The Dual Fluid Reactor - a new concept for a highly effective fast reactor

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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 coolant. The fuel liquid is pumped through an interconnected array of conduits immersed in the coolant liquid which constitute the reactor core in its vessel. Both cycles can then be optimized for the respective purpose. The exploitation of this concept leads to advantageous consequences. An optimized reactor has a compact design with a very high power density and is self regulating through a highly negative temperature reactivity at an operating temperature of 1300 K.The DFR is being designed with respect to the EROI (Energy Return on Invested) measure and passive safety standards and with attention to the state of technology in mechanical, plant and chemical engineering and applied material sciences. The specific combination of the liquids in the very high temperature regime requires structural materials which withstands corrosive attacks. Refractory metal alloys fulfill these requirements and modern manufacturing engineering is capable of producing durable components for the reactor. Because of the small size of the reactor core the utilization of these expensive metals has no significant impact on the EROI which is more than 20 times higher than for a LWR. The DFR inherits the positive properties of the MSFR and the LFR without their disadvantages, especially the outstanding passive safety features of the MSFR.

1. Basic Principle

The disentangling of the cooling and fuel supply function has many advantageous properties in comparison to the MSFR, where both functions must be satisfied by one material in a compromise. In the MSFR, the material is essentially restricted to molten salt which is a trade-off between high-temperature fuel, low-temperature cooling, and an acceptable heat capacity. In the concept of Dual Fluid Reactor (DFR), the fuel liquid is pumped through an interconnected array of conduits immersed in the coolant liquid which constitute the reactor core in its vessel. Both cycles can now be optimized for the respective purpose.

Similar to the MSFR the fuel can be reprocessed on-line in a connected facility inside the plant's containment. The core fuel conduit array is designed in a manner that the fuel can be drained gravitationally into subcritical storage tanks through a melting fuse plug just below the core. The coolant liquid is required to have the highest possible heat transportation capability and best neutronic properties. With pure liquid lead as the best choice it is possible to employ undiluted fissionable material as liquid fuel as opposed to the MSFR with <20% actinide fluoride. This results in a very hard neutron spectrum improving the neutron economy. The DFR resembles so the LFR, where the fuel rods are filled with a liquid fuel. For the LFR the wall material of the exchangeable fuel rods is limited to steel alloys which are prone to lead corrosion due to economic reasons. Since the fuel conduit array of the DFR need not be replaced regularly it is economically feasible to employ expensive refractory metal alloys which are the most favourable candidates withstanding molten fuel

salts as well as liquid lead at very high temperatures well above 1000 °C [1][2][3][4]. In comparison to the conditions in thermal neutron reactors, the choice of isotopes for the structural materials opens widely because of the low neutron capture cross sections for fast neutrons. Appropriate materials have been developed decades ago and though they contain rarer and more expensive chemical elements, their impact on the total costs of the plant is low.

The liquid fuel may be but is not limited to actinide salts. 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 of the reactor core due to the better heat transportation capability and a possible higher operating temperature because of the lower corrosive potential of the metal alloy. In such a manner the basic design allows for a high bandwidth of variations which can be trimmed to the specific purpose.

In the result, a compact reactor core arose with a very high power density, an operating temperature of about 1000 °C, passive safety features of MSFR's, and a hard neutron spectrum. The abundant neutron excess can be used for multiple transmutation purposes, like nuclear waste incineration, and breeding for both cycles, ^{238}U and ^{232}Th. All therefrom is essential for a nuclear power plant with a jutting economic competitiveness.

2. System Overview

In the following the components of an DFR power plant are described where given quantitative parameters refer to a reference plant with a power output of 3 GW_{th} and electric output of 1.5 GW_e. Fig. 1, right picture, depicts the reactor core and part of the coolant tubes. The conduits for the fuel liquid inside the core are exaggerated for illustration, there are actually ~10000 vertical rods. The parallel arrangement of the vertical rods guarantees a quick drainage of the fuel liquid within minutes. An equal flow velocity through all vertical rods is desirable. This is achieved by an horizontal array of fuel distribution conduits with varying cross sections providing equal pressure differences at the vertical junctions. A sparse sketch is depicted in Fig. 2 (left) with the inlet being at the lower left, details with all vertical rods are shown in the right picture. The core array of the 3 GW_{th} power plant based on salt fuel would have the dimensions of 3.6 m edge length. The cubic form of the core is chosen for the reason of easier fabrication of the fuel ducts. The fuel ducts are made of refractory metal alloys. Refractory metals are processed with the methods of the powder metallurgy particularly because of their high melting temperatures and durability.

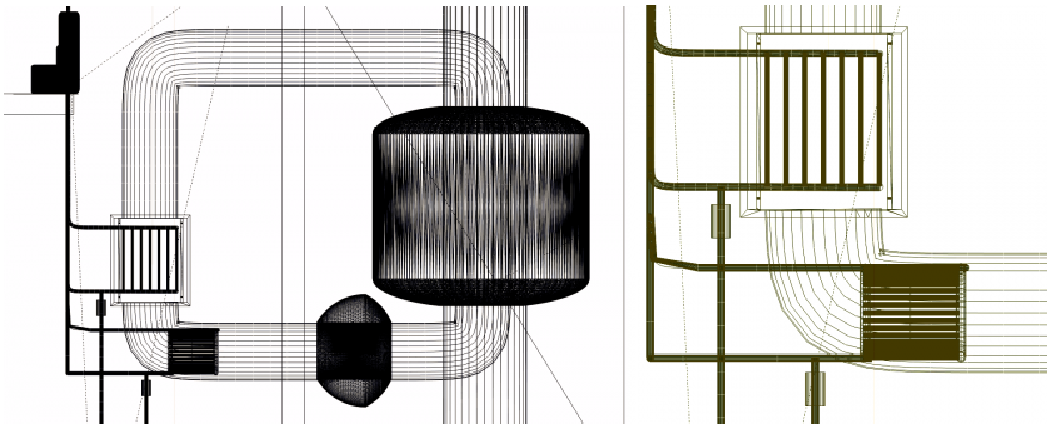

FIG. 1. DFR front view (left) and close-up of the DFR core region (right) with part of the coolant cycle and the short lived fission products storage inside the coolant conduit ahead of the core.

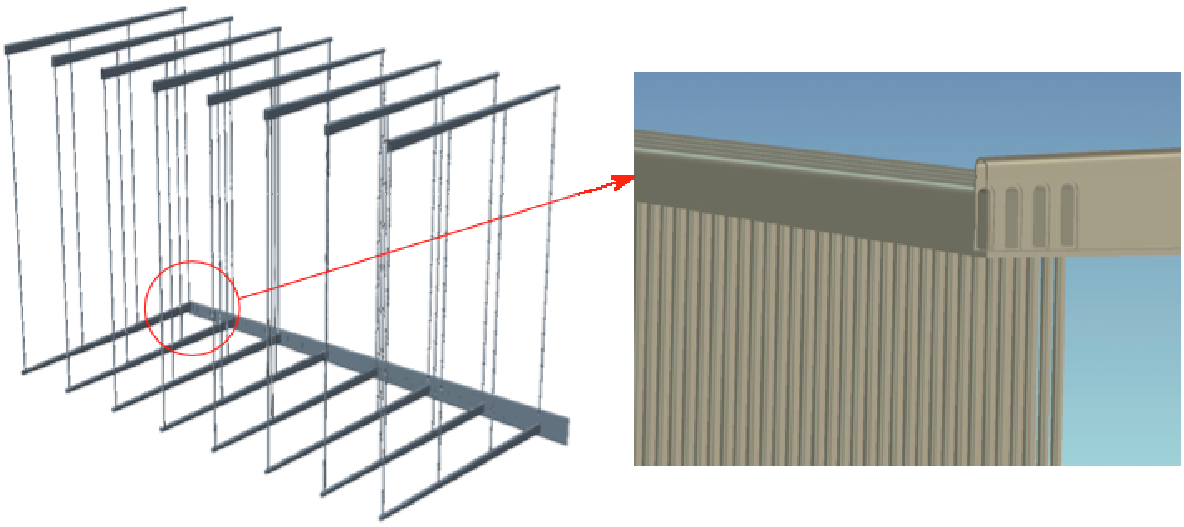

FIG. 2. DFR core tube system.

The sintering process limits the size and shape of workparts. The new laser sintering method will eventually relieve of many restrictions. However, it is not yet usable for this purpose since the fraction of voids is still too high. Today sintering extruders are capable of producing monolithic pipes with smooth surfaces. The whole array is assembled with electron beam and/or laser welding in vacuum [5][6]. Hence, the curre nt design of the DFR respects the state of art in industrial manufacturing technology.

The coolant supply pipes have a large cross section in order to reduce the circulation speed for the reduction of abrasion at the metal surfaces. Concentric to the fuel duct array is a separate volume filled with lead which serves as a neutron reflector reducing the loss of neutrons and participates at the reactivity regulation. The separation walls have small vents at the top and bottom in order to corespondent with the lead loop. At the bottom the coolant is pumped into the core vessel. When it moves up it takes the heat from the fuel duct by conduction and leaves the vessel on top towards the heat exchanger, Fig. 1.

The fuel liquid of the reference plant is a mixture of actinide salts. The fuel liquid enters the core vessel at the bottom. The high neutron flux in the core triggers nuclear fissions of some of the actinides in the fuel. The fission energy heats the fuel liquid which transfers its heat to the coolant. The nuclear fissions produce fast neutrons with a rate sufficiently high to sustain a nuclear chain reaction inside the reactor core region. The fuel liquid leaves the reactor core through the outlet on top of the vessel and moves towards the pyrochemical processing unit (PPU). While passing the core region through the conduit array more and more actinides are fissioned and transmuted and the fuel changes its chemical composition. It should be accentuated that the fuel volume of the reference plant is only a few m³, which further simplifies its handling and processing

Now that the cooling function is relieved from the liquid fuel the period of use of the fuel can be adjusted to nuclear purposes like maximum burnup, transuranium element incineration, isotope production, fertile material conversion (aka breeding), specific deactivation of fission products, etc..

Before the lead reaches the core there is a special coolant duct segment shown in the bottom part of Fig. 1. At the inner wall of this cylindrical segment coaxially alligned pipes are located with connections to toroidal ducts at both ends. These pipes contain the separated short lived fission products (roughly 1 m^3) which are highly radioactive and heat generating. Those fission products pose the main problem for reactors with solid fuel rods and cause core meltdown unless sufficiently cooled. In the DFR like the MSFR this fission products are regularly separated from the fuel liquid so that it contains only few quantities of fission products and its handling in case of an emergency is unproblematic. However, the problem is then transfered to the storage of the fission products which requires effective cooling in the first ten to fourteen days after shutdown. In the DFR this problem is

solved in the way that the short lived fission products are stored in the pipes of the said coolant duct segment just before the reactor where they are cooled by the liquid lead stream during normal operation of the plant. In case of an emergency where this active coolant cannot be maintained the fission product liquid is drained through a molten fuse plug to a storage system below gravitationally. For that the duct segment is veered. This storage system buffers the initial high heat production in a volume filled with salt or aluminium and transduces the quickly fading heat energy through the outer walls to the surrounding. The heat production lowers from 200 MW immediately after shutdown to some 5 MW after 12 days, which then can dissipate passively.

The lead enters the heat exchanger after leaving the reactor. Depending on the need of power a 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, after is being pumped back to the reactor vessel. This is accomplished by a propeller pump which produces a steady stream without generating sonic shock oszillations in the liquid metal. For maintainance 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.

For maintainance or in case of an emergency a subcritical fuel storage is provided. It comprises several tanks each of which has a capacity of only a deep subcritical mass of the fuel liquid. The tanks can be filled either through the melting fuse plug at the bottom of the reactor vessel or through a pump from the PPU.

The actively cooled melting fuse plug can be used for a regular shutdown. It is essentially a pipe segment which is cooled with a constant heat transportation. The heat produced by the fission in the fuel inside the reactor determines the temperature of the fuel liquid loop and also abut on the melting fuse plug. The cooling power of the fuse is fixed, so that the plug does not yet melt at 1000 ◎. For higher core temperatures or if powered off the fuel heat will melt the plug, which opens, and drains the fuel to the subcritical tanks. From the subcritical fuel storage the fuel liquid can be pumped up, entering the fuel loop again.

3. Fuel processing

For an online fuel processing the employed technique must be congruously fast, so only dry high temperature methods come into consideration, and the fuel must be impervious to radiolysis within the process, too. The fuel liquid of the DFR can be a molten salt or a metallic melt. 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, both liquids are impervious to radiolysis and as such directly apts for physicochemical separation methods at high temperatures.

The reference plant uses a molten actinide salt. Though there is experience with fluorine salts from the MSFR they are disadvantageous for the following reasons. Fluorine salts have still 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 metals 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 combination of a fertile and a fissile actinide salt which can be $^{238}U/^{239}Pu$ or $^{232}Th/^{233}U$ [7] .When the uranium-plutonium fuel cycle is utilized the reactor requires an initial load of plutonium (alternatively enriched ^{235}U may be utilized if no plutonium is available). The fraction of plutonium depends on the size of the reactor core because of neutron losses through the surface. The maximum is a ^{239}Pu fraction of 35% required for the smallest useful set-up while larger cores can manage smaller fractions. The other fraction is ^{238}U as fertile material. The fuel salt would here 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 by capture at ^{35}Cl and production of the long-lived radioactive isotope ^{36}Cl.

So both previously developed and tested reprocessing methods of the generation IV reactors can be employed for the DFR, too. The capacity of the pyrochemical processing unit can be designed even much smaller because of the low fuel volume [8] .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 be accomplished by fractionated distillation / rectification only which is beyond the MSFR principle.

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. A range extension can be implemented with a fuel liquid centrifuge which precipitates some of the fission product compounds by density separation.

For a metallic fuel melt there are several options ranging from a more heterogeneous system with liquid plutonium over a solution of actinides in Bi/Pb/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 [9] . 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 do not necessarily need to be an eutectic. Even if the liquidus temperature is above the operating temperature the mixture is in this pasty phase sufficiently pumpable. The processing of the metallic melt can be performed with a first fractionated destillation step where the metals with low boiling points 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. The resulting salt fractions need then to be converted to metals back again by electrolysis before re-insertion into the reactor fuel loop.

Basically whenever liquid fuels are used certain preprocessing steps has 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 hardly form chloride compounds, notably Mo, Ru, and Rh. In the frame of the MSRE this issue were investigated in view of the possible problem of segregation of the said fission products. It turned out that the segregation is not a progressive process but instead an equilibrium accrues between segregation and solvation [10]. This equilibrium level can be controlled by the overall chemical potential of the salt melt which may be adjusted by the quantity of chlorine ions and possibly certain minor additives. The chemical potential determines the corrosive properties of the salt melt, too. In a preprocessing step the noble metals in the fuel comming from the reactor can be precipitated by bubbling noble gas (He, Ar) through the fuel salt. The metals precipitate at the phase border between the gas bubble and the salt liquid as plateletts which can be retrieved by a rake subsequently. Concurrently to the gas bubbling the volatile fission products Kr, Xe, and I_2 are expelled as well and can be decaled.

4. Reactor operation and regulation

4.1 Negative temperature feedback

The PPU fabricates a fuel mixture that is critical inside the reactor at the desired operating temperature of 1000 ◎. 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.

3. Density decrease of the liquid lead which reduces the concentration of the neutron reflecting lead nuclei.

The reactivity change by a temperature induced density change is almost instantan because it is determined by the speed of sound in the respective medium.

Because of its high atomic mass and its many stable isotopes due to nuclear shell closure lead is an excellent neutron reflector with low moderation qualities and low neutron capture cross sections. These effects together cause a strong negative temperature coefficient in the fast neutron spectrum. This is in contrast to liquid sodium as coolant which has a much higher neutron capture cross section, higher neutron moderation and lower reflection quality which means an increase of the neutron flux with raising temperature, i.e. positive temperature coefficient.

Since lead is also the end of the decay chains prolonged neutron radiation can only induce an equilibrium level of radioactivity that is comparable to natural uranium. Only after multiple neutron captures the radioactive nucleus ^{210}Po is formed which quickly decays to the stable ^{206}Pb again. In consequence the low radioactivity of lead renders an intermediary cooling loop superfluous and the primary coolant loop can be extended into the conventional part of the plant directly, different to sodium, which enables a considerable cost reduction.

4.2 Startup procedure

To start up the reactor the system is pre-heated until the coolant and the fuel salt becomes liquid. 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. Inside the reactor the fuel becomes critical.

Now the reactor is regulated by the described physical control loops. 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 levelled off at the nominal temperature. In such a manner the fission rate in the reactor follows the power extraction.

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

4.3 Shutdown procedure

For a regular shut down the coolant circulation and the fuse cooling is stopped. The fuel salt empties to the storage tanks. The same happens if the power to the plant's aggregates fails. If for any reason like malfunction and sabotage the fraction of the fissile material is exalted the equilibrium temperature raises, too. For this incident, again the melting fuse plug kicks in.

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

4.4 Possible accidents

The PPU continuously removes the fission products from the fuel salt and replaces them with fertile material, i.e. ^{238}U. The residual decay heat of the few fission products in a core load can easily passively be dissipated from the storage tanks. In summary, for all known typical dangerous reactor accidents like 'loss of power accident', 'loss of coolant accident', 'criticality accident', 'decay heat' the DFR behaves well mannered like for a regular shut down.

5. 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. If only ^{238}U is fed into the

fuel this neutron surplus will end up as additional plutonium. The conversion rate is larger than one, the reactor works in the breeder mode.

The neutron surplus can be used for other transmutaion 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 the neutron surplus is consumed ulterior the reactor works as a self-burner, i.e. conversion rate equal one.

Alternatively the PPU can mix in thorium or inert materials to even out the neutron surplus. The fission neutron yield of ^{233}U from the thorium-uranium fuel cycle is considerably lower than for the plutonium fission. It is possible to operate the DFR as a fast neutron Th-U breeder with a conversion rate slightly larger than 1. The transmutation of the own long-lived fission products may be feasible. For that, the PPU needs to seperate out and store the ^{233}Pa until decay to ^{233}U. The PPU can frame 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 seperating 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.

6. DFR power plant

Fig. 3 shows a DFR reference power plant with an power output of 3 GW_{th} and an electric output of ~1.5 GW_e which is nonce the optimal plant size for the electric grid of industrialized countries. The nuclear part resides in a subterranean bunker which withstands high magnitude earthquakes, direct aircraft impacts and non-concentrated conventional military attacks. The conventional part utilizes supercritical water and is not fortified for improved economy, albeit a fortification to the desired degree can easily be achieved.

6.1 Fission product treatment

The Pyrochemical Processing Unit (PPU) removes the fission products from the fuel liquid and replenishes the actinides which may come from natural/depleted uranium, burned fuel elements, and thorium consuming 1200 kg/year. Fission products are sorted by chemical elements and the longer living are cast into small globes which are packed and hermetically sealed in ripple tubes. The tubes are transferred to the decay storage below by a manipulator arm. The bunker can scavenge all fission products from the whole life-time of the reactor and store it until decay which amounts to 500 kg/year. 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.

The decay heat deposit at the bottom storey contains the storage tanks for the reactor fuel inventory and the concentrated highly radioactive short-lived fission products from the storage in the main coolant loop. The decay heat deposit consists of iron assembled from 'Lego'-like bricks which establish full heat contact by temperature expansion. It is designed to absorb and buffer the quickly decaying initial heat after scram and dissipates it slowly through the outer walls to the surrounding.

6.2 Conventional part

Due to the low radioactivity of liquid lead it is possible to extend the primary coolant loop directliy into the conventional part of the plant. There the heat energy needs to be transduced from the liquid

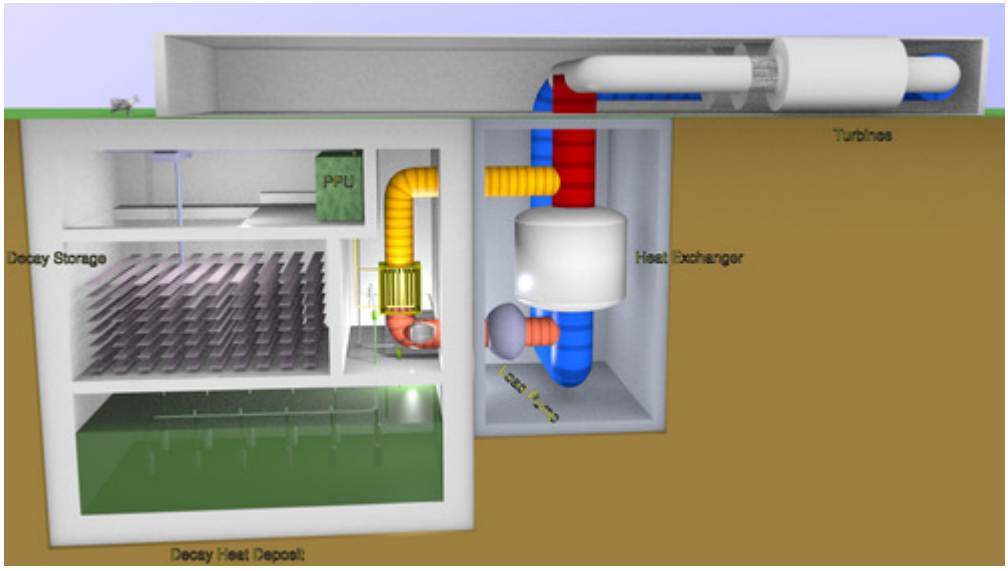

FIG. 3. Possible power plant based on the DFR. The compactness allows for a subterranean installation.

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 is nowadays a supercritical water cycle. Albeit the newest coal fired plants work at 700 °C there is no principal problem to increase to 1000 °C. Generally scH_2O 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.

6.3 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.

6.4 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 than converted to electricity. The still considerable residual heat after the MHD generator my be used in a subsequent heat exchanger with a water cycle as above. Such a system may be significantly less costly than multiple turbines.

6.5 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). One example is the irradiation of compressed air in order to produce NO and O_3, which would be considerable less expensive than the Ostwald process and dielectric barrier discharge [11].

7. EROI consideration

The Energy Return on Invested, is probably the most important factor to characterize the economical efficiency of an energy technique. It is defined as as the ratio of the total electricity output of a power plant during its lifetime to the expended exergy for construction, fuel supply expense, maintainance, and decommissioning [12][13]. 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.

Table 1. Input energy amounts of the DFR

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 performace 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
Unfabricated, 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**

The resulting EROI is therefore roughly 2000 which is 20-1000 times higher than that of any other technique [12]. This is due to the very compact design, lowering the construction energy demand down almost to the level of CCGT plants on a per-watt basis, and the fuel-related are tiny compared to light water reactors due to the efficient usage. 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.

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