A preliminary proposal for a hybrid lattice confinement fusion-fission reactor for mobile nuclear power plants

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Scientists detected 2,45MeV neutrons, and in smaller yields, 4 and 5 MeV neutrons in deuterated metals under a 2,9MeV electron beam. Such discovery could allow the use of deuterated metals at temperatures below their melting point to provide nuclear fusion reactions. Such reactions could provide fast neutrons and energy in the form of heat. This work analysed the results of some experiments to infer the neutron multiplication rate in such environments. It also considered the possible roles that such phenomenon could play in a commercial nuclear power reactor under economic and compactness constraints. It seems the best way to promote nuclear fusion is the irradiation of deuterated metals by fast neutrons. This work presented a concept of hybrid fission-fusion reactor using fissile or fertile fuel to generate heat and fast neutrons along deuterated metals providing excess neutrons (reactivity boost). Additionally, deuterated metals also may have a role in neutrons moderation requiring less volume than other moderators (water or graphite). Such reactor, given its reactivity boost, may burn radioactive residuals (transmutation) at affordable costs while generating power. Alternatively, this hybrid fission-fusion concept could also breed fissile fuel from fertile isotopes using natural Uranium as seed.

Keywords: lattice confinement fusion; molten salt reactor; generation IV reactor; hybrid fusion-fission reactor; mobile nuclear power plants

I. INTRODUCTION

Novel nuclear reactions were detected in deuterated metals under a 2.9MeV photon beam, generating 2.45MeV neutrons, and in smaller yields, 4 and 5 MeV neutrons. [1] That work theorizes that the photon beam generates average 145keV neutrons by photodisintegration ($D(\gamma, n)^1H$ reaction), and those neutrons heat deuterium ions in metal lattice. In turn, the metal lattice enhances the $D(d, n)^3He$ reactions, which produce 2.45 MeV neutrons. After that, those 2.45 MeV neutrons heat other deuterons and start a second generation of $D(d, n)^3He$ reactions, now producing 4MeV neutrons. This work is preceded by a theoretical work which predicts such results and provides the formulation for this phenomenon. [2] This theoretical work also states that in deuterated metals, the most efficient process to heat deuterons is kinetic energy transfer from hot neutrons.

It is well known that achieving criticality to sustain nuclear reactions presents some engineering challenges, typically overcome by fissile content augmentation. The processes for this end are typically enrichment and breeding, both requiring complex technologies, leaving residuals, and increasing costs, besides the nuclear weapons proliferation issue.

Current fuel cycles use a small fraction of potentially useful fuel, leaving a quantity of residuals whose disposal is complex and costly. Therefore, a solution could be burning of residuals in a transmutation reactor, which also have difficulties with criticality. Some proposals are accelerator-driven systems (ADS) which would generate neutrons by spallation in a subcritical reactor. However, such system would be quite complex and expensive.

All nuclear fission reactors roles (power generation, fuel breeding and transmutation) require large amounts of neutrons, which, to date, is difficult to obtain without achieving criticality in a reactor.

Nuclear fusion reactors do not need neutrons to start a reaction and their residuals are not harmful like fission reactors, besides being able to use abundant isotopes in nature. However, fusion reactions generate neutrons and require complex and expensive technologies to make the nuclei overcome the Coulomb barrier. Another issue is the need of tritium as a fuel because it is currently expensive.

Some authors have proposed hybrid concepts of fusion-fission reactors where fusion reactions provide neutrons and fission reactions burn actinides besides producing power.

The current work focuses on a possible application of fusion reactions in deuterated metals (lattice confinement fusion) for mobile nuclear power reactors, keeping the compactness and economic constraints in mind. A secondary objective is to identify points to study to make such reactors feasible.

II. ASSUMPTIONS

This section lists a series of assumptions made to make this work applicable from the point of view of nuclear power plant vendors and merchant ships builders and operators.

The first assumption is that the roles of nuclear reactors are (neglecting research activities, like material test reactors):

1. To produce power.
2. To breed fissile material.
3. To produce isotopes (medical isotopes, for instance).
4. To burn fission products.

The second assumption is the reproducibility of the experiment of [1], meaning that significant amounts of fusion reactions occur in deuterated metals under gamma or neutrons radiation.

The third assumption is that deuterated metals allow fusion neutrons multiplication in second or third generation of neutrons with higher energies. [2]

The fourth assumption is a compact reactor needs to be a thermal neutrons reactor.

III. METHOD

This work employs the systems engineering approach to develop solutions:

1. identification of systems as Wymore definition. [3]
2. identification of functions that need to be fulfilled.
3. analysis of candidate options.
4. choice justification based on a qualitative cost analysis and radiation protection aspects.

Such approach is recursive, meaning this work will repeat such steps for two levels in the product breakdown, from top level to bottom. To fit in an article length, this work will limit to the top and first level subsystems, as this already allows a clear comprehension of the proposed concept.

IV. DEVELOPMENT

IV.A. Nuclear heat supply system

In current designs, there is a domain where the nuclear part is concentrated and stays inside the nuclear confinement system. This system receives many services (typically including, but not limited to electrical energy supply, pneumatic air supply, operators' commands, cooling water, feedwater, residual heat removal) but provides a single service: supply heat to the power conversion system, typically in form of steam enthalpy. It is commonly called "nuclear island" or nuclear steam supply system.

Fig. 1 presents the nuclear steam supply system and its main relations with other systems. At this level, some choices need to be done before more detailed analysis. The first is the reactor technology, which may be:

1. Pressurized Water Reactor (PWR): most known solution for mobile nuclear power reactors, like merchant ships, icebreakers, military ships, and nuclear barges. Its drawbacks are the use of high-pressure systems with strict nuclear safety requirements, which makes them uneconomical for ships and grid generators smaller than 600MWe nominal power.
2. Boiling Water Reactor (BWR): not used for mobile nuclear power reactors, probably due reactivity issues with heave motions.
3. Molten Salt Reactor (MSR): it is a compact design originally for airplanes. It may operate at atmospheric pressure and does not require high pressure vessels. Additionally, it does not require fuel assembly fabrication, as its fuel is in liquid state, making its costs even lower. Finally, the liquid state of the fuel keeps it homogeneous and gaseous fission products spontaneously exit the reactor core. Consequently, such design needs less positive reactive margin, and it accumulates less thermal source that may leak in case of core meltdown. In short, it may achieve the same safety level as a PWR design with less investment in safety systems.
4. Very-high-temperature reactor (VHTR): typically uses the Pebble Bed Modular Reactor architecture and is cooled with gas. The size of the reactor is too big to be employed in mobile applications. Besides, it is rather an experimental design and has many challenges with the high temperature.

Based on previous analysis, this work chose to investigate further the MSR option. A second choice is the way the heat will be delivered to the power conversion system, which may be:

1. Steam enthalpy: in such design, the steam generator is within the nuclear confinement system, and given the temperatures involved, there will be high pressures in case of accidents. As such accidents would be relevant and potentially damage the reactor (which is not able to bear pressure), all pressure vessels probably would need to comply with strict nuclear quality requirements. That means such option would remove part of the advantage of low pressure of the molten salt.
2. Gas enthalpy: even if the pressures would be smaller than water, still the pressure could damage the low-pressure reactor. That means such option would remove part of the advantage of low pressure of the molten salt.
3. Molten salt enthalpy: in this option, the design of the nuclear heat supply system is simpler because it does not need to include a heat exchanger to the steam, gas, or water. Further, as such heat exchanger stays out of the nuclear confinement, the physical isolation passively protects the reactor if safety valves, isolation valves and pressure regulating tanks are present. Evidently, the molten salt that exits the nuclear confinement must not irradiate nor contain fission products. Another advantage is the nuclear design becomes simpler and less expensive. The power conversion system, which typically does not comply with strict nuclear quality rules, will take care of the risk of steam or high temperature gas leaks. It is important to note that for capital protection, safety measures will be taken. Further, such option decouples the design in two parts (nuclear and non-nuclear) giving more design flexibility and enhances the probability of design reuse. For instance, it allows the adaptation of proven solutions

from concentrated solar power for the power conversion system. In case a given client needs a plant for another application (process heat, for instance), only the non-nuclear part needs to be designed as the nuclear part design may be reused.

Therefore, this work decided to adopt the molten salt as the medium to deliver heat to the power conversion system. Fig. 1 presents the top-level systems and functions identification.

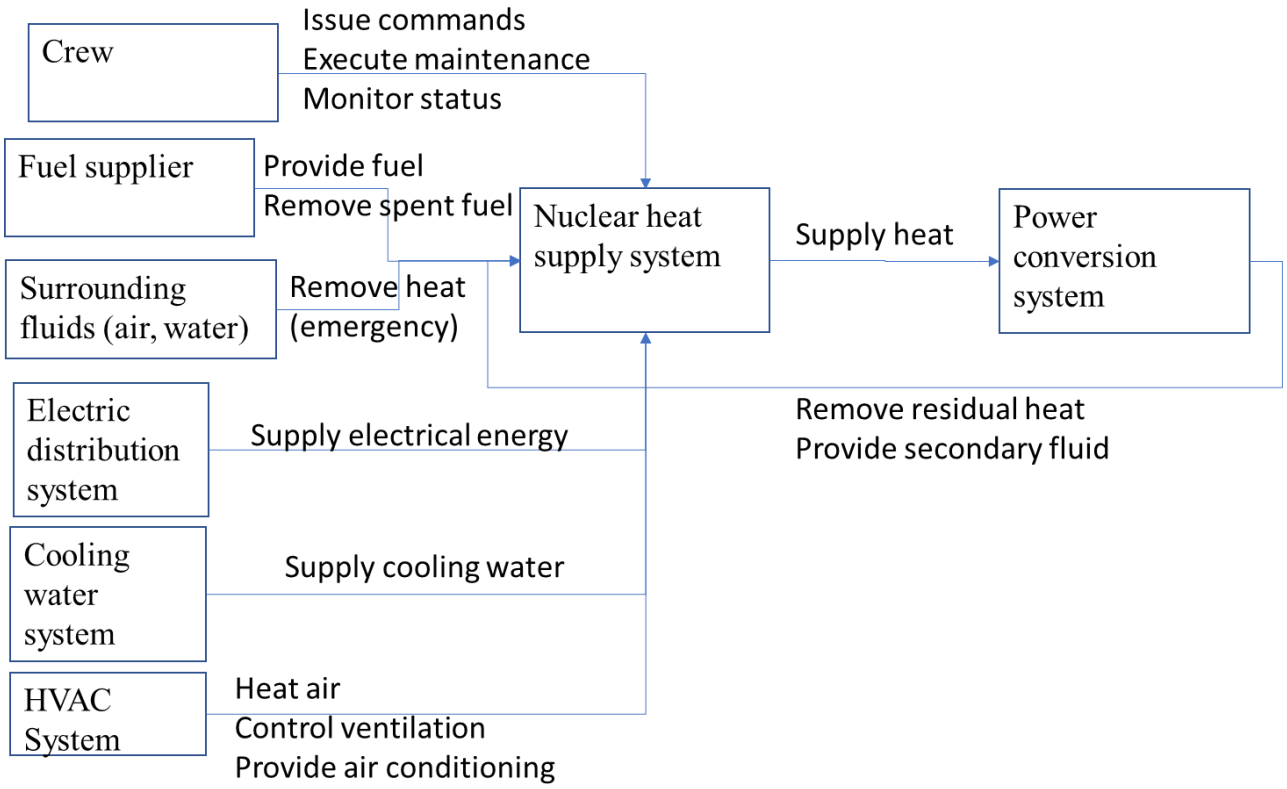

Fig. 1. Identification of systems and their functions - top-level systems.

Once the main architectural choices at the top level were done, one may start the subsystems identification along is functions. Its typical subsystems at Fig. 2, which shows an architecture complying with the defence in depth principle, meaning that the “retain reactivity” functions must not share a single common mode failure in their pressure vessels. In other words, the following systems must be independent:

1. fuel cladding system.

2. primary coolant system.
3. nuclear confinement system.

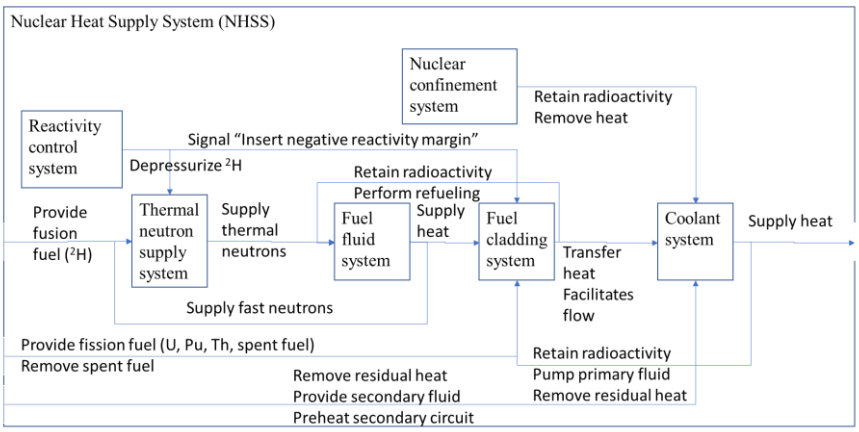

Fig. 2. Identification of subsystems and their functions - nuclear heat supply system.

IV.B. Thermal Neutron Supply System (TNSS)

This system contains the innovative aspect of lattice confinement fusion. It receives deuterium gas, charges it in a metal lattice and uses the fast neutrons coming from the fuel to heat the deuterons, which in turn, may undergo fusion reactions. The process of heating the deuterons thermalize the fast neutrons, making them adequate for fission reactions in the fuel. The fusion reactions also produce more neutrons, boosting the reactivity of the reactor. Additionally, the energetic gamma rays from the fuel may also generate neutrons by photodisintegration, further enhancing the reactor reactivity.

This reactivity boost allows the use of fuels that would not achieve criticality using light water as moderator, like natural Uranium with long lived actinides or Thorium. This system has similar effect as the accelerator in the Accelerator-Driven System (ADS). Unlike the ADS, which has a controlled neutron generation, the reactivity boost is proportional to the neutron

population and reactor power. The reactivity boost may also be controlled in the long term by the deuterium gas pressure, but it may take hours to increase or decrease the reactivity boost.

The fusion reactions do not generate only neutrons and energy, but also ^{1}H, ^{3}H, ^{3}He, ^{4}He. While ^{3}H contributes further to reactivity boost by the $^{3}H(d, n)^{4}H$ reaction, the others do not generate neutrons, and ^{1}H or ^{3}He may absorb neutrons, reducing the system effectiveness. Therefore, as the concentration of deuterium decreases, the reactivity boost also decreases. For this reason, to keep the reactivity in controllable range, it may be necessary to make online fusion fuel refuelling, depending on the mission profile.

Therefore, the TNSS needs a set of subsystems shown in Fig. 3.

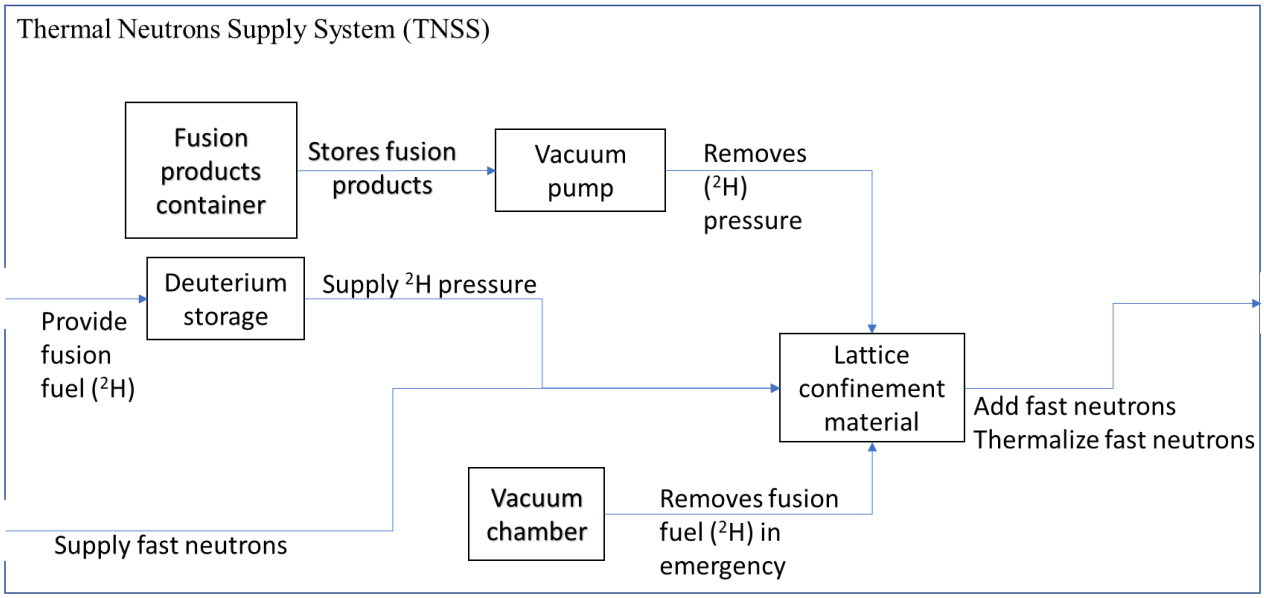

Fig. 3. Identification of subsystems and their functions - Thermal Neutron Supply System.

It is important to remember that the 0.64% of delayed neutrons of ^{235}U fission allow the reactor controlability and the populations of prompt and delayed neutrons in a reactor are comparable. The TNSS would multiply equally prompt and delayed neutrons keeping the reaction controllable.. The effective reactivity coefficient Keff (ratio of a new generation of neutrons over the last one) multiplied by the reactivity boost coeficient B (ratio of energetic

neutrons entering the TNSS over the thermal neutrons exiting) must be around 1. This means that the reactivity boost coefficient in practical designs should be in 1 to 1,1 range.

Fig. 4 presents the simplified diagram of the TNSS, to clarify some details for some readers more used to diagrams.

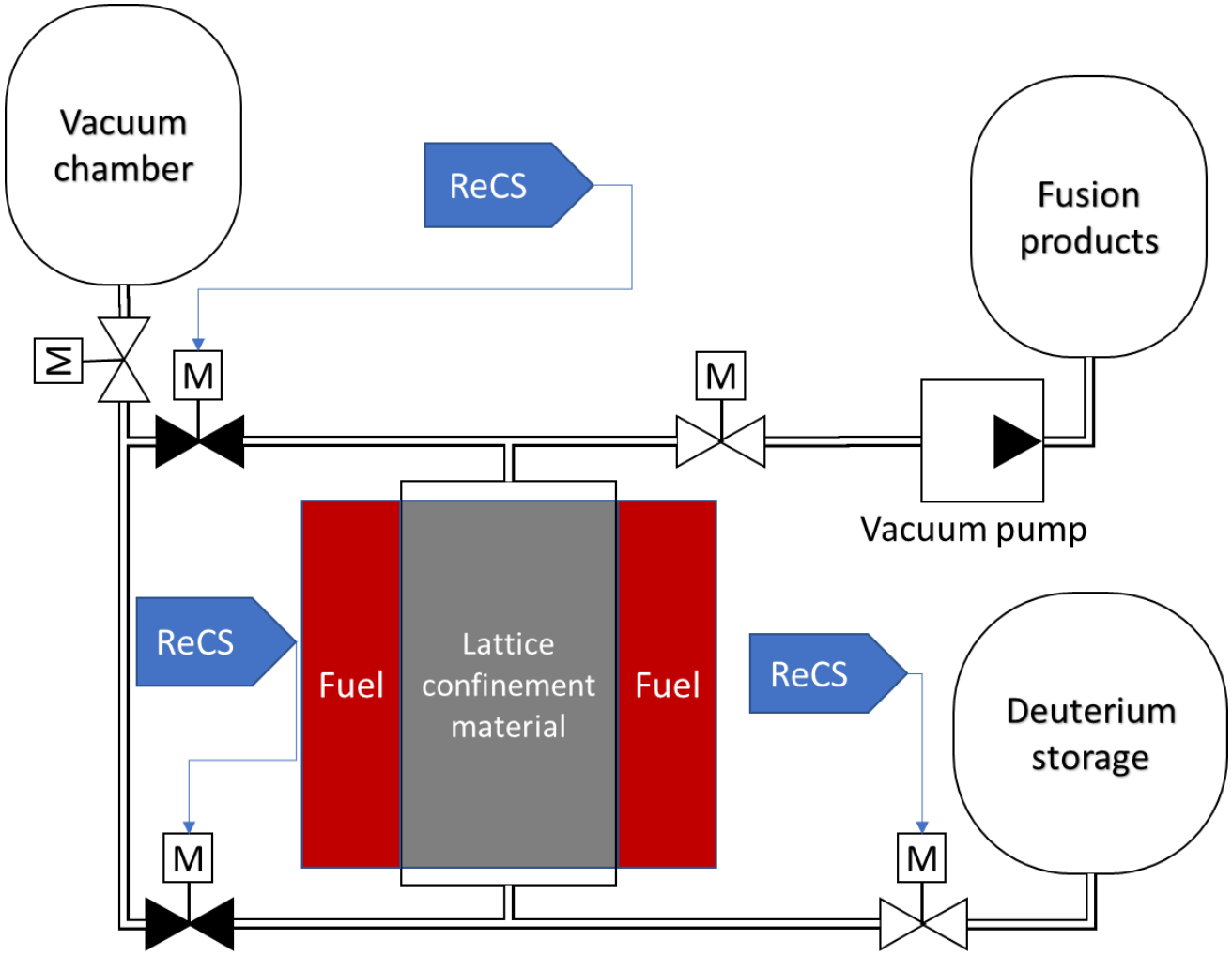

Fig. 4. Diagram of the Thermal Neutron Supply System.

A decision to take is what material to employ for lattice confinement. This material must:

1. be at solid state at MSR operating temperature ranges.
2. have small thermal neutrons cross-sections.
3. have small cost.

4. have large atomic mass (it seems larger atomic numbers favors lattice confinement and remove less energy from scattering neutrons, leaving it for deuteron heating).
5. have small pressure for retaining hydrogen.

Erro! Fonte de referência não encontrada. presents some characteristics of selected materials. Assumed price is a rough estimation based on [4] or Amazon offers displaying only one or two significative digits. Because the prices change over time or conditions of supply, there is no point in using exact 2020 values. This work chose the prices of high purity material because a nuclear reactor needs high purity to avoid neutron activation and, if the purification process is expensive, the cost is elevated.

TABLE I. Analysis of material options for lattice confinement.

Metal	Symbol	Melting point (ºC)	Thermal neutrons cross section [barns]	Assumed price (US$/kg)	Atomic mass
Beryllium	Be	1285	0.0076	800 (99.95% purity)	9
Niobium	Nb	2470	1.15	500 (99.95% purity)	92.9
Silicon	Si	1411	0.171	300 (99.99% purity)	28.1
Yttrium	Y	1526	1.28	30 (99.9% purity)	88.9
Zirconium	Zr	1854	0.185	100 (99.9%)	91.2
Graphite	C	3730	0.0035	200 (99.95%)	12

As a first choice, this work chose Zircaloy 2, which is based on Zirconium, as the material for the lattice confinement. However, further calculations and experiments are needed to check if another option (graphite or silicon) could be adapted.

IV.C. Fuel

The fuel includes all the fuel (spent, in use or spare) present in the system. As it needs to provide fast neutrons to the TNSS, it should minimize the content of light nuclei. Additionally, it should reduce radioactivity generation, like Tritium generation. It should use only isotopes with small cross-section. Last, but not least, the salt should be cheap. The typical salts used are:

1. ZrF_4-NaF-UF_4 salt (used in the Aircraft Reactor Experiment): Zr and Na have relatively high atomic numbers. The problem is Fluorine, with atomic number equal to 19, takes in average 10% of energy of each scattered neutron.
2. LiF-BeF_2-ZrF_4-UF_4 salt (used in the Molten Salt Reactor Experiment): Li and Be take in average, 22% and 18% of energy of scattered neutrons. If present, considerable neutron energy will not be available to heat Deuterium ions on the TNSS. As Lithium need enrichment, its price is also elevated.
3. NaCl-UCl_3 salt (used in fast molten salt reactor designs).
4. BeF_2-NaF-UF_4 (option avoiding the use of enriched Li due cost): Beryllium take in average, 18% of energy of scattered neutrons.

Therefore, as a first choice, this work selected NaCl-UCl_3 salt to harden the neutron spectrum to keep neutrons energy available to heat the Deuterium atoms and to reduce costs.

Because fuel is only a substance, this work skipped the functional diagram because it would not add value.

IV.D. Fuel Cladding System (FCS)

The fuel cladding includes all containers of fuel salt (new, in use and spent) and associated valves, pumps and equipment. Fig. 5 presents its main subsystems and the related functions.

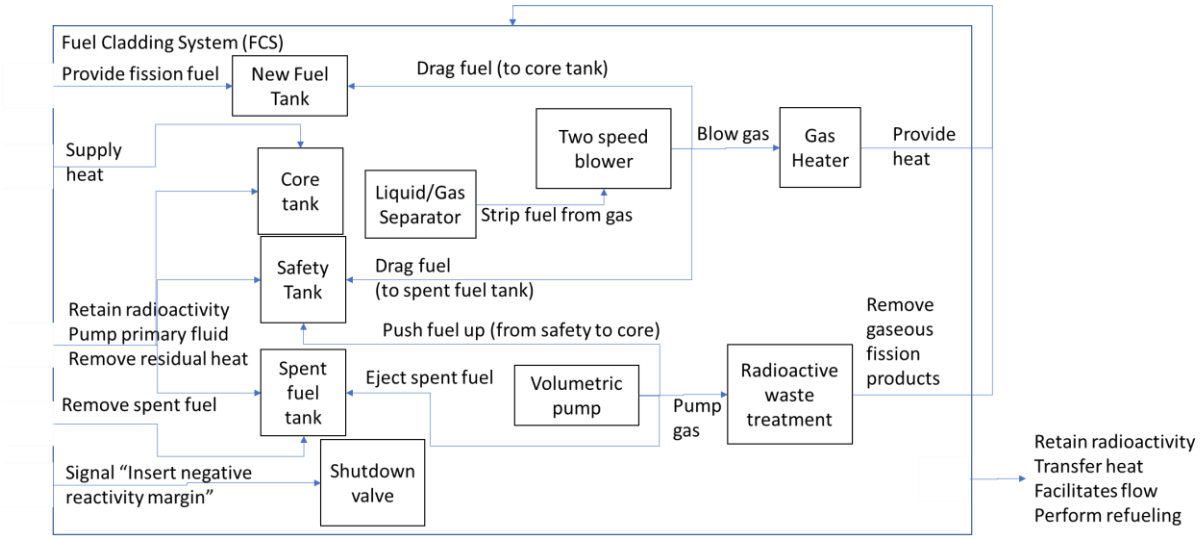

Fig. 5. Identification of subsystems and their functions - Fuel Cladding System.

To clarify how it works, Fig. 6 presents the fuel cladding diagram where traced boxes are components of other subsystems. Note that the two-speed blower may perform various tasks:

1. Preheat the circuit before receiving the salt (high speed).
2. Maintain the tanks temperature when the reactor is subcritical and residual heat is smaller than heat dissipation (low speed).
3. Drag new fuel from tank to the core (low speed).
4. Drag spent fuel from safe tank to the spent fuel tank (high speed)

Note that the Safety Tank is arranged to allow two possible outcomes when the gas is blown through Core Tank and Safety Tank:

1. In low-speed blowing, the gas just passes through the tank delivering the heat.
2. In high-speed blowing, the gas drags along the fuel salt, allowing transfer to the spent fuel tank.

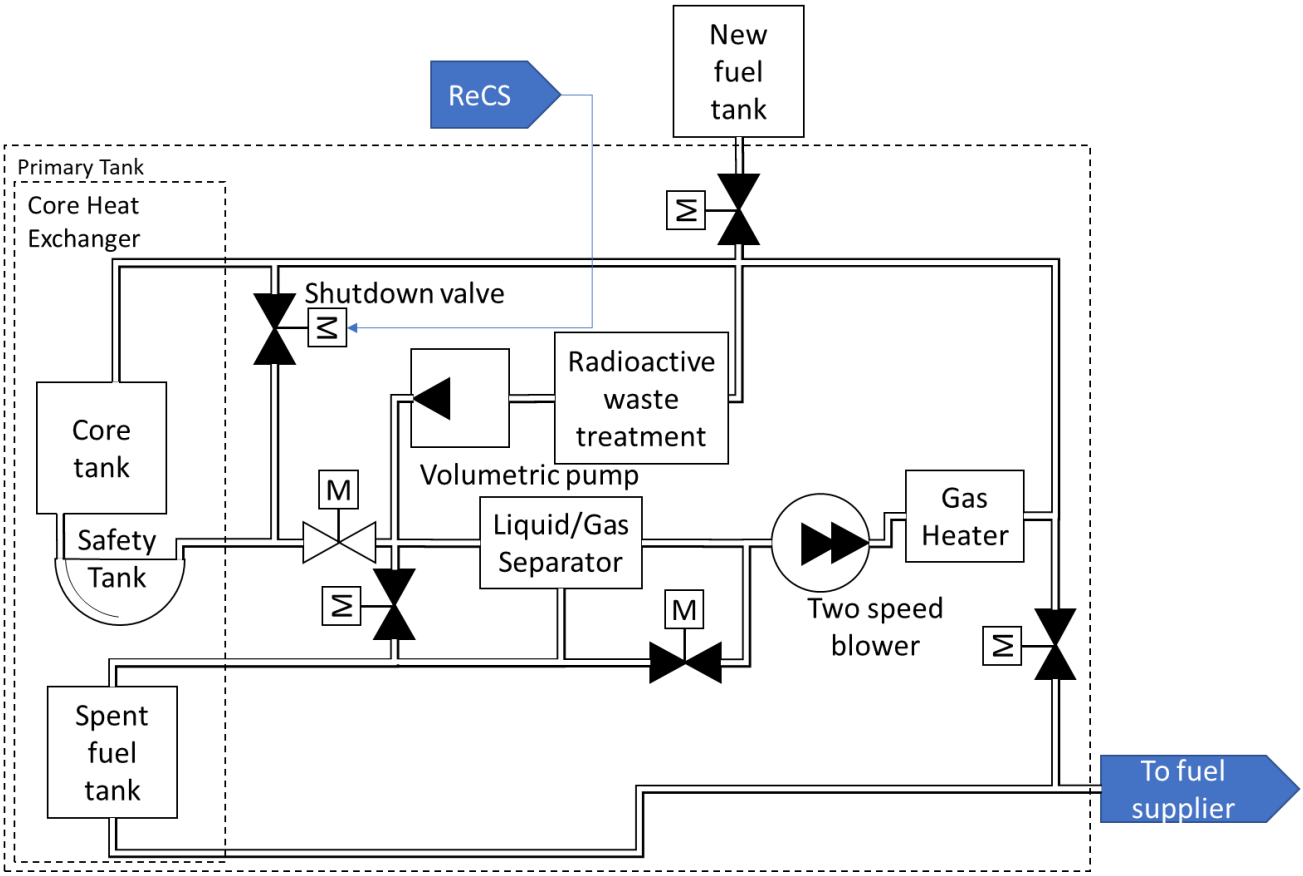

Fig. 6. Diagram of the fuel cladding.

Another critical aspect is the need of high surface to volume ratio for the Core, Safety and Spent fuel tanks, which are inside the primary coolant heat exchanger.

IV.E. Coolant system (CS)

The Coolant System (CS) removes heat from the FCS and delivers it to the Power Conversion System (PCS, the turbogenerator, for instance) in normal operation. Figure 7 shows the CS internal subsystems and their functions, and traced boxes are components of other subsystems. After normal shutdown, the PCS removes the residual heat of the reactor. When

the residual heat becomes comparable to the thermal dissipation, the PCS substitutes the secondary fluid with an inert gas, passing to the hot shutdown state. Otherwise, that secondary salt would freeze when the reactor temperature drops because the residual heat becomes lower than the thermal dissipation to the Nuclear Confinement atmosphere. Before loading the secondary salt, the PCS also must preheat the secondary circuit to avoid freezing of the salt.

The function “retain radioactivity” means to collect any irradiated fuel leakage before it goes to the Nuclear Confinement System atmosphere, and as such fuel will have a certain level of residual heat, it needs cooling. Therefore, the Primary Tank needs all Heat Exchangers (HE) to be at the lowest level to remove the residual heat in case of leakages.

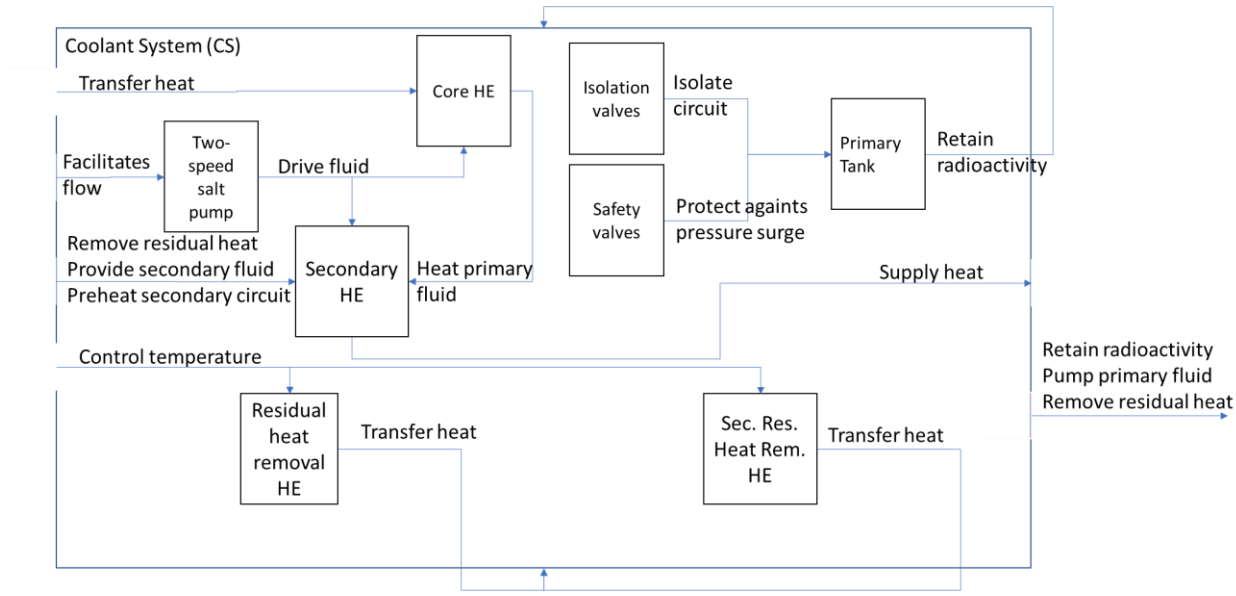

Fig. 7. Identification of subsystems and their functions - Coolant System.

Fig. 8 presents the diagram of the Coolant System (traced boxes are components of other subsystems), showing some critical aspects, like the use of fluidic diodes and safety and isolation valves. Fluidic diodes allow high natural circulation flow in case of complete loss of electrical power while keeping the flow through the residual heat removal Heat Exchanger (HE) small in normal operation, when the pump is running. The safety valves prevent a heat exchanger burst in PCS from generating a pressure surge in the secondary circuit inside the

Nuclear Confinement System (NCS). The isolation valves prevent the steam leakage entering the NCS from increasing its pressure to a point of a rupture. Also, in case of excessive heat demand by the PCS, or low temperature in primary or secondary circuits, the isolation valves act to avoid salt freezing.

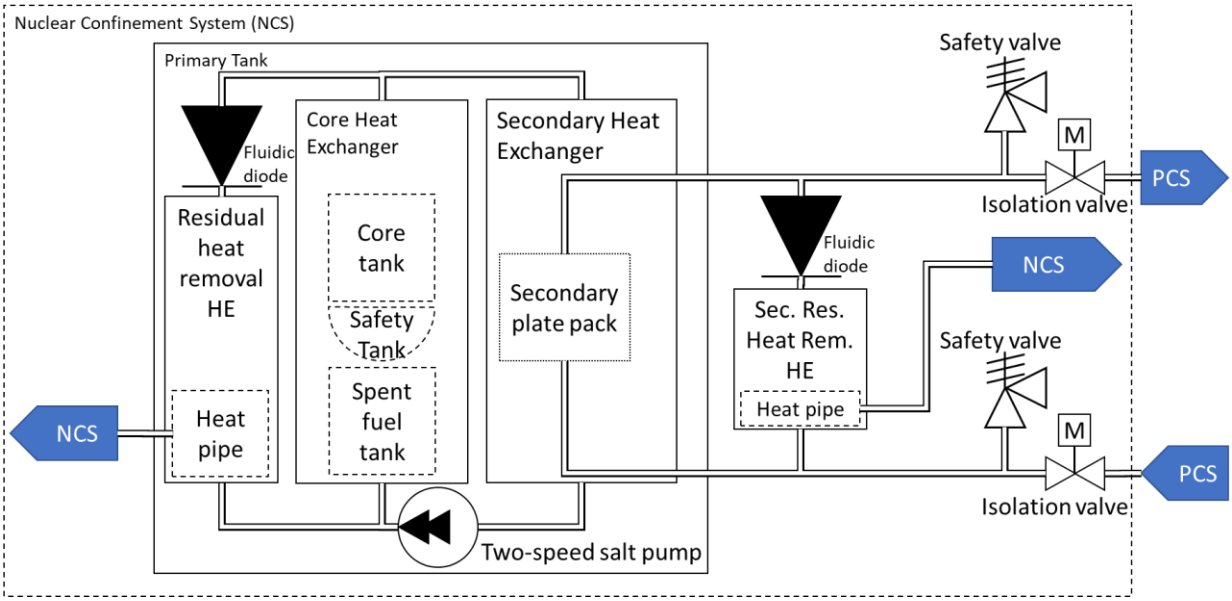

Fig. 8. Diagram of the fuel cladding.

A major decision is what salt to use for primary circuit, which should have low melting point (below 525ºC)[5], high boiling point (keep chemical stability at 800ºC at least), low thermal neutrons absorption cross sections, high atomic numbers, low corrosivity, high heat capacity. As the atomic number of all components must be high to prevent neutron moderation in the coolant salt, fluorides are excluded. The considered options are in **TABLE II.**

TABLE II. Analysis of salt options for primary coolant.

Salt	Neutron cross section (barn)	Melting point (ºC)	Heat capacity (kJ/kg/K)	Mean neutron energy absorption (%/collision)	Boiling point (ºC)
70% KCl- 30% $MgCl_2$	0.97945	426	0.984	5.2%	1412

Salt	Neutron cross section (barn)	Melting point (ºC)	Heat capacity (kJ/kg/K)	Mean neutron energy absorption (%/collision)	Boiling point (ºC)
55% NaCl – 45% $MgCl_2$	0.404175	445	1.0415	6.3%	1412
75% KCl - 25% $CaCl_2$	1.057875	600	0.9725	5.0%	1420
47% NaCl - 53% CaCl2	0.455265	500	1.0046	5.7%	1465

Due the smaller cross-section and reasonable melting point, this work chose the 55% NaCl – 45% MgCl2 for the primary coolant salt.

Another decision is the salt to use in the secondary circuit, which should have low melting point (smaller than 400ºC to enable use in steam generators)[5], high boiling point, low corrosivity, low viscosity, low cost, high heat capacity and small generation of radioactive isotopes under radiation. As Lithium generates Tritium under neutron irradiation by the $^{6}Li(n, \alpha)^{3}H$ reaction, all Lithium salts were not studied. To avoid such reaction, Lithium needs to be enriched to ^{7}Li, which makes it more expensive, and once the secondary circuit will be relatively large, the costs would impact the economic feasibility. Because the salt will be out of the nuclear confinement system, it must not contain elements prone to neutron activation. The considered options are in **TABLE III**.

TABLE III. Qualitative analysis of candidate elements. [5, 6]

Elements	Assumed Price (US$/kg)	Short-lived activation	Long-lived activation
Lithium (natural)	85	Very good	Poor (^{3}H)
Lithium-7 (99.9%)	10000	Very good	Very good
Beryllium	860	Very good	Good
Fluorine	2	Very good	Very good
Sodium	3	Acceptable	Good
Potassium	13	Acceptable	Poor (^{39}Ar)

Elements	Assumed Price (US$/kg)	Short-lived activation	Long-lived activation
Rubidium	16000	Poor	Good
Zirconium	36	Poor	Acceptable
Boron	4	Very good	Very good
Calcium	2	Poor (^{49}Ca)	Poor(^{41}Ca)
Magnesium	2	Acceptable	Very good
Chlorine	0.1	Acceptable	Very good

Therefore, only salts with Beryllium, Fluorine, Sodium, Boron and Chlorine are interesting considering economical and radioprotection issues. Therefore, according to Table 4, there are not many salt options.

TABLE IV. Characteristics of candidate salts.

Salt	Price ($/liter)	Melting point (ºC)	Heat capacity (kJ/kg/K)	Viscosity at 700ºC (cP)	Boiling point (ºC)
8%NaF-92%NaBF4	1.5	384	1.5	1.1	690
43%BeF2-57%NaF	26	340	2.17568	7	1400
55% NaCl – 45% $MgCl_2$	1.5	445	1.0415		1412

On grounds of cost, melting point, heat capacity and viscosity, this work chose 8%NaF-92%NaBF4 salt for the secondary circuit. A preliminary approach for the tanks (core, safety and spent fuel) is the use of the plate side of a plate and shell heat exchanger, like those manufactured by GESMEX (http://www.gesmex.com/en/), being the coolant at the shell side. Those heat exchangers allow the use of 3 fluids, so the Uranium salt would be intercalated with the deuterium plus Zirconium in the plate side, while the coolant would run in the shell side, cooling both fuel and moderator. Due technological restrictions, the diameter is restricted to a maximum of 1,4m and the length is restricted to a maximum of 5m [7]. It seems to be enough for a 200MWth heat exchange, which is comparable to a nuclear barge like ACPRS 50 and

Akademic Lomonosov. In fact, like pressurized water reactors (PWR), the size of the reactor is constrained by the heat exchange surface. Fig. 9 presents the arrangement of the coolant system and the associated shielding, which has an external diameter of 4,9 meters and length of 14 meters.

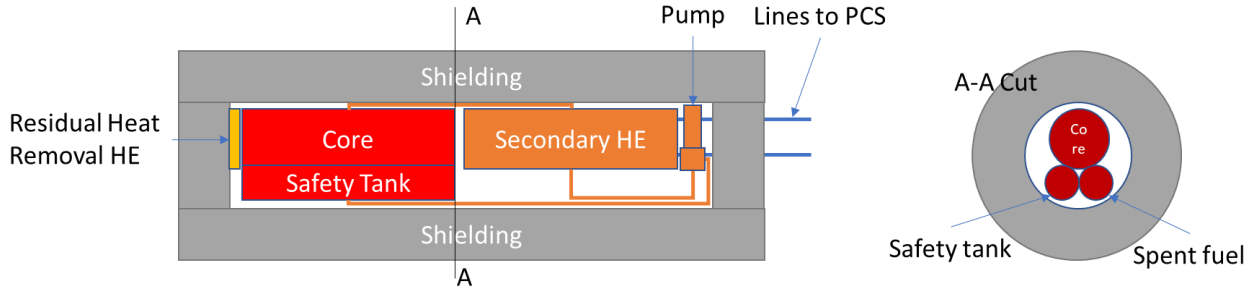

Fig. 9. Arrangement layout for the Coolant System.

TABLE V presents the weight estimation for the coolant system and the shielding system which are the heaviest elements, allowing the verify the feasibility of this design. For comparison, an integral PWR reactor coolant system and shielding with similar rated power would have a weight of 1400 Ton [8].

TABLE V. Weight estimation for the nuclear reactor and its shielding.

Part	Mass (Ton)
Shielding (Lead)	1174,0
Shielding (water)	101,8
Primary coolant salt	14,9
Moderator	10,2
Heat exchangers	14,3
Fuel	4,8
Safety heat exchanger	2,0
Spent fuel tank	2,0
Total	1323,9

IV.F. Reactivity control system

In this design, the Reactivity Control System does not have actuators of its own, but generates signals to:

1. Remove fuel from core (fast shutdown).

2. Remove Deuterium pressure on lattice confinement material (slow shutdown).

At 685ºC, the reactor become subcritical, being the reactivity control based on reactor temperature, which is a passive solution. Fig. 10 presents the ReCS subsystems and their functions. The operators may change the equilibrium temperature by:

1. Inserting more fissile isotopes in fuel.
2. Increasing Deuterium pressure in TNSS.
3. Changing fuel level in core tank (the volumetric pump allows precise inventory control in the core).

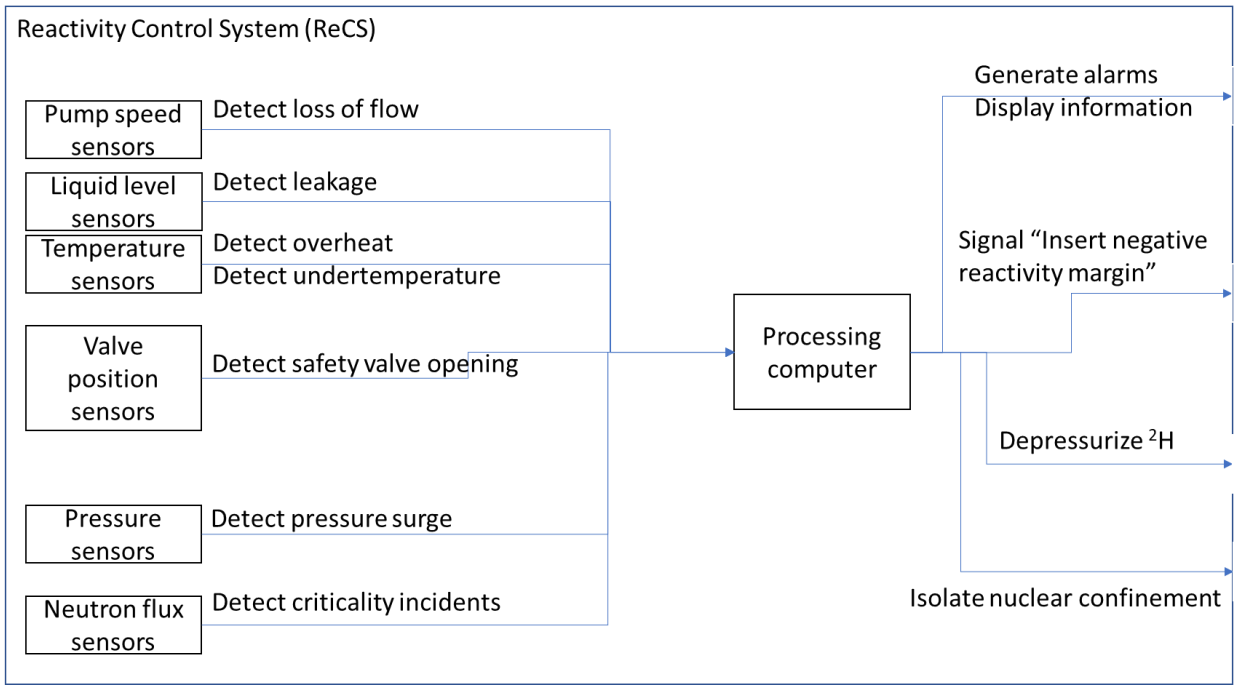

Fig. 10. Identification of subsystems and their functions - Reactivity Control System.

The choice is to profit of the molten salt characteristics to avoid large reactivity margins and adopt a passive reactivity control, which probably should be more reliable than control rods.

IV.G. Nuclear confinement system (NCS)

Besides segregating a portion of atmospheric air to prevent liberation of eventual fission products from the reactor, the NCS also must absorb residual heat in case of an emergency shutdown in absence of electric power. This means the NCS must be able to transfer the heat (coming through heat pipes fluid) from the primary or secondary circuits towards an ultimate heat sink. In fact, the confinement vessel must have form and contact with external fluids allowing heat transfer.

One must remember that this vessel does not need to bear high pressures and its walls may be much thinner than in current PWR designs. Fig. 11 presents the main subsystems of the NCS.

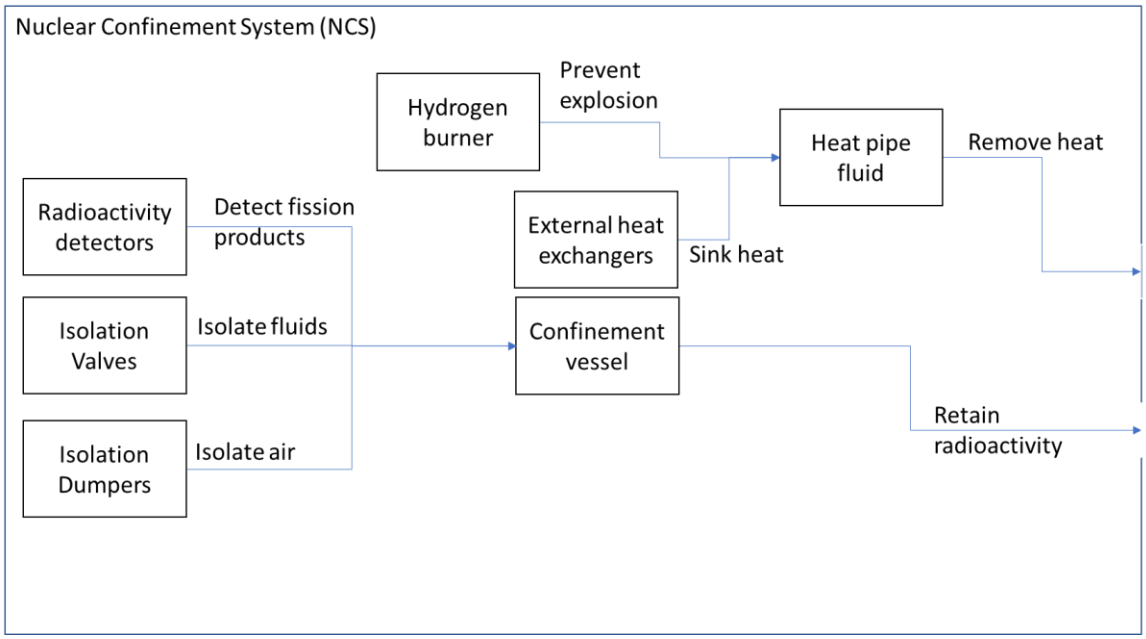

Fig. 11. Identification of subsystems and their functions - Nuclear Confinement System.

This design adopts a passive external heat exchanger for primary circuit and another for secondary circuit, keeping the removal of residual heat in case of a single failure.

V. RESULTS

The overall design is a hybrid concept of fission Molten Salt Reactor with lattice confinement fusion reactor as developed by [7]. The result is a safe and cheap reactor with a great flexibility for fuels.

It is cheap because it has noticeably light nuclear safety-related pressure vessels, which are one order of magnitude more expensive than similar pressure vessels for other industries. Further, its design is simpler in terms of components, reducing the capital cost of building such reactor. Another aspect is the careful choice of salt materials, avoiding enriched Lithium or long-term radioactivation, which reduces life cycle cost.

Given its relative neutron abundance, it may run on natural Uranium and possibly breed fissile atoms from fertile materials. Except for ^{37}Cl and ^{2}H, it does not need large expenses on isotopic enrichment, like current reactor designs. Given its compactness, the quantity of isotopically enriched material is low compared to CANDU design, yet it may use natural Uranium. As it does not need fuel element construction and enrichment, its cost is further lowered, even if fuel is not the major cost driver.

Its heat exchangers need periodic replacement due radiation damage and corrosion at similar intervals as PWR does refuelling. However, such stop times should be much smaller, as it is possible to remove the spent fuel completely and perform the replacements without much radiation protection issues. Therefore, it should have a better reliability and availability than current designs, even because it has less components.

From safety point of view, its risk (potential radioactivity leakage) is smaller than current designs based on solid fuel because the gaseous fission products are immediately removed. Furthermore, the fuel cannot melt because it is already molten, excluding the core meltdown event. The cladding may melt if residual heat is not removed, but even if it does, the quantity of thermal source liberated in the CS is small. The reliability of the residual heat

removal solutions is larger than current designs, which depend on valves, pumps, electricity, and electronic control systems. The heat pipes proposed in this work are automatically activated by overtemperature of the primary or secondary circuits. They contain liquid metal at a given pressure inside the heat pipes and when the liquid metal surpasses 690ºC, it starts to evaporate removing heat. The vaporized metal cools down in the NCS external heat exchangers and become liquid again, returning to the primary or secondary circuits. Upon cooldown below 690ºC, the heat pipes stop operation, avoiding salt freeze in the circuits. Therefore, heat pipes are an automatic and reliable solution due its simplicity, avoiding many failure modes on instrumentation, valves, pumps, and electrical supply. Due its inherent design, the reactivity margin is small, making reactivity accidents unlikely.

Besides its low cost as a power reactor, it may also sell services of isotopes burning, increasing its revenue. Such possibility comes from the neutron abundance provided by fusion reactions.

VI. DISCUSSION

[2] demonstrate that the best way to heat Deuterium atoms is by neutrons. Only fission reactors are powerful enough as source of neutrons to enable enough fusion reactions to allow power generation given the neutrons yield demonstrated by [1].

However, there are doubts on the real mechanism behind the 4 and 5MeV neutrons presented in Fig. 12, which may be second and third generation of neutrons from D(d, n)^{3}He reactions or product of other type of reactions. [1] That work supposes that stripping reactions of type ^{x}Er(d, n)$^{x+1}$Tm may explain the 4, 5 and 5.5 neutrons.

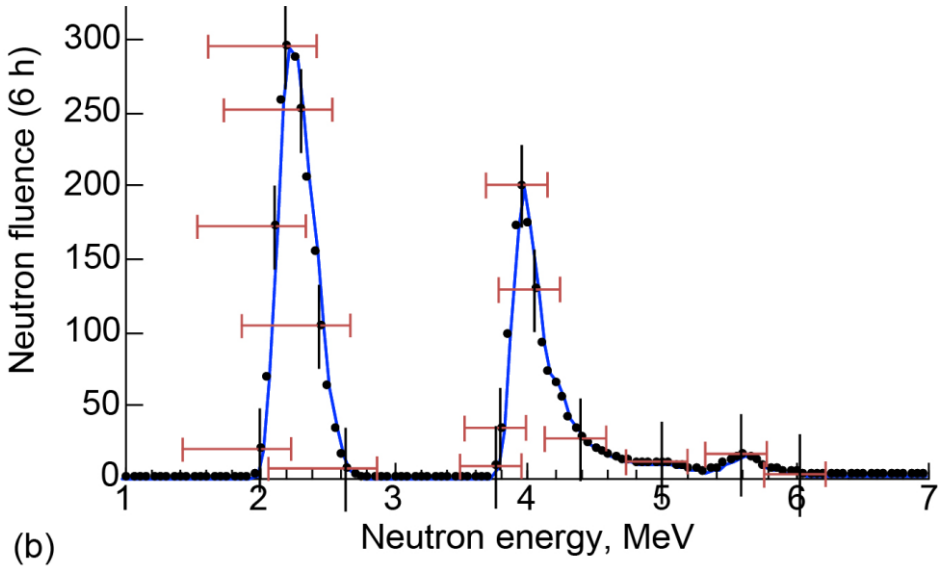

Fig. 12. Neutron fluence versus neutron energy. [1]

However, current models (TALYS, TENDL-2015) do not predict that 2.45 MeV neutrons could induce stripping reactions, requiring far more elevated energies (larger than 5MeV). Considering that known cross-sections were obtained in metallic Erbium, which is a highly screened environment, this setup should not experience different cross-sections unless the presence of Deuterium in metal lattice has other effects. This work made a fast analysis of the possible reactions in this experiment, as shown in Fig. 13.

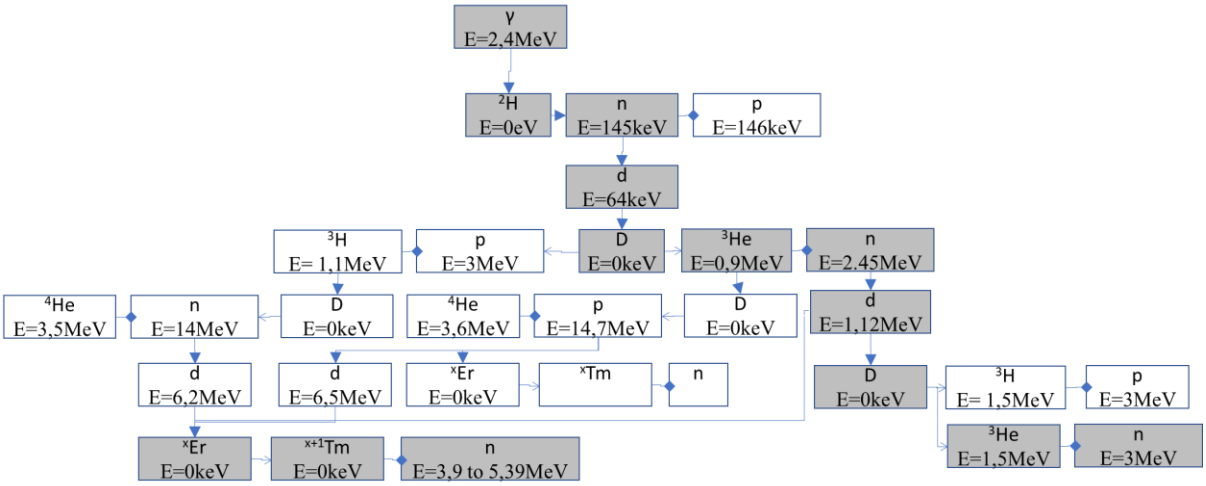

Fig. 13. Possible outcomes given a γ ray. In grey are isotopes states considered by Ref. [1].

Once Tritium outcomes enter in consideration, there is generation of 14MeV neutrons that could heat Deuterium atoms to the 6MeV energy range, approaching the known energy range where the ^{x}Er(d, n)$^{x+1}$Tm reactions start to occur. Although Ref. [1] do not report presence of 14MeV neutrons nor presence of isotopes besides those generated by neutron capture, other similar experimental work reported both.[8] This earlier work is an evidence that Tritium (and potentially Helium-3) reactions do occur in such experiments. Fig. 14 shows that for a considerable projectile energy range, Tritium and Helium-3 reactions are more likely than Deuterium reactions.

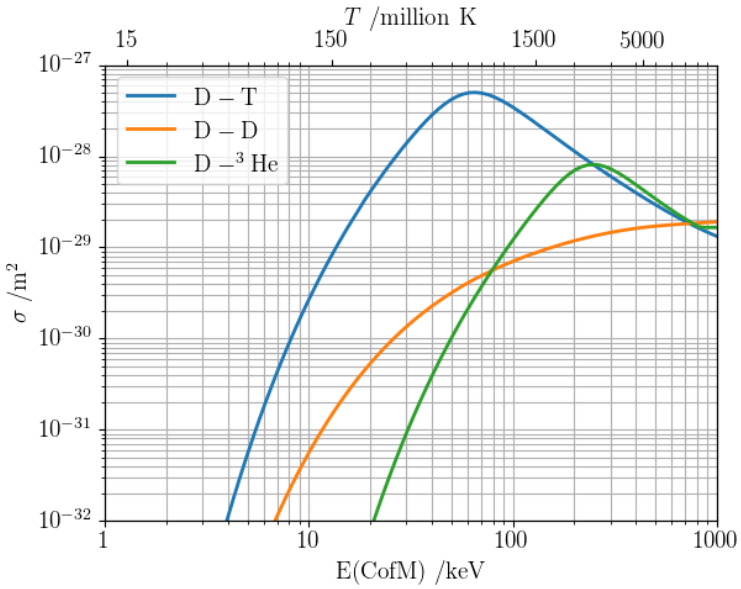

Fig. 14. Cross sections of fusion reactions (ENDF/B-VIII).

Known models also report that ^{x}Er(p, γ)$^{x+1}$Tm and ^{x}Er(p, n)^{x}Tm reactions are more likely than ^{x}Er(d, n)$^{x+1}$Tm (Fig. 15) and such reactions would also benefit from the highly screened environment.

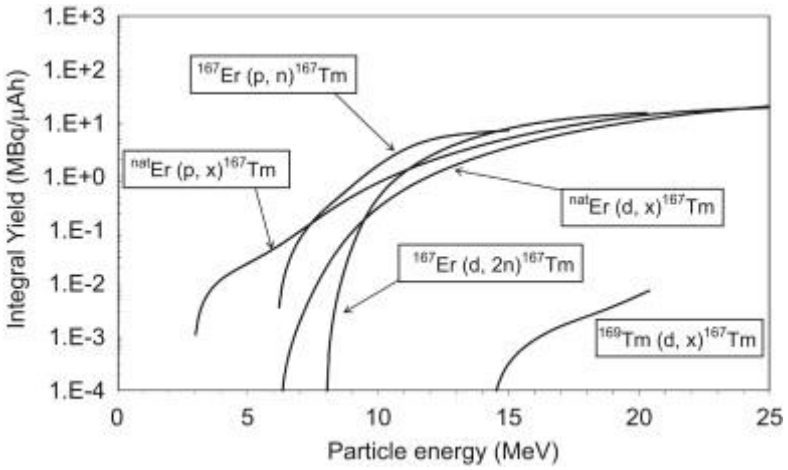

Fig. 15. Cross sections of proton and Deuterium reactions with Erbium.[9]

One aspect is the ratio between the 2.45MeV and 4MeV neutrons in Fig. 12, which seems to be around half or two thirds. Given the samples size (2.5cm diameter, 5cm high) and Deuterium scattering macroscopic cross sections for neutrons (4.17cm), this work estimates that two thirds of neutrons leave the sample without interaction at each generation. This suggests that either those neutrons have a common source (meaning they are not parent and child) or there are phenomena not considered the analysis.

A possible phenomenon would be the occurrence of electron–positron pair production, which has threshold energy of 1.022MeV and is stronger in higher atomic numbers. This interaction generates a recoil in the atom nucleus, which could lead to the following reactions: D(^{x}Er, d) ^{x}Er (Deuterium heating), D(^{x}Er, n)$^{x+1}$Tm (inverse Oppenheimer-Phillips stripping reactions), D(^{x}Er, p)$^{x+1}$Er (Oppenheimer-Phillips stripping reactions). Such hypothesis would explain why, according with [1] results, the 4MeV peak is higher in deuterated Erbium than Titanium (electron–positron pair production is larger in atoms with high atomic number). Fig. 16 presents the cross-section of the pair production reaction for Erbium, calculated using Maximon equation, which, comparing with Fig. 17, makes evident that its cross sections are superior to Deuterium photodissociation.

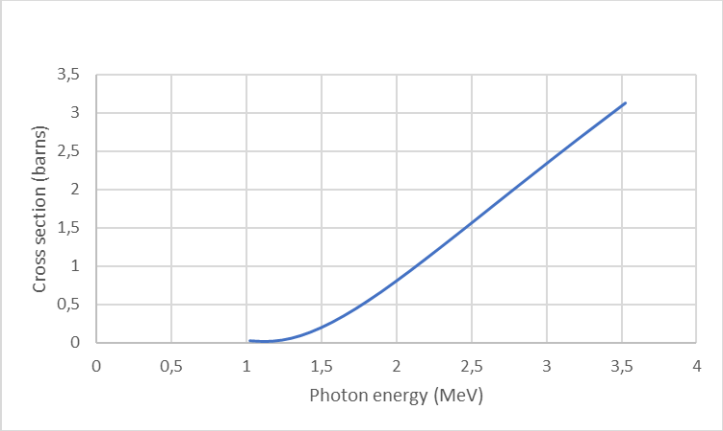

Fig. 16. Cross section for Erbium electron–positron pair production. [10]

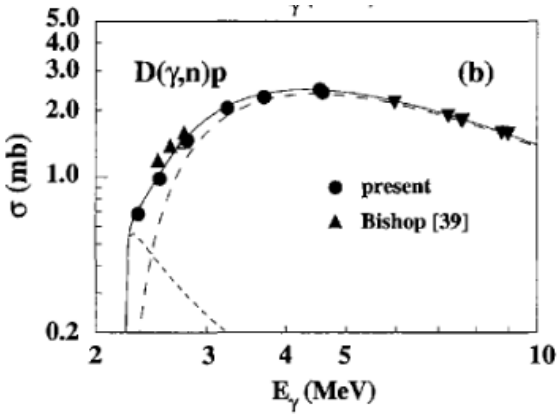

Fig. 17. Cross section for Deuterium photodisintegration reactions. Courtesy from [11].

This design has a risk of the neutron yield from the lattice confinement fusion reactions being too small to have a significant effect on reactivity. However, even if this is true, the photodissociation effect should provide a reactivity increase in the order of a few neutrons per thousand. Another aspect is many Deuterium atoms are heated by a single average fission-born neutron. Considering both fusion neutrons and photodissociation neutrons, Deuterium in metal lattice may increase reactivity coefficient enough to enable design options that are currently impossible.

However, various independent authors report the phenomenon of enhanced fusion reactions in metals. [12, 13, 14, 15, 16]

On the other hand, if the 4MeV neutrons are indirect products from the 2.45MeV neutrons as one of Ref. [1] hypothesis, about one third of each neutron generation makes a new neutron. This would mean a reactivity boost of one third, which means this proposed design would need revision reducing the quantity of fusion reactions to make the reactor controllable.

It is important to mention the work of Ref. [17] that irradiated deuterated Palladium samples with neutrons from a Am-Be source. The samples were subjected to a molecular Deuterium atmosphere of 35 bar, and according to Monte Carlo simulations, produced several neutrons for each incident neutron. However, this experiment was performed with deuterated Palladium and at room temperature and it is not possible to state that deuterated Zirconium at 700ºC would have similar behavior. Another work, using deuterated Palladium under irradiation from a Am-Be neutron source, suggested the number of neutrons obtained is 2 or 3 orders of magnitude larger than expected. [18]

An evidence that Zirconium could have good properties for enhancement of nuclear reactions, is the experiment of Ref. [19], that compared some metals and alloys in terms of Tritium production upon Deuterium loading. The results suggest the Tritium production increase with atomic number, in line with Ref. [1]. The results also suggest that Zircaloy 2 produces one order of size more Tritium than Titanium or Zirconium, seeming that some alloys are better than pure metals.

Another issue is the absence of experiments with metals at the 600ºC – 700ºC. Ref. [14] reported metals in the periodic table group of Zirconium do not have a large cross section enhancement at room temperature (20ºC). However, Titanium and Hafnium at 200ºC showed high cross section enhancements. Ref. [16] reported an enhancement of cross-section in deuterated metallic Lithium at the phase transition (from solid to liquid), having measurements at temperatures up to 400ºC. However, only experiments involving neutron and gamma beams

on targets at the 600ºC – 700ºC temperature range would confirm the feasibility of the proposed TNSS.

Another interesting fact is the cavitation experiments of Ref. [20] which obtained a much larger increase in $^{2}H(d, p)^{3}H$ reactions in molten Lithium by ultrasound-induced cavitation. Such phenomenon could be an option to improve the TNSS design. However, as it involves molten metal and cavitation, which is a very harmful phenomenon to equipment, the use of such concept requires deep analysis.

It is important to keep the mind open to other materials besides metals. For instance, Ref. [21] reported a considerable enhancement in $^{1}H(^{7}Li, \alpha)\ ^{4}He$ reactions in graphite, which is an option for Hydrogen storage. If $^{2}H(d, p)^{3}H$ and $^{2}H(d, n)^{3}He$ reactions are also boosted in graphite at MSR operating temperatures, Zirconium could be substituted by a less neutron absorbant material. Therefore, the use of deuterated graphite requires experiments with neutron and gamma beams on targets at the MSR operating temperature range (600ºC – 700ºC).

Last, but not least, in the worst case scenario, it may be proved that the achievable nuclear fusions are negligible and the proposed design becomes practically a fission reactor. Such reactor would be economically competitive and still be able to run on natural Uranium and breed fissile material, besides being easily adaptable to many applications. In the “best” case scenario, the neutron multiplication in TNSS is proven to be too high from a nuclear safety point of view. In this scenario, graphite would substitute part of the lattice confinement material, reducing the TNSS neutron multiplication ratio and providing neutron moderation. In this scenario, the reactor could have the simultaneous functions of power generation and burning of radioactive waste.

VII. CONCLUSIONS

This work presented a reactor concept with its main systems using simultaneous fission (to generate energy) and lattice confinement fusion (to boost reactivity). Such reactor design allows simultaneous power generation, breeding of fissile isotopes and burning of radioactive waste at a low cost. Furthermore, it does not require isotopic enrichment, being a flexible design.

This design follows the principle of defense in depth and concentric barriers to prevent radioactivity leakage to the environment. It kept the same level of safety of current designs but at a smaller cost and it is compact and adaptable to various applications, like nuclear barges, merchant ships propulsion, or process heat supply.

This work does not claim that the use of lattice confinement fusion in fission reactors is feasible, but notes that it may be feasible or, perhaps with some changes in this design, may be made feasible. A small change in reactivity may enable fuel options and reactor roles that today are not feasible without enrichement or Accelerator-Driven Systems.

To verify the feasibility of such design, more information on the fusion reactions cross-section enhancement is needed for the MSR temperature operating range. For instance, experiments of deuterated Zirconium and Graphite targets at 600 to 700ºC under neutron and gamma beams would check if such concept were feasible.

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