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SPS Focus

A special publication of the Swiss Physical Society

Nuclear Energy Generation

Progress in Fission, Breeding, and Fusion Technology

Picture source: www.swissgrid.ch

Preface

SPS Focus is a new publication series of the Swiss Physical Society where a single topic is presented and placed in focus for a broader audience, hence its name. The series will be published irregularly and is aiming at topics that can provoke broad interest. Research highlights causing a paradigm change like e.g. quantum computing would be among those topics destined for a ***SPS Focus***, but also interactions of physics with other disciplines are of high interest. Interdisciplinary focus topics, like in life sciences, often need to work out physical facts and apply tools developed from physics to reliably model, predict or even control complicated organisms from the micro- to the macro scale. Therefore, the presentation style of any ***SPS Focus*** is intended to appeal not only to physicists, but to scientists in general and including the interested public. To achieve this goal, renowned experts are invited to describe the state of art of a specific topic in an accessible way for the non-expert.

This first volume of the ***SPS Focus*** series describes the generation of energy by methods of nuclear technology that are probably not familiar to everyone. Switzerland and many other western countries have decided to abandon nuclear energy or will do so in the near future. Other countries, in turn, are investing in new concepts with focus on safety, efficiency and economy. We feel it is necessary to observe and understand how energy production based on nuclear technologies is evolving in many countries. It is necessary to establish an understanding of the dangers, the problems, their proposed solutions and the hopes that are put in various fission technologies and also where we are with fusion based technologies, with the aim of providing objective and comprehensible facts.

Bernhard Braunecker, Chief Scientific Editor

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SPS Focus is a special publication of the Swiss Physical Society. The series will appear irregularly and be distributed to all members as well as further interested parties.

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Contents

Motivation

Today, nuclear power supplies about 10 % of the world's electricity production, down from 13 % in 2010. World electricity production increased by 25 % in the same decade, which means that the absolute amount of electricity produced via nuclear supplies stayed almost constant, with only a slight decrease by 3 % in ten years. Furthermore, new plants are in construction or in planning and the fraction of electricity produced via nuclear fission world-wide will start increasing again. Renewable energies (hydropower, solar, wind, geothermal, bioenergy, wave and tidal) for electricity production contribute 29 % of the total electricity produced in 2020, up from 20 % in 2010, with hydropower still the major contributor. Fossil fuel covers the rest and contributes to 61 % in 2020, which is down from 69 % in 2010, for the world total electricity production.

After the disaster in Fukushima ten years ago many western countries decided to step out of nuclear energy, including Switzerland. Replacing nuclear power fully by renewable energies is the declared goal, while also replacing fossil fuels for energy production (transport, heating, production and manufacturing, electricity, etc.) needs to be achieved in the next few decades.

Even if those problems can be mastered in the future, the continuous supply of renewable energy is still difficult and expensive to achieve, as long as the problem of energy storage is not solved. This caused countries like the USA, India, China, France, UK, Finland, etc. not to stop nuclear energy production, in contrary to design and build new generations of nuclear power plants. They recognized that modern concepts can get rid of the problems of current nuclear reactors and that they offer higher safety and better efficiencies. Further, they can avoid the production of long-lived isotopes that otherwise remain as nuclear waste, and they also allow the reduction of existing nuclear waste to levels that no long-term threads occur anymore. Those countries consider nuclear technologies as relevant sources for energy production for many decades to come.

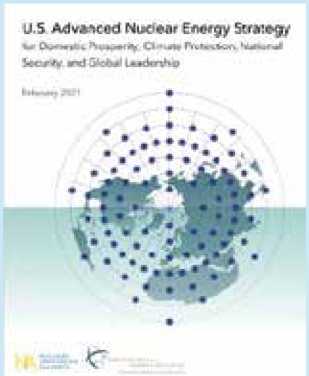
It is essential to be informed about the current state of nuclear technologies from a first-hand account. Especially as existing long-lived nuclear waste needs to be taken care of even when nuclear power has been abandoned, these new technologies have the potential to provide solution.

The following three articles written by respected, prominent authors describe the state of art of new generation uranium fission plants (by W. Kröger), the use of thorium rather than uranium as fission fuel (by M. Bourquin) and finally the road map of nuclear fusion concepts (by L. Porte).

Our motivation as national physical society is to show that nuclear fission technology is not the product of two generations behind us and thus an out-phasing technique, and also that fusion technology is not the product of many generations ahead of us and thus fusion is not an utopia. Both, fission and fusion, are based on a deep physical understanding of the underlying processes and thus are of relevance for tomorrow's worldwide electricity share.

The goal for a sustainable and global energy policy must be to consider renewable and nuclear energy production as equivalent technologies, which due to their different operation concepts complement each other advantageously and collectively ensure a reliable, environmentally friendly and cost-effective energy supply in the future.

Not meeting the climate goals will lead to unprecedented disasters for the ecosystem of the entire planet, affecting all life and including society as a whole – worldwide. With the huge task ahead of us in changing completely the worlds energy supply chains in only a few decades, all climate friendly options need to be pursued, which includes new and modern concepts of using nuclear power safely.



Recently a joint report [1] was released by two major US-think tanks defining a comprehensive strategy for the USA to become the global leader in advanced nuclear power. They said the strategy outlines the domestic and international activities that will be required to ensure the USA can lead in the development and deployment of next generation nuclear technologies through collaboration between government, industry, civil society, and other nations. And it is added, that "… *For the United States - let alone the world - to meet mid-century climate goals we will need an array of new zero-carbon energy technologies including advanced nuclear reactors for power and industrial heat generation. This report lays out a blueprint for America to become the global leader of this clean industry of the future.*"

1 https://www.ans.org/news/article-2675/strategy-for-us-leadership-in-advanced-nuclear-released/

Executive Summary

A careful balancing between climate protection, reliable energy supply, profitability and public opinion is needed to achieve a sustainable and global energy policy. This calls, aside of decentralized, smaller-scale environmentally friendly energy production, also and in addition, for the development of new large non-fossil power plants that are safe, environment clean and economical. Together with hydropower and wind-based electricity, nuclear power is among the lowest greenhouse gas and air pollution emitters, when their entire life cycle is considered. However nuclear energy has to overcome many of its well-known hurdles, in terms of safety, waste management and non-proliferation. This challenge may turn out to be an opportunity, as the innovation required will drive economic growth.

This issue of ***SPS Focus*** presents in three articles novel concepts and new approaches in nuclear technologies for the generation of electricity that all address the challenges conventional reactor concepts haven't solved and that have the potential to complement global energy demand and be a relevant pillar next to hydro-, wind-, solar and other renewable energy sources in the global quest of decarbonizing energy production while the demand on electricity is increasing world-wide.

Novel Reactor Concepts by *Wolfgang Kröger*:

A high degree of decarbonization is necessary to meet far-reaching climate protection goals. That's why some countries are focusing on an energy mix that includes nuclear power in addition to wind and solar power. To achieve this, nuclear reactors must be made catastrophe-free, fuels must be better utilized, and the question of final storage and proliferation risks must be addressed thoroughly. This is promised by concepts under development that use inert gas, molten lead, sodium or salt as coolants instead of water, can breed fuel thanks to fast neutrons or burn waste (actinides). Small modular (gas-cooled) reactors, which are suitable for modern power grids and market models and would soon be ready for the market, appear to be particularly attractive.

Thorium based Systems by *Maurice Bourquin*:

Innovative systems, based on thorium fuel, are being developed in different parts of the world. Aimed at contributing to the protection of the climate and the reduction of atmospheric pollution, they will produce electricity, while at the same time they will also incinerate accumulated radioactive wastes from past and still running fission plants. Thorium-fuel cycles differ from conventional uranium-fuel cycles in several essential aspects, resolving in the future the main issues of past-generation nuclear systems. Firstly, thorium is more abundant and wide-spread than uranium. ThO_2 is cheaper than UO_2 on the world market and its price is not expected to rise as much as that of UO_2. Secondly, the use of thorium minimizes long-lived nuclear waste production such as plutonium, since it takes for instance seven successive neutron captures to produce Pu-239 from Th-232, an unlikely chain. For similar reasons, the production of minor actinides is highly suppressed, thus reducing the size and complexity of long-term nuclear waste storage sites. Thirdly, in a thorium fueled reactor, the production of fissile U-233 also produces U-232 in small amounts. U-232 decays with a half-life of about 70 years continuously producing thallium-208, which is a strong gamma emitter. This intense radiation and heat produced make the manufacture of a nuclear weapon practically impossible. Finally, it is advantageous to use thorium fuels in an Accelerator Driven System, where a proton accelerator produces the missing neutrons necessary to maintain a fission chain reaction. When the beam from the accelerator is interrupted, the reaction stops, giving an undeniable level of safety. And in a fast neutron spectrum, plutonium and other nuclear waste, mixed with thorium, can be burned (i.e. transmuted), thereby avoiding long-lived radiotoxic isotopes in the remaining waste, which thus will not require very long term storage.

ITER — An Essential Step Toward Fusion Energy by *Laurie Porte*:

Fusion is the way stars are powered. On Earth, fusion fuel resources are almost inexhaustible and evenly distributed. To domesticate fusion on Earth, we need to replicate the hot plasma conditions found in stars, using magnetic instead of gravitational confinement. The fusion reaction of deuterium and tritium leaves no radioactive ash and doesn't rely on a chain reaction. The escaping neutrons give their energy to the blanket surrounding the plasma, from which the heat is extracted to produce electricity. The neutrons induce some secondary radioactivity, which is kept to a minimum by the use of low activation steels that do not produce long-lived isotopes and that can be safely recycled in the normal steel production chain after hundred years, as no rest-activity will remain. No intrinsic risks requiring the evacuation of the neighbouring population have been identified. The fuel supply in the plasma lasts only a few seconds, leading to a full control of the operation and immediate stopping possibility within seconds. Fusion does not produce CO_2. The progress made over the last few decades has been considerable and requires now the construction of larger devices for the next stage to meet the confinement requirements of burning plasmas. The task of the international ITER project, currently under construction in the south of France, is to produce a net gain in fusion. A considerable challenge, in view of a future DEMO reactor, the first real prototype fusion reactor, is to tame the power released by the plasma - which must be steady and distributed over a large surface - and to develop materials resistant to high thermal loads and neutron fluxes. The interest and appeal of fusion investment today in the private sector developing fusion alongside governmental projects like ITER and DEMO represents one more proof of the high expectations placed in fusion.

Introduction

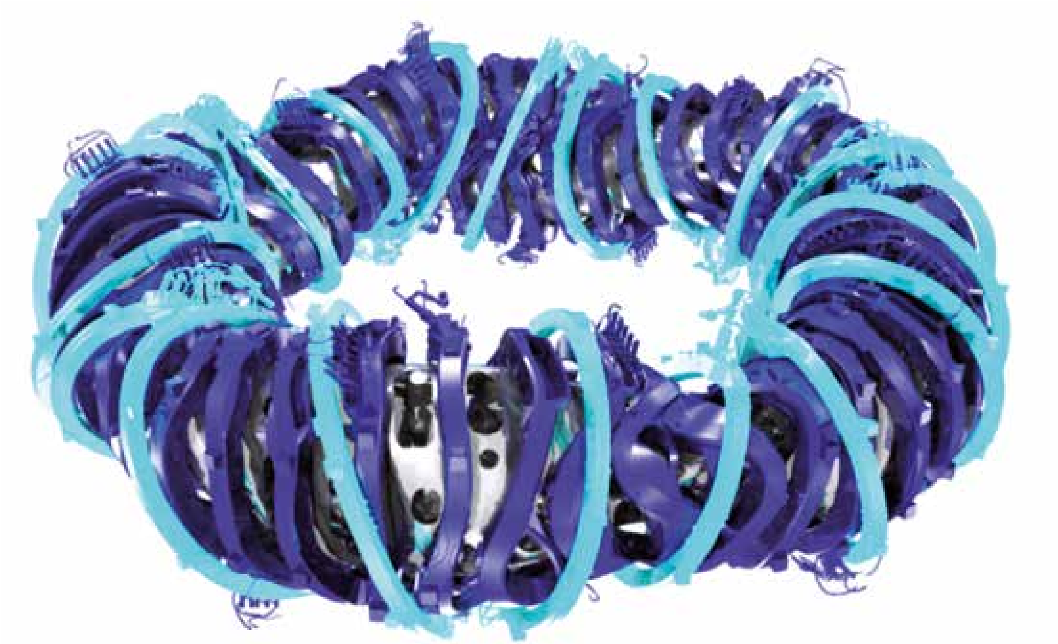
The mentioned problems of today's nuclear fission and fusion technology lead to the conclusion that both play no part in a middle to long-term energy solution concept. But is this an undisputed fact? Global warming forces us to seek urgently low-carbon solutions. The demand for CO_2 free, affordable energy will continue to rise due to the increasing digitalization, mobility and standard of living of an ever-increasing share of the world population. Abundant availability of electricity will be required globally, where hydropower, solar and wind play big roles and where new generation nuclear reactor efficiently contribute adding up the numbers for satisfying the world's demand.

Three different and complementary concepts for a safe usage of nuclear power are discussed:

- **Novel Reactor Concepts**: Nuclear reactors must be made disaster-free, fuels must be used more efficiently and the issue of waste management and proliferation risks must be resolved. This is promised by concepts currently under development, which use inert gas instead of water, lead, sodium or salt melts as coolant, allow the use of thorium, breed fuel thanks to fast neutrons or burn waste. Active safety systems with a huge number of necessary components like different kinds of pumps and valves, requiring AC/DC power and reliable actuation mechanisms, can be replaced or made redundant with passive components requiring only natural forces and inherent safety features, based on physics like natural convection, sufficient heat transfer and storage mechanisms and basic properties of materials. Applied fuel cycle concepts allow for more efficient use of resources and alleviate requirements to high-level waste disposal including partitioning and transmutation.

- **Thorium based Systems**: Thorium breeding addresses the needs for proliferation-resistance, longer fuel cycles, higher burnup, improved waste-form characteristics, reduction of plutonium inventories, and incinerate accumulated radioactive wastes. Although the energy produced is of nuclear origin, it follows a completely different physical process with respect to current uranium-based nuclear power production. Most importantly, it would eliminate the production of long-lived nuclear waste, which are constituted of transuranic elements, i.e. plutonium and minor actinides (neptunium, americium, curium…), which are those responsible for the bulk of the radiotoxicity and heat generation of used nuclear fuel. Waste management times can be reduced this way from hundreds of thousand years for conventional uranium-based fission plants to few hundred years, which is manageable at relatively low costs. This concept could accompany or replace over time uranium-fueled nuclear reactors, of which presently four hundred are in operation around the world.

- **Nuclear Fusion Energy:** Fusion reactions hold enormous potential for clean and sustainable energy production from more equitably distributed resources, but a demonstration of technical and economic viability remains to be carried out. Deuterium-Tritium fusion needs temperatures 10 times larger than in the solar interior, ~ 150 Mio degrees. In magnetic fusion, confinement is provided by magnetic fields, with high temperature plasmas of typically atmospheric pressures and energy confinement time of few seconds. Out of several magnetic confinement concepts explored during the last 50 years two toroidal device concepts have been sucessful, the tokamak and the stellarator. The ITER tokamak, now under construction in France, represents an essential step toward a practical technical demonstration of fusion energy. ITER is at the threshold of the conditions suitable for baseload power plant operation, consistent with the goal of minimizing physics uncertainty in the next-step device, which would be a prototype power plant.



Coil System of Wendelstein 7-X, consisting of 50 non-planar and 20 planar coils.

Picture source: www.kernenergie.ch

Picture source: http://watt-logic.com

Picture source: https://cdn.pocket-lint.com

Novel Reactor Concepts: "Asset in a Future De-carbonized Electricity Mix?"

Wolfgang Kröger

"Nuclear energy is the fast track to decarbonization" – Agneta Rising, Director General of World Nuclear Association

1 Summary

There is an urgent need to de-fossilize the energy sector under constraints of growing demand and to increase the share of low-CO_2 emitting assets in electricity sector to meet challenging climate change targets, respectively. Most countries base their strategies on "renewables" while concerns are growing that "renewables" alone are sufficient and diversify the electricity generation mix appears advisable. Nuclear energy has proven to be a clean mature technology, demonstrated by large fleet of mainly light water reactors (LWR) operating for more than 40 years, but the prospects for its continued, even expanded use are dim in many parts of the world. Barriers would need to be overcome, notably lack of public acceptance due to risk aversion and unresolved waste issues, calling for fundamental changes in reactor technology and associated fuel cycles.

Key requirements are proposed, basically a shift from active safety to passive safety systems and strengthened inherent safety features to practically eliminate catastrophic reactor accidents, furthermore, means to reduce the waste burden, increased robustness against extreme external events and malicious attacks, human errors and socio-political instabilities. They are used for a comparative assessment of novel reactor concepts of varying purpose including fuel breeding and waste burning, different by neutron spectrum from thermal to fast, and coolant including liquid metals, molten salt and inert gas besides water; most of these concepts belong to the family of small, simplified, modular designs (SMR). They show a high potential for significant improvements against current LWR, however, none of them fulfills all stringent requirements fully, yet. A water-cooled SMR (NuScale) comes close and a gas-cooled high temperature SMR (HTR-PM) closest, while these thermal reactors do not allow for fuel breeding or actinide transmutation.

To resolve some limitations and to make nuclear energy a persuasive, early deployable asset in a future sustainable electricity mix, a clear decision to keep the nuclear option really open and further develop it in view of its generic merits is needed; associated RD&D efforts must be intensified.

2 Background and Motivation

The global primary energy consumption has doubled within the last 50 years. By the end of 2019 [1] it totaled to 162'324 TWh while the growth slowed down to 1.3 % compared to 2018; almost 17 % are converted into electricity. Scenario analyses predict a massive growth of primary energy, mainly driven by developing countries, to cope with the expected increase of world population and expand energy access and economic opportunities to billions of people. The electricity sector is expected to grow disproportionally, by a factor of 2.5 till 2050 [2], notably to penetrate non-traditional domains, i.e. e-mobility, digitalization, buildings.

This challenging trajectory is confronted by "climate change", the requirement to urgently deeply de-carbonize the energy system, currently relying at about 85 % on coal, gas and oil with different shares and trends (Fig. 1). The electricity production based at roughly 2/3 on fossil fuels, contributing almost 30 % to the global CO_2 emissions of roughly 34.2 Gt (increase slowed down to 0.5 % compared to 2018) [1]. Thus, the electricity sector needs a new mix and dramatically increased share of low-carbon generation assets by 2050 to meet climate targets [1], while other sustainability indicators like use of land and other resources must be kept in mind.

Most scenario-based projections and strategies focus on expanded use of renewable energy sources. Besides hydro with a share of roughly constant 15 %, wind and solar contributed 10.4 % of the global power production (20.2 % in Europe. roughly 7 % in Switzerland) in 2019, with a growth rate of 12.2 %, slightly below its historical average [1]. However, there are growing concerns about whether (a) renewable generation will grow sufficiently fast, (b) variable energy sources alone will be sufficiently secure and (c) the required infrastructure including seasonal storage, upgraded grids and flexible backups can be provided.

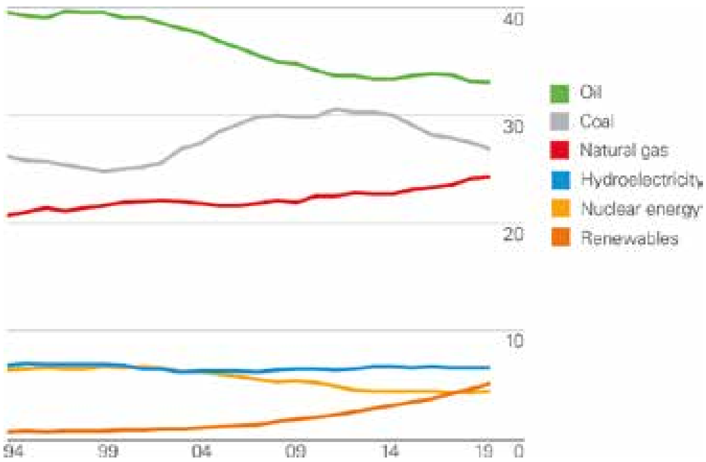


Fig. 1: Shares of global primary energy over a period of time from 1994 to 2019 [1]

Currently, nuclear power contributes 10.35 % to global electricity production – 23 % in Europe, 35.2 % in Switzerland [2]. The global share increased to 18 % in 1998, decreased

1 Recently the EU has decided to reduce CO_2 emissions by 55 % until 2030 compared to 1990; during the last 30 years the CO_2 emissions decreased by just roughly 25%.

2 Other respective shares for Switzerland are: 0.19 % of global primary energy and 0.25 % of electricity consumption, 0.1 % of global CO_2 emissions (38.2 million tons) while the primary energy consumption per capita of 131.5 GJ exceeds the world average by almost 75%.

afterwards but grew in 2019 by 3.2 %, the fastest growth since 2004, to which China and Japan provided the largest increments [1]. However, its prospects of nuclear energy are dim in many parts of the world, with costs [4], lack of public acceptance and some unresolved issues including disposal of radioactive wastes as key problems [3]. Future shares of nuclear power are ambiguous, vary from zero [5] to a growth of 28 % till 2040 [2].

3 Characteristics of Nuclear Energy and Status of Use

The use of nuclear power has proven to be a mature and reliable technology, the mean capacity factor was 80 % often with peaks up to 90 %. By the end of 2019 [6], there was a fleet of 442 reactor units with 392.1 GW installed capacity in operation, distributed throughout 31 countries. The clear majority (80 %) of all operating units are light water reactors (LWR) which operate with thermal neutron spectrum [3]; demineralized light water acts as moderator and coolant, i.e. takes the heat from the reactor to the turbo-generator that utilize the heat. Most LWR are fueled by uranium with U-235 as fissionable isotope, enriched to 3 - 5 % from 0.7 % in natural uranium. Less than one quarter of these LWR are boiling water reactors (BWR) where the primary coolant undergoes phase transients to steam inside the reactor. More than three quarters are pressurized water reactors (PWR), operate at higher pressure (15.5 MPa instead of 8 MPa) on the primary cooling circuit, separated from the conventional water-main steam cycle by a heat exchanger, a steam generator, respectively.

Experience accumulated to roughly 18 000 reactor-years. There are 54 units under construction with 55.5 GW in 19 countries including five newcomers, the majority of which in China (12 units). New builds in the western world are rare and, like the European Pressurized Water Reactor (EPR) in Finland and France, confronted with massive cost and construction time overruns, while projects in Asia tend to stay within basic conditions.

Uranium has incomparably high energy density, defined as the deployable energy per weight unit. Under optimal conditions, while undergoing full breeding and fission, one kilogram of uranium is the equivalent of burning 3500 tons of black coal [3]. Considering just the current proven uranium reserves in the low- and higher-cost range extraction the world can produce enough uranium for the next 125 years, with the current yearly consumption of uranium of roughly 63 000 tons. These long-lasting reserves are estimated to double, when taking reasonably assured resources into account, and to become practically unlimited when moving to advanced nuclear technology options and application of new mining and extraction technologies [7].

Current nuclear technology has very low greenhouse gas emissions, slightly less than 10 gram per kilowatt-hour, that means 50 to 100 times less than natural gas and hard coal, respectively, while comparable to hydro and wind, four times less than PV roof, all when considering the whole life cycle and today's technology [8].

Nuclear power is not without its drawbacks, both in the physical process and current technologies. When uranium isotope 235 (U-235) undergoes fission, it typically releases between one to seven neutrons (2.4 on average) while one is sufficient for causing another fission, thus inherently incorporating the potential of an exponential power increase ("power excursion"). However, opposed to being captured for fission, neutrons are being absorbed without causing fission or escaping from the fissile core, helping to settle the neutron balance. The fission energy appears as kinetic energy of the two nuclei flying apart. Most of these "fission products" are radioactive at a level far higher than the heavy elements of the raw material (uranium) in the reactor core for a differently long period of time. The decay heat of short-lived fission products is accountable for heat production after reactor nuclear shutdown [4] calling for sufficient continuous heat removal while long-lived fission products together with actinides [5] after neutron absorption call for ultra-long confinement times. This leads to major design challenges and implementation of safety functions as regards to reactivity control, fission product confinement and decay heat removal, under all conceivable circumstances, as well as for management and long-term storage of nuclear waste [6].

Under the umbrella of the International Atomic Energy Agency (IAEA) a design philosophy was developed, and 10 fundamental safety principles were agreed. They constitute a basis on which safety requirements were deduced and safety measures prescribed. The primary means of preventing and mitigating the consequences of accidents is the application of the concept of defense in depth, which requires the combination of a number of consecutive and independent levels of protection that all would have to fail before harmful effects could be caused to people or the environment [9].

However, certain aspects of current LWR are still problematic, such as high system pressure, the vulnerability to loss of coolant and reliance on properly functioning "active" safety systems with pumps and valves, requiring electrical or mechanical power and reliable actuation mechanisms as well as alternative sources of water and sometimes early operator actions. LWR comprehend vulnerable structural metallic material and incorporate little grace time (one to two hours) in case safety systems failure. Such failures are rare due to design provisions such as redundancy and diversity. Major safety improvements are demonstrated, e.g., by decreasing frequency estimates of core damage (CDF) caused by failure of decay heat removal and control systems after internal or external events – CDF vary from 10^{-4} to 10^{-5} for operating LWR to as low as 10^{-6} for advanced and some retro-fitted plants, each per reactor-year, or once in 10 to 100/1000 thousand years per reactor [23]. The likelihood of large radioactive releases is roughly by one order of magnitude smaller, depending on the containment design. Such catastrophic events can practically be excluded rather than totally and provoke public fear.

3 Neutrons born fast and slowed down by collision with a moderator.

4 Heat production due to radioactive decay is in the range of 6 % one second, 4% one minute and still 1% one day of the original thermal power (typically 4 000 MWt) after reactor shutdown.

5 Actinides are chemical elements with atomic numbers from 89 (actinium) to 103 (lawrencium) including neptunium (93) plutonium (94) and americium (95); elements beyond uranium are called transuranic; neptunium and elements beyond plutonium are called minor actinides.

6 On average a large-sized LWR with a power production of about 10 TWh annually leads to 30 tons of radioactive heavy metal including 1.4 tons of fission products and 350 kg of recyclable plutonium (Pu); the volume totals to 15 m^3.

The other issue of concern is radioactive waste burden. Three fuel cycle concepts are distinguished: once-through or open, partially closed and fully closed [3]. All fuel cycles start with natural uranium mining, refining and conversion, followed by enrichment. In the open cycle, after its useful live of 3 to 7 years, spent fuel (SF) is unloaded and sent for extended interim storage and finally, mostly favored, emplacement in deep geological repositories; about one third of the fissile material remains in the SF. On the other hand, SF can be reprocessed to extract fissile material such as uranium and plutonium before disposal and to be used in mixed oxide (MOX) fuel elements (partially closed cycle). In the fully closed fuel cycle, uranium, plutonium, and minor actinides (long-lived radionuclides) are extracted and used as fuel and burned (transmuted) in advanced fast reactors of dedicated designs. The open cycle is followed by most LWR in operation, some use MOX fuel; open fuel cycles are considered favorable in terms of proliferation issues as no separation of fissile material, weapon-grade plutonium in particular, takes place. In contrast closed fuel cycle concepts allow for better exploitation of fuel and fuel reserves, reduce the radiotoxicity of waste and required stewardship and bring down amounts of low-level nuclear waste. However, necessary reprocessing and selective separation of long-lived isotopes is challenging and costly and lacks acceptance, is forbidden in many countries.

All fuel cycle concepts require a safe and long-term disposal of radioactive wastes. However, due to inherent uncertainties, strong opposition and strict regulatory/safety requirements, the advancements are still slow, and there is no operating deep geological repository around the world, yet. Nevertheless, Finland is in the lead, granting license and starting construction at Olkiluoto site in 2015 with the disposal process expected to start by 2024.

Current LWR operated with a high degree of reliability and safety. However, there are major barriers to make future, potentially expanded use of this technology - and nuclear power in general - acceptable to the public such as fundamental safety and proliferation concerns and risk aversion, in particular, comprising the (i) unequal treatment of extra-ordinarily low probabilities and high consequences of potential accidents and (ii) the perceived cancer dread of even low doses of invisible radiation.

4 Challenges and Means to Overcome Barriers

Civil nuclear industry witnessed three core disruptive accidents [7] besides a number of less severe events and little progress regarding disposal of high-level radioactive waste. This has created the public view that nuclear power is dreadful and waste issues are unsolvable. Major efforts are needed to lull this view and overcome mainly risk aversion-related barriers, respectively. First, to avoid (eliminate) rather than further reduce the probability of high consequence accidents a ***paradigm shift*** in reactor design principles is recommended. Current LWR depend on a series of safety functions accomplished by active safety systems with a huge number of necessary components like different kinds of pumps and valves, requiring AC/DC power and reliable actuation mechanisms, besides alternate water sources. Instead, innovative designs should incorporate passive components requiring only natural forces and inherent safety features, based on physics like natural convection, sufficient heat transfer and storage mechanisms and basic properties of materials. This shift would eliminate station blackout events as initiator of serious accident sequences which statistically dominate experienced nuclear events and CDF contributions [8].

Second, nuclear plants should be less sensitive to adequate protection against natural and civilian events (earthquakes, flooding, aircraft impact, etc.) and malicious man-made physical (bomb) or cyber-based attacks. Further, they should warrant higher tolerability to human errors by the plant operator or maintenance crew, lack of safety culture at plant level and socio-political instability within the operational environment. Finally, applied fuel cycle concepts should allow more efficient use of resources and alleviate requirements to high-level waste disposal including partitioning and transmutation (P&T).

The following ***key requirements*** are put forward, helping get close to deterministic exclusion of serious conditions and states (see [3] for details):

Control of nuclear reactivity, i.e. elimination of potential power excursion accidents, by core design with weak/negative reactivity coefficients and small reactivity surplus at start-up with fresh fuel.

Assurance of heat removal from the reactor core to an ultimate heat sink and retention of fission products, by
- a) lowered power density and power size (to avoid exceeding critical temperature limits),
- b) fuel cladding and structural material that will not melt or react chemically, and
- c) sufficient heat storage and transfer capability in case of loss of normal (forced) cooling.

Securing structural integrity to avoid loss of core cooling capability/confinement of radioactive inventory, by
- a) low primary circuit pressure or rupture proof components (reactor pressure vessel),
- b) radiation resistant, chemically and physically robust core structures,
- c) underground siting for protection against extreme external impact, including weapons' attack.

Use of non-reactive, non-toxic materials/fluids or avoid direct contact of reacting substances.

Avoidance/incineration of long-lived radioisotopes, by
- a) core designs allowing to burn long-lived waste and/or
- b) switching to thorium with drastically smaller generation of long-lived minor actinides or
- c) striving for long-term stable (rock type), high burn-up spent fuel as an open fuel cycle option.

Enhanced proliferation resistance characteristics, e.g., by no use of highly enriched uranium and off-line reprocessing, the latter, if there is no strategy to minimize the time during which weapons-grade plutonium is in separated form and avoid accumulating a stockpile.

7 Considering 18 000 reactor-years of accumulated experience this leads to a historical average CDF of 2.8 × 10^{-4} per reactor-year, not far from international average CDF based on theoretical analysis (PSA), see [3, chapter 4.5.1.] for details.

8 According to evaluations based on the ETH curated database - with about 1250 worldwide safety-significant events - loss of offsite power (LOOP) accounted for about 30 % of safety-relevant initiators [21].

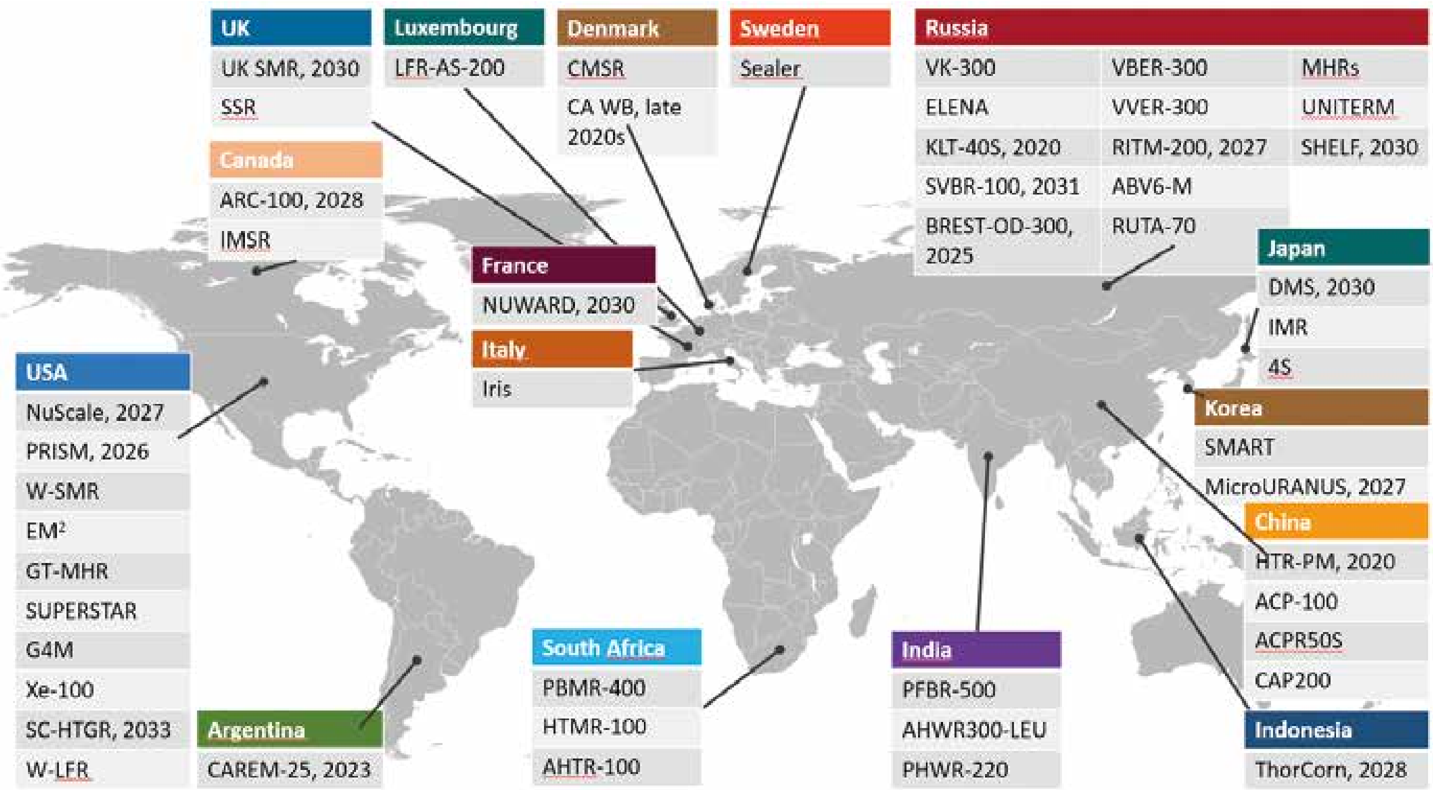


Fig. 2: World map of small and medium modular reactor designs under development [20]

To achieve these ambitious requirements, ***key design features*** for nuclear systems can be identified and different types of advanced reactors and associated fuel cycles can be checked against them. Key characteristics include the neutron spectrum and coolants as well as other features. Reactors must be designed to ensure compatibility with.

A look at the fission probabilities ("cross sections") of selected actinides demonstrates the attractiveness of *fast neutrons* compared to slowed down neutrons that dominate the spectrum of today's LWR. While thermal fission cross sections of fissile U-233 and U-235 and Pu-239 are significantly larger than those for fast fission, and most fissions occur at low energy, their important fission-to-absorption ratio is of the same order but significantly higher for other selected isotopes, in particular atoms heavier than uranium. Such large fission-to-absorption ratios are favorable to avoid or minimize the formation of radioactive waste and minor actinides, in particular. Eliminating these isotopes from spent nuclear fuel would reduce stewardship times of the long-lived wastes up to a factor 100.

Fast neutron spectra allow for high neutron economy and reactor designs that are favorable to produce as much or more fissile material than consumed ("breeder reactor") and/or incinerate radioactive waste ("waste or actinides burner"). However, the cores of fast reactors are not in the state of highest reactivity under steady-state operational conditions; changes of physical parameters could lead to disruptive power excursions.

Coolants – different from water and attractive for advanced, even exotic reactors – are briefly characterized here, for details see [3]: that are liquid metals like sodium, lead or lead/bismuth, molten salt (fluorides or chlorides) and gas (helium). All liquid metals and salts feature good heat storage and transfer capabilities and no need for pressurization for operation in a single-phase mode while high density and mass may lead to high static loads of up to 4 MPa, notably for lead. All liquids and gas allow for core outlet temperatures of about 510 °C (molten sodium) to almost 600 °C (molten lead, molten salt) or even 750 / 950 °C (helium), significantly higher than for water. This results in thermodynamic efficiencies [9] for power production clearly above 40 % (up to 50 % for helium-cooled high temperature reactors rather than 33 % for LWR) and potential use for chemical heat applications including "green hydrogen production".

Current reactors base their *fuel* on metal oxide (UO_2) rather than metals themselves, because the melting point is much higher (2850 instead of 1133 °C) and it cannot burn, although its thermal conductivity is very low. Ceramic fuels have the advantage of high heat conductivities and melting points (2700 - 2800 °C) but are more prone to swelling than oxide fuels. Uranium-carbide, most notably in the form of coated micro particles together with ceramic (or graphite) structural material, are regarded attractive for certain future reactors. Liquid fuels, i.e. dissolved in molten salts, offer numerous operational advantages due to inherently stable self-adjusting reactor dynamics, rapid drain ability into dump-tanks and continuous release of xenon gas that acts as a neutron absorber.

Making fuel, fuel cladding and structural material more resistant to temperature rise and resulting core damage is a promising way to increase the robustness of nuclear reactors against potential accidents. A huge industrial program on "accident tolerant fuel" is focused on high temperature resistant fuel pellets and protecting claddings from oxidation by coating.

9 Thermal efficiency is the fraction of the energy added by heat (primary energy, here fission) that is converted to net work output (here electricity). A value of 33 % means that slightly more than two thirds of the primary energy are wasted.

Moreover, *thorium* (namely Th-232) is becoming a promising fuel option (see the article by M. Bourquin on p. 19) for which all uranium fuel cycles apply. Th-232 does not undergo fission itself but, on capturing a neutron, it leads to U-233 as final fissile product of the reaction chain which could be misused for weapon production and, as its forerunner Pa-233 can be separated effectively, the proliferation resistance of the thorium-cycle is put in question.

Steel alloys dominate the *material for reactor* (pressure) *vessels and piping*; "absolutely" rupture proof pre-stressed concrete reactor pressure vessels are technically feasible.

Nuclear fission enables reactors with high power density and power rating: typical power densities vary from 70 for current LWR to about 290 MW/m^3 (core volume) for conceptual designs of sodium cooled fast reactors, while those of liquid lead or salt cooled fast reactors are less than half that high and those of gas-cooled thermal reactors are in the range of 3 - 4 MW/m^3. Power ratings follow economy of scale with 4800 MWt / 1600 MWe of large LWR as a reference point. In principle, high power density and rating make reactors more susceptible to loss of decay heat removal accidents. In other words, limiting the power densities and power rating, together with other means, could provide flexibility to increase the robustness of nuclear reactors.

There is a worldwide revival of interest in *small* (up to 300 MWe), *simpler modular reactors* (SMR, see Fig. 2) for electricity production and other purposes, driven by a strong belief [10] that SMR would

- open additional market sectors, e.g., heat for chemical processes including hydrogen production, and, based on enhanced safety characteristics, allow for site flexibility;
- better adapt to low growth rates of energy demand, are more suitable to replace aging fossil-fired plants;
- allow for greater simplicity of design, enable economy of serial production largely in factories and, thus, shorter construction times, lower upfront capital cost and ease financing and earlier revenues.

As the inventory of fission products is proportional to the power level, a smaller amount could be released into the environment by SMR under loss of confinement conditions, in principle. However, some question the economic competitiveness of SMR and raise concerns regarding adequacy of the current regulatory system.

Site characteristics are relevant for ensuring that societal risks due to severe nuclear accidents are acceptably low and remote sites are deemed most suitable. However, driven by scarcity of actual remote sites and aspired use of nuclear reactors beyond power production sites closer to consumer centers may have to be permitted. Accordingly, the combination of small, inherently "super-safe" reactors and underground siting has been proposed, the latter allows protecting the plant against extreme external physical impacts including weapon attacks.

5 Innovative Technical Concepts under Development

Innovative reactor and fuel cycle concepts differ by purpose, associated neutron spectrum and coolant, fuel cycle strategies (with low to fairly high enrichment and burnups, open to closed cycles with offsite or onsite reprocessing) and other features. Concept designs and developments are driven by key countries such as USA, China and Russia and pertinent industries. Besides next generation thermal reactors, many prominent reactor concepts are fast reactors that allows them to breed more fissile fuel than they consume or even burn wastes. Most of their proposed designs can use various fuels including spent fuel from LWR or burn (transmute) actinides, hence closing the fuel cycle, thus increasing the utilization of uranium significantly compared to current LWR

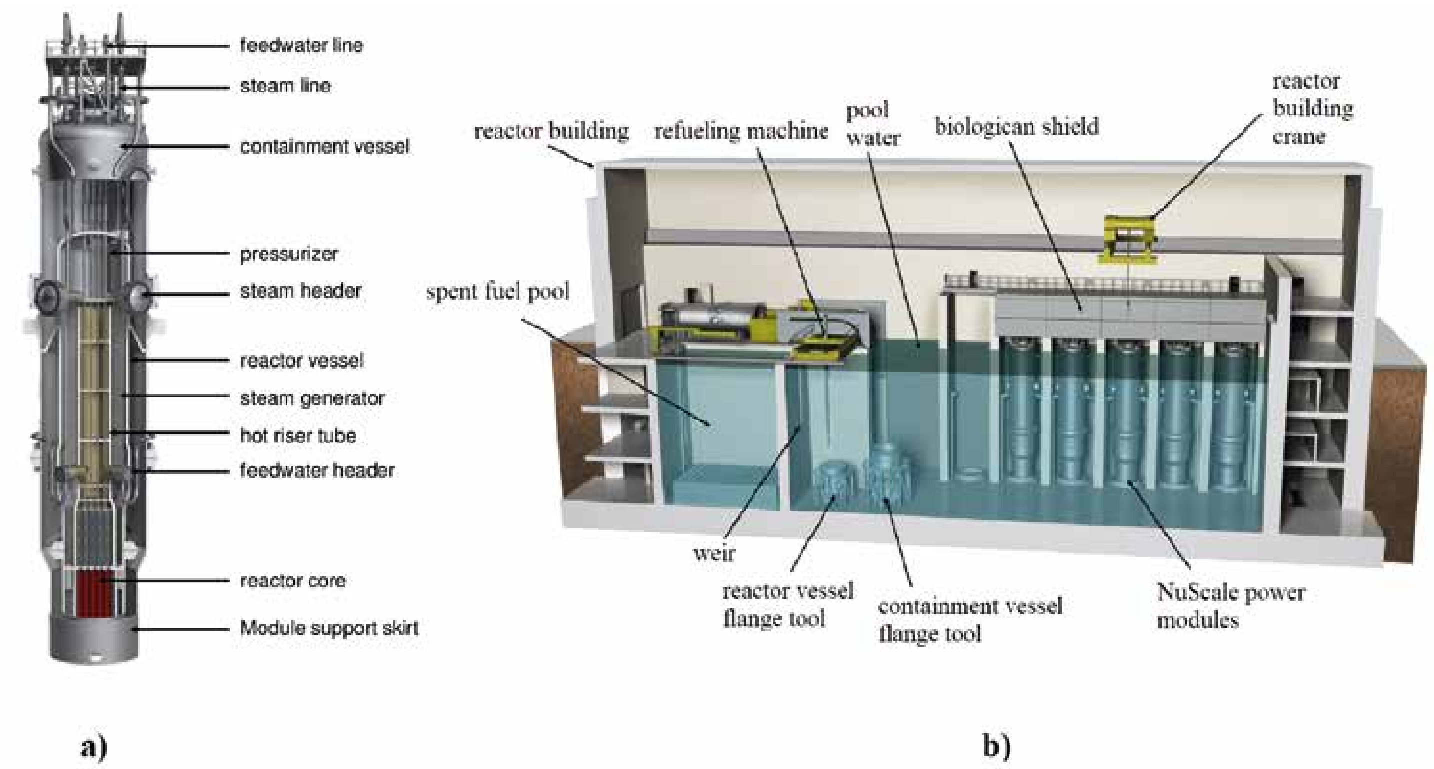


Fig. 3: Schematic view of the NuScale reactor concept – a) power module of 77 MWe, b) cut away of power plant, up to 12 modules can be submerged into one cooling pool inside the reactor building, generating 924 MWe [25].

and/or reducing husbandry times of disposed long-lived waste [11]. Moreover, most new designs strive for lifetimes of up to 60 years, claim to be inherently safe (“super-safe” or “disaster proof”) and highly resistant to proliferation. Most promising concepts are selected and will be introduced below including state of readiness.

Two designs base on proven thermal reactor technologies: the NuScale light water reactor and the HTR-PM gas-cooled reactor, both appear to incorporate low development risks and have acquired regulatory design approval in their respective countries. The third concept is PRISM, a sodium-cooled fast reactor, currently intended to use spent fuel from LWR and provide an answer to the ever-increasing stockpile of nuclear waste, but is flexible to be used as breeder or waste/actinides burner. Other innovative to exotic concepts - with liquid lead or molten salts as coolant - will be briefly addressed and included in the assessment against key requirements outlined before. All selected concepts belong to the family of small to medium sized modular reactors of 50 - 600 MW electrical power output, termed SMR, most of them are suitable for mass production and shipping to sites.

5.1. Light Water Cooled - NuScale

The NuScale light water reactor concept, being developed in the USA, leverages the large operating experience of the current LWR fleet with smaller and simpler configurations. It claims to have many technological advancements over conventional large-scale PWR:

- Small core and low fission product inventory resulting in simpler neutron flux control and low decay heat. Combined with the negative void and temperature reactivity coefficients, reactivity induced accidents and power excursion, respectively, deem eliminated. In hypothetical (beyond design-basis) core damage scenarios, the low inventory will result in a small release of radioactive substances with doses below safe limits at the site boundaries, thus superseding emergency planning zones.
- Compact helical coil steam generators integrated in the small containment allow to use natural circulation for heat exchange, eliminating the need for reactor coolant pumps (Fig. 3a).
- Reactor modules submerged in the cooling pool (Fig. 3b), providing a passive heat sink, aid in reactor cooling and pressure control and eliminate the need for emergency core cooling systems with water addition, typical for conventional PWR. The heat sink is sufficient for long-term core cooling via natural circulation, that makes this concept impervious to station blackout events and provides indefinite grace periods [24].

Besides these notable improvements, some drawbacks of conventional PWR are still present in this design with open fuel cycle: low operating temperatures (321 °C) are synonymous with low thermal efficiency (30 - 35 %) and the highly radioactive spent fuel still raises nuclear waste concerns. NuScale reactors are fueled with uranium-oxide pellets of less than 4.95 % U-235 enrichment, operate at 13.8 MPa; multiple modules submerged into one cooling pool can generate power at a level rivaling the generation capacities of conventional PWR, albeit with boosted inherent safety features. As of August 2020, the NuScale project with passive instead of active safety systems has received a greenlight from the nuclear regulatory commission (USNRC) – making it the first SMR to gain design approval in the USA; the first reactors are expected to become operational by 2027 [26].

5.2 High Temperature Gas-Cooled Thermal Reactors – HTR-PM

Modern *high temperature gas-cooled reactor* (HTR) designs focus on using graphite as moderator and helium as coolant at low pressure. The high operating temperatures allow high thermal efficiency of about 40 % and could also open new perspectives for nuclear power beyond electricity production. The moderately enriched fuel in the form of ceramic pebbles is comprised of thousands of robust TRISO coated particles embedded in a graphite matrix. The TRISO coated particles consist of a moderately enriched uranium kernel, an inner and outer dense and a silicon carbide (SiC) layer in between pyrolytic graphite layers for fission products retention (Fig. 4a). The reactor’s relatively low power density (slightly above 3 MW/m^3) coupled with a high heat capacity graphite moderator and fission products retention up to fuel temperatures of about 1600 °C as well as pronounced negative temper-

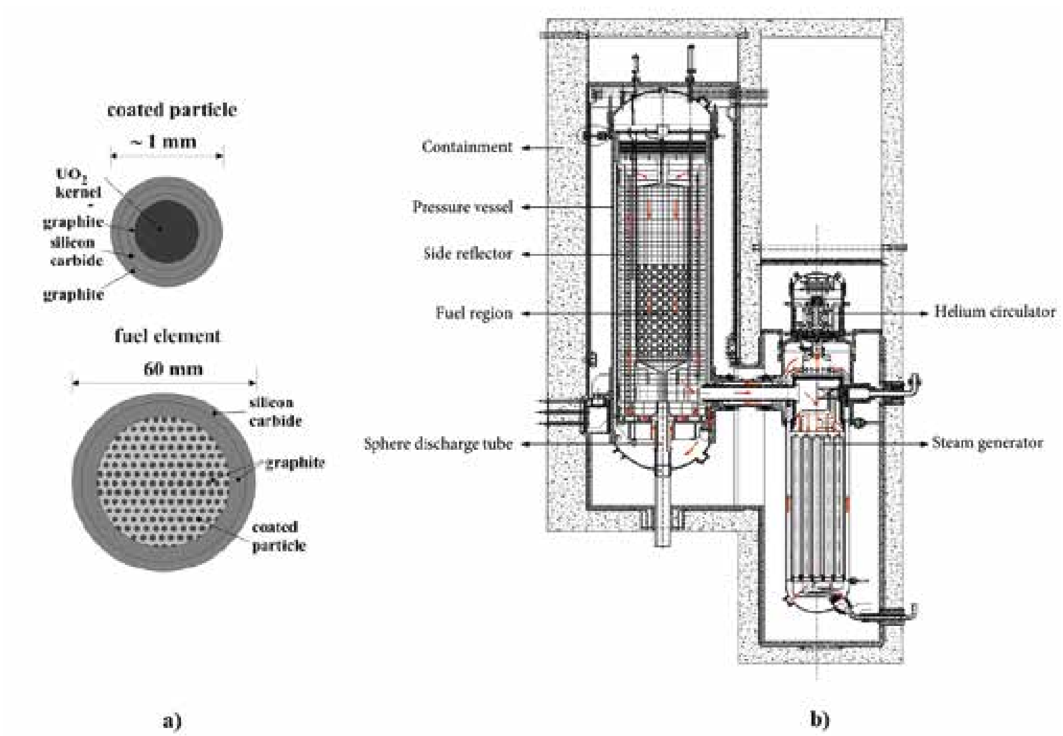


Fig. 4: Schematic view of HTR – PM a) TRISO coated particle and fuel element and b) reactor layout [18]. Coated particles consist of a uranium kernel with a U-235 enrichment of 8.5 %, a porous pyrolytic graphite layer to accommodate for fuel expansion, an inner and outer dense pyrolytic graphite layer and a silicon carbide layer in between for fission product retention.

ature reactivity coefficient and continuous refueling make these reactors deemed inherently safe. However, the concept is not without disadvantages, e.g., potential unrestricted air or water ingress could cause graphite corrosion and difficult reprocessing of the ceramic fuel elements may raise concerns about the increasing amount of nuclear waste.

Multiple prototypes employing HTR pebble-bed technology were taken into operation, such as the AVR (1966), THTR-300 (1983), both in Germany, and HTR-10 in China (2003). The ***HTR-PM*** (pebble-bed modular) reactor (Fig. 4b) is under construction in China since late 2012 and currently in its commissioning phase, waiting on approval for the first fuel loading [18]. The plant will feature two 250 MWt modules, intended to operate at 7 MPa pressure and helium outlet temperatures of 750 °C, connected to power a single 210 MW electrical turbo-generator. The reactor fully applies features outlined above which provide a high degree of inherent safety including decay heat removal by passive means/ systems without requiring reliable power and actuation mechanisms. The strong negative temperature reactivity coefficient limits the vulnerability of reactivity induced accidents; the low operating pressure curtails concerns about losing the structural integrity of the reactor vessel. HTR-PM currently adopt an open fuel cycle concept; however, the fuel is used more efficiently due to high burnup (60 GWdays per ton heavy metal, almost two, up to three times higher than future and current LWR, respectively).

5.3 Sodium Cooled Fast Reactors - PRISM

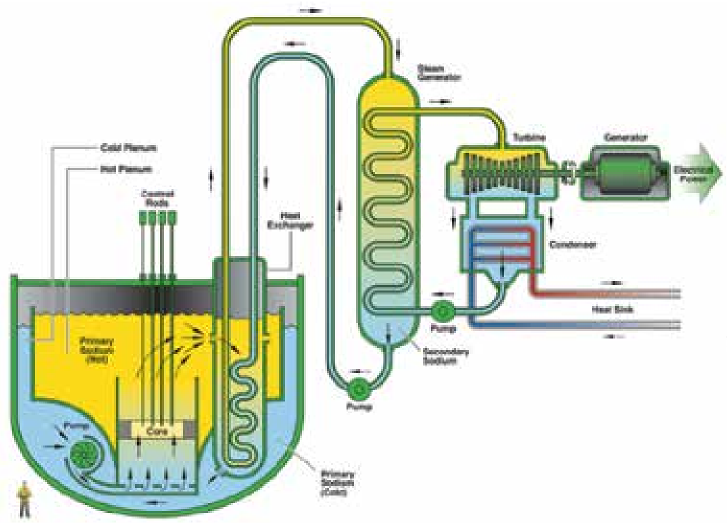
Heralded as one of the more promising next generation fast breeder reactor concepts, *sodium cooled fast reactors* (SFR) – as other liquid metal cooled fast reactors - have a high neutron economy and offer a variety of advantages over conventional thermal reactors; outlet temperature are in the range of 500 °C, which allows thermal efficiency of 37 %. The usual design of SFR employs a pool or loop type reactor filled with molten sodium and helium as cover gas at atmospheric pressure, an intermediate sodium circuit and a secondary steam generator circuit (Fig. 5a). SFR designs and fuel composition can vary by mission, e.g., metal alloy fuel of uranium-plutonium-zirconium can be used for small and medium sized designs to burn spent fuel from LWR, easing the nuclear waste problem [13]. Combined with re-processing techniques which cannot extract plutonium (e.g., pyro-metallurgical for metal alloy fuel), modern SFR designs deem proliferation resistant. While sodium exhibits excellent heat conduction properties, valuable for heat removal and increased conversion rate, the primary disadvantages of SFR are the positive void and temperature reactivity coefficients (pronounced in larger cores) and exothermic reactivity of sodium with water and air.

Approximately ten liquid metal reactors are expected to be deployed in the near future, out of which **PRISM** appears as one of the most prominent concepts [10]. The design (Fig. 5b) comes with two reactor modules, each of 311 MWe power output, using uranium-plutonium-zirconium alloy fuel and burn spent fuel from LWR. Other missions and related fuel composition and configuration could include recycling of actinides, fuel breeding with U-238 breeding blanket and even weapons material consumption; burnups are in the range of 100 GWdays per ton heavy metal, depending on the mission [13]. The core outlet temperature is about 500 °C. The design is proven to be both mature and soon deployable, with additional unique safety features such as negative temperature reactivity coefficient due to the small core size, passive decay heat removal via natural air circulation, and digital instrumentation and control. The reactor is operating at atmospheric pressure, putting concerns regarding the structural integrity of the vessel aside.

5.4 Other Innovative Technical Concepts

Lead-cooled fast reactors (LFR) use molten lead or lead-bismuth (Pb-Bi) eutectic as a coolant and share many of the positive characteristics of SFR. However, the coolant is not chemically reactive with water, making an intermediate coolant loop unnecessary, has a higher boiling point and the temperature reactivity coefficient is only slightly positive due to its neutronic properties [3]. In contrast, the higher melting temperature of the coolant, which raises freezing concerns,

10 Sodium fast breeder reactors (SRF) have been in development for more than 60 years, facing huge technical problems and public resistance. PRISM (Power Reactor Innovative Small Module) is a "Generation IV" SFR, developed by GE Hitachi Nuclear Energy, based on the experimental breeder reactor EBR-II. PRISM is in an advanced stage and as of 2019 has entered the US Versatile Test Reactor program, which aims to build a fast-breeder reactor by 2026 [14].



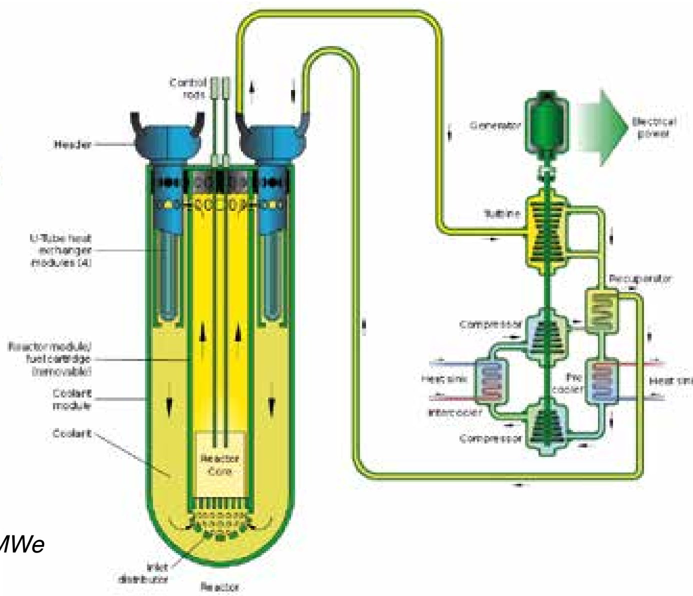


Fig. 5 Schematic view a) large SFR and b) PRISM module with 311 MWe power output, both of a pool type with intermediate sodium loop [12].

build-up of toxic Po-210, corrosive reaction with steel and high price for Pb-Bi are listed as major disadvantages.

BREST-OD-300 MWe, developed by RDIPE in Russia, is a pool-type LFR with passive decay heat removal using natural air circulation. The fuel used is uranium-plutonium mononitride mainly comprised of spent fuel from LWR. The design claims to be resistant to loss-of-coolant and heat removal accidents, while the small operating reactivity margin prevents power excursions in normal operating conditions [15]. The reactor construction was approved in 2016, with the first plant expected to be operating by 2025 [16]. A larger 1200 MWe version is planned to be built if operation of BREST-OD-300 proves to be successful.

Molten salt cooled reactors (MSR) [11] can operate with thermal or fast neutron spectra, with power densities similar to LWR. The main coolant is a molten salt mixture which can have different properties depending on the salt used (fluoride, chloride), while lithium salts with higher boiling points are preferable (> 1400 °C) as they allow operating at higher temperatures (700 - 900 °C). MSR use solid fuel or fuel dissolved into the coolant, the latter is the preferable option of next generation unpressurized breeder or waste burner designs [3]. Both uranium and thorium-based fuel can be used, optionally with added minor actinides. The coolant is constantly circulated through the core and chemical processing plant, in which volatile fission products are separated and the fuel concentration is controlled. In case of overheating, a freeze plug melts and dumps the coolant into tanks, which immediately stops the fission reaction. The decay heat from the tanks is passively removed, making the design safe in station blackout scenarios. Main drawbacks of MSR are the corrosive properties of the coolant and potential criticality spikes.

There are multiple MSR concepts under early stage development, with the Danish "**Seaborg Waste Burner**" as one of them, designed as a compact modular thermal reactor of 270 MWt which uses spent fuel and thorium, mixed in a molten fluoride salt which also acts as coolant. The reactor has inherent/passive safety features including a reliable overflow system which would dump the fuel in both, overheating and prompt criticality scenarios [17]. Even in the worst-case scenarios, such as meltdown due to failure of the system to dump the fuel, the company claims that a redundant dump tank and a secondary barrier would prevent fission products release to the environment. The start-up company aims to start building a full-scale prototype by 2025.

Accelerator-driven systems (ADS) are novel concepts comprised of a subcritical reactor and an external neutron source, usually a high-intensity proton accelerator [3]. The proton beam is focused on a metal target and produces neutrons by spallation. As the reactor is incapable of self-sustaining fission reactions, the chain reaction stops by turning off the accelerator. Therefore, these systems do not require the installation of control rods and eliminate the possibility of reactivity induced accidents. The reactor is conceptualized as a lead or lead-bismuth (Pb-Bi) cooled fast breeder reactor, introduced before. These characteristics make the ADS perfect for the burning of minor actinides (transmutation) which greatly reduces the husbandry times of nuclear waste.

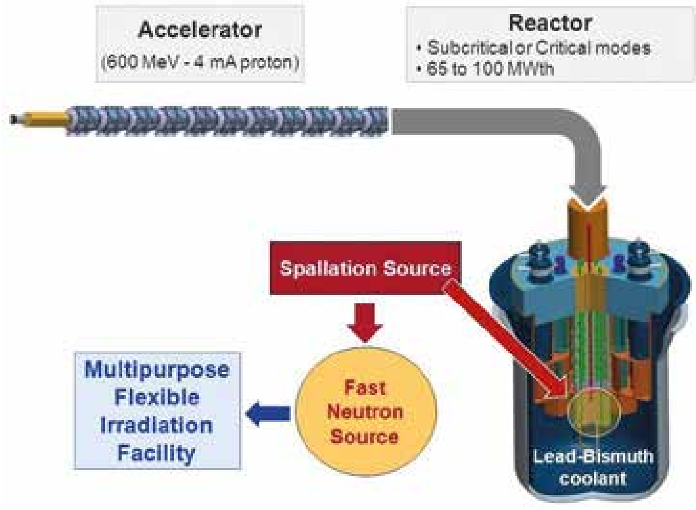


Fig. 6: Schematic view of MYRRHA (Multi-purpose Hybrid Research Reactor for High-tech Applications) [3].

One of the most advanced concepts is **MYRRHA** (Fig. 6), an actinide burner developed by the Belgian Centre for Nuclear Research. The design couples a subcritical (multiplication factor 0.95) Pb-Bi cooled fast reactor with a proton accelerator, focused on a liquid Pb-Bi spallation target to produce additional neutrons. With a total budget of 1.6 billion euros, the system is expected to be commissioned by 2036 [19].

Other interesting concepts are the **floating SMR**, built at shipbuilding facilities and towed to designated areas where they could provide electricity, district heating and seawater desalination. The first plant of this kind is Akademik Lomonosov, recently commissioned in Russia. This plant is powered by two 35 MWe PWR, based on the KLT-40 marine propulsion reactor, with passive decay heat removal, modernized active safety systems and instrumentation [22].

6 Evaluation and Ranking of Selected Concepts against Key Requirements

The results of a concept-by-concept comparison indicate a high potential for far-reaching improvements compared to the most advanced LWR (Generation III+) as the benchmark. As can be seen from Table 1, none of the best versions of reactors with thermal or fast neutron spectrum and different coolants fully meet ***all*** requirements convincingly, yet [3][23]. Notably most of the small sized concepts come close, follow the postulated shift from active safety systems to passive safety systems and incorporated inherent safety features for decay heat removal from the reactor which allows to practically exclude major core meltdown accidents. This applies also to water-cooled NuScale which shows remarkable advantages as against modern large PWR in this respect although some of the disadvantages remain. Thermal helium cooled reactors (HTR-PM) come closest, promising inherent robustness against severe accidents, using uranium fuel more effectively due to very high burnup and largely avoiding long-lived radioisotopes when using thorium fuel. However, as other thermal reactors HTR-PM are

11 MSR have been of interest since the 1960s, one experimental reactor was operable in the USA from 1965 to 1969. Large MSR are pursued as one of six technologies under the Generation IV development international framework GIF [12].

Key requirements	Candidate reactor concepts – varying coolant, selected designs in brackets						
	Water – thermal (large EPR)	Water– thermal (NuScale)	Sodium – fast (PRISM)	Molten Salt – fast (Seaborg)	Helium – thermal (HTR-PM)	Lead – fast (BREST-OD-300)	ADS (MYRRHA)
Elimination of Reactivity Induced Accidents	**4**	**4**	**2**	**1**	**5**	**2 - 3**	**5**
Invulnerability against Loss of Active Core Cooling	**1**	**4**	**2**	**3**	**5**	**2 - 3**	**3**
- avoid exceeding critical temperatures	1	3	n.a.	n.a.	5	n.a.	n.a.
- avoid high fission product inventory	1	4 [1]	4 [1]	5 [2]	4 [1]	4 [1]	4 [1]
- provide sufficient heat storage & transfer capacity	4	5	5	4	4	5	5
Structural Integrity	**2**	**3**	**4**	**4**	**5**	**4**	**4**
- avoid high operating pressure	1	3	4 [3]	5	4	4 [3]	4 [3] [4]
[suitability of underground siting]	[2]	[4] [4]	[?]	[5] [4]	[5] [4]	[4]	
Use Non-chemically Reactive / Non-Toxic Materials	**4**	**4**	**1** [5]	**2** [5] (non-stable)	**5**	**4**	**4**
Avoid Long-lived Radioisotopes	**1**	**1**	**4**	**5**	**4**	**5**	**5**
Enhance Proliferation Resistance	**4**	**4**	**2**	**2**	**3**	**2**	**2**
- avoid high enriched uranium	5	4	2 [6]	2 [6]	2-3	2 [6]	2 [6]

[1] due to small power size
[2] in case of dispersed fuel and due to small power size
[3] not pressurized but high static load
[4] foreseen
[5] intermediate cycle (IHX) foreseen
[6] close to / above HEU lower limit

Table 1: Selected reactor concepts ranked against key requirements from excellent (5) to neutral (3) to very poor (1) with the Generation III+ 1600 MWe PWR (EPR) as the benchmark.

not being capable of burning waste and reducing the stockpiles of radioactive nuclides. With respect to burning waste including actinides transmutation, molten salt fast reactors promise to do best, but appear most susceptible to reactivity-induced accidents (RIA), as all liquid metal cooled fast reactors are, albeit to different degrees, depending on the core geometry. The only exception are accelerator-driven systems (ADS), which are inherently resistant to RIA due to their subcritical core design. There is also a potential of new concept specific accidents, such as overcooling/freezing of coolant, chemical reactions following coolant outflows after leaks or air/water ingress into hot graphite cores, which deserve special attention.

All concepts seem to have limited capabilities to achieve the goal of reducing proliferation risk or even to maintain the current level, mainly due to partially elevated and/or significantly increased enrichment or significantly heightened by the need for off-site reprocessing.

It is also important to note that some of the innovative designs like NuScale base on proven simplified technology or experience with large-scale experimental or demonstration facilities like HTR-PM which curtails development risks and enables near-term deployment. The “revolutionary” designs and technologies often start from scratch and introduce new man-machine interfaces and tend to represent a jump in complexity. The molten salt cooled systems with dissolved fuel and fission products and off-gas systems may serve as example; some features of coolants, e.g., production of activation products, chemical toxicity, non-transparency, freezing at high temperatures, may require complex operations and maintenance procedures [4].

7 Conclusion and Outlook

The global demand of energy, of electricity in particular, is expected to grow, simultaneously confronted by the requirement of urgent de-carbonization or de-fossilization, respectively. Most countries base their future energy strategies on “renewables” while there are growing concerns that renewables alone will be adequate and sufficient, prompting fears of a “green energy” gap. Diversification and use of low-carbon energy sources according to their merits seem to be a prudent principle. The nuclear option should be kept open as clean nuclear energy has the potential to become an asset in a future low-carbon energy mix. However, its prospects are dim in many parts of the world and major barriers including unresolved waste problems and risk aversion must be overcome to make its use acceptable to the public which current technologies barely achieve and call for major improvements.

Therefore, we set up key requirements and recommend a fundamental shift towards designs that incorporate passive and inherent safety features, that are less sensitive to stable operating conditions and apply fuel cycle concepts that are more sustainable and reduce husbandry times of nuclear wastes to historical timescales. We strive for a deterministic exclusion of serious plant sates (without taking probabilities into account at all) whenever possible, this is deemed attractive but turned out hard to achieve in practice.

Novel reactor designs mostly with coolants different from water, with thermal or fast spectrum, the latter allowing for fuel breeding and waste burning, and fuel advanced cycle concepts are under development. Those designs indicate a high potential for far-reaching improvements compared to the most advanced current LWR. However, none of the best versions of the candidate concepts fully meets all requirements convincingly, yet, while small to medium sized modular concepts (SMR) deem favorable, in general. Most of them use passive safety systems and incorporate inherent safety features for decay heat removal from the reactor, which allows to practically exclude major core damage states or meltdown accidents, where applicable. Simplified water-cooled SMR, based on best proven technology like NuScale, come close to meet the stringent requirements while thermal helium cooled high temperature reactors (HTR-PM) come closest. They promise inherent robustness against severe accidents and largely avoiding long-lived radioisotopes when using thorium fuel. Concepts allowing for fuel breeding and, more importantly, for waste burning (actinides transmutation) deserve fast reactors with “exotic” coolants and novel separation/reprocessing technologies.

The further development of nuclear technology does not stand still. Programs are underway in key countries; some concepts show high degree of readiness. However, boosted R&D efforts appear necessary, in general, aiming at further improving some essential characteristics and features of evaluated concepts and mastering some jumps in complexity (including overcoming of regulatory barriers) as well as to shorten commercial deployment times.

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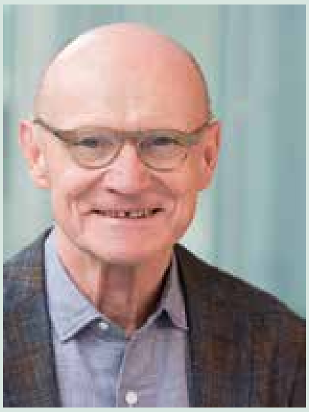
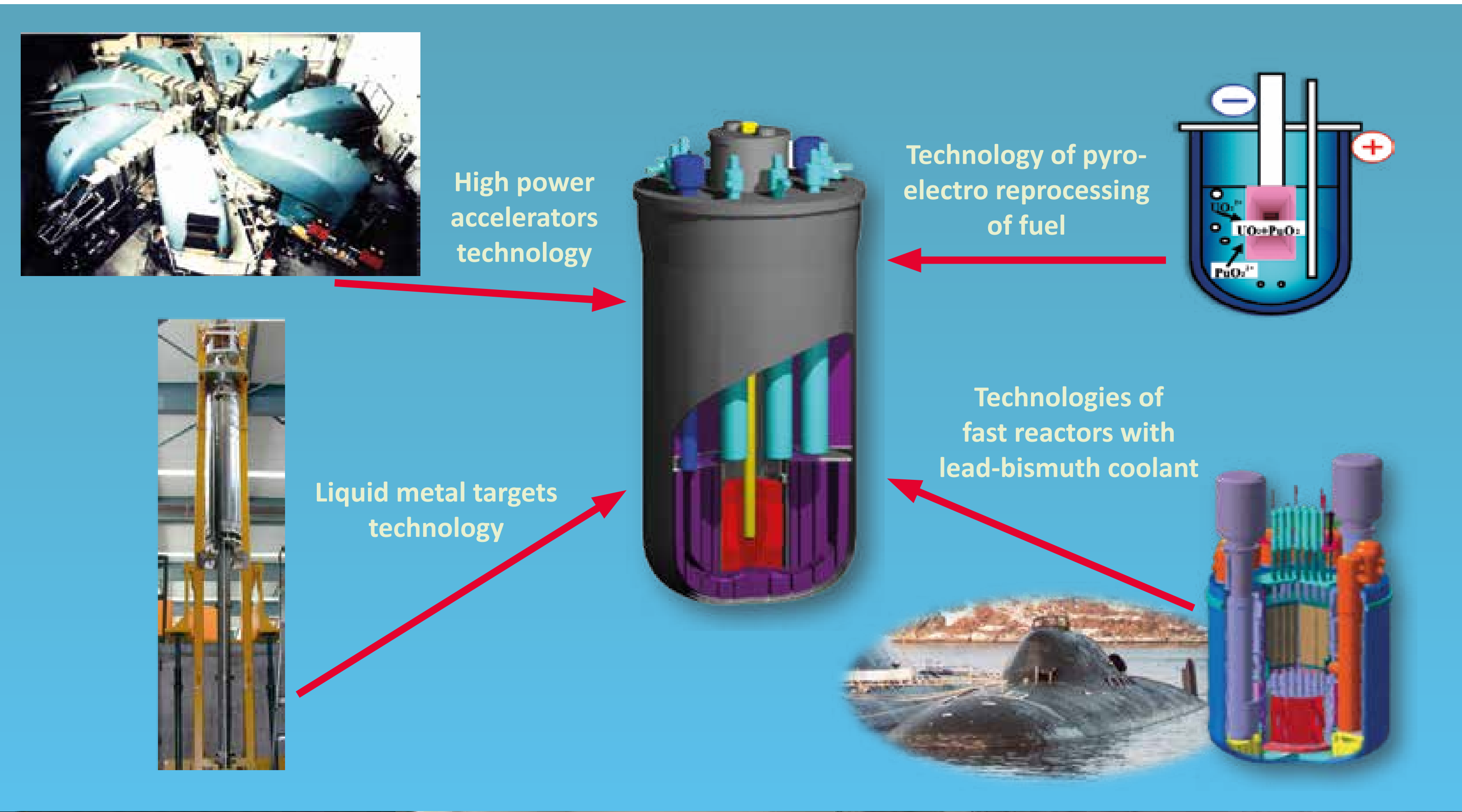
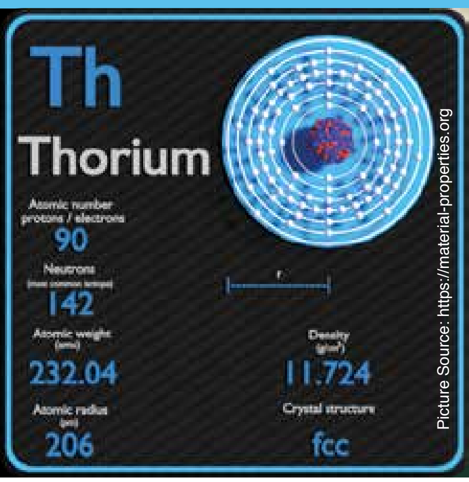


Wolfgang Kröger studied mechanical engineering, specializing on nuclear technology, at the RWTH Aachen. He completed his diploma degree in 1972, doctoral degree in 1974 and the habitation in 1986. He has been full professor of Safety Technology at the ETH Zurich since 1990 and director of the Laboratory for Safety Analysis. Before being elected Founding Rector of the International Risk Governance Council (IRGC), Geneva in 2003 he headed the nuclear energy and safety research directorate at the Swiss Paul Scherrer Institute (PSI). After his retirement early 2011 he became the Executive Director of the newly established ETH Risk Centre and stepped back from this position end of 2014.

Presently he is acting as a scientific advisor and consultant on future technical systems and member of distinguished committees. Inter alia he is elected member of the SATW heading the topical platform “Autonomous mobility” and has been awarded “Distinguished Affiliate Professor” by the TU Munich. He is member of the International Review Group of the Japanese Nuclear Safety Institute and the project on Future Energy Systems (ESYS) of three German academies. He (co-)authored numerous publications in reviewed journals and books, the latest on "Vulnerable Systems", "New Ways and Needs for Exploiting Nuclear Energy", and "Resilient Structures and Infrastructures", all published by Springer.





Top: Main components of Thorium based Accelerator Driven System ADS. Middle left: Physical data of Thorium. center: M. Bourquin at Accelerator Driven Advanced Nuclear Energy System (ADANES), CAS, China; September 2018. right: Stored containers of Thorium Nitrate in Nevada / USA. From [21]. Bottom: High density thorium mixed oxide fuel pellets.

Thorium Based Systems: A new Direction for Nuclear Waste Reduction and Energy Production

Maurice Bourquin

"Innovation is the most powerful of our renewable resources" – Carlo Rubbia, Nobel Prize in physics

1 Background and Motivation

Today, humanity is facing critical challenges ranging from climate change, the fight against epidemics and poverty, the lack of water and food in many parts of the world, the production of clean and sustainable energy, the proliferation of nuclear weapons, and the protection of the environment. Science plays an essential role in addressing these and other challenges and must be supported in all its aspects. Investments in science are relatively small at the macroeconomic level, while their impact on the future of humanity is considerable. Indeed, history shows that basic research is a driver for innovation [1]. In this section, accelerator particle physics research, which is the mission of the European Organization for Nuclear Research (CERN) in Geneva, is particularly highlighted. Already, scientific research at CERN has led to many technical advances that have benefitted society, including the World Wide Web, medical imaging, and techniques for the treatment of cancerous tumors.

Generally, in order to implement new inventions, much effort and time are required, particularly because new ideas often scare many people. It is the case for advanced nuclear reactor development, although the advantages of nuclear energy are well known: minimum CO_2 emission, no atmospheric pollution, and non-intermittent electricity production. Nuclear energy covers about 10 % of the electricity production in the world (and about 35 % in Switzerland). New power plants are being constructed in countries where clean energy needs are immense, such as in China, India, Russia, or Brazil. Still, the future developments of this technology using uranium as fuel are hindered. To be sustainable it would depend, in a large part, on the unresolved capability to cope with the issue of the management of spent nuclear fuels. In a recent population survey on energy [2], nuclear waste management is the main concern of the French population, at the same level as the fear of nuclear accidents.

According to updated inventory data [3], of the total 1 million m^3 of nuclear waste in Europe, about 1/3 is classified high level waste and intermediate level waste, and, due to its degree of possible contamination, is supposed to be disposed in deep geological repositories. However, the public concern, along with that of many experts in the sector, is very high, because of the uncertainty in the ability to guarantee a safe and secure system for the extremely long period during which nuclear wastes must be isolated in those repositories, and because of the extremely high cost of the technology. Innovation and ambition are needed to invent an alternative effective way of reducing the burden of their final disposal.

In this section, a breakthrough concept experimentally demonstrated at CERN is discussed, which has not been implemented yet, but increasingly motivates scientists and investors in the energy sector. It is the concept of Prof. Carlo Rubbia and co-workers of a fast neutron fission process in a subcritical reactor core, where the initiating fast neutrons are constantly generated by a proton beam from an accelerator. This "Energy Amplifier" promises to "burn" spent nuclear fuel, while producing sustainable energy through the use of a "mix" of spent fuel and fuels based on thorium rather uranium for reasons which will become clear below. Furthermore, this design would incorporate passive and inherent safety features, suppressing risks of accidents [4].

In the 1960s and 1970s, the development of thorium fuel for fission energy was of great interest worldwide. It was shown that thorium could be used practically in any type of existing reactor [5]. However, due to the focus on uranium, modern technologies, such as automated fuel processing, have not been tested on thorium. In recent times, however, the need for proliferation-resistance, longer fuel cycles, higher burnup, improved waste form characteristics, and reduction of plutonium inventories has led to renewed interest in thorium-based fuels. Although the energy produced is of nuclear origin, it follows a completely different physical process with respect to current uranium-based nuclear power production. Most importantly, it would eliminate the production of long-lived nuclear waste, which are constituted of transuranic elements, i.e. plutonium and minor actinides (neptunium, americium, curium…), which are responsible for the bulk of the radiotoxicity and heat generation of the used nuclear fuel. This would reduce waste management times from hundreds of thousand years to hundreds of years. This concept could accompany or replace over time uranium-fueled nuclear reactors, of which presently four hundred are in operation around the world, including four units in Switzerland. However, the thorium fuel cycle is a complex subject even for those familiar with nuclear technology. The presentation below should be considered as a partial introduction, by a partial author. The interested reader would find more information in the references quoted below.

2 Characteristics and Status of Thorium Technology

Thorium is a weakly radioactive element that is more widely available on the planet than uranium, about as frequent as lead, with estimated resources of 6.4 million tons, and its presence on the surface of the globe is much more uniformly distributed than uranium [6]. It disintegrates more slowly than most other radioactive materials, and the alpha radiation emitted cannot penetrate human skin. The possession and handling of small quantities of thorium are considered not dangerous as long as they are not inhaled or ingested. Thorium is found in small quantities in most rocks and soil. It is found in several minerals, including monazite, a thorium and rare earth phosphate, which can contain up to about

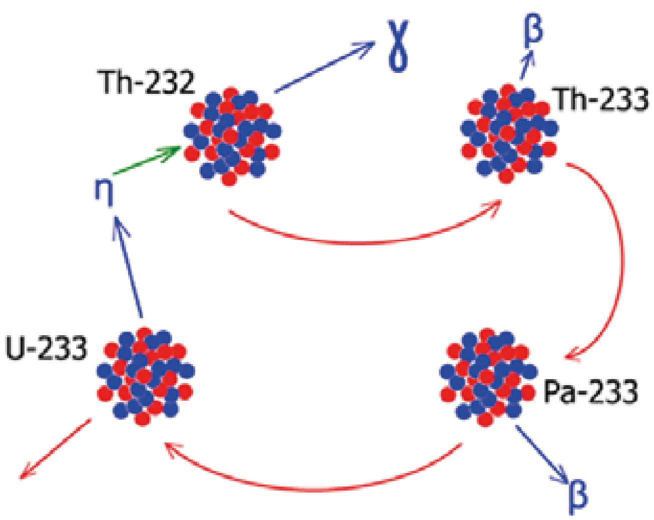


Figure 1. Sketch of the thorium fuel cycle

10 % thorium oxide. Substantial reserves of thorium already exist as unused by-product of rare earths mining. The isotope Th-232, practically the only isotope of thorium, is not fissile, that is it does not undergo nuclear fission, but it can be transformed into U-233 by neutron capture in the very core of a dedicated reactor. And then U-233 is an excellent fissile fuel, which leaves after fission only short-lived fission fragments (figure 1).

Many practical questions stand about the best way to design today a thorium-fueled reactor. Among the “Generation IV International Forum” reactors, fast breeder reactors, molten salt reactors and high temperature reactors are most suitable. They would need either a fissile material (uranium or plutonium) or a particle accelerator to “drive” the system. This has been well documented [7].

Among the fast neutron reactors, the **Accelerator-Driven System** (**ADS**) with thorium fuel, apart from producing energy, has the capability to function as a nuclear waste incinerator, where minor actinides and plutonium, which needs not be separated from the waste by prior reprocessing, are "burned" [8]. The minor actinides and plutonium are in fact the most harmful components and the most difficult to eliminate or store which are produced by the nuclear fission reactions, because they are highly radioactive and have very long lifespans. They constitute the hard core of the problem of radioactive waste from conventional nuclear reactors. In an ADS, a mixture of thorium and transuranic elements (TRU’s) can be used as fuel, thanks to the flexibility brought by the accelerator in the definition of the fuel.

An ADS is also called a hybrid reactor because it couples a particle accelerator (of an energy and power similar to the main cyclotron of the Paul Scherrer Institute in Villigen (AG)) and a subcritical nuclear reactor [9]. The term subcritical means that the core is incapable, for lack of neutrons, to maintain by itself a fission chain reaction. The fraction of missing neutrons is produced by the bombardment of a target of heavy nuclei (lead or tungsten for example) by a beam of protons from the accelerator, a reaction called spallation. These neutrons can produce U-233 nuclei by the fertilization of the thorium (that is, by capture of a neutron in the nucleus of the thorium atom) surrounding the target in question and causing the fission of fissile U-233 nuclei. The central point is that the fission reaction is intrinsically in a subcritical state, i.e., the maintenance of a sustained nuclear reaction is possible only thanks to the external contribution of neutrons from the accelerator, which gives these systems an undeniable level of safety. Indeed, when the beam from the accelerator is interrupted (voluntarily or involuntarily during an earthquake, for example), the fission reactions stop instantaneously in the reactor.

The thorium component is required for the ADS to operate in stable conditions in terms of the neutron flux and sub-criticality factor. Progressive destruction of fissionable TRUs in the fresh fuel load, and the increased neutron capture on the accumulating fission fragments, are compensated by the fission of the freshly formed U-233, which is partially consumed to maintain stable neutronic characteristics of the facility. Liquid lead is used as coolant, not water. It has the advantage of not readily reacting with air or water, and thus this subcritical core does not need an intermediate loop in the heat exchanger or in the steam generator unlike sodium coolant. Also, the core has a hard neutron spectrum due to the heavy atomic mass of lead. Most of the fission cross sections of minor actinides are higher than the neutron capture cross section at high neutron energies, thus “transmuting” the waste introduced with the thorium fuel (“transmutation” is a process in which the long-lived radioactive elements in waste are converted by fission to shorter-lived particles that produce radiation for a much shorter period and are less radiotoxic). The heat is finally recovered via a heat exchanger and a steam turbine that produces electricity. Thanks to its piloting by a particle accelerator, the ADS can easily modulate its power, if the operation of the reactor requires it. It can operate in tandem with renewable but fluctuating sources of electricity, such as solar photovoltaic and wind power, and make up for their shortfalls in production.

The possibility to eliminate long-lived fission products is a second aspect of the long-lived waste disposal problem that the ADS transmutation technology may resolve. In essence, from a view of reducing radiotoxicity, transmutation of fission products is of limited interest. The majority of the fission products would have decayed after about 250 years, and their contribution to the radiotoxicity of the spent fuel, which was very high during the first 100 years of storage, would become negligible. However, some fission products may contribute significantly to the radiological effects of disposal in underground repositories due to their geological mobility. In addition, the processing of spent fuel results in releases through gaseous and liquid effluents, which also contribute to the long-term radiological effects of nuclear power generation. The fission products that deserve most attention in this respect are I-129 and Tc-99. These long-lived fission fragments (LLFF’s) may be transmuted through neutron capture reactions, which transform them into short-lived radionuclides. This may be obtained through the use of “Adiabatic Resonance Crossing”, enhancing neutron capture probability in pure lead, which appears to hold the potential to transmute effectively both the contribution from the light water reactor (LWR) waste and the one produced by the ADS as the result of the TRU incineration through fission [10].

Thus an ADS fueled with thorium has some clear advantages compared with currently operating reactors; much smaller production of long-lived actinides, minimal probability of

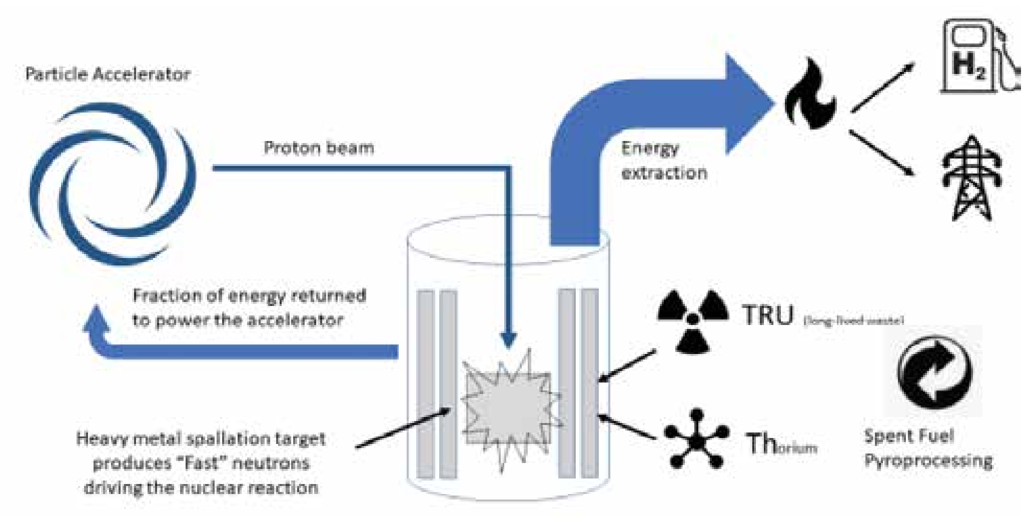


Figure 2. Sketch of a thorium Accelerator-Driven System (courtesy Transmutex S.A.)

a runaway reactor and efficient burning of actinides and fission fragments (figure 2).

Another family of thorium reactors is the **Molten Salt Reactor** (**MSR**) family. Several variants exist and are being studied around the world. However, their general design is comparable: they are reactors in which the nuclear fuel is in the form of liquid molten salt at high temperature, which acts both as a source of energy and as a coolant (which transfers the heat produced in the reactor to turn the turbines that produce electricity). The reactor can be either moderated with graphite (thermal neutrons) or without a moderator (fast neutrons). In the latter case, it is called the "Molten Salt Fast Reactor". The concept was studied in the laboratory during the 1960s, then abandoned in the 1970s, in particular because it was not exploitable for military applications.

Starting in the 2000s, the MSR system was re-evaluated, then retained within the Generation IV International Forum. Molten salt reactors are based on the use of a molten salt, such as lithium fluoride, which serves as a heat transfer fluid, moderator and first containment barrier. These salts are extremely stable and can be brought to high temperature - at atmospheric pressure - to be melted without risk to the environment (no emission of radioactive gases or particles in case of vessel cracking, no interaction with water and air). The reactor takes the form of a metal vessel containing the salt at high temperature (600 to 900 °C), but at ambient pressure. The nuclear reaction is triggered by the concentration of fissile material, in this case U-233 from the fertilization of thorium under the effect of the nuclear reaction. In the design of a fast neutron reactor, there is no moderator, which requires a greater initial load of fissile fuel. The power of the reactor is controlled by salt expansion: from the design stage, the maximum regime is defined by the concentration of fissile material and the volume of the reactor. Under the effect of temperature, salt expansion reduces the probability of fission and slows the process down to the point of equilibrium: the system is naturally self-regulated. The concept associates to the reactor a spent fuel processing unit integrated into the process, in charge of separating fission products and minor actinides as they are produced in the reactor. The latter are re-injected into the reactor to be eliminated during the process. When a thorium reactor cooled with molten salt has an emergency shutdown, the liquid salt can be dumped into a reservoir under the reactor, where it would quickly cool down enough to harden so that leaks would not even be a problem.

The **Sodium-cooled Fast Reactor** (**SFR**) concept is one of the four fast neutron concepts selected by the Generation IV International Forum. The partners for the SFR system presently are the USA, Japan, China, Russia, South Korea and EURATOM [11]. Approximately twenty prototypes or demonstrators have been built throughout the world. In France, the ASTRID project (ASTRID means "Advanced Sodium Technological Reactor for Industrial Demonstration") had been initiated as a technological integration prototype to demonstrate the safety and its operation on an industrial scale with mixed oxide (U, Pu)O_2, but without thorium fuel.

Thorium-based fuels have also been successfully utilized in **High Temperature Gas-cooled Reactors** (**HTGR**), in particular in Germany, where the fuels were in the form of 'coated particles' of ThO_2 in graphite matrix [12]. Two "Pebble Bed" HTGRs, namely AVR 15 MW(e) and THTR 300 MW(e), successfully operated until the late 1980s, after which they were terminated.

The replacement of uranium reactors by non-fissile thorium reactors would be a new paradigm. The uranium-plutonium fuel cycle necessarily had to be established first (for producing the plutonium to be used in atomic weapons) and once the infrastructure was in place the thorium fuel cycle was disadvantaged. Thorium constitutes today a source of energy still completely unexploited. Its use could lead to a totally different perception of nuclear energy in the public, since it would suppress long-lived nuclear waste production. It represents significant long-term potentialities, but also important challenges before reaching the industrial scale.

3 Challenges and Means to Overcome Barriers

In 2019, for the first time, the generation of non-hydro renewables, i.e. wind, solar, biomass and others like geothermal, exceeded the electricity generation of nuclear power plants. Furthermore, according to the World Nuclear Industry Status Report, 2020 [13], COVID-19 was directly, significantly impacting the nuclear industry economically, as operational costs went up, while bulk prices temporarily dropped and electricity consumption plunged. But when the demand for electricity will grow again under massive pressure from mobility and information technology, as well as from the increase of the world population, nuclear industry will react to the need, and offer an acceptable and economical solution to carbon-free energy without long-lived waste. A technology able to recycle waste and produce energy. Is thorium part of the solution?

The challenges on using thorium fuels and fuel cycles before large investments are made for commercial utilization depend upon the reactor types. Taking the case of an ADS,

- the **databases and experience on fabricating and using thorium fuels** are very limited, as compared to UO_2 and (U, Pu)O_2 fuels, and need to be augmented; the choice of the fuel nature and composition should be thoroughly considered with respect to several competing motivations. For solid fuel a metallic option is primarily related to the need to achieve the hardest neutron spectrum in order to enhance fission. It also appears to be rather convenient for the subsequent pyro processing, the initial electrolytic oxide reduction being a supplementary energy- and time-consuming step. The advantage of using oxide or ceramic fuels consists in their capability to operate at generally higher temperatures;
- the **processing of the light water reactor uranium spent-fuel inventory** has to be developed to extract the transuranic elements and long-lived fission fragments, mainly technetium and iodine, for manufacturing the transmutation fuel and fission fragments target assemblies;
- the **irradiated thorium fuel** has to be processed to extract the unfissioned TRU elements and newly generated LLFF's for manufacturing the next cycle fuel and separate the produced U-233 enriched uranium for future use; this includes the difficulty of dissolving spent ThO_2-based fuels in HNO_3, and using remote reprocessing and refabricating in heavily shielded hot cells, because of the high gamma radiation associated with the short-lived daughter products of U-232; but the conceptual design of a pilot-scale (100 T/year) pyro processing facility for the treatment of light water reactor used fuel and high-level waste treatment has already been documented at Argonne National Laboratory in the USA [14]; the concentration of short- and medium-lived fission fragments into waste forms for disposal in a geologic repository has already being completed;
- the **high reliability** required of the high power accelerator and its interfaces with the subcritical core is problematic. Cyclotrons, compared to linear accelerators, could be relatively small and cost effective, the classical PSI scheme being good for 5 MW up to an energy of 600 to 800 MeV energy, but the down times have to be drastically reduced;
- a liquid metal high-power **spallation target** with lead-bismuth eutectic (LBE) material has to be developed, following the target successfully tested in the framework of the MEGAPIE-Swiss Spallation Neutron Source project at PSI [15];
- a **subcritical core** cooled with molten lead or LBE would benefit from the designs developed in Russia;
- a **fast neutron spectrum** implementation is essential to achieve reasonable transmutation rates for TRU isotopes, as in that spectrum almost all transuranium isotopes show a significantly higher fission-to-absorption ratio than in thermal reactors;
- the main technological obstacles of using high temperature lead or LBE coolants concern the development of structure materials able to resist **lead corrosion**, and the risk of blocking due to freezing.

Concerning MSR and SFR, specific challenges include the significant effect on **reactor stability**, and thus operability, that insertion of transmutation fuel, mainly a high amount of americium, will have. Beyond the questions related to on-line fuel reprocessing, materials able to withstand **salt corrosion** need to be designed and developed. The **safety approach** also has to be entirely redefined since there is no cladding to contain the fuel, the first barrier being relocated at the limits of the primary system. It is to be noted that the operation and safety of an MSR strongly depend on **chemical processes** whose control is very complex and which are still poorly known, thus leading to risks of leakage.

In any case, before industry launches a thorium prototype, for any reactor concept, it appears necessary that an experiment demonstrates the **safe operation** at significant power. The capability to **burn minor actinides** at rates suitable for an industrial scale has to be demonstrated. Extensive work on governmental support for **licensing procedures** has to be conducted from the initial phases of R&D to final designs. Due to the lack of data on nuclear energy systems using thorium fuels, it seems impractical today to develop meaningful **cost projections**.

4 Innovative Technical Concepts under Development

In the short term, it should be possible to incorporate a thorium fuel cycle in some of the existing reactors without major modifications in the engineered systems, reactor control and reactivity devices. For example, the company *Thor Energy* in Norway is currently studying thorium fuel in the Halden Research Reactor with the goal of marketing it for water-cooled reactors. This is important to gain experience with the open thorium cycle. Thorium could also be used as a fertile cover in a fast neutron reactor to produce fissile U-233 directly. It could be used as a mixed thorium/plutonium fuel, usable under the same conditions as MOX fuel in a pressurized or boiling water reactor, to burn plutonium produced by the uranium cycle.

However, for innovative reactors and fuel cycles, substantial reactor physics studies and technological developments are required. The preferred proposed solutions are either the application of molten salt reactor technologies or the application of accelerator-driven systems for the whole partitioning and transmutation process.

Molten salt reactor (MSR) development is being pursued by many start-ups in Europe and elsewhere, ahead of nuclear industry. The molten salts play the role of both fuel and coolant. This development is currently very diversified, in particular by *Flibe Energy*, *Terrestrial Energy*, *Elysium Industries*, *ThorCon Power* (planning the construction of thorium/uranium-fueled molten salt reactor power plants in Indonesia), *Moltex Energy*, *Copenhagen Atomics*, and *TerraPower*. *Seaborg Technologies* is developing an advanced thorium-based MSR, known as the Seaborg Cube-100. The company plans to develop small mass-produced floating nuclear power plants, or barges, and market them for developing countries in global regions where the use of renewable energy sources is unfavorable, such as in South East Asia. At Petten, in the Netherlands, an experimental molten salt loop including fissile fuel (LUMOS) is being conceived on the High Flux Reactor. In China, the Shanghai Institute of Nuclear Applied Physics is following two parallel paths of development of a molten salt thorium reactor, one with solid fuel and the other with liquid fuel dissolved in a fluorine cooler, with the aim of replacing uranium fuels in the long term. This diversity is considered healthy, similar to the initial development of personal computers in the 1970s, until one particular concept made a breakthrough. Concerning Sodium-cooled Fast Reactors, it is believed that the insertion of transmutation fuel, mainly a high amount of americium, will have a significant effect on reactor stability and thus operability.

Figure 3. Thorium from monazite deposits exist in high concentration in beach sands (credit P. K. Wattal, BARC, India).

India, with about one third of the world's thorium reserves, has clearly embarked on the thorium path as part of its ambitious civil nuclear development program. Indigenous technologies have been developed for all aspects of the thorium fuel cycle, i.e. mining, fuel fabrication, fuel irradiation, reprocessing and waste management (Figure 3). The design of different types of reactor systems has been studied. The design of an advanced system (AHWR 300), for which site evaluation is in progress, will use thorium-based fuel and includes many enhanced safety concepts. It is being developed in the form of a technology demonstrator for a thorium cycle on an industrial scale. India has also planned to use thorium in a High-Temperature Reactor, the purpose of which will be the production of hydrogen by water fractionation, reducing the country's dependence on imported oil. For the third phase of the development of the Indian nuclear program, the large-scale deployment of regenerative reactors with U-233/thorium fuel in the form of molten salts with on-line reprocessing is envisaged [5].

In the area of Accelerator-Driven Systems, on September 7, 2018, the Belgian federal government decided to build a new large research infrastructure, MYRRHA, on the site of the SCK-CEN laboratory. Its role will include an international contribution to the treatment of nuclear waste by separation and transmutation, the development of medical radioisotope applications, research into materials for nuclear fusion and innovative accelerator technologies. Ultimately, this project will also contribute to the development of the use of thorium in a subcritical reactor with solid fuel driven by a linear accelerator. The coolant will be a molten lead alloy. In Japan, reprocessing and transmutation technology is in the research and development phase, with the construction of new experimental infrastructures at the JPARC laboratory for the study of the feasibility of molten salt-cooled ADS. The Institute of Modern Physics in Lanzhou in the province of Gansu in China is developing the project called ADANES, according to a 20-year plan, to transmute waste with an accelerator coupled to a molten lead-cooled reactor. Two versions of the linear accelerator injector were built. The development of the spallation target and the reactor will be continued in a new laboratory under construction in Huizhou, under the acronym CiADS [16].

With regard to the manufacture of thorium fuel, experience has been developed in several countries such as India and Norway. An adapted reprocessing technology, pyro metallurgical treatment, which has the advantage of not separating plutonium from other actinides, has been developed at the Argonne National Laboratory (ANL) in the United States. The technology of a purely pyroelectrochemical process for the thorium fuel reprocessing and renewal appears economically advantageous in comparison with the costly aqueous separation processes currently in use, and sufficiently performant in terms of separation efficiency for the elemental groups partitioning required (uranium – thorium – TRU – fission fragments).

In our view ADS have the potential to realize the transmutation of TRUs, since a higher load is possible to improve the efficiency of the transmutation and to reduce the number of multi-recycling cycles. This is due to the expected enhanced neutron physical reactor stability and the external neutron supply. This approach is competitive with MSR and SFR, if the ANL process is adopted for its solid fuel.

5 Examination and Ranking against Requests

Radiotoxicity, strictly related to the chemical and nuclear characteristics of a radionuclide, may be combined with other quantitative factors, determining the long-term risk of the radionuclide dissemination in the environment, such as geological mobility, volatility, etc. The resulting semi-quantitative notion of "potential hazard index" adequately qualifies the overall danger the HLW represents for the future at each moment in the course of its radioactive decay. Among such supplementary considerations are the safety aspects related to the intensive heat release by the TRU's in the HLW, susceptible to provoke HLW container damage and reconfiguration, and a consequent increased criticity risk. These points generally motivate the HLW volume increase in order to decrease the mass (volume) TRU concentration in the HLW matrix. Complete elimination of TRU's by transmutation constitutes an ultimate resolution of these constraints.

In a fast neutron spectrum, almost all transuranium isotopes show a significantly higher fission-to-absorption ratio than in thermal reactors. This demonstrates that a fast neutron spectrum reactor is essential to achieve reasonable transmutation rates for TRU isotopes into mostly short-lived fission fragments. In particular, all plutonium isotopes are strongly fissionable (fission branching from 0.412 for Pu-242 to 0.883 for Pu-241). There are some radionuclides, like Np-237, Am-241 and Am-243, which have a fission probability of the order of 10 to 20 % and for which an additional neutron capture is required in order to reach a well fissionable nuclide. However, their presence can be easily accommodated and the required neutron multiplication in the overall chain is sustained by the largely fissionable elements [17].

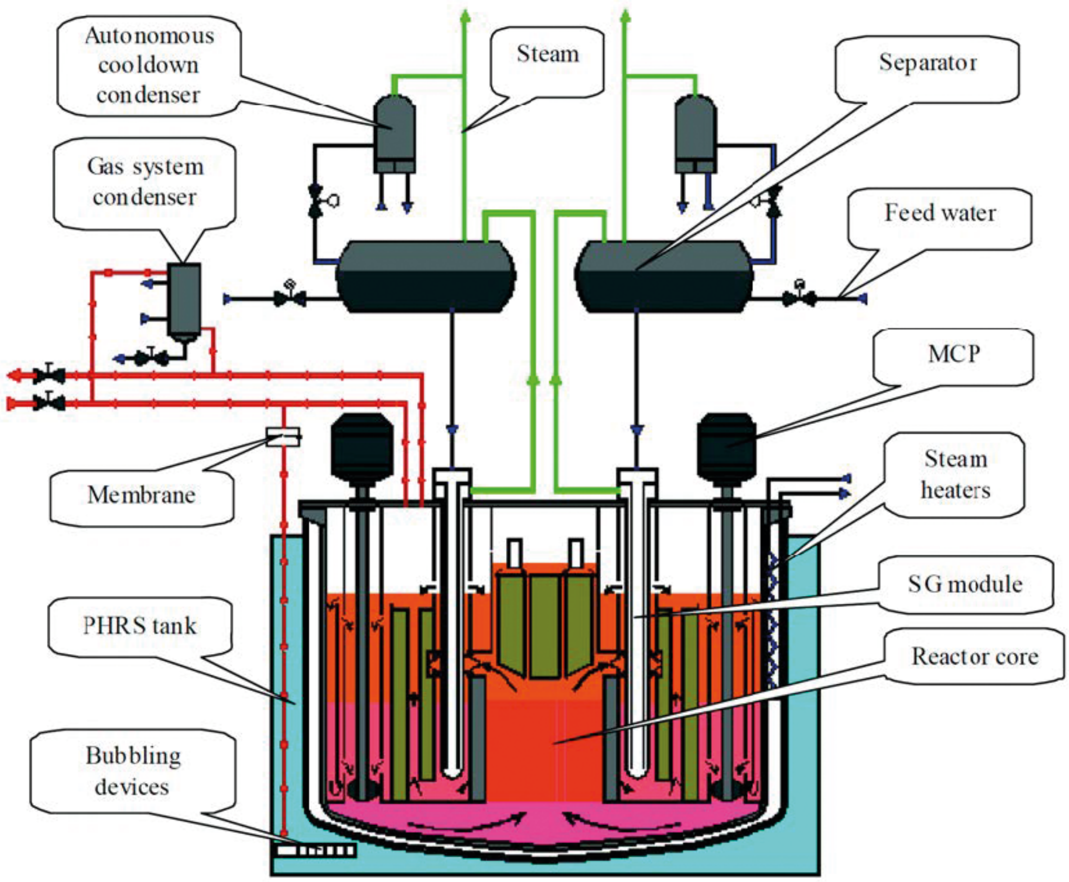


Figure 4. SVBR-100 system arrangement (IAEA Nuclear Energy Series, No. NP-T-1.6, 2012)

It would thus be necessary to demonstrate an industrial level of fast reactor operation, employing a closed fuel cycle whilst applying transmutation. This would drastically impact the deep geological repositories as they are designed today, considerably reduce the cost, size and associated risk and show that the remaining waste can be stored safely at last. And if one breeds large enough amounts of U-233 with thorium fuel, one can eventually dream replacing U-235 and not need recycling plutonium in the form of MOX, therefore stopping reprocessing plutonium, and thus reconfiguring reprocessing plants!

Large efforts have been deployed in France since many years on sodium fast reactor technology. However, they have recently received a significant setback due to the decision to abandon plans to build the industrial demonstration 600 MW fast-breeder ASTRID project [18].

A Swiss company, *Transmutex S.A.*, together with international partners, is planning the first ADS experimental demonstration of coupling at significant power a particle accelerator (70 MeV) with a subcritical core at 1 MW(t). It will allow the concept to be validated from operation and safety viewpoints. In parallel *Transmutex* is coordinating the design, construction, and commissioning of a fully functioning 100 MW(e) demonstrator at a site to be determined. This work relies on progress being made in establishing strategic partnerships regarding the main elements of a thorium ADS, i.e. the development of the industrial thorium fuel cycle technology, the design of a high-power 3 to 4 MW cyclotron, the LBE spallation target, and a LBE-cooled subcritical core on the model of the Russian fast-neutron power unit SVBR-100, with a thermal output of 280 MW(th) (Figure 4). When successful, this demonstrator will be a viable solution to the nuclear waste challenge on a human time scale, morally acceptable, technically feasible, and possibly also economically more sustainable.

The incorporation of transmutation systems will occur differently according to national situations and policies. In particular, it will differ if plutonium and minor actinides are managed separately (as in France) or together (as in the United States). In the US, the reprocessing of the LWR spent fuel being forbidden since 1977, the accumulated inventory of the indefinitely stored spent fuel approaches 100,000 tons nowadays. One may estimate that 64 thorium ADS will have to operate during 50 years for complete transmutation of all TRU (plutonium and MA) contained in this stock.

With regard to the 303 GW(e)·year electrical energy currently produced by the nuclear sector world-wide in 2019 [19], the elimination of their TRU long-lived waste by thorium ADS would require construction of about 200 units. The added value in this scenario is the production of about 120 GW(e)·year of electricity, which would help to meet increasing world energy demands and relieve dependence on fossil fuels, reducing greenhouse gas emission [20].

6 Conclusion and Outlook

The successful application of partitioning and transmutation with a thorium Accelerator-Driven System on industrial level has the potential for a significant volume reduction of the high-level nuclear waste which has to be disposed, a significant reduction of the long-term radiotoxicity, i.e. a hundred-fold, a negligible plutonium content, and a strong reduction of the heat after an intermediate storage time of some 70 years. In particular, this last point is considered by the Swiss Federal Nuclear Safety Inspectorate (IFSN) as a good solution to reduce the volume of the high-level waste repositories.

Thorium Accelerator-Driven Systems for waste transmutation and for energy applications are currently being constructed in China, and it is strategically important for Europe not to lag behind in this field. The mission should mobilize a large community of stakeholders, gathering around the idea of providing a realistic solution to a worldwide problem, including both the supporters of nuclear industry and those who are persistently opposing it. The impact of the development and implementation of these new systems is expected to be very high: spanning from the possible elimination of the military-grade radioactive material, to improvement of the technology base for medical radioisotope production, up to the deployment of a CO_2 free and safe energy source. High-level waste would not be accumulated anymore from the new built plants.

In view of the many advantages of Thorium Accelerator-Driven Systems, one can ask if instead of having a negative perception of nuclear power, after Chernobyl, followed by Fukushima, their implementation could lead to a totally different public perception, with fewer fears for the safety, health and military uses of nuclear energy. But still their implementation would require strong support from many individuals and industry. A great deal of testing, analysis, licensing and qualification work is required before any ADS and thorium fuel cycle can enter into service. Subsequently, for the industrial nuclear installation construction phase, involvement of the governments is needed in order to support financial risks, before private enterprise can operate the facilities. In Switzerland carbon-free nuclear innovative projects should be included in all green plans, alongside sustainable renewables.

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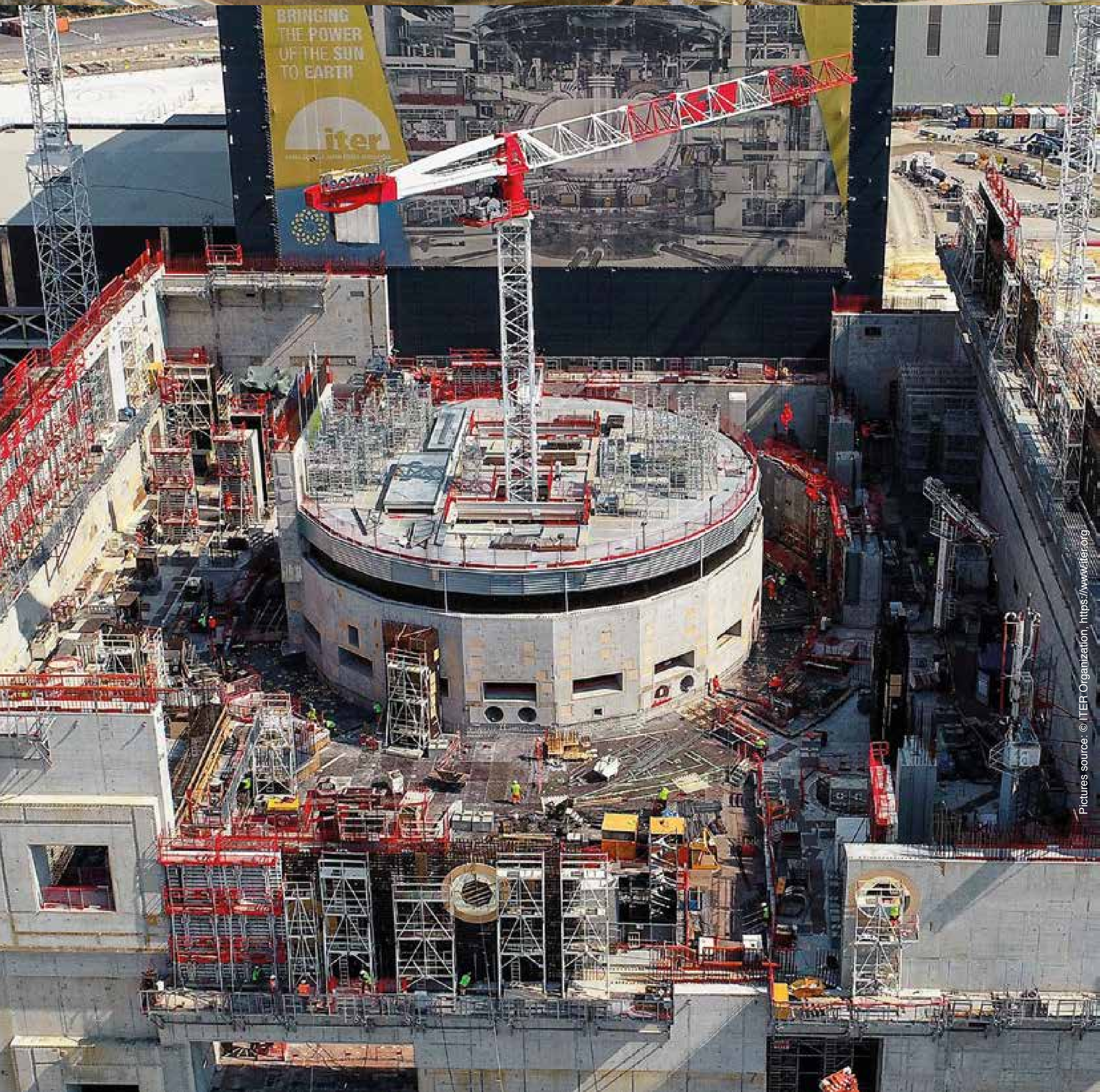
Since 1994, he has turned his scientific interests towards the detection of particles from space with the Alpha Magnetic Spectrometer project, first in the Space Shuttle "Discovery", and then on the International Space Station. This activity has required the implementation of a space qualified infrastructure as well as research and technical teams at the University of Geneva. He has contributed to several organizations responsible for astroparticle physics coordination, such as the Astroparticle physics European Coordination and the Astroparticle Physics International Forum.

As Professor emeritus, he has initiated applications of accelerator-based methods for medical applications and reduction of radioactive waste from nuclear power plants with private companies. He is a founding member of the Scientific Board of Transmutex SA.


BRINGING
THE POWER
OF THE SUN
TO EARTH
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ITER—An Essential Step Toward Fusion Energy

Laurie Porte, EPFL-SPC, Station 13, 1015 Lausanne

"Fusion will be there when society needs it" – Lev Artsimovich, 1972

1 Introduction

The energy of the atomic nucleus contains an enormous amount of energy. This energy can be tapped in two ways: by splitting large heavy, nuclei into smaller ones (fission) or by combining smaller ones into larger nuclei (fusion). The former gives us fission energy (see *Kröger* and *Bourquin* in this collection) while the latter provides fusion energy.

Controlled Thermonuclear Fusion (CTF) has been a subject of research for civil purposes since before 1958. The first public conference on CTF, where previously classified work was presented, took place in Geneva in 1958. Since then, progress in CTF has been at times rapid and at other times slow but enormous progress has been made in these past 60 years.

As shown in Figure 1, one relies on the fusion of the heavy isotopes of hydrogen, deuterium and tritium, to release energy for use in electricity production. Why is this so attractive? In a fusion device there is no release of greenhouse gases and there are no long-lived radioactive by-products that must be stored for thousands of years before they are safe. At the same time, despite that the energy source is nuclear, there can be no meltdown of the reactor. In addition, the fuels, deuterium and lithium [1], are evenly distributed across the globe and are practically inexhaustible.

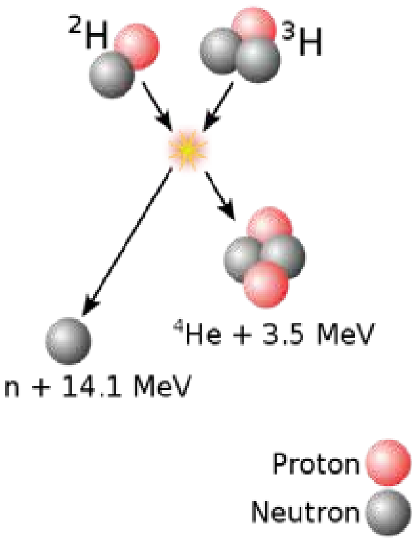

Figure 1: Deuterium (^{2}H) can fuse with Tritium (^{3}H) to release an alpha particle (^{4}He + 3.25 MeV) plus a neutron (n + 14.1 MeV). The energy carried by the neutron can be used to generate electricity.

CTF research is pursued along two parallel lines. On the one hand inertial confinement fusion (ICF) attempts to compress a fuel pellet to such high density that fusion may occur. On the other hand, a fully ionised gas, a plasma, consisting of a Deuterium/Tritium (D-T) mix is confined in a closed magnetic field and heated until fusion reactions may occur. This type of CTF is termed Magnetic Confinement Fusion (MCF) and is the subject of this text.

This report will very briefly summarise the state of the art in MCF to date and will subsequently describe the next step in the quest for CTF: ITER under construction in Provence, France. Following that a description of different approaches to MCF will be given. Subsequent sections will describe the major hurdles to overcome in the quest for fusion and finally a summary will be provided.

2 Background and Motivation

To achieve CTF reactions the fuel, in this case the plasma, must be confined at a sufficiently high density (n) and a sufficiently high temperature (T) with a sufficiently long energy confinement time (τ). These three necessary conditions are summarised in their triple product $nT\tau$ [1]. Figure 2 shows the 2-year period for doubling of the fusion triple product between 1967 and 2000; it increased by 4 orders of magnitude during this period. Shown also in the figure is the fact that the triple product is still a factor ten below the requirement for sustained thermonuclear fusion to occur.

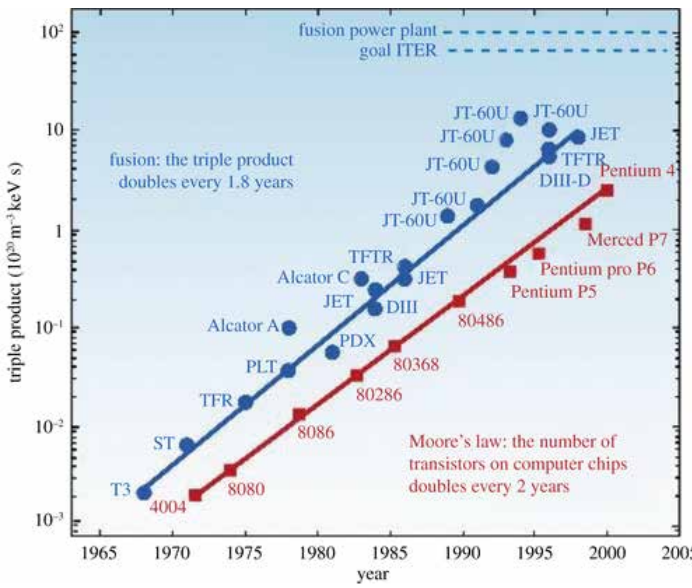

Figure 2: The progress in the triple product towards fusion, compared with Moore's law for transistor performance. Both have shown a power law, doubling around every 2 years [2].

In addition to the fusion triple product the fusion gain, Q, must be considered. Q is the ratio of the fusion power, produced in the plasma, to the power required to maintain the plasma in steady state. At ignition, the fusion power would maintain the plasma and $Q \to \infty$; the plasma is self-sustained. At $Q = 1$, the fusion power is equal to the power required to maintain the plasma, the plasma cannot self-sustain and there is no net power gain.

ITER itself will approach $Q = 10$ but is not designed to produce electricity.

1 Tritium does not occur naturally and is produced by the absorption of a neutron by lithium.

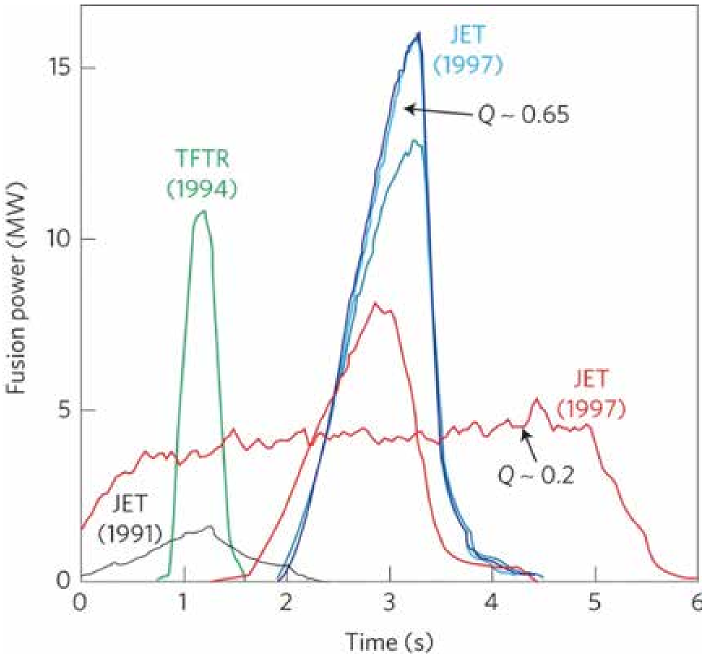

Figure 3: Shown are the time evolutions of the measured fusion power output in historical DT experiments in TFTR and JET. Q-values shown here are conservative.

Typical MCF experiments do not use a D-T mix to fuel the plasma. Indeed, fusion reactions are avoided as the main research goals are to improve the triple product and to improve engineering aspects of control and stability. This can be done in a non-nuclear environment, which obviates the need for nuclear licencing. Two machines, two tokamaks [3], have run true D-T experimental campaigns. In the mid-nineties, the Tokamak Fusion Test Reactor (TFTR) in Princeton NJ, USA [4,5] and the Joint European Torus (JET) [6,7] in Oxfordshire UK, conducted experiments to maximise the fusion output of their plasmas. Figure 3 compares TFTR result to the JET result [8]. JET achieved 16.7 MW of fusion power and its results laid the basis for ITER.

Figure 2, showing the 2 year doubling of the fusion triple product, $nT\tau$, achieved over four decades, is for the so-called large tokamaks of the 80s and 90s. We see JT-60, TFTR and JET prominent among the big machines. The Japanese Torus-60 (JT-60) was the flagship of Japan's fusion program and a machine of similar design and size to JET, but which never operated with tritium. In Figure 3, the D-T results of TFTR and JET are compared. The last time that D-T experiments were performed was in 1997 and TFTR shut down in that year. JET continues to run but, for the time being, no longer with tritium. Since 1997, the chase for high Q and large triple product has been superseded by research on developing high energy confinement scenarios with no edge plasma instabilities (the so-called Edge localised Modes or ELMs), advanced plasma control and on studying the properties of all metal plasma facing walls. All of these will be briefly discussed below. Progress has been steady. The European effort has been led by smaller, very flexible and configurable machines doing basic research in preparation for ITER.

3 Characteristics and Status of Fusion

Tokamaks produce plasma current by transformer action. A small current, large voltage in the multi-turn primary circuit drives a large current, at low voltage, in the secondary circuit: the plasma. The cycle of ramping up the plasma current to flat top, allowing the plasma to evolve and fusion reactions to occur and finally allowing the plasma current to ramp down is called a pulse. Figure 4 shows in schematic form the main events during a tokamak plasma pulse.

As stated above, the triple product of density, temperature and energy confinement time must be greater than some threshold value. For a 50:50 mix of D-T plasma, Lawson [1] showed that, individually, the plasma temperature must exceed approximately 25 keV (1 eV corresponds to 11600 Kelvin), which means that $n\tau \geq 10^{20}$ m^{-3}s is required. Individually all these requirements have been achieved and exceeded in all cases, but the triple product eludes us. ITER will achieve the necessary triple product to permit fusion gain and is expected to do so by the mid to late 2030's.

As far as fusion gain, Q, is concerned, JET holds the record for Q at $Q = 0.65$. ITER has been designed for $Q \geq 10$; with 50 MW input, ITER is designed to produce 500 MW of fusion power.

The projected increase of Q on ITER, as compared to JET, is due mainly to the increased plasma current and size of ITER. Exhaustive empirical studies of energy confinement have shown that, among other variables [9],

$$\tau \propto R^{1.93} \cdot I_p^{0.93} \cdot B_t^{0.15}$$

showing that by increasing the size, R, and plasma current, I_p, large increase of the energy confinement time can be made. To accommodate the increased plasma current, it is necessary to increase the toroidal magnetic field, B_t, which confines the plasma. Table 1 below compares some of the key engineering parameters of JET, the largest tokamak

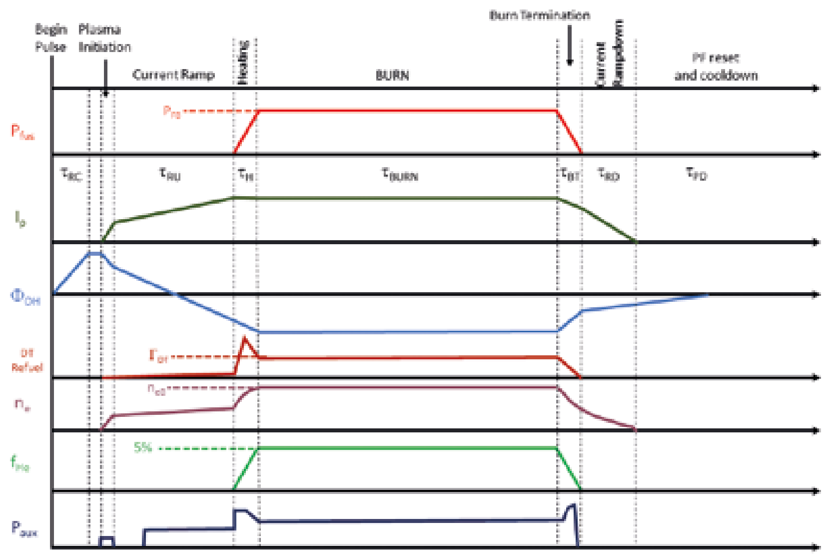

Figure 4: Schematic showing sequence of events in a plasma pulse. Parameters: I_p: Plasma Current; Φ_{OH}: Ohmic Heating Flux; n_e: Electron Density; f_{He}: Helium fraction; P_{aux}: Power for auxiliary heating; P_{fus}: Fusion Power Times / Events: RC: Recharge Coil; RU: Ramp Up: BT: Burn Termination; RD: Ramp Down; PD: Pump Down; SOP: Start of Pulse; SOB: Start of Burn; EOB: End of Burn

	JET	ITER
Major Radius	3 m	6.2 m
Plasma Volume	100 m^{-3}	830 m^{-3}
Magnetic Field	3.4 T	5.3 T
Plasma Current	5 MA	17 MA
Coil System	copper	SC / cryostat
Auxiliary Heating	38 MW	50 MW
Fusion Power	16 MW	**500 MW**

Table 1: some key engineering parameters of JET and ITER. Improvement of the energy confinement time can be achieved with a larger machine and increased plasma current at the expense of higher magnetic field.

ever to have operated with the design parameters of ITER.

Fusion gain, *Q*, has been mentioned and the idea of a self-sustaining plasma has been muted. What maintains the plasma? In the D-T reaction, mentioned above, a neutron and an alpha particle are produced with every fusion of a D-T pair. The neutron escapes the plasma passing through the metal wall. It's kinetic energy (14.1 MeV) is used to generate heat in a moderator, which can be used to generate electricity. The alpha remains confined in the plasma and it's kinetic energy (3.5 MeV) allows for a self-sustaining plasma. So called 'alpha heating' has been observed in both TFTR [4] and JET [6]. The JET results were very positive, the authors writing:

> *"Alpha heating was observed, …. This is a strong indication that there are no unpleasant surprises with respect to alpha heating and that there are no anomalous effects … Furthermore, it is highly encouraging that the peaked alpha heating profile shows up in the heating rate and the energy confinement time."*

The D-T results for both JET and TFTR leave room for much optimism. However, the power density and density of alphas was too low for the excitation of plasma instability driven by the fast alpha particles.

The conditions under which both TFTR and JET obtained their highest fusion power are not considered to be reactor relevant. In fact, the scenario in which the $Q \approx 0.2$ result, shown in Figure 3, was achieved is closer to the operating scenario foreseen for ITER; the 'ELMy H-mode'. This mode of operation is a quasi-stationary state exhibiting good energy confinement, moderate particle confinement and high edge plasma pressure. The high edge pressure leads to high frequency relaxations of the edge plasma pressure [10]. The ELMs provide a means of controlling the density of the plasma but eject particles and energy that would, eventually, damage the plasma facing components (first wall) necessitating its replacement.

Until very recently all MCF devices used carbon as their first wall material. Carbon has been used because it resists high temperature, is robust and has a low atomic number. Carbon impurities, therefore, do not radiate a large amount of power. Carbon also traps tritium, and the possibility exists to create hazardous hydrocarbon molecules. To avoid tritium retention and avoid hydrocarbon creation, a metal wall will be used instead. Tungsten will be used as it has the highest melting temperature of any metal [11]. This is one of the main research topics of JET envisaged for ITER.

Construction and component integration is expected to be completed in 2025 and first plasma should be achieved the same year. A decade long period of experimentation and installation will take ITER through to 2035 when full D-T operation will start.

4 ITER Scientific Goals and Challenges

ITER is designed to be a machine that will explore the properties of burning plasma. It is not designed to generate electricity. The first DEMOnstration of electricity production from MCF will be left to a DEMO machine. A European DEMO is already being designed.

ITER has 5 main scientific goals [12].

1) Produce 500 MW of fusion power for pulses of 400 s

ITER will produce pulses that are 400 s long. In 1997 JET produced 16.7 MW of fusion power requiring 14 MW of heating power to do so resulting in $Q = 0.67$ when the full energy balance is considered (power dissipated in magnetic field coils, pumping etc.). ITER is designed for much higher fusion power gain or $Q \geq 10$. For 50 MW of injected heating power, it will produce 500 MW of fusion power for long pulses of 400 to 600 seconds. ITER will not produce electricity, but as the first fusion experiment to produce net energy, it will prepare the way for a machine that can. See tritium breeding below.

2) Demonstrate the integrated operation of technologies for a fusion power plant

ITER will bridge the gap between today's smaller-scale experimental fusion devices and the demonstration fusion power plants of the future. Scientists will be able to study plasmas under conditions approaching those expected in a future power plant and test technologies such as heating, control, diagnostics, cryogenics and remote maintenance in an integrated way.
Heating and control technologies are being developed for ITER and are tested in non-nuclear environments. ITER will be the test bed for these technologies requiring hardened materials and remote handling capability.

3) Achieve a deuterium-tritium plasma in which the reaction is sustained through internal heating

Fusion research today is at the threshold of exploring the properties of *burning plasma*. In such a plasma, the energy of the helium nuclei produced when hydrogen isotopes fuse becomes large enough—because of the large number of reactions—to exceed the plasma heating that is injected from external sources. As the first such burning plasma device in the world, ITER will offer scientists a unique opportunity to chart new territory in controlled nuclear fusion.

The TFTR and JET results showed transient alpha heating. It is expected that on ITER high *Q* will be maintained in quasi-stationary state and that the alpha heating will take *Q* beyond unity. In this situation the possibly deleterious effects of fast particle instability will be observed. Present day machines can produce many of the fast particles instabilities that will be present in ITER and DEMO but not all [13]. Indeed, it is expected that new phenomena, related to fast particles will arise in a burning plasma. It is only in ITER that the full extent of the fast particle problem will become evident. It is only in ITER that strategies to prevent and/or mitigate fast particle instability will be developed.

4) Test tritium breeding

Deuterium occurs naturally and can be extracted from water. Tritium is an unstable isotope of hydrogen with a half-life of 12.3 years and only occurs in minute quantities in nature. It must be bred using lithium and a neutron.

$$^{6}Li + n \rightarrow {}^{3}H + {}^{4}He + 4.8\ MeV$$

Lithium occurs in nature in 2 isotopes: ^{7}Li and ^{6}Li. ^{7}Li is the more abundant isotope but it is the ^{6}Li which is useful. Tritium breeding blankets will, most likely, be used with enriched ^{6}Li. The neutron from the plasma is born with an energy of 14 MeV. It is slowed down in the blanket by moderator material and collides with a ^{6}Li nucleus producing an alpha particle (2.1 MeV) and a tritium nucleus (2.7 MeV). The energy of the neutron and the energy produced by splitting the ^{6}Li nucleus is transferred to a coolant and eventually used to generate steam to produce electricity.

For an energy producing reactor, tritium will have to be bred to satisfy the requirements of > 375 g of tritium per day for a 1 GWe installation. Besides posing a significant radiation hazard, tritium cannot be supplied from an external source as there is not the capacity to do so. The tritium must be generated by the fusion reactor itself in tritium breeding blankets. It is unlikely that in the simple ^{6}Li scheme outlined above enough tritium will be produced as many of the neutrons escaping the plasma are lost through gaps in the breeding blanket necessary for heating or measurement devices. Others are lost by striking support structures or simply pass through the blanket without striking a lithium nucleus. To increase the rate of tritium production, neutron multipliers (beryllium and lead) will be used. They can produce two neutrons for each incoming neutron.

The biggest problem in the blanket, however, is to remove the heat generated in it; that is the power output of the reactor. Various means of heat extraction are being studied.

ITER will test means of producing tritium in blankets containing lithium, lead, berylllium and structural material. ITER will provide a unique opportunity to test mock-up in-vessel tritium breeding blankets in a real fusion environment.

ITER will use existing reserves of tritium for its own use.

5) Demonstrate the safety characteristics of a fusion device

In 2012, when the ITER Organization obtained licensing as a nuclear operator in France, the ITER fusion device became the first in the world to have successfully undergone the rigorous examination of its safety case. One of the primary goals of ITER operation is to demonstrate control of the plasma and fusion reactions with negligible consequences to the environment.

5 The Challenges before us

Over the last 60 years or so our understanding of the physics behind MCF has advanced enormously and this is evidenced in Figure 2. At least in physics terms fusion is realizable. There are serious engineering and materials challenges ahead. These challenges will be very briefly described here.

Considered are the challenges directly to ITER but also to a future demonstration reactor (DEMO).

Plasma Facing Components

Carbon fiber composites (CFC) are used in today's machines as first wall materials. They are resistant to high temperature and are strong. CFC's also absorb tritium and so cannot be used due to the risk of hydrocarbon formation. CFC also erodes rather quickly. Tungsten, a high temperature, refractory metal, will be used in its stead. It is, however, a high Z material which are known to cool plasma by radiation. Means will have to be found to avoid tungsten pollution of the plasma core. One possibility may be to use silicon carbide (SiC). It is highly resistant to temperature, is strong and is resistant to radiation damage (see below) but it is not known how to produce SiC in sufficient quantity nor how to machine it [14].

Table 2 shows the first wall loads for ITER, DEMO and a future fusion reactor [15].

The heat flux shown above for both ITER and DEMO are low, not much higher than the surface of an electric iron. In the so-called divertor of a fusion device, where the flux of heat and particles is significantly higher, heat loading is a major problem and will be briefly discussed below.

The difficulty lies in the neutron flux. The neutrons traverse the first wall, colliding with the atoms of the structural material displacing them. Neutron damage is measured in displacement per atom (dpa). Many dpa's lead to structural weakness and the necessity to replace the first wall.

The plasma exhaust, comprising charged particles of the main plasma constituent gases, must be deposited somewhere. Approximately 60% of the exhaust will be guided along magnetic field lines to the divertor. This [16] is a toroidally symmetric volume of cool, very dense plasma that is in close proximity to material surfaces. The divertor increases the efficiency by which impurities and helium ash can be removed from and also be prevented from re-entering the main plasma. The divertor will subsequently be subject to heat loads of 20 MWm^{-2} and so adequate cooling must be provided. There is so much heat flux to the divertor because particles escaping the main plasma are preferentially chan-

	ITER	DEMO	Reactor	Units
Fusion Power	0.5	5	5	GW
Heat Flux	0.3	0.5	0.5	MWm^{-2}
Neutron Load	0.78	< 2	2	MWm^{-2}
Life Neutron load	0.07	8	15	MW - years / m^2
Neutron damage	< 3	80	150	dpa

Table 2: first wall loads on ITER, DEMO and a future reactor.

neled to it to avoid damage to the first wall. A cool, very dense plasma is established in the divertor to avoid impurities entering the main plasma. Water cooling can be used on ITER but on DEMO or a future reactor other means of cooling must be found. Helium cooling is being explored.

Structural Materials

The structural materials that will be used on ITER (DEMO or a future reactor) must be strong enough to support the colossal weight of the device but also resist elevated neutron flux. Special steel alloys will be used. Two reduced activation ferritic martensitic steels have been designed: Eurofer in Europe and F82H in Japan [17]. These steels, when activated by neutron bombardment, build up only short-lived radioactive isotopes (≈ 100 years) that are non-volatile. To avoid the creation of long lived radio-isotopes in Eurofer and F82H, only iron, vanadium, chromium, yttrium, silicon, carbon, tantalum and tungsten are used in the alloys. Swelling and embrittlement are due to helium and hydrogen bubbles trapped in the steel.
Novel oxide dispersion strengthened (ODS) steels are under development that exhibit reduced creep and increased strength after irradiation, but much work must be done to prove their applicability to DEMO or a future power plant.

Tritium

A future power plant producing 1 GW of electricity will consume about 150 kg of tritium per year. The tritium will be produced in blankets surrounding the plasma that contain lithium; ^{6}Li. The same 1 GW electric (1 GWe) plant will require ≈ 300 kg ^{6}Li. There exists on earth, on the land and in the oceans ≈ 10^{14} kg: 30 million years-worth if all electricity is produced by D-T fusion [17]. (Deuterium would last 30 billion years!). Much design work has been done on the design of tritium breeding blankets, addressing problems of cooling, irradiation damage, tritium extraction among many other aspects and constraints. The development of tritium breeding technology is an urgent task. It is expected that ITER will consume all the world's reserves of tritium and that DEMO alone will require 10 kg to start. This will be sourced from existing fission plants.

Tritium decays by beta-decay producing 3.65 × 10^{14} Bqg^{-1}. Tritium is not dangerous externally; its beta particles are of low energy and are unable to penetrate the skin, but it is dangerous if ingested and it must be kept out of the water supply.

Magnets

The main component in a MCF reactor are the magnetic field coils. To generate the magnetic fields necessary to confine plasma, ≈ 5 T, mega-Amperes of current are necessary. To reduce the cost of running magnets at the necessarily high fields required for MCF, superconducting magnets will be used. A mixture of niobium-titanium and niobium-tin windings will be used. Superconducting cables carry electric current only on their surface and so a superconducting cable for a magnet is made up of thousands of thin strands that are surrounded by copper strands. The copper is required to mitigate quenches when one part of the cable goes normal: the copper conducts the huge current preventing dangerously large voltages appearing.

Magnet technology is mature now and does not present a large engineering problem for ITER, DEMO or a future power plant. However, the superconducting coils must be cooled to below 4.2 K and this requires liquid helium. Helium inventory and helium availability are problematic as most helium comes as a by-product of natural gas production. Helium is becoming difficult to procure and this problem will worsen as hydrocarbon supplies dry up.

Additional Heating

To heat the plasma to fusion temperatures (26 keV, ≈ 300,000,000 °C) external sources of heat are required. Once fusion temperatures have been achieved and fusion reactions are ongoing the alpha heating, mentioned above, maintains the plasma temperature. Techniques employed include neutral beam injection and the excitation of plasma waves. Wesson [3] provides a simple introduction to the principles behind plasma heating.

Neutral Beam Injection Heating (NBH) at the scale of ITER or DEMO requires beams at the MeV level of energy. To generate a neutral beam, first of all atoms of hydrogen (or deuterium) are stripped of their electrons. Then the charged particles are accelerated in an electrostatic field. The accelerated ions are subsequently re-neutralised and the remaining charged particles are steered out of the neutral beam in a magnetic field and 'dumped'. The directed, energetic neutrals penetrate the plasma and deposit their energy in it through collisions. NBH is a standard technique for heating present day MCF devices but, at the time of writing, efficient and reliable sources at the MeV level have not been produced.

Wave heating can either couple to ions or to electrons. Generally, a high-power source of electromagnetic radiation furnishes radio-frequency power at a specific frequency. In the case of ion heating the required frequency is, typically, around 50 MHz. Radiation at this frequency requires a large antenna close to the plasma to couple efficiently. The antenna will be bombarded by ions and antenna material will sputter into the plasma cooling it. RF power for electron heating is at a much higher frequency than for ion heating; 170 GHz for ITER. It is relatively straightforward to couple this power to the plasma and does not pose any risk of contamination of the plasma by metallic impurities.

NBH and wave heating methods are all standard on present day MCF devices which require a few MW for a few seconds. ITER and DEMO will require many tens of MW continuously. At the same time, the reliability of additional heating systems must be close to 100 % (today's heating systems have reliability closer to 60 %). With increased source power requirements comes increased demand for cooling and this is a major concern and engineering problem. A 50 MW heating installation, operating at 30 % electrical efficiency then requires the evacuation of 110 MW of dissipated heat.

Edge Localized Modes and Disruptions

As mentioned above, the operating scenario for ITER is the ELMy H-mode as it has high energy confinement and allows density control at the expense of edge plasma instability that expels energy and particles that will damage the first wall. The ELMy H-mode is not adequate for a DEMO or a future power plant. Plasma scenarios have been discovered that have high confinement and allow density control [18, 19, 20, 21, 22]. It is incumbent upon ITER to prove the benefit (or otherwise) of the new ELM-free scenarios for high *Q* machines.

Disruptions

Tokamaks carry mega-amperes of electric current. The current helps confine the plasma and heats it. Unfortunately, under some well understood circumstances, the plasma current and all confinement is lost in a few milliseconds [23]. All plasma energy is dumped into the vacuum vessel causing damage. It is of value to approach the limits where the disruptions occur because it is often at these limits that plasma performance is best (highest *Q*). It is possible to mitigate disruptions preventing their most damaging effects [24]. ITER will suffer the occasional disruption but DEMO and any future power plant cannot do so.

Fast Particle Instability

The 3.5 MeV alpha particles that are born in the D-T fusion reaction are slowed down and transfer their heat to the background plasma through collisions. As they slow down, it is possible for the alphas to interact resonantly with a longitudinal plasma wave [25] which may grow leading to a disruption. ITER will be the first machine to be able to study the so-called Alfvén wave instability.

6 DEMO

ITER is the necessary next step in MCF. To facilitate progress during 2014, as part of the Roadmap to Fusion Electricity Horizon 2020 [26], Europe launched a comprehensive design study of a DEMOnstration Fusion Reactor (DEMO) with the aim of generating, around the middle of the century, several hundred MWs of net electricity and operating with a closed tritium fuel-cycle [27]. Details of the European DEMO design activity can be found in [28].

At the time of writing, DEMO is envisaged to be a 18 MA, 6 T device with a major radius of 9 m. The specified goals of DEMO are to produce electricity from fusion, demonstrate tritium self-sufficiency, demonstrate 'reasonable' availability over a lifetime of several years, act as a test facility for a first of kind fusion reactor and to minimise the still occurring short-lived nuclear waste, which will disintegrate naturally within somewhat less than one hundred years; fusion plants produce no long-lived waste.

Much of the detailed engineering design for DEMO is dependent upon results from the D-T phase of ITER operations and on the results of tritium breeding tests. As such it is not yet possible to draw a specific timeline to the design and construction of DEMO.

7 Other Concepts in MCF

All of what has gone before pertains to tokamaks which are by far the most advanced concept in MCF. Governments have invested enormously in MCF and in tokamaks in particular. The stellarator [29] has not been discussed here but, in this section, we will describe Wendelstein 7-X.

Wendelstein 7-X stellarator

A stellarator is, like a tokamak, a toroidal plasma device where magnetic fields are used to confine the plasma. There is no need for a large toroidal electric current in the plasma as the magnetic field configuration – produced by coils outside of the plasma - is sufficient, alone, to confine the plasma. Therefore, there can be no disruptions. Historically, the stellarator was at least an order of magnitude less performant than the tokamak which is why the tokamak has taken precedence. Wendelstein 7-X (W7X) is an optimised stellarator; optimised so that the magnetic field configuration should minimise heat and particle loss from the plasma [25]. It has a plasma volume of 30 m^{-3}, is located in northern Germany and has been in operation since 2015. Its goal is to achieve steady plasma at fusion relevant temperature and density. The goal, then, is to prove the stellarator as a viable alternative to the tokamak. Several years of experimentation lie ahead of W7X before pronouncement can be made as to the stellarator concept.

The private sector is becoming increasingly involved in MCF and both new and not so new ideas are being pursued. Some of the private sector developments will be introduced.

Commonwealth Fusion Systems (CFS)

CFS (https://cfs.energy/) is a company based in Cambridge Massachusetts and is a spin-off of MIT. In collaboration with MIT, CFS is planning to build an extremely high field tokamak. The SPARC tokamak [30] is designed as a high-field (B_0 = 12.2 T), compact (R_0 = 1.85 m), superconducting, D-T tokamak with the goal of producing fusion gain from a magnetically confined fusion plasma for the first time. Currently under design, SPARC will pursue the high-field path to fusion utilizing new magnets based on rare earth barium copper oxide high-temperature superconductors to achieve high performance in a compact device. SPARC is scheduled to start operations in 2025 with the projected goal of achieving $Q \approx 11$.

Tokamak Energy

Based in Oxfordshire England, Tokamak Energy (https://www.tokamakenergy.co.uk/) has a stated goal of achieving fusion power production by 2030 in their ST40 tokamak. ST40 is a 'spherical tokamak' (ST) [31] using a high toroidal field to confine the plasma. The field coils for ST40 use the rare earth barium copper oxide high-temperature superconductor which can be operated at ≈ -250 °C. They can generate much higher magnetic fields than other superconducting coils and occupy much less volume because the superconducting tape is very thin [32]. The confinement scaling for STs favours greatly the toroidal magnetic field [33] and STs exhibit better stability compared to tokamaks like JET. The goals of ST40 are (i) to demonstrate the feasibility of constructing and operating a high field ST based on a high-temperature superconductor, (ii) to show the benefits of a high field in a ST, and (iii) to achieve fusion-relevant conditions with high fusion triple product, $nT\tau$.

TAE Technologies Inc.

Based in California, USA TAE (https://tae.com/) pursues a path to fusion using a so-called field reversed configuration (FRC) [34]. FRCs are simple to build (compared to a tokamak) and, because the magnetic field is very low in the plasma, may be inexpensive to run. In addition, TAE follows a route fusion that does not count on fast neutrons, using hydrogen and boron as fusion fuel relying on the $^{11}B(p,3\alpha)$ [35] reaction

$$^{1}p + {}^{11}B \rightarrow 3\,{}^{4}He + 8.7\ MeV$$

which produces three alpha particles whose energy is used to produce electricity by direct conversion: a means of converting a charged particle's kinetic energy into electrical energy (a voltage) [36]. Direct conversion has the potential to achieve efficiency in the region of 90%.

8 Economics

Any future fusion power plant must produce affordable electricity. Estimates of the cost of electricity (COE) have been made and we summarise Ward *et al.* [37, 38, 39]. According to Ward *et al.*

$$COE \propto \left(\frac{rL}{A}\right)^{0.6} \cdot \frac{1}{\eta_{th}^{0.5} p_e^{0.4} \beta_n^{0.4} N^{0.3}}$$

Here r is the discount rate, L is a 'learning' factor (efficiency improves in time), A availability of plant which is the ratio of plant time on-line to time off-line. η_{th} is the efficiency of converting heat into electricity and P_e is the amount of electrical power produced. β_N is the efficiency by which the plant can confine the plasma and is the ratio of plasma pressure to magnetic field pressure ($\sim B^2$). N is the ratio of the plasma density to the maximum achievable density. Ward took various models of plant, varied the size of plant (P_e) and went from conservative physics ($N \approx 0.7$, $\beta_N \approx 2.5$) to more speculative physics ($N \approx 1.4$, $\beta_N \approx 5.5$). COE for fusion varied from 5 cents/kW to 15 cents/kW making fusion at least competitive with other means of electricity production. The general conclusion emanating from this set of studies is that fusion energy can play a significant role in a carbon-controlled energy (efforts made in carbon capture and sequestration) market.

Independent work by Gnansounou & Bednyagin, [40, 41, 42] using classical economics' analysis techniques (Black – Scholes type analysis and stochastic differential equations) come to several important conclusions for fusion. In [40] they conclude that fusion can be deployed to most regions and occupy up to 20 % of the energy market and contribute to a reduction of 1.9 % in CO_2 emissions from energy production. In [42] the same two authors provide, among others, an important conclusion:

"The analyses performed in this paper clearly demonstrate that, besides a high-level mission to assure sustainable energy supply, fusion research, development, demonstration and deployment programme may yield substantial net socio-economic benefits that may be at least two times higher compared to the expected RD&D costs, and hence the pursuit of even more ambitious programme is economically justified despite the uncertainties".

Entler *et al.* [43] provide a comparison of cost between fusion power and power provided by photovoltaics and wind and conclude that fusion power will be of comparable cost to these two and may even become significantly cheaper as fusion technology improves. The comparison does not include the costs of energy storage.

Lopes Cardozo [44] encourages the development of smaller, cheaper and, very importantly, quick to build fusion plants, moving away from the large plant models like DEMO and the economics of previous authors, arguing that such develop is most likely to accelerate the development of fusion energy. He provides no answer to the question of whether such small plants are feasible but this argument is in line with the methodology advocated by TAE, Tokamak Solutions and CFS.

9 Conclusion and Outlook

According to the physics of MCF, it is with optimism that ITER and DEMO should be designed, built and operated. Some physics questions remain open but advances in plasma control and very recent advances in scenario development provide avenues for research that will lead to solutions to the physics problems.

The real, major difficulty for MCF now lies in the engineering challenges associated with extremely high heat and neutron loading on the first wall and divertor surfaces and in the problem of tritium breeding. These challenges will be faced in ITER and on DEMO.

Private sector investment in MCF is increasing and there are companies, staffed by very experienced fusion professionals, who are working towards the goal of delivering fusion within the next 10 to 15 years.

The economics of fusion is interesting and point to the value of developing fusion as a means of generating clean, safe and abundant electricity.

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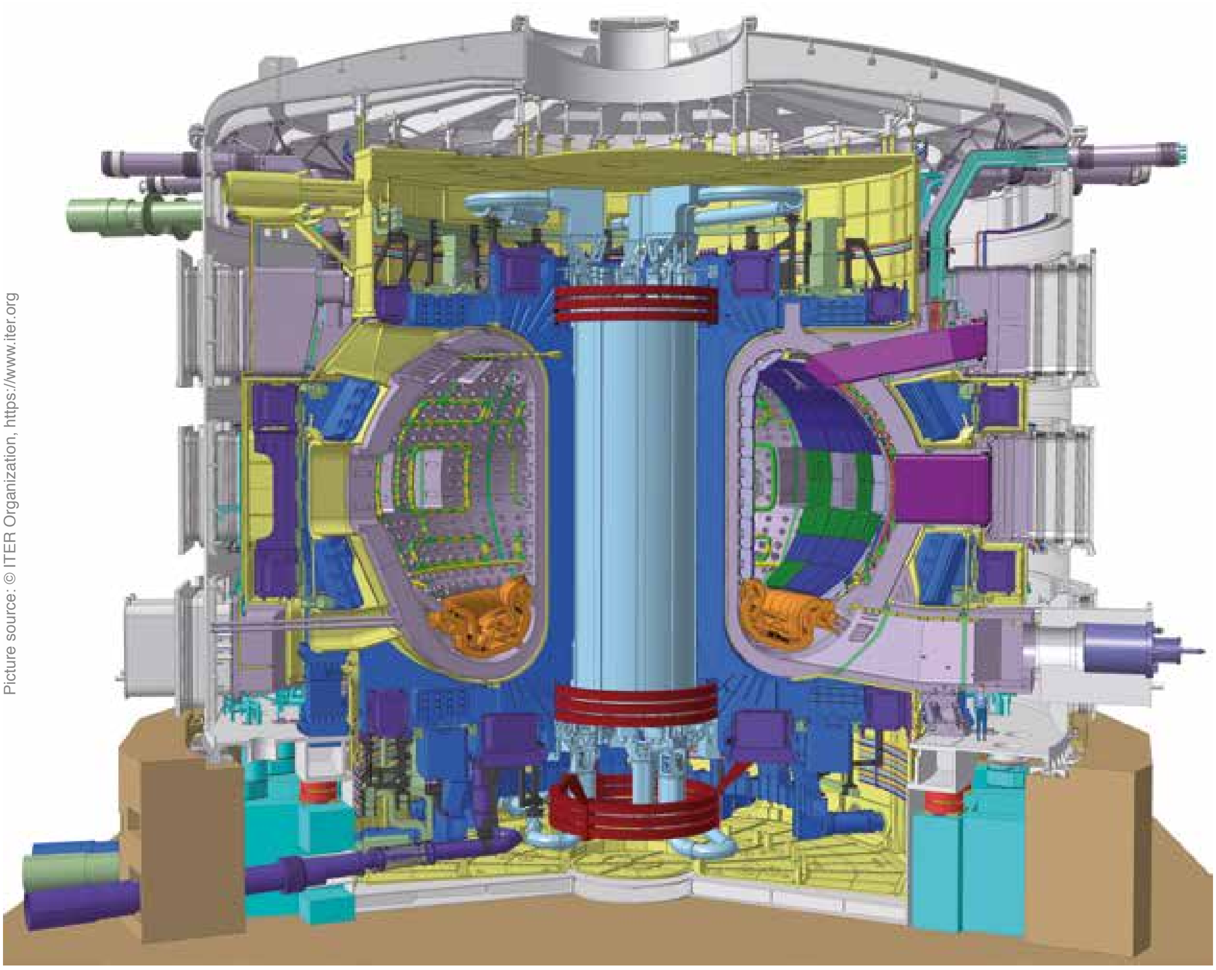

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Born in the town of Ayr in the west coast of Scotland, **Laurie Porte** was educated at the Kyle Academy before proceeding to the University of Strathclyde where he read physics. Graduating with first class honours in 1989 he then proceeded to study for a PhD. Working at the JET Joint Undertaking he developed and built a millimeter wave heterodyne radiometer for highly resolved measurements of electron temperature in the JET plasma. Laurie completed his PhD in 1992. After finishing a post-doc at JET he moved to UCLA where he studied plasma generated by helicon waves. After this brief cold sojourn Laurie migrated back to hot, fusion plasma and participated in collective Thomson scattering experiments on the TEXTOR tokamak in Jülich, Germany. In 2001 he joined the team at the Swiss Plasma Center where he still works. His interests include millimeter wave plasma diagnostics and plasma heating using millimeter waves. He has an interest in the effects of shaping on plasma confinement.

Glossary

ADS
Accelerator driven system

BWR
Boiling water reactor, is a type of light water nuclear reactor where the reactor core heats water, which turns to steam and then drives a steam turbine.

CDF
Core damage frequency, is a term used in probabilistic risk assessment (PRA) that indicates the likelihood of an accident that would cause severe damage to a nuclear fuel in nuclear reactor core.

ELM
Edge Localized Mode. Regular, energetic bursts of energy and particles that escape from the magnetic field surrounding the plasma and cause loss of energy. The mitigation of this phenomenon is an important preoccupation of tokamak physicists.

Energy confinement time
The ratio of instantaneous plasma energy content to the net power flow into the plasma required to maintain that energy content.

EUROfusion
The European Consortium for the Development of Fusion Energy, manages European fusion research activities on behalf of Euratom. See: *https://www.euro-fusion.org/*.

Fusion triple product
Product of density, confinement time and plasma temperature which is used by researchers to measure the performance of a fusion plasma. The triple product has seen an increase of a factor of 10,000 in the last thirty years of fusion experimentation; another factor of six is needed to arrive at the level of performance required for a power plant.

Helium ash
The name given to the helium nuclei produced by fusion reactions in a deuterium-tritium plasma. Once the helium nuclei have shared their energy with the rest of the plasma, they have no further use; their removal and replacement by deuterium-tritium fuel is required to prevent dilution of the plasma.

H-mode
The baseline mode of plasma operation on all of today's major tokamaks. As the plasma auxiliary heating exceeds a certain threshold power the energy confinement of the plasma spontaneously doubles.

HTGR
High temperature gas-cooled reactor

LFR
Lead cooled fast reactor, is a nuclear reactor design that features a lead or lead-bismuth eutectic coolant.

LLFF
Long-lived fission fragments are radioactive materials with a long half-life (more than 200,000 years) produced by nuclear fission of uranium and plutonium.

Lawson's criterium
Introduced in 1955, British physicist John Lawson (1923-2008) demonstrated that the conditions for fusion rely on three vital parameters: temperature (T), density (n) and confinement time (τ).

LWR
Light water reactor, is a type of thermal-neutron reactor that uses normal water, as opposed to heavy water, as both its coolant and neutron moderator. There are three varieties of light-water reactors: the pressurized water reactor (PWR), the boiling water reactor (BWR), and (most designs of) the supercritical water reactor (SCWR).

MSR
Molten salt fast reactor, is a class of nuclear fission reactor in which the primary nuclear reactor coolant and/or the fuel is a molten salt mixture.

PWR
Pressurized water reactor, is a type of light-water nuclear reactor, where the primary coolant (water) is pumped under high pressure to the reactor core. The heated, high pressure water then flows to a steam generator.

SFR
Sodium cooled fast reactor is a fast neutron reactor cooled by liquid sodium. It particularly refers to two Generation IV reactor proposals, one based on existing liquid metal cooled reactor (LMFR) technology using mixed oxide fuel (MOX), the other based on the metal-fueled integral fast reactor.

Stellarator
A toroidal device for the containment of a plasma inside a racetrack-shape-like tube. The device produces both the toroidal and poloidal magnetic field in the plasma with the use of external magnetic field coils.

Tokamak
A fusion device for containing a plasma inside a toroidal chamber through the use of two magnetic fields - one created by magnetic coils around the torus, the other (the poloidal field) created by a large electric current in the plasma itself. The term tokamak is a transliteration of a Russian expression (toroidalnaya kamera + magnitnaya katushka) meaning toroidal chamber with magnetic coils.

TRU
Thorium and transuranic element