Clean and safe nuclear power – emerging fusion technologies for near future

Abstract. New research developments suggest that nuclear reactors using fusion may enter the market sooner than imagined even for mobile applications, like merchant ship propulsion and remote power generation. This article aims at pointing such developments and how they could affect nuclear fusion. The method is enumerating the main nuclear reactors concepts, identifying new technological or theoretical developments, and analysing how new recombination could affect feasibility of nuclear fusion. New technologies or experimental results do not always work the way people imagine, being better or worse for intended effects or even bringing completely unforeseen effects. Results point the following designs could be successful, in descending order of potential: aneutronic nuclear reactions using lattice confinement, hybrid fission-lattice confinement fusion, aneutronic nuclear reactions using inertial along magnetic confinement, and fission reactions.

1. Introduction

Most commerce is done by the seas and ships contribute significantly to greenhouse gases emission and most of costs come from the fuel, which may increase with new regulations. From an energy security point of view, the fact that petrol is concentrated in few politically unstable countries is a large incentive to search for new forms of energy.

Furthermore, economic development requires growing and stable energy matrix and any interruption in energy supply may be catastrophic as even food production, transport and conservation depend on energy.

Today, some enterprises claim they may deliver mobile nuclear reactor within 10 to 20 years from now, providing cheap and clean energy. Recent breakthroughs on superconducting materials and magnetic fields give hints that those claims may even be truer than those enterprises imagined. On top of that, new discoveries suggest that current nuclear models need revision and that new types of nuclear reactors could be feasible.

It is important to recall some definitions to the reader, being the first the concept of fission and fusion. Fission is the phenomenon where a larger atom is divided in smaller atoms while fusion is the junction of two atoms into a larger one. The fissions of Uranium and Plutonium are the most famous, but light elements also suffer fission, like Boron in the ^{11}B(p, 2 alpha)^{4}He or Lithium in the ^{7}Li(p, alpha)^{4}He reactions. However, for those last two examples, people tend to use the word “fusion” because they are technologically more akin to fusion reactions than fission reactions, in the sense they are clean and leave no radioactivity.

Other important concepts are those of neutronic and aneutronic reactions, as neutrons are the best way to heat atoms and cause fission but have a large array of undesirable effects. Energetic neutrons are ionizing radiation, and they have a high penetration power, requiring large radiological shielding, besides causing radiation damage to materials. Many nuclides capture neutrons, becoming radioactive elements (neutron activation) and other nuclides generate intense gamma radiation under neutron radiation due inelastic scattering. Neutron damage imposes frequent material replacement, neutron activation generates radioactive waste, shielding add volume and weight. Material replacement, radioactive waste, volume, and weight together contribute to increase life cycle costs of a nuclear power plant, particularly if it is mobile.

On the other hand, aneutronic nuclear reactions, like $^{11}B(p, 2\ alpha)^{4}He$ or Lithium in the $^{7}Li(p, alpha)^{4}He$, are clean, do not require large shielding and do not generate material damage. The drawback is they require larger energies to overcome Coulomb barrier, so people directed the larger portion of investment in research on fusion reactors to neutronic reactions.

Another fundamental concept is the Technological Readiness Levels (TRL), that are objective stages of maturity of a technology for use and constitute a powerful risk mitigation technique for systems engineering. This work adopted the NASA technological readiness levels, presented at Figure 1.

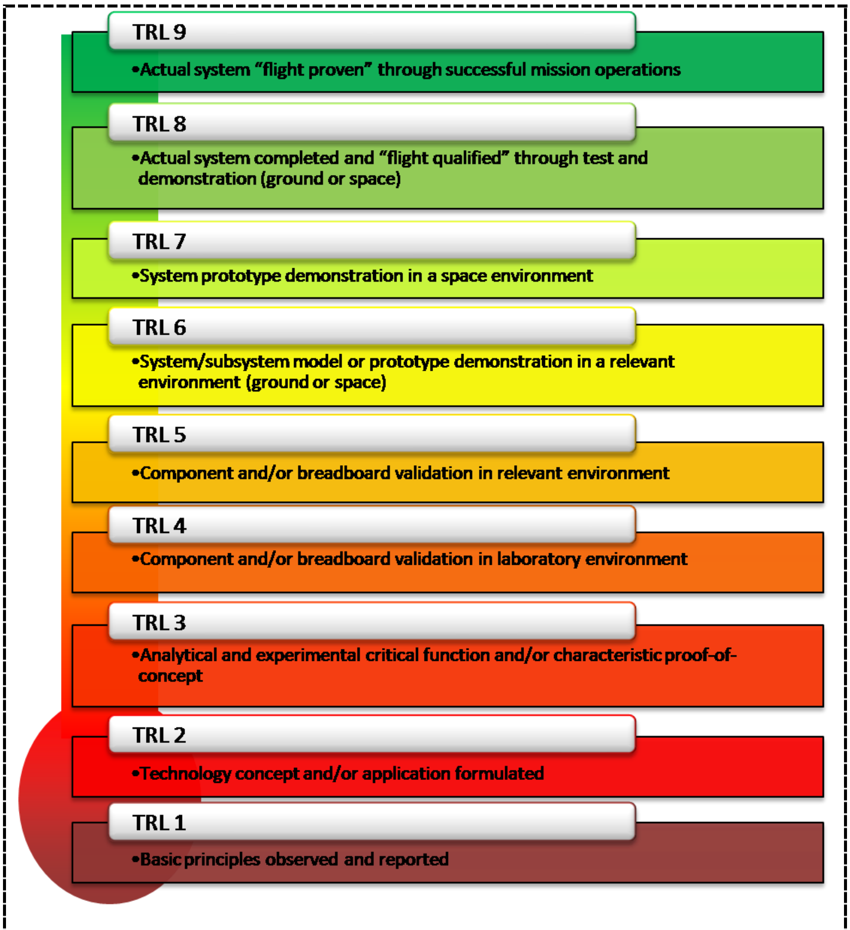

Figure 1. NASA Technology Readiness Level (TRL).

In fusion reactors, the concept of "Coefficient Of Performance" (COP) is the ratio of energy output over energy input. Assuming the input is electrical energy and a global thermal cycle of 40%, a reactor with COP = 2,5 barely sustains itself, so this level is absolute minimum to consider in mobile nuclear power plants. In practice, COP should be beyond 5 (50% of generated power is used by reactor) to allow commercial applications, meaning that for mobile NPP, to go beyond TRL3, COP must be larger than 5.

This work evaluates TRL only for the black box receiving electric power and generating heat, and not for the global system generating electricity, as integration problems add further development but should not present large risks.

Another assumption is that the technical difficulty to develop a technology is proportional to the required financial investment alone, ignoring time or personnel qualification.

Nuclear reactors are divided in generations, where the first generation were prototypes, the second were the first commercial solutions, the third are the advanced PWR designs and fourth are concepts of future reactors. The fourth generation would be highly economical and proliferation resistant, it would have minimal waste and enhanced safety. Amongst the fourth-generation concepts are the molten salt reactors. This work focuses on another generation, yet beyond fourth generation, having truly little or no radioactive waste, little need for radiological protection, being much more economical than fossil fuels. That would be the fifth generation, based on nuclear reactions of light elements and emerging technologies, representing a true game changer in energy market and in greenhouse gases emissions.

This work concentrates in mobile applications because they are also applicable to larger land-based or static power plants, but technologies applicable to land-based energy production are not necessarily applicable for mobile applications. Currently, given the global supply chains, transportation is so vital as energy production, so research on mobile applications (merchant ship propulsion, remote power plants, aircraft propulsion, space propulsion) has a broader impact.

2. Method

The first step is to identify the main nuclear reactors families along their technological readiness for mobile applications.

The second step is to identify recent discoveries of physical laws and new technologies that could impact the status of nuclear reactors.

The third step is to combine those developments with each family to wonder which new concept could emerge.

The fourth step is to analyse the risks and potential gains associated with each concept, identifying interesting avenues for research.

3. Development

Pressurized Water Reactors are sea-proven, used for several merchant ships and many military ships, particularly for submarines. However, the quantity of high-quality pressure vessels has made them too expensive because of capital costs, while fuel is inexpensive. As nuclear reactors experience scale economy, larger reactors have better changes of becoming competitive, and authors estimate that the minimal nominal power (to compete with diesel propulsion) would be about 50MW electrical (around 200-240MW thermal).

Molten-Salt Reactors (MSR) eliminate the need of pressure vessels, but because of lack of political support, the US Oak Ridge National Laboratory stopped the development of this technology. The MSR experiment run without problems from 1965 to 1969 and was an evolution of Aircraft Reactor Experiment (ARE), being compact and light. As it worked around 650ºC, it allowed high efficiency thermal cycles, but this concept stopped at laboratory demonstrations stage. If research is done, authors estimate that 17MW electrical MSR could be competitive with diesel propulsion.

Liquid Metal Reactors (LMR) already powered military submarines both in URSS and US, but had safety issues and PWR became the standard, although LMR had better power density than PWR.

This work considered RMBK, CANDU and HTGR to have low power density (too large) for ship propulsion, where volume and weight are critical. Boiling Water Reactors (BWR) could be even more compact than PWR, but heave motions or shocks could have impact in reactivity by changing the moderator density within the reactor, meaning that BWR cannot be an option.

For ships, even with recent advances in superconductors, magnetic confinement fusion reactors (TOMAKAK, stellarators) probably would not fit in a ship because they need large coils, cooling for those coils, shielding for the neutrons and their shape is not the most adequate for arrangement in a ship. Therefore, the hybrid fission-fusion concepts, which use a fissionable blanket to generate heat and a fusion reactor to provide neutrons, also do not fit in ships.

Inertial confinement fusion reactors typically use lasers to compress light atoms to the point to obtain fusion reactions in a small sphere of fuel (deuterium, tritium), generating heat and neutrons. Although compact, this approach has trouble with low efficiency of lasers and with the radiation damage issues. Therefore, for the medium term, ships probably will not have nuclear reactors based on inertial confinement fusion nor in hybrid concepts using fission.

Some enterprises start to make claims of researching compact fusion reactors designs that could be so compact that they would fit in a truck load and could power airplanes. Such designs rely in a mix of magnetic and inertial confinement and use formats more adequate to embark in a ship. Examples of innovative enterprises are Lockheed Martin Compact Fusion Reactor, General Fusion, TAE Technologies (former Tri-Alpha Energy), Lawrenceville Plasma Physics (LPP), HB11 and Zap Energy. Some of those use aneutronic reactions, the proton plus Boron-11 fission reaction that produces 3 alpha particles, reducing the need of shield, costs, volume, and weight. Further, some designs use direct energy conversion, which uses the energy from plasma to generate electricity, or photoelectric effects to generate electricity from X-rays. However promising, those technologies did not demonstrate yet a COP larger than 1.

Lattice Confinement uses loading of Hydrogen isotopes in conductors' lattice by diverse methods (electrolysis, glow discharge, gas loading, ion beams) and heating the lattice with radiation, thermal energy, lasers or accelerated ions. Another group of enterprises develop energy products based on Lattice Confinement reactors, like E-Cat, Defkalion, Brillouin Energy, Energetics Technologies. E-Cat, an invention of Andrea Rossi, uses a mixture of Nickel, Aluminium, Lithium and Hydrogen to catalyse apparently aneutronic nuclear reactions using lattice confinement. A report by Fabio Penon (third-party validator agreed by Industrial Heat and Andrea Rossi), available at E-Cat website (1), claims to have achieved COP ranging from 62 to 142, having an overall of 80 in a 350 days demonstration.

The nuclear reactors families are listed in Table 1.

Table 1. Families of nuclear reactors and their technological readiness

Family	Subfamily	Readiness Level
Fission	PWR	9
	MSR	4
	RMBK	Theoretically unfeasible
	CANDU	Theoretically unfeasible
	HTGR	Theoretically unfeasible
	BWR	Theoretically unfeasible
	LMR	8
Hybrid Fission-Fusion	Molten salt – Magnetic Confinement	Theoretically unfeasible
	Molten salt – Inertial Confinement	Theoretically unfeasible
	Magnetic Confinement	Theoretically unfeasible
Fusion*	Inertial Confinement	Theoretically unfeasible
	Magnetic and Inertial Confinement	3
	Lattice Confinement	7

* Technically, some of the technologies are fission reactions, like ^{11}B(p, 3alpha) reactions, but people call indistinctively "fusion" when using light elements.

After reviewing the current promising technologies, Table 2 presents recent discoveries in the nuclear reactions field.

Table 2. Recent discoveries

Name	Description
Cross section enhancements in conductors	The probability of fusion reactions in conductors' lattice is higher than in gas or plasma. This effect is often called "Screening", meaning that the Coulomb barrier is lowered in a conductive solid. (2) (3)
Neutron multiplication in deuterated Pd	Researchers found that saturating Palladium metal with Deuterium and submitting it to neutron beam results in a neutron multiplication, suggesting neutrons can start nuclear chain reactions in deuterated Palladium (4) (5)

Table 2. Recent discoveries

Name	Description
Nuclear Transmutations in Solids	Some conductors, typically Palladium, Nickel, Gold, graphite, upon Hydrogen isotopes loading (for instance, by electrolysis, gas loading, glow discharge), present a large array of new elements, both lighter and heavier, suggesting fission and fusion reactions (6), along large liberation of heat
New superconductors at higher temperatures	High-temperature superconductors (like Bismuth strontium calcium copper oxide, Yttrium barium copper oxide) have superconducting properties at temperatures above liquid nitrogen boiling point (77ºK), easing the cooling of magnets
Neutron generation in deuterated metals	Deuterated metals, like Titanium, Palladium, Erbium, present neutron emissions under background radiation. If subjected to a radiation beam, the quantity of neutrons (and nuclear reactions along a large number of new elements) increases greatly (5) (7) (8)

After listing the theoretical and technological advances, it is important to identify the potential impacts in technologies. PWR could use deuterated metal rods to help in moderation and produce extra neutrons, allowing the use of natural Uranium, Thorium and spent fuel from PWR. It could be a cheap refit, but the potential gains are small, as the fuel cost is small (about 5% of energy price), even with enrichment, and fuel rod life depends also on radiation damage, not only on reactivity. As enrichment is about one third of fuel cost, costs improvements would be in 1-2% range.

For LMR, aneutronic reactions in a deuteride/hydride metallic fuel could help to remove part of radioactive waste, improve moderation (better reactivity due presence of Hydrogen or Deuterium). Screened fusion reactions of Deuterium with Deuterium (either in a metallic fuel or in molten coolant) could also provide reactivity boost allowing the use of natural Uranium, Thorium, or even radioactive waste. However, the transmutation in coolant may generate corrosion and neutron-absorbing isotopes, meaning that this potential use is not certain. Further, those potential advantages do not correct the fundamental problems of LMR, like corrosion, plugging, and high exothermal chemical reactions with water (for Sodium cooled reactors).

For designs using magnetic confinement (including fusion-fission hybrids and inertial-magnetic hybrids), the advent of high temperature superconductors allows the generation of higher intensity fields. Such fields allow confinement of particles at higher temperatures, improving fusion rates or reducing magnets size, which is critical for mobile applications.

MSR could have a large improvement in fuel flexibility by adding deuterated metals to moderate neutrons and generate extra neutrons, boosting reactivity and allowing the use of natural Uranium, Thorium, and radioactive waste as fuel. As MSR does not have heavy and high-quality pressure vessels, its capital cost should be smaller than PWR, meaning that fuel cost would be more relevant, in 10% – 15% range, meaning that up to 5% reduction in energy costs could be achieved. However, there is risk that the generation of new elements in the deuterated metal lattice would absorb neutrons and prevent long term operation.

For combined inertial and magnetic confinement designs, the use of a deuterated or tritiated metal pellet could enhance the reaction yield by various orders of magnitude, as Hydrogen isotopes in metals are about 7 to 9 orders of magnitude denser than in current magnetic confinement plasmas. Besides, there is also the screening effect that enhances the reaction yield by reducing the Coulomb barrier along with the higher mass of metal atoms acting as a cage for small time periods. Similar arrangement is used in nuclear weapons, that may use deuterated Lithium and an external shell of Uranium.

Lattice confinement reactors using Nickel-Hydrogen and $LiAl_4$ additive, theoretically use the cross-section enhancement in conductors to allow proton capture by metal atoms nucleus. Current nuclear models do not predict such phenomena, which, if proven true, should require a revision of nuclear forces theory, which would not be the first theoretical shift in history.

The cross-section enhancement in conductors apparently enables the occurrence of chain reactions of aneutronic nuclear reactions in specific combinations of atoms, like Palladium-Deuterium, Nickel-Hydrogen, Tungsten-Hydrogen, Carbon-Hydrogen. Such chain reactions lead to the appearance of hot spots with new elements in the solid lattice, along with heat, X-rays, charged particles and, in some cases, a few neutrons. Those reactions tend to increase with application of energy on the solid and enables the development of solutions like E-Cat or Brillouin Energy's CECR.

Such type of reactor generates X-rays that easily shielded and do not produce radioactive products, meaning they should provide a very inexpensive power source. Table 3 presents the summary of potential impacts.

Table 3. Potential impacts

Subfamily	Cross section enhancements in conductors	Neutron multiplication in deuterated Pd/ Neutron generation in deuterated metals	Nuclear Transmutations in Solids	New superconductors at higher temperatures
PWR	Not applicable	Deuterated metals could boost reactivity	New elements may generate poison	Not applicable
MSR	Deuterated metals could boost reactivity	Deuterated metals could boost reactivity	New elements may generate poison	Not applicable
LMR	Aneutronic reactions could enhance power density, burn waste, Hydrogen isotopes would help moderation	Deuterium in coolant could boost reactivity and moderate	New elements may generate poison	Not applicable
Molten salt – Magnetic Confinement	Not applicable	Not applicable	Not applicable	Increase temperatures and fusion rates
Magnetic and Inertial Confinement	Use of deuterides/hydrides metals targets may enhance reaction rates	Impose shielding for use of deuterated metals	No relevant effect	Increase temperatures and fusion rates
Lattice Confinement	Allows chain aneutronic reactions	Impose shielding for use of deuterated metals	Limits the burn-up	Not applicable

4. Results

It is important to summarize the effective gains in energy costs, as estimated by the authors and Table 4 presents both foreseen upsides and downsides of investing at each subfamily of reactors.

Table 4. Risk and potential gains table

Subfamily	Potential gain (upside)	Risks (downside)
PWR	1-2% cost reduction	Generate neutron absorbing elements
MSR	3-5% cost reduction, radioactive waste burning at low cost	Generate neutron absorbing elements

LMR	Not estimated	Does not solve fundamental problems
Magnetic and Inertial Confinement	Orders of magnitude in COP enhancement	Insertion of solids increases design complexity and number of possible reaction products, possibly generating radioactive waste
Lattice Confinement	Orders of magnitude in costs reduction	The claimed COP may be not practical in real life situations or reaction control may be impossible

5. Discussion

Magnetic confinement fusion reactors have already received billions of investments, ITER project receiving about 25 billion with a target of COP>10, but to date, no magnetic confinement fusion reactor achieved COP=1.

Although no public figures exist for E-Cat (mean COP around 80) and Brillouin Energy's CECR (COP around 2,5) investments, one may assume it was less than tens of millions, given current investments (9). Therefore, if those lattice confinement reactors prove someday to be practical, one can say that lattice confinement is one thousand times easier to achieve than magnetic confinement.

It is important to mention that Andrea Rossi filled a lawsuit against Industrial Heat in 2016 alleging the licensing deal included a US$89 million fee after a one year successful demonstration (1), which Industrial Heat refused to pay on grounds of lack of proof (10). Both parties settled in 2017 and Industrial Heat renewed its commitment to keep pursuing this kind of technology, and Industrial Heat valuation reached US$ 918 valuation in 2019 (11). In April of 2021, Industrial Heat counted with 9 patents listed in https://uspto.report/company/Industrial-Heat-L-L-C/patents.

Not only private enterprises worked about Nickel-Hydrogen lattice-confinement reactors, but many researchers from academy have reported success in generating heat beyond chemical energy (12) (13) (14) (15).

Other interesting facts are Airbus filled two patents that apparently uses lattice confinement fusion and plasmas (16) (17) and Boing in partnership with NASA drafted a plan to develop the Subsonic Ultra Green Aircraft up to 2035 considering a Ni-H lattice confinement reactor as one possible alternative.

After researching some public information about private nuclear fusion enterprises, this work presents some valuations or gathered investments for some of them at Table 5.

Table 5. Risk and potential gains table

Enterprise	Value US$M	Year value
Industrial Heat	918	2019
TAE Technologies (former Tri-Alpha Energy)	750	2020
General Fusion	200	2016
Commonwealth Fusion Systems	200	2020
Tokamak Energy	193	2020
Zap Energy	14,5	2020
HB11	4,6	2021
Lawrenceville Plasma Physics (LPP)	2,4	2020

The reader can see that Industrial Heat seems to be ahead of competitors, having worked with E-Cat and Brillouin Energy and dozens of other "cold fusion" start-ups.

Energy is not only about price, but also about security, as an interruption in supply may have catastrophic effects in modern societies. Therefore, every large enterprise or government should avoid dependence on a single supplier or in an energy source that has few suppliers, like petrol. Uranium and Thorium are better distributed, and its suppliers are more politically stable. The Nickel is yet more distributed and far more abundant than Uranium, yet Boron concentrates in Turkey and Lithium concentrates in Australia. Anyway, such materials are quite common and abundant in global market, so a shortage or drastic rise in prices perhaps would not affect much the life cycle costs, at least in short term. As nuclear reactors should be quite complex and fuel preparation should be more expensive than raw materials, one can expect that even for lattice confinement reactors capital costs should dominate.

Because energy tariffs are the base of industry competitivity, it is probable that such technologies should be export-restricted due national strategy, the same way as nuclear weapons and Uranium enrichment. This means that the risk of not investing in the field is quite high, given the long times required to arrive to a commercial technology from first principles. A country or a large company without access to fusion technologies should have difficulties to survive if one or more competitors gain access to an energy source one order of magnitude cheaper than current sources. This means fusion technologies are disruptive, as nobody should survive without it, and new businesses could emerge from the abundance of energy.

6. Conclusion

The nuclear reactors have the tendency to become more employed in future given the new technological and experimental advances and lattice confinement fusion may arise as a disruptive technology. Given earlier investments and claimed results obtained, it seems one thousand times easier to achieve lattice confinement fusion than inertial confinement fusion. Anyway, research and development are still needed to achieve at practical applications, and although this work cannot state if any of new concepts is truly feasible (or competitive), it is probable that the fifth generation of nuclear reactors will be disruptive. To avoid a scenario of loss of competitivity, this work suggests investing in research following the descending order of potential: aneutronic nuclear reactions using lattice confinement, hybrid fission-lattice confinement fusion, aneutronic nuclear reactions using inertial along magnetic confinement, and fission reactions.

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