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Molten Salt Fast Reactor Technology – An Overview

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With a few exceptions [1], environmental lobbies have tended to oppose nuclear power with a vengeance similar to their opposition to coal and natural gas. In certain quarters [2] this has changed with the promise of abundant, cheap and safe electricity that may be produced using thorium (Th) fuelled molten salt reactors. This guest post by French physicist *Hubert Flocard* places the status of molten salt reactor technology within the historical context of how the nuclear industry has evolved and examines some of the key challenges facing the development and deployment of this magical and elusive energy source. We have both written the extended summary below based on Hubert's article that follows on after the summary. Hubert's impressive bio is at the end of the post.

[1] James Lovelock, The Revenge of Gaia
[2] Baroness Worthington, Why Thorium Nuclear Power Shouldn't be Written Off

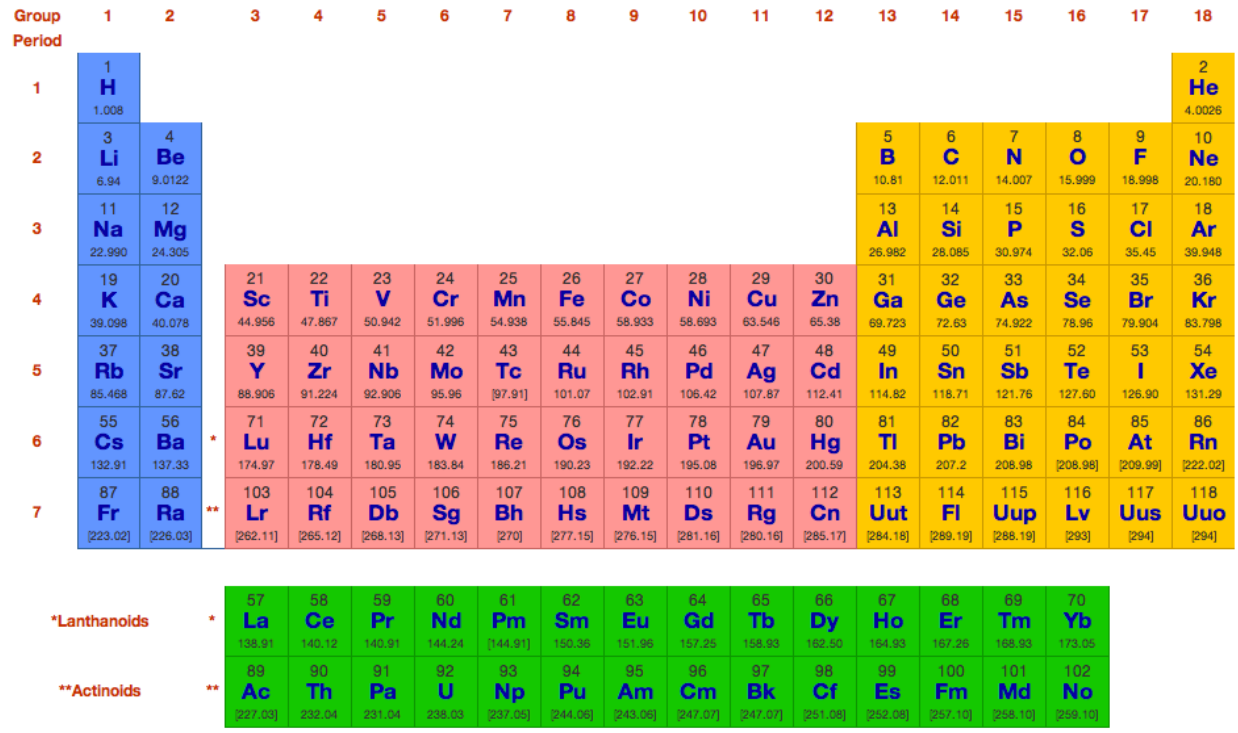
Extended Summary

The world nuclear industry currently runs on Generation II and Generation III reactor technology. The presently active reactors (whether moderated by pressurised water – PWR – or boiling water – BWR) are said to belong to the GII generation while more modern versions such as the EPR or the AP1000 correspond to GIII. At the beginning of the twenty first century a forum was convened to establish an international collaboration to prepare the next generation of reactor technology (GIV). A number of design options were on the table (see below) among them molten salt reactors.

1) Liquid Sodium Fast Reactor (SFR)
2) Helium Cooled Fast Reactor (HeFR)
3) Liquid Lead Fast Reactor (LFR)
4) Supercritical Water Fast Reactor (SCFR)
5) Molten Salt Fast Reactor (MSFR)
6) Very High Temperature Thermal Reactor (VHTR)

With the exception of the MSFR, that is specifically designed to run on Th fuel, all other technologies will run on U fuel. It is also worth noting that 5 of the 6 designs are fast breeder reactors designed to consume any nuclear waste that they may produce and to extend the life of the global inventory of U and Th that is available to us.

To appreciate the evolution of reactor technology it is important to understand a little bit about the natural elements on Earth which can be made to fission following the capture of neutrons. They are the actinides located at the bottom of the periodic table. Everyone has heard of uranium (U), thorium (Th) and plutonium (Pu) but are less aware of elements like protactinium (Pa), americium and curium. Some of these less common actinides do exist in nature in minute quantities for brief periods as part of the natural radioactive decay of U to Pb. Others result from the nuclear reactions happening in reactors or at laboratory accelerators.



Periodic table from [Web Elements](#)

The isotopes of interest are 235U, 238U and 232Th. Presently, the 235U isotope is by far the most useful because it is the only one which can easily be made to fission, releasing a substantial amount of energy. Thus 235U is described as fissile while 238U and 232Th are described as fertile. Today, 99.3 % of natural U is 238 and only 0.7 % is 235. That is because most of the 235U has already decayed away to stable Pb.

Out of these three isotopes only fissile 235U can be used to initiate a nuclear chain reaction such as those that occur in nuclear reactors or atomic bombs. To achieve a chain reaction it is necessary to enrich the uranium in its 235 isotope. For nuclear power, enrichment is typically about 3.7 %, i.e. a five-fold uplift in concentration as compared to natural uranium. For atomic bombs, the enrichment is much higher, but the same procedure is used, hence concern over civilian nuclear programs in certain countries.

While fissile 235U is required to initiate a chain reaction, the fertile 238U that makes up 96.3 % of the fuel participates also in the energy production since some of it is converted to fissile 239Pu. In this respect all U based reactors breed fissile fuel by tapping into the fertile resource. Breeder reactors are simply designed to breed more fissile fuel than they consume.

Three important points need to be made before continuing. The first is that an MSFR can't start by using only 232Th. The reactor will first require that either natural 235U or man-made 239Pu be added to initiate the fission chain reaction, since fertile 232Th cannot achieve criticality on its own. The second is that the MSFR is a breeder reactor and environmentalists have in the past opposed breeder technology. In a breeder of any design, fertile 238U or 232Th isotopes are converted to fissile isotopes like 239Pu (U cycle) or 233U (Th cycle). A MSFR will run exclusively on the thorium cycle (i.e. without addition of U5 or Pu9) when it will have bred enough 233U to maintain the chain reaction. It will take time. The "clean" label that some attach to MSFRs derives from the fact that ultimately they are designed to work in a closed cycle as opposed to the present open cycle strategy adopted for most of presently active reactors. In other words, the spent fuel is reprocessed and fissioned again and again until a stable regime is reached in which as many fissile isotopes are created than are destroyed. It has little to do with the fact that 232Th is used as the breeder fuel stock. A uranium cycle fast breeder will also burn its "waste". And as already mentioned, the idea underlying breeding is to greatly expand the fissionable resource

by converting the abundant fertile isotopes (238U as well as 232Th) into the fissile variety.

This leads to a misconception about the quantities of nuclear waste generated by an MSFR. An MSFR burning 232Th fuel will not produce significantly smaller amounts of "waste" than a fast reactor burning 238U. It is just that as already detailed, recycling the breeder isotopes eventually removes them from the environment and stabilises the inventory within the reactor.

A further misconception is that MSFR technology employing 232Th as the fertile proto- fuel will eliminate risks of nuclear proliferation. While it is true that the 232Th cycle does not produce plutonium that may relatively easily be enriched to weapons grade 239Pu, it does produce 233U instead which may also be weaponised. Anyhow a 232Th MSFR started today will require either 235U or 239Pu to initiate the fission reaction. Any country with the appropriate enrichment facilities could divert the use of these isotopes and convert them to weapons grade material if they so wish. Recent history has also shown that one does not really need a reactor to manufacture a bomb. It is enough to have efficient centrifuges.

In conclusion, the technical challenges of MSFR technology need to be considered. The molten fluorine based salts that are envisaged need to work at temperatures in the region 500 to 800˚C and containment vessels and pumps need to be designed which resist erosion, corrosion and the neutron flux from this high temperature salt. An MSFR requires a fuel reprocessing plant and for the Th cycle no such plant has thus far been designed built, tested and approved by safety authorities. Finally, there are well-understood safety protocols for GII and GIII reactors. The radical new approach offered by MSFR technology means that a whole new set of safe design principles needs to be developed.

At the end of the 1960s The Oak Ridge National Laboratory built and ran an experiment MSR-E designed to pave the way for the MSFR technology. The experiment ran for 4 years. Apart from that realisation, MSFR with a thorium-based fuel is a concept yet to leave the drawing board. It is worth pursuing, but the claimed virtues of near inexhaustible resource, enhanced safety, less waste and elimination of weapons proliferation still need to be demonstrated.

Introduction

There are people who believe that, within this century and probably even before 2050, nuclear energy should become a major component in the energy production system, if not for the entire world at least for a large group of countries. They point to some valuable features of nuclear energy (centralized production of electricity and/or heat, reasonably low cost of final energy, a production that can easily be adjusted to society needs, low CO_2 emissions, small footprint, etc.). They are also well aware of some of its disadvantages (global bad image in the public inducing significant unpredictable political interventions, limited availability of the natural resource, radiotoxicity of the waste, plant accidents with a related risk of releasing radioactivity, security against terrorist attacks, heavy capital investment only reimbursed over a long period, etc.). They just think that given the energy and climatic problems the world is facing now or is going to face in a not too distant future, the advantages more than balance the liabilities.

However, not all these people have the same nuclear energy on their mind.

For some, the basis of a sensible nuclear program for this century must rely first on the extensive experience accumulated on thermal-fission reactors for which the terms Generation II or Generation III (shortened in GII and GIII) have been coined and second on the already significant experience gained on fast-fission reactors. "Improvement and Optimisation" is their motto while Uranium (U) is their fuel. I belong to this group to which the adjective "conservative" can certainly be attached.

GII and GIII water-cooled and water-moderated reactors are the workhorses of the present nuclear-electricity

production. If not stopped for political reasons, they will be performing their job for many more decades. On the other hand, the "fast" reactors cooled with liquid sodium have been tested successfully in many countries and together have already accumulated several hundred years of operation. They have reached a prototype status and even the pre-industrial stage. The main world safety authorities have already a thorough knowledge of the related safety questions. These reactors have also demonstrated their potential on issues such as electricity production, breeding of the fuel (a key to solve a future uranium resource shortage) and waste transmutation.

However, no western world safety authority – and therefore no utility – would consider today that their safety is such that they can be deployed at the industrial level. To simplify, one can say that they have not yet demonstrated the safety level achieved by GIII reactors which is now becoming the standard. Moreover, given the present very low price of natural uranium, they are not economically competitive.

For this reason, in the middle of the first decade of this century, a forum, the "Generation IV International Forum" (GIF), was launched associating the major nuclear industrial nations of the world (with the notable exception of India – a country named "Europe" allows also some nations, such as Germany, to participate in the activities of GIF without having to state explicitly that they are a GIF member). These nations gave themselves the task of defining the next generation of nuclear fission reactors (GIV).

According to GIF, the goals assigned to GIV reactors are the following: 1) Durability which involves a better usage of the natural resource and a minimisation of waste radiotoxicity 2) Economic performance 3) Safety and availability 4) Resistance to nuclear proliferation.

GIF identified six main lines of work suitable for an international cooperation: 1) liquid Sodium Fast Reactor (SFR); 2) Helium cooled Fast Reactor (HeFR); 3) liquid Lead Fast Reactor (LFR); 4) Super Critical water Fast Reactor (SCFR); 5) Molten Salt Fast Reactors (MSFR); 6) Very high temperature thermal reactor (VHTR). Except for MSFR all systems under study envisage uranium as their fuel. The MSFR will use thorium (Th) as a major component of its fuel. Option N°6, VHTR, being a thermal reactor precludes breeding from the start and thus very long term durability as far as the uranium resource is concerned. The rationale for keeping it within GIF is that working at high temperature and thus high Carnot efficiency, such systems will considerably extend the availability of the U resource. It should be added that other thermal-reactor options using uranium fuel and either supercritical water or molten salt as coolants are also being considered on the side-lines of GIF.

As a matter of fact, the selection of the GIV reactor options reflects as much the evaluation of their intrinsic interest as the willingness of at least a fraction of the international expert community to work on them (many more nuclear options do exist). Not too surprisingly, presently, the main effort is focused on the SFR (liquid Sodium Fast Reactor) which appears closer to reach the GIF stated goals than any of its competitors. Of course, since the Fukushima accident, which has set nuclear energy research and industry on the defensive and modified its priorities, activities have considerably slowed down within the GIF.

All the GIF-retained options other than SFR can certainly be called "innovative" (as opposed to my definition of "conservative"). Among them, the one using molten salt and thorium based fuel (MSFR) has gained many supporters in the public, if not necessarily within the community of experts. I believe that some of the enthusiasm for thorium and MSFR is misplaced in view of the present scientific and technical situation – keeping in mind that I am concerned with energy production for the 21st century, not for the centuries beyond. Because the text that follows tries to show that, for me, some supporters wave too simplistic arguments, I would like to make it clear that I think that, MSFR and Thorium fuel is definitely worth both consideration and intensive research.

First, the fact that the MSFR was retained by the international community of experts working within the programme of GIF is a sure sign of its viability. Second, thorium and molten salts have an old history dating almost from the end of the second world-war and some significant advances have been made. The main

achievement was realised by the Oakridge National Laboratory (ORNL) with the successful MSR-E experiment (which used uranium fuel). Then, over the seventies, ORNL teams worked on the design of the MSBR, a 1GWe system which intended to have Thorium within its fuel (the B stands for "breeder" and the "e" is here to indicate the expected electric power which is of course lower than the thermal power). However, at the beginning of the eighties, in the US-breeder competition, the MSBR system lost to the SFR. The decision was a complex one but the smaller breeding capacity of the MSBR had a part in it. At that time, a review conducted by the French utility EDF and the French nuclear atomic commission (CEA) analysed the MSBR project and concluded that nothing could be identified which would eliminate the option either from the point of view of chemical or material science, or of nuclear and thermal-hydraulics technology. There were still many difficult open questions but no obvious showstoppers.

Therefore, keeping molten salts and thorium as an open research option for the future makes sense today as it did earlier. There are many good reasons to investigate it that I am not going to enumerate. Here, after this long introduction, I will make a survey of what I believe are the false justifications (myths) and the many unsolved problems which make it doubtful that MSFR and Thorium can play a significant role in the global power generation of this century.

Some myths concerning thorium and molten salt reactors

Myth 1: specificity of an "inexhaustible" Th natural resource

Only elements of the actinide region of the Mendeleyev periodic table can be made to fission following the capture of a neutron. As they fission, in turn, they emit neutrons allowing a chain reaction to be established under appropriate physical and technical conditions. Of all the actinides which existed when the Earth was formed, about 4.65 billion years ago, only two have survived in sizeable quantities: thorium and uranium. Thorium only exists today as the isotope 232 (232Th shortened as Th2). From its very large radioactive half life, one can infer that almost all the Th2 which existed at the birth of the Earth is still around us. Natural uranium contains two isotopes 238U (U8) and 235U (U5). While half of the original U8 is still there, only 1/100th of the original U5 has survived, the rest has disappeared via natural radioactive decay processes ending at a stable Pb isotope. This is reflected in the present natural uranium composition: 99.3 % U8 and 0.7 % U5. When nuclear engineers or opponents of nuclear energy talk about a limited uranium resource, what they have in mind is U5, not natural uranium (or U8) which is a hundred times more abundant.

For nuclear engineers, Th2 and U8 which have an even number of neutrons belong to the same category: the "fertile" isotopes while U5 is said to be "fissile". To be started, any reactor needs a fissile element. As a matter of fact, for the vast majority of reactors in activity the concentration of U5 within natural U is not sufficient, hence the need for enrichment typically up to 3.7 %. Note that a few billion years ago, the ratio U5/U8 was larger than today, so that natural reactors could operate spontaneously as happened for instance at the Oklo site in Gabon. In today's reactors, the presence of fertile U8 within the fuel pins is also important for energy production. Indeed, a small fraction of this U8 swallows one neutron and is transmuted (in two steps) into the isotope 239 of plutonium (Pu9) which because it is also fissile can contribute to the chain reaction which ultimately produces energy. In other words some small amount of "breeding" is already occurring in thermal reactors.

Th2 is the nuclear equivalent of U8 (233U or U3 plays for Th2 the role that Pu9 plays for U8). Because there is no fissile isotope present within natural thorium, in order to start a thorium-fuelled reactor one must add first some fissile material. Since it can't be U3 which does not exist on Earth it could be U5 (from the same natural uranium which provides the fuel of today reactors) or Pu9 (coming for instance from the burnt fuel of standard reactors) or other fissile materials to be found for instance in the radioactive waste of standard reactors. In other words Th2, like U8, only acquires the status of an energy resource when breeding is envisaged. The only available natural resource to initiate breeding is U5.

In some presentations to the public, “breeding” appears to perform a sort of miracle: “producing more fuel than was present within the input”. It should rather be described as “producing more fissile material than was present within the input”. It is the energy potential of a fertile isotope (Th2 or U8), a kind of “fission-proto-fuel”, which is then exploited following an appropriate transmutation into either U3 or Pu9.

The U8 resource appears almost as inexhaustible as the Th2 resource (a factor 2, or 4 less does not really modify the issue, given the geology-related uncertainties). In addition, over the years, the U8 resource has acquired a significant advantage: it does not have to be mined anymore. It is already on the shelves in large quantities at least in countries which have a nuclear enrichment industry and its commercial value is zero, if not negative. As a matter of fact U8 is sometimes considered as a sort of “waste” extracted from natural uranium to obtain the U5-enriched fuel for standard reactors. Indeed for each U8 nucleus still kept in the fuel of a GII or GIII reactor, about four U8 nuclei have been removed from natural uranium and stored away. As an illustration, presently, the stock of U8 stored in France corresponds to about one thousand year of this country’s present energy production in fast reactors. Note that the former French rare-earth chemical industry has also left on the shelf a quantity of Th2 amounting to about 100 years of nuclear energy production in a MSFR. The “nuclear-fertile” resource, Th2 as well as U8, is plentiful.

In fact if there is to be a resource shortage preventing a future GIV breeder-reactor generation to replace the reactors of GII and GIII generations, it will certainly not be one of fertile isotopes (Th2 or U8) but rather a shortage of fissile elements and more specifically one of Pu9. It also appears that only those countries which have exploited PWR or BWR reactors for a long time will have produced enough Pu9 within the burnt fuel of their GII and GIII reactors to be in position to start reactors of the GIV generation at a significant level.

Myth2: the waste of Th fuelled reactor waste is less dangerous.

There are few points to keep in mind when one discusses nuclear waste:

1) How to define nuclear waste is not simple when breeding and recycling is involved (always the case with Th). Indeed, the only unambiguous waste produced by a nuclear reactor consists of the fission products. All elements, Th, U, Pu or other isotopes generally classified as “minor actinides” present in the burnt-fuel when it is discharged from the reactor vessel still have potentially an energetic value if they can be made to fission. It is thus a matter of technical, safety and political decisions to consider whether they belong in the waste or whether they are a fuel to be recycled in the next stage of the operation of the nuclear system.

2) To illustrate this last sentence we can, for instance, consider how most countries today define the nuclear waste resulting from the operation of their GII or GIII reactors. These countries have opted for the “open-cycle” or “once-through” strategy: there is no reprocessing; the fuel pins and their casing discharged from the reactor are considered to be a waste and destined to an ultimate repository. A typical composition of the burnt fuel of a GII reactor is: fission products 5 %, fissile isotopes 1.5 %, and fertile isotopes 93.5 %. Thus 95 % of what is today defined as a nuclear waste has, “fissionwise”, an energetic potential. One can also note that the ratio of the mass fissile output (U5 plus Pu9) over that of the mass fissile input (only U5) is close to 40 %. The choice has thus been made to send to the waste a significant amount of fissile isotopes which on the other hand are known to be necessary to start any reactor and also cost energy to produce via enrichment of natural uranium. In a sense, the corresponding waste underground repository can also be caricatured as a “man-made plutonium mine”.

3) In a comparison of the thorium-cycle versus the uranium-cycle, the radiotoxicity of the fission fragment waste which dominates the total radiotoxicity for the first centuries can be set aside. It is roughly the same for both cycles. Thus any difference between the two cycles will only be visible after a few centuries have passed, say 500 years.

4) How to define the danger associated with a waste which has been sent to a permanent underground storage is also a matter of discussion. One can consider the total radiotoxicity of what is being stored. This is the

radiotoxicity that, for instance, would be encountered by somebody, not too expert in questions of geology, searching for oil at the wrong place, who drills right into the underground nuclear waste repository. After a few centuries, this radiotoxicity is dominated by the actinide content of the waste. Since it is not the same for the two cycles, we shall return to that point later. On the other hand one may consider the small radiotoxicity – often smaller than natural radiotoxicity – which after many millenniums escapes to the surface through the geological barrier (the repository is typically few hundred meters below the Earth surface). Since the mobility of actinides in the ground is very small, the very-long-term escaping radiotoxicity will mostly correspond to some long lived isotopes of very mobile fission-fragment elements (for instance Zr or I). Here again there won't be much difference between the thorium and uranium cycle. For this reason, from then on, I will only discuss the radiotoxicity associated with the actinide elements, namely that which would be met by somebody who breaks into an underground nuclear waste storage.

5) Full recycling means that all the actinides coming out at one stage are reinserted into the fuel of the next stage. Thus the large radiotoxicity within the burnt fuel does not vanish; it is just made to move around circularly from the reactors to the separation cells to the fuel production factories and back to the reactors within the diverse nuclear-industry components. On the other hand, if the recycling process (whether for the U-cycle or Th-cycle) is perfect there won't be any radiotoxic waste stream other than that of the fission products.

6) After each pass through the reactor, recycling implies that a chemical separation is performed on the burnt fuel. Because no chemical process is perfect, the stream of actinides effectively going out to the waste and determining its middle-to-long term radiotoxicity (short term is governed by fission fragments) depends on the efficiency of the chemical separation techniques. For the uranium-cycle, efficiencies above 99.9 % have been demonstrated. The corresponding figures for the thorium cycle are not known.

7) Full recycling is also not currently envisaged for the U-Pu SFR technology. It is generally considered that only plutonium will be recycled while minor actinides such as americium (Am) and most certainly curium (Cm) will be sent to the waste. This strategy along with the efficiency of the chemical separation determines the time evolution of the radiotoxicity of the waste stream of SFR reactors. It is several orders of magnitude below that of the burnt-fuel stream of today's reactors. I will come to that point later because I believe it gives a misleading image of the benefit of recycling as concerns waste reduction (see 10 below).

8) Assuming that the not-yet-known chemical separation efficiencies for the thorium cycle are the same as those already demonstrated for the uranium cycle, it can be shown that the radiotoxicity of the actinide waste stream of a MSFR reactor when it is working in its "asymptotic" regime, that is a system relying exclusively on the Th2-U3 cycle, is lower by at least an order of magnitude than that of a SFR reactor working exclusively within the U8-Pu9 cycle and sending americium and curium to the waste. However, this good point should also be taken with a grain of salt.

9) Indeed, while following a long period of production with GII and GIII reactors, one can envision extracting from their stored burnt fuel all the Pu9 necessary to start immediately an "asymptotic" SFR reactor. This is not possible for a MSFR. The U3 resource does not exist. No "asymptotic" MSFR reactor can be started today. The first MSFR reactors will have to use either U5 or Pu9 – or some other isotopes of higher elements – to be started. Via transmutation they will therefore produce the same undesirable elements (Am and Cu) and thus the same kind of waste as SFRs. It will take almost a century before a MSFR breeds enough U3 to avoid tapping into the U5 and Pu9 resource and thus become "asymptotic".

10) Finally, many presentations on the actinide waste generated by fast reactors implicitly assume that mankind will rely on them forever. In other words, these presentations only consider the radiotoxicity of the waste stream which leaves the chemical reprocessing factories while electricity is still being produced by reactors. In such a case, the radiotoxic gain over the present situation (the nuclear burnt fuel is disposed without reprocessing into the long term repository as it leaves the reactor) is indeed large (several orders of magnitude). On the other

hand, if one day, fusion becomes an economically viable option or if there is a major breakthrough on the energy storage question rescuing renewable intermittent energies, humans may decide to stop producing electricity via nuclear fission. At that point, all the radiotoxic isotopes present within the system – reactors, chemical and fuel fabrication factories – become a waste that must be added to the stream of the earlier electricity production period. If one assumes for instance that it will take 200 years of operation of breeder reactors before one reaches this "end of the game" situation, one finds that it is the addition of this "in-cycle" radiotoxicity which mostly determines the radiotoxic evolution of the waste during the following millenniums. Then, the radiotoxicity of the total MSFR waste will only be slightly lower than that of a SFR. There will also still be a small gain over the present strategy in which only GII and GIII reactors are used and their burnt-fuel is disposed without reprocessing. Typically we are talking here of decreases by one order of magnitude if everything in the complicated recycling scheme works optimally.

11) It is doubtful that such a small gain can suppress the opposition to the usage of nuclear energy of somebody whose main concern is the very-long-term radiotoxicity of the waste. It will also not enable societies to find a stable and long-term safe waste management solution if only for containing the radiotoxicity of the fission fragments. One can say that the nuclear waste issue – and the need for underground repositories – is not going to be removed by SFRs or by MSFRs. At most, it will be alleviated, which certainly is a plus. In addition, one may note that at least, it will be up to the countries which have benefitted from the associated electricity production to solve their own nuclear waste problem. This appears more ethically defendable than the fossil-fuel-powered electricity production in which the CO_2 emitted by the beneficiaries of the electricity is graciously "offered" to the rest of the world.

12) To conclude this section on nuclear waste, one should not forget that volume, chemical properties and short-term heat production also play an important role when it comes to designing a repository.

Myth3 The thorium cycle will eliminate the nuclear proliferation issue

A bomb needs fissile material. Neither U8 nor Th2 are good materials for making bombs. It is certainly the case that no bomb has been produced using U3 since there is no U3 available. Whether that will still be the case when U3 becomes plentiful and is routinely handled in reprocessing units is certainly not clear to me. Discussions about larger or smaller critical masses are essentially irrelevant here. In addition, as was discussed above, for a very long time a MSFR will be using U5 or Pu9, which means that the possibility of diverting these isotopes for a dangerous purpose will remain.

I believe one should not count on the physics (Th vs U) or the technology (MSFR vs SFR) to stop humans from doing foolish things. Non-proliferation has certainly technical aspects which require nuclear expertise to be present and heard in international discussions but, for me, proliferation is mostly a political issue.

Problems still to be solved problems for a molten salt thorium fuelled reactor

Here, I list some of the problems still faced by the MSFR technology.

Problem 1: Design and Material science.

The associated questions concern the salt, the vessel and the heat exchanger.

- In a MSFR, the salt acts both as a heat carrier and nuclear fuel carrier. It also has some moderating (i.e. slowing down neutrons) effect which precludes for instance its usage for breeding with the uranium cycle. The salt must stay stable within a wide range of rather high temperatures (typically from 500°C to 800°C). A family of fluorine based salts is presently being considered. These salts should resist the high neutron fluxes

within the vessels (their chemical structure must remain intact and their elements should not suffer transmutation). They should dissolve the actinides of the fuel at the required concentrations and keep them dissolved all along the circuits of the reactor (vessel, heat exchanger and connecting pipes) in variable temperature and fluid velocity conditions so as not to create unwanted deposits of nuclear material.
- The material for the vessel and the heat exchanger (Ni-based alloys are being considered) should resist both mechanical and chemical corrosion by the salts on the inside surface and oxygen corrosion at high temperature on the external surface.
- Salt is not as good a heat carrier as liquid metals. The design of heat exchangers capable of rapidly (typically less than 10s) extracting heat while resisting the mechanical corrosion by a fast moving salt is still a challenge.
- The demonstration that valves and pumps capable of working reliably for many years with such salts under the planned temperature and fluid velocity conditions is not yet done.
- The most harmful fission fragments that can poison the reactor must be eliminated on-line via the helium bubbling technique. This has not yet been demonstrated in situations close to those that will exist in a future MSFR. The material for the vessel and the heat exchanger (Ni-based alloys are being considered) should resist both mechanical and chemical corrosion by the salts on the inside surface and oxygen corrosion at high temperature on the external surface.

Each of these points should reach a status such as to receive an agreement from the safety authorities.

Problem 2: Chemistry of the combined uranium and thorium cycles

A thorium-fuelled molten-salt reactor has to be coupled to a highly efficient chemical unit to reprocess the fuel and the salt. The element-separation efficiencies should be as high as those which have already been reached at units designed for reprocessing within the uranium cycle. Presently, the scientific knowledge and technological knowhow needed to build a working prototype of a Th-cycle reprocessing unit with such performances does not exist.

Two reasons for this situation can be advanced. First the amount of man-year work on the thorium cycle is minuscule compared to that already spent for the uranium cycle. Second, the chemistry is different. First, some oxidation-potential properties of Th are not as favourable as those of U. Second, since U3 is not available and because the U5 resource is limited, one generally presents the first MSFRs as “nuclear waste burners” which will use (and destroy) the plutonium of the waste of GII and GIII reactors (some even mention higher actinides) as their initiating fissile isotope. This makes the chemistry more complicated since it must be able to handle simultaneously elements belonging to the Th and U cycles.

Problem 3: Design of a global strategy for safety

The general philosophy underlying the safety scheme of today’s reactors was elaborated over many years. It relies on the so-called “in depth defence” which requires the existence within the reactor of three barriers which have to be breached before some radiotoxic material is released to the outside world. Typically, in GII and GIII reactors, they correspond in succession to the metallic envelope of the fuel pins, the boundary of the primary circuit (vessel, primary heat exchanger) and finally the reactor building.

Even when reprocessing is performed (the situation in France) so that other sets of safety regulations have to be defined (approved and enforced) for the chemical separation unit, and the fuel-pin fabrication factory, this does not affect the general safety programme for the reactor itself. Indeed, there is still a clear physical separation between these three components of the global nuclear system. This means that the safety scheme as it exists today for GII and GIII reactors and is understood jointly by the designers of reactors, the electric utilities operators and the members of safety authorities can also be applied to SFRs. These three groups of experts may certainly argue over the implementation of the various safety items and their performance levels but at least

they agree on the goals and they share a common safety language.

Nothing of the sort exists for the MSFR in which at least one barrier is *a priori* missing (the metallic envelope of the fuel) and which combines on the same site the reactor and the chemical reprocessing unit whose activities directly affect each other. It is my guess that no significant work has been done to define a safety scheme for molten salt reactors since the MSBR was abandoned in the first half of the eighties. What competence on this subject existed at that time is probably either obsolete today in view of the steady reinforcement of nuclear safety or simply lost. This competence has to be rebuilt, something which today appears rather problematic.

Conclusion

In my opinion, Thorium and molten salt reactors technologies belong definitely in the domain of research. They certainly have a potential which deserves scientific and technical investigation. On the other hand, given the present situation of the nuclear energy research institutes of the western world and the general decline in their enrolment of high-quality well-trained young engineers, it is improbable that much work will be invested into such an innovative, far-reaching but also risky option. Therefore if nuclear energy is to provide a significant contribution to the world energy mix of the 21st century, it is doubtful that thorium and molten salt technologies will be ready in time to take part.

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[1] The adjective « thermal » refers here to the average kinetic energy of neutrons as they impact the heavy nuclei in the nuclear fuel. They are close to 1/40 eV (or 273°K or 0°C). On the contrary, in a “fast” reactor, the fission-neutrons are not slowed down by water so that their kinetic energy remains in an MeV range that is a factor of 107 above that in a thermal reactor. Without getting into nuclear physics details, it suffices to say here that only fast neutrons allow efficient breeding at least for the uranium cycle. The situation is different for the thorium cycle which can breed over a wide range of neutron kinetic energies, albeit less efficiently that in a fast U-Pu reactor.

Short Bio for Hubert Flocard

hubert.flocard at gmail.com

A former student of the Ecole Normale Supérieure (St Cloud) Hubert Flocard is a retired director of research at the French basic science institute CNRS. He worked mostly in the theory of Fermi liquids with a special emphasis on nuclear physics. He has taught at the French Ecole Polytechnique and at the Paris University at Orsay. He was for several years a visiting fellow of the Lawrence Berkeley Laboratory and he spent a year as visiting professor at the theory department of MIT (Cambridge). He has worked as an editor for the journals Physical Review C and Review of Modern Physics (APS, USA) and Reports on Progress in Physics (IoP, UK). He has chaired the nuclear physics scientific committee INTC at CERN (Switzerland). When the French parliament asked CNRS to get involved in research on civilian nuclear energy, he was charged to set up and to manage the corresponding CNRS interdisciplinary programme. He still acts as a referee to evaluate research projects submitted to Euratom.

40 Responses to *Molten Salt Fast Reactor Technology – An Overview*

Roger Andrews *says:*
July 20, 2015 at 1:49 am

Euan: Thanks to Hubert and yourself for this detailed and highly instructive article. Even an aged mining consultant can understand it.

Hubert says:

…. "fast" reactors cooled with liquid sodium have been tested successfully in many countries and together have already accumulated several hundred years of operation ….. However, no western world safety authority – and therefore no utility – would consider today that their safety is such that they can be deployed at the industrial level …. Moreover, given the present very low price of natural uranium, they are not economically competitive.

Which raises the question, when *might* fast reactors be ready to be deployed at the industrial level? This is an important consideration because the world probably doesn't have enough uranium to "go nuclear" without them:

http://euanmearns.com/do-we-have-enough-uranium-to-go-nuclear/

Reply

Flocard *says:*
July 20, 2015 at 9:17 am

I suspect that in the coming years the main advances on fast reactor technology will come from Russia, India and China.
Not because, these countries are more knowledgeable (at least still today) about this technology than engineers of the OECD countries but because their governments or parliaments are not setting up (implicit or explicit) barriers to the necessary R&D in nuclear energy, because they recruit enough young nuclear engineers (for Russia I am not too sure) to move forward and also because these countries allocate the appropriate fundings.
In a OECD country , the motivation to go forward is provided by the utilities which in turn attempt to understand where politics want them to go. Presently these utilities are not in position to devise a long-term strategy. They can only react. Presently, for them it is more advantageous to built and exploit wind turbines and solar parks. Whatever research they might have on future nuclear options is not renewed as the old engineers are retiring.
Over two years,, in France, the OVERCOST of renewable intermittent energies (France has only 8GW of wind and 5GW of solar) would allow the building of a fast reactor new generation GIV prototype.such as the ASTRID project (the I stands for industrial) project of the atomic energy commission (CEA). I am ready to bet that no significant funding will be allocated to ASTRID in what remains of my lifetime.

Reply

Euan Mearns *says:*
July 20, 2015 at 1:08 pm

Hubert, I'm sure you are familiar with the Dounreay fast reactor experiment that I believe produced power, about 250WMe, for a number of years. I was told by an engineer who worked there that the decision to close it down was the result of political pressure from the Green lobby.

Can you tell us a little bit about the technology used at Dounreay and what the safety concerns would be if there are any. Your article implies that fast U cycle reactors are not currently safe or at the commercialisation stage.

Reply

Flocard *says:*
July 20, 2015 at 6:49 pm

The last reactor of Dournway was a SFR reactor of the pool type just as Phenix in France (the other design is the loop type prefered by the japanese).
Dournway suffered the same fate as all fast reactors in the western world, at about the same time and for the same reasons.

I did'nt follow in detail the questions raised recently by safety authorities for SFR's.

For instance one generic problem is the void problem. If a water cooled reactor looses its water, the chain reaction stops. It is a kind of intrinsic safety. feature
With the old designs when a sodium cooled reactor lost its sodium, the chain reaction was amplified. Of course it could be
stopped by means of black control bars. But the safety here was not intrinsic but dynamic and extrinsic (human or system reaction and action was required).The question would also appear if bubble appeared in the cooling Na. Safety authorities nowodays tend to prefer intrinsic safety.
(an exemple of this kind of non intrinsic safety scheme was given by the Tchernobyl reactor. When finally the decision was made to stop the chain reaction by lowering control bars, their channel was so damaged that they could not be lowered).

There is also the generic safety issue with the heat exchangers where on one side there is a flow of Na and on the other side a flow of water (liquid or vapor).

On the other hand an in-depth safety analysis is only performed on a specific design submited to the safety authority. There are of course several steps back and forth with questions asked answers provided, improvements asked and so on..

Reply

donb *says:*
July 20, 2015 at 2:20 am

This is the broadest and most lucid explanation of the advantages and disadvantages of the 235U and 232Th+233U reactor concepts I have read, by far. It should make those advocating abandonment of present 235U reactors and moving to 232Th reactors think hard on that decision.

Reply

Javier *says:*
July 20, 2015 at 4:16 am

In these days of internet it is very easy to read arguments that Thorium based Molten Salt Reactors will save the day. Over the years I have become very skeptical about promises from revolutionary technologies as most of such announcements never deliver on their promises. I am also skeptical about fusion and Thorium based Molten Salt Reactors as I don't see significant progress over the years and they are always a few decades away.

This article is very enlightening and now I understand better the difficulties of the issues involved. Now my skepticism has a more solid base. I don't think I will see Fusion Reactors or Thorium based Molten Salt Reactors in my lifetime. Let's just hope that improvements to Uranium reactors are enough, although that won't help many countries that have decided to stay away from nuclear.

For what I read, the South Korean strategy of building several units of the same nuclear plant is also sensible at cost reducing compared to the Western policy of making every nuclear plant unique and thus more expensive.

Reply

roberto *says:*
July 20, 2015 at 8:12 pm

"For what I read, the South Korean strategy of building several units of the same nuclear plant is also sensible at cost reducing compared to the Western policy of making every nuclear plant unique and thus more expensive."

Hi: I thought that France was a western country!… just kidding, of course… as Dr. Flocard (which I thank for the very thorough article, difficult to find something this clear on this subject) could confirm, France has basically ONE type of reactor, PWR, coming in 3 different sizes, from 920 to a bit more than 1400 MWe (if I remember correctly).
I think you were thinking of the USA, or UK, which have developed a larger variety of reactors.

Incidentally, it makes me laugh out loud when I hear any green anti-nuclear guy claim that "no technology has even grown faster than PV and wind!", when just looking at this

https://fr.wikipedia.org/wiki/Liste_des_r%C3%A9acteurs_nucl%C3%A9aires_en_France#/media/File:Chrono-parc-nucleaire-francais.svg

one can see that France alone has put on line more than 51 GWe in a matter of 14 years… the equivalent of 350 GWp (in Germany)… and this without counting for the intermittent vs dispatchable nature of PV vs nuclear (which at this level of penetration would mean an additional factor of 2x at least in favor of nuclear):

1980-1993: 28x 900 MWe + 20x 1300 MWe

Cheers,

R.

Reply

Graeme No.3 *says:*
July 20, 2015 at 7:17 am

A fascinating article, and the expertise is very evident.

Reply

Leo Smith *says:*
July 20, 2015 at 9:21 am

"A further misconception is that MSFR technology employing 232Th as the fertile proto- fuel will eliminate risks of nuclear proliferation. While it is true that the 232Th cycle does not produce plutonium that may relatively easily be enriched to weapons grade 239Pu, it does produce 233U instead which may also be weaponised. Anyhow a 232Th MSFR started today will require either 235U or 239Pu to initiate the fission reaction. Any country with the appropriate enrichment facilities could divert the use of these isotopes and convert them to weapons grade material if they so wish. Recent history has also shown that one does not really need a reactor to manufacture a bomb. It is enough to have efficient centrifuges."

My understanding is that the U233 that is the fissile component of a thorium reactor is highly radioactive all by itself. Unlike the relatively stable U235 or plutonium employed in 'normal' weapons, it represents an extreme hazard to bomb constructors and to any electronics associated with the weapons.

The pro thorium argument seems to hark back to this analysis:

"The uranium-233 produced from thorium-232 is necessarily accompanied by uranium-232,… [which] has a relatively short half-life of 73.6 years, burning itself out by producing decay products that include strong emitters of high-energy gamma radiation. The gamma emissions are easily detectable and highly destructive to ordnance components, circuitry and especially personnel. Uranium-232 is chemically identical to and essentially inseparable from uranium-233." Hargraves, American Scientist Vol 98, July 2010

"Only a determined, well-funded effort on the scale of a national program could overcome the obstacles to illicit use of uranium-232/233 produced in a LFTR reactor. Such an effort would certainly find that it was less problematic to pursue the enrichment of natural uranium or the generation of plutonium. In a world where widespread adoption of LFTR technology undermines the entire, hugely expensive enterprise of uranium enrichment — the necessary first step on the way to plutonium production — bad actors could find their choices narrowing down to unusable uranium and unobtainable plutonium." Hargraves, American Scientist Vol 98, July 2010

Additionally, its not *recent* history that shows us you don't need a reactor to make weapons grade uranium: "Three methods were employed for uranium enrichment: electromagnetic, gaseous and thermal. Most of this work was performed at Oak Ridge, Tennessee."

https://en.wikipedia.org/wiki/Manhattan_Project

Without wishing to detract from an excellent demythologisation process of thorium reactors, I do want to prevent further myths arising! 🙂

Thorium won't prevent nuclear proliferation, but it makes it harder – much harder.

Reply

Flocard *says:*
July 20, 2015 at 10:47 am

You have noted that during my career I have not been involved in anything close to military usage and certainly never looked for it. In this text I gave here my opinion based on what I learned.

On the other hand in few occasions as part of my duty I had to attend security related seminars. where I suppose that the experts talking from various countries (mostly US as I remember) were knowledgeable. I have not noticed that for these people the Thorium cycle decreased the danger. The question was specifically asked during the seminars.

Can you quote somebody from the military establishment (retired of course) that would explain why he is an advocate of Th for security reasons ?

You are right about this high radioactivity present in the Th cycle (especially the often put-forward 3MeV gamma-ray). As a matter of fact, I believe that it is a strange mental distortion to consider it as an advantage. For me it is much more another liability. Indeed it makes the Th cycle more dangerous (much more shielding is necessary) for all the operators of the civilian programme. People are often thinking too much of "future generations" sometimes over ridiculously long periods of time (compared for instance to the time interval between the Neanderthal man and today) and not enough of "today's generation" that is the workers of nuclear industry. The same kind of shielding that will be necessary to protect civilians workers can be used to protect military workers.

As a matter of fact, nuclear security has two facets (at least, since as I said I am no expert)
facet one : A state wants to make a bomb and organizes itself to achieve that goal. It would be stupid to use a reactor to do it, as much simpler means exist to have access to the necessary fissile enriched material. From that point of view even if you are right that the Th reactor in its "asymptotic" form (Th2-U3) makes the process more difficult it alleviates a problem that does not really exist. In addition, as I said the chemical unit of the MSFR will take a very long time (close to a century) to reach this asymptotic regime In the mean time time around the MSFR one will manipulate either U5 or Pu9. I mentioned that I am not the sort of person that tries to think for more than one century ahead. The fact that there is no centralization of the recycling process (each reactor is coupled to a separation unit) makes international surveillance more complex. In my opinion, only international cooperation can protect the world from nuclear arms. I certainly would not count on thorium.

facet two: terrorists who have neither the knowhow to manufacture a bomb that would not explode in their hands, nor the time to do it or because it does not fit their political agenda, nor the means to deliver a bomb, break into a reactor-chemical plant complex and steal some stuff. Their plan is to disperse it in the streets of a major city in order to generate radioactive terror. Then the higher radioactivity of the Th cycle components becomes very important as it will create a more significant danger and make cleaning operations more complex. Of course, the dispersion of chemical separation units close to each reactor makes it easier for terrorists to find a target and for the national authorities to enforce the appropriate security.

I was vonluntarily short on security issues. I certainly do not believe the arguments advanced (I knew them since it is impossible to work on the subject without hearing them) that a dangerous radioactivity generates a "protection". Of course I would be interested to read a text on the subject written by a military expert (moderately in view of what I think is the chance to see many Th-fueled reactors for a long time)..

In the mean time. I keep my opinion. It is a myth to say that the Th cycle improves the security of the world with respect to nuclear arms or nuclear danger.

Reply

Flocard *says:*
July 20, 2015 at 10:59 am

Sorry
I wanted to say
"… easier for terrorists to find a target and MORE DIFFICULT for the national autorities to enforce the appropriate security."

Reply

Leo Smith *says:*

July 21, 2015 at 9:29 am

From a terrorist point of view a bomb comprised of enough dumped smoke alarms would be disruptive enough.

From the point of view of states developing usable weapons, probably they will find a way no matter what.

So although I am not 100% sure I agree with your reasons why, the end result is the partially the same. Nuclear weaponry is independent of the power technology in use.

However I still stand by the main point, that U232/233 is a very nasty material to try and make bombs out of.

https://en.wikipedia.org/wiki/Uranium-233 outlines the main points: the raw material is highly radioactive and needs to be remotely manipulated, and the presence of U232 in any beyond very small trace quantities also stops detonation.

If you want an atomic bomb, you dont start with thorium unless you have to, and thorium itself can't be turned into U232/233 without some U235 or plutonium anyway.

So if you have a thorium breeder you de facto have access to semi-enriched U235 or plutonium.

I think the final point I wanted to make is that in terms of a nuclear weapons program – building an arsenal – thorium reactors are relatively useless. However in terms of building one or two weapons, it makes no difference. You would not make your first bomb out of U233 but out of U235 or plutonium having bred it from U238.

And the ex world nuclear powers are awash with plutonium.

As for 'experts at conferences' – well I have attended enough of those to realise that being an expert in one narrow field is almost a guarantee that the expertise barely overlaps the next field along.

My engineering life is littered with the relics of projects that failed because experts didn't ask the right question (or ignored the answer) before they started developing the solution that didn't in the end work because of a fundamental show stopping detail.

Renewable energy is a case in point.

Reply

Euan Mearns *says:*
July 20, 2015 at 10:47 am

Leo, I think the whole proliferation argument is bogus. As you point out you don't actually need a reactor to get enriched 235U. Any nation intent on developing nuclear weapons simply needs to find a source of U and buy or build some centrifuges. The fact that many nations are accumulating stock piles of 239Pu that is mixed in small quantities with nuclear waste is rather irrelevant. If a country wants to build a bomb it easier to go the 235U route as opposed to scavenging other country's waste for 239Pu.

And lets face it, if a country is intent on building a bomb it would chose the U cycle for power – even though as already noted it is not necessary to build a reactor. The option of choosing Th cycle does not exist, and it sounds it like it won't exist for a 100 years.

Like many Green arguments this one just doesn't stand up to scrutiny. It is in fact difficult to construct a logical argument against it since the primary argument is not based on logic in the first place. Its another Green wild goose chase designed to thwart the deployment of civilian nuclear power.

Reply

Leo Smith *says:*
July 21, 2015 at 9:37 am

I agree. I think that the two points – firstly that U233/232 is a highly unsuitable material to make bombs out of, and the fact that that wont stop anyone who has deep pockets and access to big resources making one,

cancel each other out.

I just wanted to make the point that it IS an entirely unsuitable material.

From a terrorist point of view, half a ton of dismantled smoke alarms and assorted nuclear materials dumped in a plastic bag with a half a pound of HE would create a large area more radioactive than the Fukushima evacuation zone*.

https://en.wikipedia.org/wiki/David_Hahn

*Mind you you only have to take a trip to Dartmoor, for that.

Reply

Rob *says:*
July 20, 2015 at 11:55 am

What about GE Hitachi PRISIM reactors seems like a viable reactor design.
We need to make a decision on the 500 tonnes of plutonium stored in the UK.
Alternatively building a new MOX plant might be a better option.

http://gehitachiprism.com/

Reply

Flocard *says:*
July 20, 2015 at 12:14 pm

It seems to me from reading the text that PRISM is another sodium cooled fast reactor. Japan has a mixed experience with such SFR reactors (Monju).
MOX used in GII and GIII does not remove completely the Plutonium issue. It makes certainly a better usage of Pu9 (and thus of U5-U8). In this way it amounts to extending the U5 resource. On the other hand the isotopic mix of plutonium at the output is degraded as compared to initial plutonium input (plutonium gets enriched in 240Pu). Thus after one pass (may be two) in a GII reactor the plutonium is not good enough to enter the fuel anymore. Destruction of plutonium (odd and even isotopes alike) requires a fast reactor.

Reply

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roberthargraves *says:*
July 20, 2015 at 12:43 pm

ThorCon is an example of the practical engineering that is actually going on right now to produce molten salt reactors that use thorium as fuel. ThorCon is a thermal hybrid thorium/uranium molten salt reactor designed for mass production by shipyard-like factories. It derives energy from Th232/U235/U238 in the ratio 25/50/25.

The key strategies for ThorCon are “no new technology” and “cheaper than coal”. If we are to solve the global climate/energy/poverty issues we need to produce affordable, nonpolluting electricity for the developing world, now, at a scale of 100 GW of added capacity each year. The US EIA projects 2300 GW of additional power plants by 2040; 1400 GW of coal-fired power plants are already on the drawing boards. ThorCon expects to capture this market, with energy cheaper than coal. To meet the demand soon enough, we can not wait for new technology to be developed. ThorCon is a capitalist solution to problem politicians can not solve.

The MSRE work at ORNL was followed by the design of a denatured MSR. That work has been updated and adapted for mass production by Jack Devanney and the team at Martingale. The plant is built of prefabricated blocks weighing up to 500 tons, shipped by barge to an excavated site, then welded together. Each module of ThorCon has duplexed 250 MWe sealed reactor Cans. After 4 years one Can is cooled for 4 more years and replaced. With funding the second of two prototypes can be delivering power from fission in 5 years, and commercial deliveries of operating plants can begin in 8 years.

Skeptical? Visit thorconpower.com to understand the ideas. An extensive, detailed technical description is available in the Executive Summary in the Documents section of that website.

Reply

Flocard *says:*
July 20, 2015 at 6:28 pm

My text contains the sentence :
" It should be added that other thermal-reactor options using uranium fuel and either supercritical water or molten salt as coolants are also being considered on the side-lines of GIF"

The only point is that these are thermal reactors. They do not achieve breeding. They depend on our limited U5 resource to work.

This kind of technology (using Th in a thermal reactor) has been studied for many years by the indians because they were shut out of the uranium market and wanted to use the thorium because of its specific properties. These essentially allow to extend the use of the U5 resource because the small breeding that I mention already exists in GII-GIII reactors is slightly improved with a Th2 base as compared to U8 base.

In fact using these properties of s Th2 support to extend the U5 resource can be found in many scenarios which do not require new thermal reactors. Burning a fuel with some Th2 contained in it has already been done in a US water moderated reactor.

What I am interested is not so much by molten salt reactor designs (there are plenty and people have their prefered one) it is the chemical processing unit and the waste handling that I would like to see described in detail. Unless each of these cans that you mention the reactor contains is send directly to the waste once it has been used ?

I'll certainly follow what happens to this "capitalistic solution"

Reply

roberthargraves *says:*
July 21, 2015 at 2:05 am

Answering your question, from an internal document, after 4 years of power production a Can is left in place in its silo while fission product contaminants decay for 4 more years. Then the Can is rinsed with clean fuel salt, loaded by the travel lift onto the Canship, and transported to the can recycling plant. There the Can is disassembled, ultrasonically washed, inspected, parts replaced as required, and reassembled. The resulting low level radioactive waste will processed for disposal. The slightly radioactive Can will be sent by Canship to a ThorCon site for reuse.

The 190 tons of nuclear graphite worth $4 million will be heated to 2000°C to remove surface fission products and be annealed. Graphite logs that pass inspection will be reused in recycled Cans.

After 8 years of power production use the fuel salt, saturated with fission products, is allowed to cool for 4 years. Still radioactive, it will generate nearly 80 kW of heat in its special shipping cask, which is transferred by Canship to the fuel salt recycling facility. There the valuable uranium will be removed by the fluoride volatility process demonstrated by Oak Ridge. The uranium can be re-enriched and reused as future fuel.

The second step will be to separate the salt and thorium from the fission products and transuranics by vacuum distillation. That salt will be returned for use in power plants. The distillation residue can be stored to cool for a few decades, then sequestered,

Reply

Euan Mearns *says:*
July 21, 2015 at 10:49 am

Robert, just to be clear, Hubert says your concept is a thermal and not breeder reactor. Is that so?

I think its an important distinction. One thing that surprised me from Hubert's article was that 5 of 6 designs are breeders. Thus the international nuclear energy community seems to acknowledge that for nuclear power to have a long-term future, breeding is essential.

Reply

roberthargraves *says:*
July 21, 2015 at 11:55 am

The ThorCon thorium/uranium molten salt reactor is indeed thermal. The molten salt is pumped through slots between planks of moderating graphite in the Can reactor vessel, where fission takes place. In an overheat failure, a fuze plug melts and the molten salt drains to an unmoderated tank. This also avoids the risk in a fast reactor accident of fissile material getting close to moderating material and becoming supercritical. There's a diagram of the Can on pages 17 and 51 in the Executive Summary at http://thorconpower.com/docs/exec_summary2.pdf .

roger in florida *says:*
July 20, 2015 at 10:30 pm

roberthargraves,
Sir,
I would like to thank you for taking the huge time and effort to produce your incredible book: "THORIUM, energy cheaper than coal", you are a wonderful educator. Thank you.
I have no technical input to make in this conversation, however I will make this observation: There are several references to problems with Th fueled reactors to the effect that they can make no contribution to our energy production this century. I can't help thinking of Robert Oppenheimer and General Groves in 1941, are the problems with LFTR technology that much larger than they faced? They had a bomb from nothing in 4 years, that is the kind of effort we need to make. A modular, "walk away safe" source of electrical/thermal energy is exactly what the world needs.

Reply

Syndroma *says:*
July 20, 2015 at 2:26 pm

Utilization of minor actinides itself is a big problem, even in a closed fuel cycle with fast breeders and reprocessing. Curium seems to be the most troublesome actinide of all. Current Russian plans of fuel reprocessing call for the separation of curium and storing it indefinitely. Neptunium and americium on the other hand are planned to be recycled and burned in the reactor either as a homogenous U-Pu-Np-Am mix or a separate americium-only fuel rods. European EFIT project is another interesting idea of minor actinides disposal: industrial-scale particle accelerator to transmute the actinides.

By the way, reactor technology is not the only area of research in nuclear industry with multitude of options and high hopes for the future. Nuclear fuel composition is another one. Fuel can be metallic, oxide, nitride, carbide, with various enrichment levels and burnable poisons. And all the options have pros and cons; and could be used to upgrade existing reactors or affect designs of the new ones. India is developing carbide fuels, Russia is developing nitride fuels. Such development process requires many decades of experiments and monitoring. It's hard to tell what options are the best for the future reactors, but the research definitely has a potential. It's just a question of not giving up.

Reply

Euan Mearns *says:*
July 20, 2015 at 6:41 pm

Baroness Worthington

Author of the UK 2008 Climate Change Act and champion of Th MSFR technology. Degree in English Literature from Cambridge. What on Earth is the UK establishment playing at? Some quotes from the article linked to up top:

> *We worry about a "meltdown" in a solid-uranium reactor because it can lead to the release of radioactivity. But many features of a LFTR make it inherently safer. A liquid fuel is the normal mode of operation, which means the reactor can be designed to automatically drain itself into a walk-away safe configuration in the event of a problem.*

The liquid fuel drain safety feature seems to be one of the main virtues bestowed on the technology. I wonder how real this virtue actually is? In an MSFR The core doesn't have to melt because its already molten 🙂

> *The fluoride fuel form doesn't react with air and water and traps potentially dangerous elements like strontium and cesium as chemically-stable salts.*

I think Baroness Worthington should be invited to stand beside molten salt at 600˚C flowing into a pond or coming in contact with ground water.

> *We are right to be concerned about the risk of military proliferation, but thorium was rejected early in the nuclear age because it is vastly more difficult to weaponise. There are 70,000 nuclear weapons in the world and none are based on thorium or its derivatives.*

Well this is true, but I still don't get the proliferation logic. Any country looking to build a bomb will obviously go the U route. If the OECD is running on Th, what difference does that make?

> *But a LFTR uses thorium and burns it up nearly completely. Even the miniscule amount of waste has beneficial uses in medicine and exploration.*

Miniscule amount of waste 🙂 Well Hubert goes to great length in his discussion about defining waste. A U fast breeder would also produce minimal waste given time. But the whole point is that in the interim couple of centuries, the stock of fissile material is increased hundreds of times over. What has Bryony been smokin?

> *But LFTRs can be built small and they can be distributed geographically – even to generate combined heat and power. They can also be operated in a responsive and flexible manner – thus complementing rather than competing with intermittent renewables.*

Is a LFTR coming to your neighbourhood? The nearest nuke to where I stay is Torness, a 1.2GWe AGR. Its about 100 miles away and I never worry about it. I'm not sure I'd want a 250 MWe molten salt reactor up the road.

> *We worry about the environmental effects of mining and processing uranium. But thorium is far more abundant than uranium and is being mined already in the search for rare-earth minerals for renewable energy generators. Thus we don't need new mining for LFTRs—actually much less—and we can use thorium highly efficiently.*

This is totally deceptive. As hubert points out 232Th needs to be compared with 238U and the difference in abundance is not material. And we already have thousands of tonnes of 238U on the shelf. At this point I don't know if the intention is to deceive or is it born out of plain ignorance?

> *To successfully reduce the risk of climate change we need to commericalise affordable, safe, flexible, long-lasting, low carbon sources of energy. We do not know yet if LFTRs fit the bill but they look extremely promising. It would be irresponsible to dismiss them out of hand before finding out. If the UK is serious about pursuing nuclear power, and it appears that it is, then we must include the pursuit of thorium power in this endeavour. On paper it looks like it may just save us.*

Agreed. But we need to pursue the 21st century U-Pu breeder options first.

Reply

Roger Andrews *says:*
July 20, 2015 at 11:41 pm

Baroness W's statement *But thorium is far more abundant than uranium and is being mined already* … prompted me to look into the question of how much thorium the world actually has. And even though thorium is three times as abundant in the crust as uranium I came to the conclusion that world thorium reserves – i.e. the amount of thorium that can be economically mined – could be considerably smaller than world uranium reserves. I don't know whether this has any impact on the discussion but thought I should mention it.

Reply

Leo Smith *says:*
July 21, 2015 at 10:07 am

I think that the issues of economic reserves has been gone into pretty well – and once again there is a devil in the detail that makes nonsense of the argument that there isn't enough uranium or thorium economically extractable.

What economically extractable means, is that its still cheaper than the next worst alternative:

From sketchy memory – and M. Flocard may have better information – the cost contribution of a fully manufactured fuel rod to nuclear electricity is 15% of the levelised cost – a very small component. The cost of the unrefined yellow cake is far far less than that – perhaps only one or two percent.

So an effective ten times increase in the price of unrefined uranium from around $50 a kg to say $500/kg would in the end only add 10% – 20% to the cost of nuclear electricity.

The Japanese have already developed a pilot process that they estimate could extract uranium from seawater at around $300/kg.

http://large.stanford.edu/courses/2012/ph241/ferguson2/

There is an enormous amount – billions of tonnes – of uranium in sea water of which a reasonably large fraction – say 50% could be extracted.

That means there is as David Mackay has stated, enough economically extractable uranium for several thousand years – which should be even be long enough to get fusion working.:)

Chuck in Thorium and there is even more fertile material around.
Maybe we needed fossil energy to bootstrap uranium fission, uranium fission to bootstrap breeder reactors and breeder reactors to bootstrap fusion.

The economic reality of nuclear power is that if it could be promoted as heavily as renewable energy has been, and the regulatory regimes relaxed to a point of sanity, it would be – not could be, **would be** – the cheapest form of electricity generation on the planet, with enough fuel economically available for thousands of years at today's energy requirements.

LFTR, MOX, PWR, ABWR – it really doesn't matter. What matters is the public perception of it needs to be corrected and the demon of radioactivity cut down to a sane level of respect, not the current irrational level of panic.

Reply

Flocard *says:*
July 21, 2015 at 11:14 am

From what I heard from EdF colleagues the nuclear fuel enters for less than 10 % in the cost or the electricity produced. The cost of capital is much more important.

You move the discussion to the question of uranium resource and as I said we are only concerned with the 235U (U5) resource. There is no point in talking about fertile resource (238U or 232Th which are so plentiful that one cannot imagine that mankind will use it to the end except for those people who can imagine the future of mankind more than 10 000 years from now).

When I teach students I tell them that it is a good starting point to consider that just as oil and gas and coal the uranium resource is infinite no matter that it contradicts obvious mathematics concerning a finite earth.

On the other hand there are two limits to consider
1) the economic limit which means that the impact on the end product (here electricity) is such that other means of production are prefered or that people decide that they should reduce their consumption of the end product (they balance its interest against other priorities). There is obviously a lot of uncertainty on where to place this limit (it boils down to the value attributed to 1$, 1€, 1$, …) and on how it restricts the resource (U5 resource for instance). One could imagine
drawing a curve giving the amount of resource as a function of the extraction cost in dollars. It has to be a growing curve that of course nobody knows.

2) the physical limit. Given the efficiency of the all systems along the chain from the mineral to the end product (energy) do we obtain more end product than we have spent to get it (some people say that for energy we should get few times more but too begin a discussion with students it is not important).This limit can only be lowered by technology improvements and generally the easiest improvements are performed first. In the end, the geology will win.

By its definition, the second limit is below the first since it is independant of currency value and human preferences. The associated total resource is larger but also sets a limit.which one can consider to be ultimate

Coming back to the U5 resource the question can be asked where are the limits and how do they translate in concentration of uranium in the soil mg/kg which make that a place on earth (this includes the oceans) can be considered a potential mine.

Presently people are only interested in the economic limit (the other limit is too far away given the fact that each fission delivers 200MeV). The least that can be said is that there is a lot of uncertainty on this economic limit. Nobody for instance knows how the "red-book" of uranium resource published regularly by IAEA should be trusted since there is no independant cross checking of the information it contains. States tend to maximize their national resource, Firms tend to lower them in order to keep prices high. The situation is much more uncertain than for instance for oil given the fact that geology studies have been abandoned for many years. There are no independent evaluation firms.

This leads to vast differences of opinion among people in the nuclear world as to when fast breeder reactors will become economically competitive compared to present thermal reactors. Not too surprisingly, nuclear research institutes say it will happen soon (say 2040-50) while utilities bet on the fact that they can use present reactors for at least a full century.

Note also that when a country stops using nuclear energy it makes its usage cheaper and extended for the countries which still rely on it. The contrary happens when a country steps in. Thus on has to bet on the future expansion of nuclear energy. History shows that predictions of the past on this subject can certainly compete in the championship of the wrong predictions.

Reply

Rob *says:*
July 21, 2015 at 2:54 pm

What people forget about new generation reactors is that in order to get there we need a viable nuclear industry in the first place. Discussions always focus on research of thorium forgetting we need an army of Engineers to build conventional reactors. Nuclear Engineering covers a wide variety of disciplines Process Piping Civil, Structural, Electrical Instrumentation Architects Planning and Management Construction.
Nuclear professional's need the experience of building a conventional reactor and it is taking 10 years to pass the generic design assessment state aid inquires final investor decision.
Despite premature talk of a skills shortages the industry is stagnating and desperately needs Hinkley point C to kick off rather than another experimental reactor

A C Osborn *says:*
July 21, 2015 at 4:56 pm

Rob, I agree about the need to build one or more Reactors for the experience and knowledge gained.
But not the Hinckley Point Design, which is fraught with design, build quality and cost issues.

One other point, I wonder how many of those "professionals" you say we need we actually had in the 50s when the UK first started building Reactors?
The first of which only took 3 years to complete.

Roger Andrews *says:*
July 21, 2015 at 7:02 pm

There is an enormous amount – billions of tonnes – of uranium in sea water of which a reasonably large fraction – say 50% could be extracted.

To extract a ton of U from sea water at a concentration of 3 parts/billion and 50% recovery you would have to process over 600 million tons of sea water. To extract the 68,000 tons of U consumed worldwide in 2013 you would have to process over 40 trillion tons of sea water, or over 40,000 cubic

kilometers. I just don't see it happening.

Reply

Euan Mearns *says:*
July 21, 2015 at 11:11 am

Roger, average crust abundances are a good starting point but there are more important considerations when it comes to defining U and Th ore grade deposits.

I think all U ores are made from two or three U ore minerals like uraninite and coffinite. These minerals are soluble in dilute acid. Hence, you dig up the ground, grind up the rock, and leach it with dilute acid and it washes out the U and when dried you have yellow cake (U3O8).

U has two oxidation states – 4+ and 6+. The oxidised state (6+) is highly water soluble, while the reduced state (4+) totally insoluble. Thus many U ores occur at redox boundaries where conditions change from oxidising to reducing. Black shales and coals are created in reducing conditions and are normally full of U.

The main Th ore mineral is monazite – the same mineral that contains loads of REE. It is a heavy mineral, very hard and extremely resistant to most forms of chemical attack. I believe ore deposits are normally formed by sedimentary processes that sort minerals according to their density. India, by chance has ended up with loads of monazite placer deposits.

Now we have thousands of tonnes of 238U sitting on the shelf. Why on earth would we pursue 232Th technology, since we have no Th and it is incredibly destructive for the environment to extract Th from monazite?

Reply

roberthargraves *says:*
July 21, 2015 at 12:20 pm

Why? We can efficiently convert Th232 to U233 in a thermal spectrum reactor, though ThorCon requires additional fissile U235 to maintain fission. Efficiently converting U238 to fissile Pu239 requires a fast reactor in order to continue fission. Bill Gates and TerraPower are pursuing the sodium cooled fast reactor path in order to utilize the plentiful U238 available. ThorCon is banking on the lower cost of its thermal reactor to produce energy cheaper than coal.

Reply

Roger Andrews *says:*
July 21, 2015 at 5:34 pm

Euan: According to the OECD Nuclear Agency the world has 5.3 million tons of uranium resources in the reasonably assured and inferred categories at prices up to $US50/lb, 7.1 million tons at prices up to $100/lb and another 10.4 million tons of "undiscovered uranium resources". According to the IAEA-NEA the world has 6.2 million tons of known and estimated thorium resources recoverable at a cost of up to $80/kg ($36/lb). The uranium numbers are backed up by decades of operating experience while the thorium numbers are not, so they will be a lot more robust. But if we take them at face value (and further assume that the extractable energy in a ton of thorium is the same as the extractable energy in a ton of uranium – is it?) then identified global uranium and thorium resources are of the same order of magnitude, so I'm going to call it a wash.

As you point out uranium is easier to mine and process than thorium (most of the world's uranium is now produced by solution mining processes that involve no rock removal). On the other hand I read that uranium processing involves an isotope separation step which thorium doesn't (correct?) So I'm going to call this a wash too.

The problem with thorium as I see it isn't the size of the resource or processing difficulties but production and marketing constraints. Except in deposits like Olympic Dam, where uranium occurs in association with copper, uranium is the primary and only product of a uranium mine, which means that production can be matched to uranium demand and price. Thorium, however, occurs mostly as a minor heavy metal constituent (monazite) in beach sand and placer deposits that contain other valuable heavy metals. An example is the Orissa beach sand deposit in India, where heavy metal

content is given as follows:

Ilmenite (titanium) 39.01 million tons
Garnet (abrasives) 29.40 million tons
Sillimanite (alumina, glass) 17.91 million tons
Rutile (optics) 1.81 million tons
Zircon (high temperature applications) 1.33 million tons
Monazite (thorium) 1.13 million tons

In a deposit like this you can't just recover the monazite and leave all the other heavy metals in the sand. Your mining method produces a heavy metal concentrate that contains all the metals on the list, and you will want to market all the ones that can profitably be sold. In this case monazite production becomes controlled by the "basket price" of all these minerals, not by the demand for thorium. Mine throughput could of course be increased to produce more monazite if the thorium price increases, but the risk here is that increasing the production of the other heavy metals in proportion could swamp markets and collapse prices. It's a complicated economic question, but my guess is that these considerations could seriously crimp monazite supplies if the world ever decides to commercialize thorium-based reactors.

Reply

ColA *says:*
July 22, 2015 at 11:56 am

Roger, you will note that the Orissa deposit is fairly typical of heavy mineral sand deposits world wide. the Mines are viable because of HMC = Illmenite, Zircon and Rutile. The HMC is usually mined from sand deposits and is considered a viable operation if there is 2 – 3% HMC in the sand, depending on location and mineralogy. That means for every ton of sand you get 20 – 30 kg of HMC and on the breakdown of Orissa this gives maybe 200 grams of Monazite!!
That being said, Monazite is easily separated in the dry separation process but actually becomes a pain because as it separates and concentrates it needs to be treated as "radioactive". My experience with this is it was a waste product not worth the difficulty to handle and was normally returned with the reject sand to refill the mine site.
Other forms of Thorium have been found but not having a viable use for the radioactive concentrate it was hidden away! http://energyfromthorium.com/2006/07/07/how-to-throw-away-eight-years-worth-of-electricity/

Roger Andrews *says:*
July 22, 2015 at 2:37 pm

Thanks ColA. I never worked in beach sands deposits but it seems you have.

A beach sand with 200 grams of monazite/ton would contain about, what? 15 grams of thorium/ton? That doesn't sound like much to be going on with. On the other hand gold is mined at concentrations of less than 1 gram/ton. It all depends on price.

A lot of thorium also occurs in narrow (sometimes very narrow) veins in hard rock environments, but I don't like to think how much it would cost to mine them or the mess it would make.

As you note, the fact that monazite is radioactive doesn't help.

A C Osborn *says:*
July 22, 2015 at 3:39 pm

Roger, but at the moment as they are mining the for HMC anyway you get the Thorium for free as far as the minig part is concerned, in fact they currently throw it away.
If you need a quicj stsrt go back to those old mines where they used as infill, it must be quite rich in ore.

Roger Andrews *says:*
July 22, 2015 at 4:00 pm

AC: All you are getting for free is monazite. To get the thorium out of the monazite requires processing, and while I don't have any cost data I suspect it wouldn't be cheap.

http://www.researchgate.net/publication/233409066_Recovery_of_thorium_%28IV%29_from_leached_current_extraction

Leo Smith *says:*
July 21, 2015 at 9:48 am

Great points.

The problem is not what nuclear technology to use, it is to get regulatory approval for *any* nuclear technology.

Look at the ABWR design already approved in Japan and the USA…

http://www.world-nuclear-news.org/RS-Second-regulatory-issue-raised-with-UK-ABWR-17071501.html

Yet another expensive delay thrown in the path of the construction of any nuclear reactor.

And that is how you stop nuclear power.

Regulatory ratcheting – the equivalent of filibustering.

The late Professor Cohen's online book http://www.phyast.pitt.edu/~blc/book/

is a must-read for anyone interested in the technical social and political issues surrounding nuclear power.

As is Wade Allison's summary paper on radiation ..

http://www.templar.co.uk/downloads/Public_Trust_in_Nuclear_Energy.pdf

With this article providing the best overview of LFTR technology yet, it is possible to educate oneself to a reasonable level in the fundamental issues of nuclear energy.

And I think we have a duty to do that.

Reply

ristvan *says:*
July 20, 2015 at 10:04 pm

Very good, long post. There is a different takeaway than just dampened LFTR enthusiasm. The research into G4 fission concepts has stagnated. Meanwhile, between the NIF and ITER the world is squandering ~$25 billion on fusion toys. A French physics Nobelist said it best: 'Fusion is a very pretty idea. Just put the Sun in a box. The problem is, we don't know how to build the box'. Essay Going Nuclear.

Reply

roger in florida *says:*
July 20, 2015 at 10:32 pm

Euan,
Thank you for this post, absolutely fascinating and informative.

Reply

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