Motivations and Basic Options for a Molten Salt Reactor Concept

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KEYWORDS: Molten Salt Reactor, Motivations, Basic Options

Abstract

The goal of this paper is to discuss the reasons why Molten Salt Reactors could be considered of interest for further assessment in the French context, as well as to define the possible basic options of a preliminary concept. It is mainly based on the work of CNRS (*Centre national de la recherche scientifique*) being at the cutting edge of research led on the molten salt reactors for more than fifteen years in France. In addition, Framatome, CEA (*Commissariat à l'énergie atomique et aux énergies alternatives*), EDF (*Electricité de France*) and CNRS are currently involved in research on the safety of molten salt reactors within the SAMOFAR European framework project (from 2015 through 2019). They also fund studies in the frame of the French research program NEEDS which includes studies on molten salt reactors.

The molten salts reactor is one of the concepts selected by the Generation IV International Forum.

The different types of reactors using molten salts as liquid fuel are presented with the objective to identify the reference concept to be chosen for the elaboration of a roadmap. Key drivers are presented with regard to the selection of fuel salt, neutron spectrum, and fissile and fertile matters.

A reference concept is introduced, with fluoride molten salt and a fast neutron spectrum, consistently with the preliminary results of the CNRS studies that have led to the development of the MSFR, "Molten Salt Fast Reactor" concept.

An assessment of the potential advantages is presented in order, in particular, to identify the strong points likely to stimulate its development. The main promising features of the MSFR concept include economy, intrinsic safety, possibility to operate with nuclear actinides waste already available after reprocessing of LWR fuel, and very good flexibility, notably to follow the grid fluctuations induced by renewable energies.

In the other hand, a rough identification of technical barriers to overcome is presented in order to identify the main R&D actions needed in the future.

1. Introduction

The goal of this paper is to discuss the reasons why Molten Salt Reactors (MSR) are considered of interest as well as to define the basic options of a preliminary concept, to be considered as a starting point for the elaboration of a roadmap toward the possible development of a demonstrator. To do so:

- 1) The different types of reactors involving molten salts are presented with the objective to identify a reference concept to be chosen for the elaboration of a roadmap.
- 2) For this reference concept, an assessment of the potential advantages and associated technical barriers to be overcome is presented in order, in particular, to identify, on the one hand, the strong points likely to motivate its development and, on the other hand, the main R&D actions needed.

2. The different types of MSR and selection of a reference concept

There are two main categories of reactors which involve molten salts: the liquid fueled reactors where the fuel is dissolved in the salt which also serves as a coolant; the solid fueled reactors where the fuel is solid, as in classical power reactors, and the salt serve only as a coolant. In this document, only the liquid fueled reactor concept is considered as it is more "disruptive" with the current reactors concepts.. It is referred to as Molten Salt Reactors (MSR).

2.1 Fuel salt selection

The liquid containing the fuel in an industrial reactor has to satisfy the following requirements:

- be relatively transparent to neutrons in order to achieve core criticality with a minimized enrichment,
- have a low enough melting temperature in order to maintain the reactor in certain shutdown states allowing maintenance and inspection operations, without any risks of freezing the fuel
- a high boiling temperature and a low saturation vapor pressure for limiting its volatility,
- have good thermal and hydraulic properties (sufficiently high specific heat, high thermal conductivity, low viscosity…) because this liquid is also the coolant,
- be compatible with the structural material; these materials having to withstand the corrosion that the hot and irradiated liquid fuel could cause,
- be stable under irradiation for limiting the needs of replacement and the amount of associated wastes,
- allow a sufficient solubility of fissile and fertile matters for achieving the core criticality, in particular with a fast neutron spectrum (where a higher fissile content in the fuel is needed), and for limiting the risk of inadvertent criticality outside the core,
- allow the control and treatment of the fuel for introduction of fissile and fertile nucllides and extraction of fission products which can decrease the reactor characteristics, e.g., the neutron-absorbing fission products.

Two types of fluid appear to be the most adapted to these requirements, both being molten salts: the fluoride, mainly lithium fluoride, and the chloride, mainly sodium chloride.

Both salts, if they are pure, present low risks of corrosion. However the corrosion risk is an important issue for MSR, due to the presence in salts of various species: actinides (U…), fission products (Te…) and possible contaminants (H_2O, O_2, metals…) that can induce different corrosion phenomena (Chromium dissolution, intergranular corrosion, radiation-enhanced corrosion etc…). Corrosion resistance will therefore govern the choice of structural materials, and will need detailed R&D

Regarding neutron physics, both are suitable. In a fast neutron spectrum, a fluoride salt reduces the neutron energy more than a chloride salt because fluorine is lighter than chlorine. This leads to slight differences in fissile matter production which is a little larger for the ^{233}U/Th (but less large for the Pu/^{238}U) with a fluoride salt. The material irradiation damage is significantly lower with a fluoride salt, other things being equal.

A fluoride salt because of UF_6 volatility seems advantageous, as regards lanthanide and uranium extraction, in case of ^{233}U/Th fuel cycle, if a high breeding ratio is sought.

Another advantage of a fluoride in comparison to a chloride is the limited production of not easily manageable radioactive isotopes such as ^{36}Cl with a long half-life of 3.10^5 years.

The main component of the fluoride salt is lithium fluoride. In order to avoid neutron poisoning due to ^{6}Li, natural lithium must be enriched with ^{7}Li. This ^{7}Li enrichment decreases the amount of tritium generated by the irradiation of ^{6}Li[1]. Also, note that the nuclear industry has acquired a wide experience

[1] In a 3GWth MSR loaded with natural lithium, the 750kg of ^{6}Li would become in a few years 375kg of tritium. This has to be compared to the about 100g of tritium annually generated by the same MSR but without ^{6}Li.

feedback with fluorine as it is used for uranium enrichment.

The thorium and plutonium solubility is significantly higher with a chloride than a fluoride, which is an advantage for chloride salt. In particular, chloride salts can cope with high plutonium contents, such as those envisioned for plutonium burners (~20% Pu or more).

These considerations lead to select a fluoride, mainly lithium (^{7}Li) fluoride, as the current reference salt for the roadmap. This salt is well adapted to ^{233}U/Th fuel cycle. Its choice for a Pu/^{238}U is being further studied according to the Pu contents (a chloride salt may thus be considered as a variant above a certain concentration).

2.2 Neutron spectrum selection (references [8] and [13])

The first aspect to be considered in the selection of the neutron spectrum is safety, i.e., the stability of the core. In a reactor whose fuel is liquid, the temperature feedback effects result from three contributions: Doppler effect, fuel/coolant density effect, both of these depending only on the salt temperature and moderator temperature effect for a thermal neutron reactor.

Concerning the density effect, an increase of the salt temperature leads to the salt expansion. The fuel circuit design allows the transfer of a fraction of the salt outside the fission zone. The reduced salt density in the critical zone increases the neutron transparency of the core, inducing two phenomena.

- On one hand, neutron leakage is increased, strongly reducing the reactivity. Compared to a solid fuel reactor, the neutron leakage is enhanced because a part of the fissile matters no longer participates to the core criticality.
- On the other hand, the neutron spectrum is less thermalized, increasing the proportion of the fastest neutrons, thus favoring the reactions that occur with these neutrons. In the case of an MSR with thermal neutrons using the ^{233}U/Th cycle, a ^{233}U fission resonance at 0.3eV is then favored, causing a reactivity increase. This effect could be compensated by introducing an element such as europium with a capture resonance at similar energies. In the case of an MSR with a fast neutron spectrum, this favors the fission of the fertile isotopes. But in the case of the ^{233}U/Th fuel cycle, ^{232}Th having a very high fission threshold, the number of its fissions stays negligible. Therefore, in this case there is no significant effect on the reactivity. On the contrary, in the case of the Pu/^{238}U fuel cycle the fission rate of ^{238}U is quite high, and the reactivity effect is significant and positive. This phenomenon partially explains the positive component of the void coefficient of liquid metal cooled fast reactors. Nevertheless, in a fast neutron spectrum MSR the reactivity increase is less than the reactivity decrease resulting from the neutron leak effect. The whole density effect remains negative even with a Pu/^{238}U fuel cycle.

To sum it up, with fast neutrons and with any fuel cycle, both components of the temperature reactivity feedback (Doppler effect and salt density effect) are negative and occur immediately when the salt temperature varies, thus contributing to an intrinsic safety feature. In addition to the strong safety asset provided by the immediate occurrence of the temperature feedback, this property allows the adjustment of the power produced to the power extracted during normal operation, without requiring any control rod system. Even in the event of large and rapid extracted power variation the produced power adjusts rapidly and the salt temperature variation is very small without important consequence on the reactor structures.

In the case of a reactor with a thermal neutron spectrum, the heating of the solid moderator moves the thermal peak of the neutron spectrum towards higher energies with the consequences stated above (positive temperature feedback for ^{233}U). In this case, the influence on the reactivity is delayed since the heating of the solid moderator by the salt is not immediate.

Besides, the thermal neutron spectrum requires the use of moderating materials such as graphite and its management as waste is currently a huge difficulty, graphite would typically have to be replaced every 10 years of reactor operation. This disadvantage is avoided with the fast neutron MSR.

One clear advantage of the thermal neutrons is to limit the fissile matters inventory. However, the thermal neutrons, contrary to the fast neutrons, lead to poisoning by certain fission products, so that the needs for salt treatment are significantly increased (typically a factor ten) as compared to a fast neutron spectrum. Moreover, with fast neutrons, the trans-uranium elements from LWR spent fuel are fissionable whatever the fuel cycle used for the MSR with the benefit they are transmuted more easily in a fast spectrum. A positive breeding ratio could also be envisaged with a Pu/^{238}U fuel cycle.

Therefore, the fast neutron spectrum is selected for the reference MSR concept.

2.3 Specific power

The specific thermal power produced per volume unit of fuel salt in the core zone (specific power), impacts a significant number of reactor characteristics such as the irradiation damage of structural material in the zone under neutron flux (e.g., neutron reflectors and shielding, thermal protections), capability for incineration of plutonium and minor actinides, the fuel circuit heat exchanger design since the fuel salt also is the coolant, or the decay heat removal systems since the decay heat is linked to the specific power.

The determination of the specific power to be aimed requires more thorough studies.

2.4 Fissile and fertile matters

From the neutronic point of view, both fuel cycles ^{233}U/Th and Pu/^{238}U[2] can be used with a fast neutron spectrum, with breeding capabilities (breeding gain > 1). The ^{233}U/Th fuel cycle can also be considered with a thermal neutron spectrum, at least in an iso-breeder mode (breeding gain ~ 1).

As regard the ^{233}U/Th fuel cycle, it is better adapted to the fast spectrum than to a thermal neutron spectrum where large amounts of salt need to be treated because of the significant neutron poisoning. The salt treatment implies reprocessing features specific to this fuel cycle (some nuclides in the ^{232}U decay chain emit high energetic gamma radiation) so that it is judged desirable to limit the amounts of treated salt and thus prefer the fast neutron spectrum. Limiting the specific power should make it possible to avoid salt treatment altogether during several decades. However, if breeder reactors in which fissile matters must be produced to start other reactors, are to be developed, the fissile matters will have to be extracted either from the fuel salt or, preferably, from a breeder salt different from the fuel salt. The reprocessing difficulties would then remain.

The use of the ^{233}U/Th fuel cycle does not exclude the addition of other fissile isotopes of uranium or plutonium within the limits of their solubility in the salt.

With fast neutron molten salt reactors, very large burnup ratios can be reached and the amount of salt to be treated can be small. Thus, the amount of minor actinides in the radioactive wastes is significantly reduced (and very significantly reduced with the ^{233}U/Th cycle).
It can also be noted that thorium is abundant at present in the earth's crust. The amounts of thorium are expected to be four times larger than the amounts of uranium. Nevertheless, thorium extraction is likely to be more difficult than that of uranium, and shift to thorium cycle would mean rebuilding the whole fuel cycle industry and facilities.

The transition from the current reactors (LWR and sodium-cooled fast reactors) that use natural uranium and produce plutonium to molten salt reactors based on the ^{233}U/Th fuel cycle would have to be considered in the event of a shortage of natural uranium which is not realistic in the near future or if it was decided for socio-economic and political reasons to stop using plutonium.
In the French context, the capability of MSR to burn transuranic elements from LWRs should be further studied in priority. In that respect, it can be noted that most MSFR studies have focused on a ^{233}U/Th fuel cycle, and there is now an incentive to look for the possibility to start with MSFR loaded

[2] This represents the association of a fissile matter with the fertile matter which generates it. The only available natural fissile matter in relatively sparseness is ^{235}U. Therefore, in the perspective of nuclear power development, natural fertile resources (^{238}U and Th) must be used. Note that the extraction and the enrichment of natural uranium for light water reactors lead already to the availability of large amount of these fertile matters.

with plutonium without thorium.

In conclusion, considering the flexibility in terms of fuel cycle provided by the MSR with a fast neutron spectrum both fuel cycles could be chosen according to the context. In particular, the selection will depend on the strategy of the utility operating the plant. In the French context [2], studies on MSFR loaded with plutonium without thorium are to be further performed.

2.5 Fuel salt treatment

Salts must be treated by means of chemical and physical processes to maintain their physicochemical properties within acceptable ranges for normal reactor operation. These physicochemical properties concern corrosion issues (e.g., redox potential, impurity), the salt stability (e.g., avoid precipitates) and neutronic issues (e.g., introduction of fissile or fertile matters, neutronic poisoning). For these reasons, the goal is to correct or limit deviations in the salt composition. These composition deviations are depending on the specific power of the fuel salt.

In case of a reactor where breeding capability is sought, a dedicated sub-critical fertile salt circuit would likely be implemented close to the core. Thus, the fertile salt would also have to be treated to extract the fissile matters generated.

Several options for the salt treatment are possible, among which to choose according to other parameters such as the fuel salt, the fuel cycle, the neutron spectrum and the specific power.

2.6 Reference reactor for the roadmap

The above considerations lead to select as reference reactor for the roadmap, an MSR with a lithium (^{7}Li) fluoride salt and a fast neutron spectrum, consistently with the MSFR concept developed by the CNRS [3] and currently studied in the SAMOFAR European project [1]. Further studies on the possibility to have high plutonium contents must be led (could motivate a chloride salt as a variant).

Indeed, most MSFR studies have been led on a ^{233}U/Th fuel cycle in breeding mode, and it is now judged necessary to investigate the possibility of having a burner with Pu/^{238}U fuel cycle.

The power density is not yet selected; this requires deeper technological and economic studies. The power level of the reactor needs not to be predetermined at this stage as no major technological jump associated to the reactor power has been identified. For a commercial reactor, the power will also have to be determined by market and financial considerations (with due account for initial investment, cost as a function of reactor power…). For a demonstrator, a relatively low power, to be defined, should allow to validate the concept, the reactor structural materials and the wide ranges of options, even for a reactor with a significantly higher power.

3. Assessment of the potential advantages and specific technical barriers to be overcome for the reference molten salt reactor concept

A first assessment of the potential advantages and associated technical barriers to be overcome for the reference MSR is presented in this chapter. This analysis is performed according to the four enhancement topics selected by GIF for the generation IV systems [12]. The capability to be flexible and adapt smoothly to the electrical grid is also considered. This is a particularly important additional requirement for the integration of nuclear reactors in an energy mix containing a large fraction of intermittent sources of electricity production.

3.1 Economy

Potential advantages

- The main potential advantage of the MSR concerns the fuel and the fuel cycle where some limitations and constraints associated to solid fuels are avoided, in particular:

  - There is no limitation on the burnup fraction and no notion of fuel loading plan. There is no need to manufacture fuel assemblies. This concerns also the minor actinide incineration for which it is no longer necessary to manufacture assemblies. Fissile and fertile matters are directly dissolved in the salt. This introduction of matters can be done without requiring to shut down the reactor.
  - If breeding is not a requirement, fuel reprocessing to retrieve the fissile matters in excess is not necessary. Fuel would stay in the salts. On the contrary with solid fuels, the burnup fraction is limited in particular by the damage to the fuel cladding (e.g., reprocessing of the LWR spent fuel to retrieve the remaining ^{235}U and the produced Pu). The need for fissile matter transportation during the operating life of the plant is thus reduced. It remains necessary for the first core and if the reactor is operated as breeder or burner.
- The architecture of the nuclear reactor could be simple, especially inside the fuel vessel, considering that there is no need to implement highly irradiated internal and fuel structures. The capacity of the concept to intrinsically adjust the power output to the level required by the grid while keeping temperature variations within limits could allow to avoid a control rod system.
- It is not necessary to design the fuel circuit and the containment barriers to withstand high operational pressure.
- Lithium fluoride and fluoride salts in general have high melting points so that the reactor operates at high-temperature i.e., in the order of 700°C[3] for the MSFR in ^{233}U/Th fuel cycle. This puts a severe constraint on the materials but it is an advantage in terms of thermodynamic efficiency. Moreover, it opens the possibility of using the MSR for applications other than electricity production, such as high temperature heat production for industrial applications.

<u>Technical barriers to be overcome</u>

- The level of maturity of MSR is very low, especially:
  - The materials of the fuel circuit and the components in contact with the salt must be defined and qualified taking into account the high temperature, the irradiation damage and the chemical characteristics of the salt and of the fission products which it contains. Assessment of corrosion risks induced by the various species contained in the salt, and varying along the life of the plant (actinides, fission products, initial impurities, impurities coming from outside or from operational incidents or accidents…) and of their interactions with additional factors such as temperature and irradiation will request to develop comprehensive corrosion models, based on fundamental data.
  - The management of the fluoride salt composition and of the redox characteristics of the salt will have to be mastered during operation, needing further definition of the purification and redox control processes [10].
  - On-line processing schemes of the fuel salt – or processing in batch – is to be further studied. This can lead to local fuel processing units, than can present advantages but also disadvantages (one processing unit per reactor).
  - Technologies for reactor equipment (pumps, valves, heat exchangers, steam generators, *etc.*) must be defined in relationship with the possibly corrosive nature and the high temperature of the irradiated salts.
  - Safety provisions (in case of air or water ingress etc…) have still to be defined/studied.
  - The needs and the technologies for in-service inspection of structure have to be defined.
  - High melting point of salt (around or even above ~500°C depending on the selected salt) will request complex heating systems of piping and vessel, to maintain the salt liquid even during reactor shutdown.

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[3] The reactor could operate at lower temperatures, in the order of 500°C, with a sodium chloride salt in Pu/^{238}U fuel cycle.

  - High operational temperature (~700°C and more in case of incidents) will induce new constraints, not only on materials, but also on instrumentation etc…Adequate technology has to be developed.
- A development [6] and qualification program must be defined and its cost assessed.
- Potential economic advantages must be confirmed and quantified.
- The need of an intermediate circuit, currently considered in the MSFR concept to avoid any risk of large water/steam ingress in the reactor, has to be confirmed.

3.2 Safety

Potential advantages

- With the liquid fuel and a fast neutron spectrum, a negative temperature feedback coefficient is obtained, whose action is immediate in the event of a salt temperature variation [8]. This ensures an intrinsic safety with respect to reactivity accidents [5].
- The fuel unloading from the core zone is easier and faster compared to the unloading of a solid fuel; this allows to maintain sub-critical the salt and to cool the fuel.
- The fuel circuit is not pressurized and the fluoride salt is not likely to cause violent exothermic chemical reactions when it is in contact with the materials of the plant. Lithium fluoride does not react violently with air; it does not represent a fire hazard. It should not react chemically with the water either.
- Fission gases (and possibly some non-volatile and non-soluble fission products) are released from the fuel during operation, reducing the radiological salt inventory, in particular that of the gaseous fission products which are the most likely to be released in case of an accident with a solid fuel. The fission products retention within the salt in the event of an accident, in particular cesium, is to be further studied.
- The absence of fuel structures in the core such as cladding and subassemblies removes the risk of fuel compaction, a risk of reactivity insertion in a fast neutron reactor with solid fuel.
- As the fuel is in the liquid state, there is no accident similar to the severe accidents with core melt-down as on solid fuel reactors, therefore no need of core catcher etc…
- The intrinsic temperature feedback effect could eliminate the need of a neutron absorber system for adjusting the operating conditions.
- Moreover, the amount of fissile matters dissolved in the critical zone of the fuel circuit is just necessary to maintain a critical state. Fertile matters can be periodically injected in the core without needing to shut down the reactor. This allows to intrinsically reduce the risk of accidental reactivity insertion.

Technical barriers to be overcome

- The analyses led until now ([1] and [4]) must proceed more in depth to make sure the identification of risks is exhaustive. This will need a comprehensive analysis of all the risks (conception or fabrication errors, internal events, external events) on a selected conceptual design, and of the countermeasures or consequences, demonstrating the safe behavior of the plant, and then the discussion with a Safety Authority.
- The prevention of corrosion of the structures in contact with the salt, especially the reactor vessel, must be shown to be sufficient. Suitable measures of surveillance are to be developed. Measures to detect accidental pollution (water or oxygen), or to control or survey defects, or to detect under-estimated corrosion phenomena have to be defined (multiple barriers avoiding common mode corrosion risk etc…).
- The absence of risk of severe chemical reactions between the salt and the other materials employed is to be confirmed, especially the absence of risk of producing some hydrogen by the dissociation of water. Also, the consequences of a contact between salt and water need to be assessed, in particular the risk of steam explosion.

- The risk of precipitation and concentration of fissile matters in the salt, as well as generally speaking the criticality risk of the salt which is not in the reactor zone are to be examined.
- Fission products extracted from the fuel circuit during operation are stored in particular in the salt treatment unit. Associated risks (i.e., presence of a radiological source term, production of residual power, criticality risk) must be analyzed in detail.
- The monitoring of the reactor and the salt treatment unit, the features for in-service inspection and repair or replacement of equipment in contact with the salt, must be defined.
- If necessary, the fuel salt is drained by gravity into a dedicated tank designed so as to maintain the salt sub-critical and to evacuate its residual power through circuits whose operation in case of loss of power supply has to be considered.
- An analysis has to be performed in order to define the needs of confinement barriers to implement as regards fuel salts and fission products, and also their performances required as regards normal and accident conditions to consider.
- Volatility of the salts has to be studied, both for operational aspects (deposits on piping…) and safety aspects (releases in case of leaks).
- The start-up and shutdown phases have to be further analyzed in detail [11].

Finally, it should be noted that there is no real operating nor licensing experience of an MSR and the suitability of the existent regulations which were principally developed for light water reactors must be assessed. Safety regulations adapted to such a concept will have to be developed and validated by the Safety authority of the country hosting the plant. However the fundamental safety principles such as the defense in depth remain applicable but their application must be adapted.

3.3 Environmental impact

Potential advantages

- The fast neutron spectrum as well as the high burnup fractions allowed by the fuel in liquid form, lead to a reduction of the production of minor actinides. They can even allow the incineration of plutonium [7] and actinides produced by the light water reactors, with supplementary provisions.
- The fast neutron spectrum can also allow the use of natural uranium and thorium as fertile materials, removing any risks of tension on the ^{235}U market at long term [9]. -

Technical barriers to be overcome

- Techniques for decontamination and waste packaging are to be developed.
- With the fast spectrum and fluoride salt concept, difficulties due to graphite and irradiated chlorine are avoided. Nevertheless, the dismantling procedures for this type of reactor must be anticipated .In particular, U and Pu separation from salt must be realized at short term after plant shutdown to avoid difficulties encountered for MSRE decommissioning, due to salt degradation (fluorine gas build-up, criticality risks…). In particular, adequate waste management must be identified.
- The life duration of MSR could be limited by the possible irradiation damages on reactor structures which cannot be replaced in economic conditions. The life duration of the heat exchangers could be limited by metallic fission product deposition on the wall.
- The selection of lithium fluoride as fuel salt requires the enrichment with ^{7}Li for avoiding neutron poisoning. This enrichment reduces the production of tritium significantly. It would otherwise be very large due to the irradiation of ^{6}Li. Despite this enrichment, however, the tritium production remains significant, equivalent to heavy water reactors. It is larger per unit of electrical power produced than that generated by light water reactor. Generally speaking, techniques allowing to limit the production and release of tritium are to be developed.
- The radiological and non-radiological impact of off-site installations in support to the reactor must also be studied. This concerns, in particular, installations required for salt manufacturing, extraction and conditioning of fissile and fertile matters, the conditioning of fission products, the waste processing, in particular salts at the end of life. Transport between these installations and the reactor also are to be considered.

- Management of fluorides salts will request particular provisions, as regards fluorine gas production or releases.

3.4 Proliferation resistance and physical protection

<u>Potential advantages</u>

- If the reactor is not operated as a breeder or as an actinide burner, the transport of fissile matters during its operation is unnecessary, strongly reducing the risk of misappropriation of fissile materials.
- If the ^{233}U/Th fuel cycle is used the risk of salt misappropriation will be intrinsically limited because the ^{232}U generated in the fuel salt during irradiation is a high gamma emitter making its detection easier and complicating its use.
- The fast neutron spectrum reduces the needs for salt handling for treatment reducing all the more the risk of misappropriation.

<u>Technical barriers to be overcome</u>

The physical protection issues associated to MSR concept are to be examined, with adequate safeguard methods, in particular considering the location of radioactive matters in the different parts of the installation.

3.5 Flexibility and adaptation to the electrical grid needs

<u>Potential advantages</u>
The MSR is particularly well adapted to load following on the grid thanks to its ability to rapidly adjust the power generated to the power extracted, the salt temperature variations remaining very small [5]. Indeed, as soon as the salt temperature and consequently the fuel temperature vary, because the power extracted has changed, the quasi instantaneous variation of their density modifies the power generated. Thus the temperature variation of the salt and as a result, of the reactor structures, is limited. This property is a valuable asset for a grid whose energy mix gives an ever larger share to intermittent and unpredictable electricity production sources. The MSR adjustment to the hardly foreseeable needs of the grid could be achieved without requiring a control rod system and should not cause damage to the reactor structures.

Besides, the MSR fuel salt temperature should be high (especially with fluoride salt), with a possibility of using the MSR for heat production or others high temperature applications.

4. Conclusions

The preliminary analysis of the selected MSR concept shows that this reactor presents some potential interests regarding several criteria, with points to be further evaluated:

- Economy: the integration of the fuel cycle in the reactor operation, the absence of limitation in terms of fuel burnup, as well as the relative simplicity of the concept, may offer potential economy sources, provided that detailed analysis do not lead to very sophisticated processing and safety systems. The possibility to operate these plants using plutonium produced by LWR fleet allows also further economy on the fuel cycle (no needs of uranium mines and uranium enrichment), provided that the plutonium salt fabrication and reprocessing remain at acceptable cost.
- Safety: the intrinsic reactivity control provided by the liquid fuel, in fast neutron spectrum, is a major element for the safety of this reactor. This property would be easily shown in real reactor conditions. The absence of fuel circuit pressurization and the possibility to choose salts presenting no risk of violent exothermic chemical reactions are also valuable assets. The other risks associated to the system (common mode corrosion risk following an accidental pollution, for example, volatility of salts …) have still to be analyzed in detail.
- Minimization of wastes: the fast neutron spectrum (no graphite) reduces the needs of salt reprocessing. However this will remain necessary, and the storage/conditioning of associated wastes, and of the salt after decommissioning, are to be defined.

- Flexibility: the high molten salt temperature allows to consider applications other than the sole electricity production. The intrinsic reactivity control should also allow ease load following capacity and facilitate the deployment of these reactors in an energy mix having an important part of intermittent electricity production sources.

However, the MSR concept does not benefit from the very important development efforts which were realized on other reactor concepts: light water reactors, sodium-cooled fast reactors and, to a lesser extent, high temperature reactors. The technical concept developments, in particular in terms of materials and chemical salt treatment require long time and expensive R&D efforts. Besides, the current fuel cycle facilities should be adapted and supplemented by new installations which will prepare the fuel to be introduced into the MSR and which will manage the resulting fission products.

Therefore, further studies should be led to confirm the potential advantages and answer the technical barriers to be overcome. The possibility and implications of the use of MSR in burner mode with a Pu/^{238}U fuel cycle will also be considered in this frame, in order to further define the concept that is the most adapted to the French context.

Acknowledgment

The authors wish to thank the NEEDS French Interdisciplinary program and the IN2P3 department of the National Centre for Scientific Research (CNRS), Grenoble Institute of Technology, and the European program SAMOFAR (H2020) for their support. The authors are also very thankful to Elisabeth Huffer for her help during the translation of this paper.

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