during its lifetime to the expended energy for construction, fuel supply expense, maintenance, and decommissioning [1] [38]. This should not be confused with a return-on-investment assessment on a monetary basis.

Unlike monetary measures, the EROI is time invariant and independent from the national economic context. It requires a full life cycle assessment (LCA) in order to determine the correct cumulative energy demand CED (the energy invested, i.e. the denominator of the EROI). For a typical 1400 MW_e PWR, a major part of the CED is needed for the enrichment of uranium which in the first decades of nuclear power applications was dominated by the very ineffective diffusion enrichment. This reduced the EROI to 24 which is comparable to

fossil fired power plants and is one explanation why the expansion of nuclear power came to a halt in the 1970s in the USA. A newly built PWR with mostly centrifuge enrichment has an EROI of 75 to 105, with complete LASER enrichment up to 115 [1]. So the PWR technology can have an advantage in the EROI factor of 4 to fossil power but this defines also the limit of the PWRs and the Generation III(++) technology in general. Another costly contribution to the low EROI are the expenses for the fuel element infrastructure industry which is also conceptually based on the military logistic chain where as much as possible is displaced from the battle field to factories in the back area. The utilization of fuel elements then again requires multiple-redundancy elaborated active and passive safety systems in order to counteract the risk of core meltdown, further reducing the EROI in effect.

The large EROI gain of the DFR mainly results from two aspects: The loss of a costly external fuel processing infrastructure (improvement of more than a factor of 3) and the much higher compactness and simplicity compared to a light water reactor (another factor of 6). Additional minor improvements arise from lower maintenance efforts and from much less fuel consumption as well as significantly lower disposal needs. The higher per-mass efforts for the refractory parts are far outweighed by the extreme reduction of material amounts needed for construction (several 1000 metric tons nickel alloys and highly alloyed steels in a light water reactor compared to a few 100 metric tons refractories in the DFR).

Tab. 1 describes the evaluation of the EROI for the DFR. Since some materials (especially refractory metals) must be investigated and modified for use in the DFR, their energy inventory must be estimated. Furthermore, the maintenance for the nuclear part is also unknown, causing the same uncertainties.

The resulting EROI is therefore roughly 2000 which is 25 times higher than that of today's PWR technique [1]. The very compact design lowers the construction energy demand down almost to the level of CCGT plants on a per-watt basis, and the fuel-related energy demands are tiny compared to light water reactors due to the efficient usage. Only further optimizing the design and extracting the fuel at basic crust concentrations (~10 ppm for Thorium) leads to a domination of the fuel-related input, showing that the DFR exhausts the potential of nuclear fission to a large extent.

10. Final remarks

The Dual Fluid principle of separating the cooling and fuel function increases the complexity of the reactor core relative to the MSR but has large synergetic effects in the fuel reprocessing, the neutron economy, the cost efficiency as well as on the possible applications. This allows to combine the advantages of different Generation IV concepts (MSFR, LFR, SCWR, VHTR) in one reactor type while considerably undercutting the costs even of today's LWRs.

The good neutron economy and the hard neutron spectrum makes the DFR an effective waste incinerator and also an excellent thorium breeder, outbidding even MSRs like the LFTR

Item	Units (or total amount in 1000 kg)	Energy inventory in TJ/(1000 kg)	Total inventory in TJ
Concrete containment for reactor, fission products and turbine building	21000	0.0014	30
High performance refractory metals and ceramics (PPU and core)	60	0.5	30
High temperature isolation material for PPU and core	100	0.1	10
Initial load, isotopically purified ^{37}Cl + fuel	25+60	2.5 / 0.4	50+25
Refractory metals and ceramics for the heat exchanger	180	0.5	90
Isolation and structural materials, heat exchanger	300	0.1	30
Untreated, low-alloyed metal for fission product encapsulation	3000	0.033	100
Structural materials (steel) for non-nuclear part	1000	0.02	20
Lead coolant	1200	0.036	45
Turbines with generators	3	40	120
Mechanical engineering parts			150
Cooling tower (special concrete)	20000	0.003	60
Refueling, 1200 kg/a actinides over 50 years	~60	0.4	~25
^{37}Cl loss compensation	2	2.5	5
Maintenance, high-performance refractories + isolation for 1 new core	30+50	0.5 / 0.1	20
Maintenance, 50% of other reactor parts, refractories + isolation	90+175	0.5 / 0.1	62.5
Maintenance, 50% of mechanical engineering and turbines			135
Maintenance electricity, 2 MW over 20 days/a and heating, 50*0.2 TJ			182.5
Sum			1190
Output over 50 years lifetime, ~1500 MW net, ~8300 full-load hours			2,250,000

Table 1: Input energy amounts of the DFR. Bold: The sum of all inputs and the total electricity output. The ratio leads to the EROI of almost 2000, see text.

while being more cost-effective. The high temperature combined with the high cost-efficiency allows the production of synthetic fuels in competition with today's refined oil and gasoline. The online separation of fission products provides pre-sorted metals that can be used after decay as important raw materials for the industry. Other fission products, e.g. Mo-99 needed for medical diagnostics, can be quickly withdrawn in large amounts with no further processing.

The liquid fuel provides the same passive safety features as already tested for the molten-salt reactor (melting fuse plug, deeply negative temperature reactivity coefficient) but the concentrated actinide fuel adds additional safety and controllability due to a higher delayed neutron fraction inside the fissile zone. The lower fissile zone salt inventory means lower heat capacity leading to a faster power reduction in the case of additional reactivity.

Manufacturing the durable workpieces for the core is feasible by state-of-the-art technical processes and well-established industrial procedures. The complete absence of control rods, valves or any other mechanical parts as well as its compact size enables the use of expensive, corrosion-resistive materials and

modern fabrication techniques like laser sintering.

In essence the Dual Fluid principle resolves the contradiction of contemporary NPP concepts between a high power density which is obligatory for the crucial economic edge to prevail in the energy market, and inherent passive safety necessary for a safe operation and eventually the public acceptance of nuclear power.

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