Perspective of R&D of small molten salt reactor (MSR) – proposal of UNOMI

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Abstract: Nuclear power still plays an important role for reducing CO_2 emission. At the same time, small scale and small capacity reactors, such called "small modular reactor (SMR)" is the recent trend of developing as new generation. On the other hand, molten salt reactor (MSR) is remarked as safe, high economy way as nuclear power. There are numbers of new proposals of MSR both for large and small capacity reactor in these just a few years. The author's proposal named "UNOMI (Universally operable molten salt reactor integrated)" is also among such small capacity MSR. In this paper, these new designs of MSR are reviewed from a view of engineering feasibility.
Keyword: small modular reactor; molten salt reactor; thorium

1 Introduction

United Nations Framework Convention on Climate Change (COP21) was held in Paris, in November 30 to December 11. 2015 and a new international framework called "Paris Agreement" was adopted. This agreement succeeds the past "Kyoto Protocol" which had been agreed at COP3 in 1997.

It is well known that the major concern in the past conference series of COP has been how to reduce greenhouse gas (GHG) emission worldwide. Since 42% of total GHG comes from energy sector which includes electricity and heat [1], development and wide use of low carbon energy has been continuously discussed in the international arena, where nuclear power is one option of the low carbon electricity production method.

This favorable aspect of nuclear power has been recognized in the past, but on the other hand, inherent concern of environmental contamination by radioactive release from nuclear power station which is different from windmills and photovoltaic cells has been prevailing over the world after the Fukushima accident in 2011. However, even though some countries such as Japan, Switzerland and Germany appealed to retreat from large use of nuclear power after Fukushima accident, there have been many countries that still continue and start their energy policy to utilize nuclear power [2].

Another important point for reducing GHG emission is to know "who" emits the gas. USA was the world largest GHG emission country until the beginning of 21st century, but these days this No.1 position is occupied by China who emits 26% of GHG in the world [1]. The second largest GHG emission country is USA with the share of 16%. The third position is India with the share of 6.2%. Although the share of India is rather small at present, her emission amount will soon increase in the future by seeing her world second largest population and growing economy. This fact implies that only the countermeasures valid for those three countries can realize the enormous GHG reduction in the world. Here, the three keywords effective for those top three emission countries are (i) small reactor, (ii) molten salt reactor (MSR) and (iii) thorium.

Among the three keywords, thorium was already discussed by the author of this paper in his previous papers [3] [4] [5], and the recent OECD report also gives comprehensive review on today's trend of utilizing thorium [6]. In this paper, the overview on the recent R&D trend of small MSR development together with the MSR in general will be given together with the author's proposed idea of small MSR called "UNOMI (Universally Operatable Molten Salt Reactor Integrated)".

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2 Trend of small-modular reactor

There had already been new trend of small modular reactor (SMR) concept before Fukushima accident [7]. Especially in USA where many different conceptual reactor designs had been proposed, a special topical meeting on SMR called “SMR2011” had been organized just after Fukushima accident. Most of the 66 papers presented at this SMR2011 meeting are based on the technology of light water reactor (LWR) but there are three papers are related with the molten salt technology[8][9][10]. In SMR2011, Idaho National Laboratory (INL) presented a new concept to utilize molten salt as coolant of nuclear reactor instead of helium gas for removing heat from coated fuel particles like High Temperature Gas cooled Reactor (HTGR). However, this idea is different from the orthodox concept of MSR. Similar concept has also been proposed by Holcomb of Oak Ridge National Laboratory (ORNL) with the name of FHR (fluoride salt-cooled high-temperature reactor) [11].

The world first electricity generation by nuclear power was very small. Output power of EBR-I (Experimental Breeder Reactor No. 1) was 1.1MWth and 200We electricity generation to be able to light only 4 bulbs in 1951. However, Shipping Port Atomic Power Station, the world first peaceful purpose nuclear power reactor in 1957 in the U.S.A., was as many as the electric generation of 100 MWe. Today, studies of SMR development aim at similar output power range.

Since 1960’s, nuclear power plants have sought for scale merit for enhancing economy on one hand, while on the other hand, to increase capacity per unit is the only way to assure the siting for nuclear power because nuclear power plants were deemed as NIMBY (Not In My Back Yard) facility by local citizen. From the aspect of public acceptance for nuclear power these days, it can be said that the SMR has a favorable feature of because small capacity reactors of distributed siting separately may give limited influence even by radioactive release accident.

In addition, SMRs also have favorable merits to nuclear industry. For example, large number of reactor shipping enables continuous design work, production, maintenance, decommissioning and re-installation. Moreover, bottleneck in supply chain can be omitted. (For example, large reactor pressure vessels needed for the large scale power nuclear power plants of more than 1000 MWe can be only supplied by a single company named JSW (Japan Steel Works) in the world.)

Other important merit for large number of small distributed SMRs is heat supply from nuclear reactor in addition to electricity supply. As mentioned in **1,** GHG is emitted mostly from the energy sector of electricity and heat. Effective heat supply is essential requirement for reducing GHG. Heat supply is not feasible for large scale nuclear power plant because heat loses its thermal energy during the long distance transportation, on the contrary to the electricity transmission line. This feature of availability of dual supply of electricity and heat is adoptable not only for civilian purpose but also for industrial purpose.

It is true that the nuclear power reactor can also provide thermal energy, however in this case, the providing temperature should be usually as high as possible. From this point of view, LWR-based SMR whose operation temperature is limited to about 300 ℃ is not necessarily suitable for industrial purpose of process heat utilization. Another disadvantage of LWR-based SMR is the concern of worsening economy which is related with the frequent exchange of fuel rods. How to solve those disadvantages and maximize the advantage of SMR? Completely different approach for the answer to solve the above question is the new MSR which uses liquid fuel as will be introduced in the subsequent chapter.

3 Recent R&D of molten salt reactor for SMR

3.1 Subjects of designing small capacity MSR

The author of this paper gave a review on the background why MSR has been noticed in these years [13]. The R&D history of MSR since 1950’s was also described in detail in other paper in 2013 [12]. Many new proposal of MSR can be seen after 2013 including some large scale design. These new ideas of MSRs are introduced in the subsequent part of this chapter.

In order to help readers, the comprehensive summary of the R&D history of various MSR concepts is given in Fig. 1. Horizontal axis is year and vertical axis is approximate reactor thermal output power. Each concept of MSR is indicated by green box. Here, the MSR concepts using molten salt as fuel salt are included in Fig.1 while other concepts using molten salt only as coolant such as FHR are not. It is also seen in Fig. 1 that many small capacity MSR concepts rather than large ones have been proposed since 21st century.

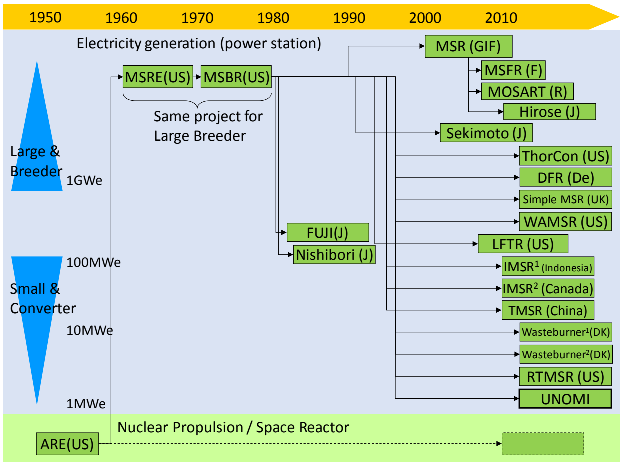


Fig.1 Outline of R&D history of MSR.

In the history of SMR, some groups propose large capacity MSR concepts from the aspects of scale merit and enhanced neutronics efficiency such as conversion ratio (CR) from fertile to fissile. As mentioned in **1**, there is also other trend of utilizing thorium as fertile but it does not contain fissionable isotope. It should be mentioned here that thorium utilization is also considered in other reactors including LWR and fast reactors.

Achieving high CR was one of the important design factors from the beginning of R&D of nuclear power. This is strongly related to very small existence of fissile of uranium-235 available from natural resource. This background has been relatively improved presently to be compared with the period of 1950's ~ 1970's when stockpile of artificial fissile plutonium. In other words, plutonium obtained from spent nuclear fuel (SNF) can also be used together with thorium [14]. Moreover, another way to utilize accelerator-based conversion of thorium are also widely developed [15], thus high CR is not the high priority for designing new nuclear reactors.

In the case of MSR, Engel [16] and Moir [17] has pointed out that higher economy can be available than LWR because of no existence of fuel rod including the fuel exchange service. However, the tendency of high economy is not still uncertain for small capacity MSR which is focused in this paper because Moir's analysis is based on 1GWe capacity. In the primary circuit of MSR, radioactive materials such as fuel and fission product (FP) are contained. Also large amount of tritium is included in the case of using lithium as salt component.

Thus fission heat cannot be directly removed to steam circuit from the primary circuit, and intermediate or secondary circuit must be used by the same way as fast breeder reactor. This system configuration increases structural cost especially for small capacity MSR. It should be noted here that replacement of any kind of main structure will bring about the worse economy even for MSR. This implies that scale merit appears the same for MSR. Therefore, some drastic progress of heat removal system is indispensable for achieving high economy of small capacity MSR.

It was also pointed out that MSR has an essential engineering difficulty by the failure of narrow tubes in the heat exchanger [12]. Steam generators, or the heat exchangers of PWR, have been operated with plugging some ratio of tubes once failure is found during inspection [18]. And the ratio of plugged tubes in total number of one heat exchanger is around 1% [19] but there are examples that the ratio exceeds 20% in Japan. Number of heat exchangers having plugged tubes is more than 50% in the world [19].

This fact shows that even MSR has to be operated by a similar way to plug failed tube of heat exchanger as long as MSR utilizes steam circuit to drive turbine for generating electricity via dynamo. However, this operation can be permitted for PWR because the circulating medium is water including merely no radioactive materials. But the same operation will be extremely difficult for MSR since its primary circuit contains large amount of radioactive materials and the secondary circuit contains tritium. It should be remarked here that the MSRE (molten salt reactor experiment) in 1960's removed heat by air-cooler from secondary circuit and there is no experience to use steam generator for MSR in the history.

Those concepts as shown in Fig. 1 have different features in salt and fuel composition, materials for moderator and so on, however, they will be evaluated only from the view of engineering feasibility of heat removal system in this paper because this feasibleness finally determines whether the design is available or not.

3.2 Reviews of recent design of MSR

3.2.1 ThorCon

ThorCon is the name of MSR proposed by Martingale, US [20]. Above mentioned Moir joins this company as a physicist and engineer. This company signed memorandum of understanding for collaborative development between Indonesian companies in December 2015 [21]. Primary circuit of ThorCon is shown in Fig. 2.

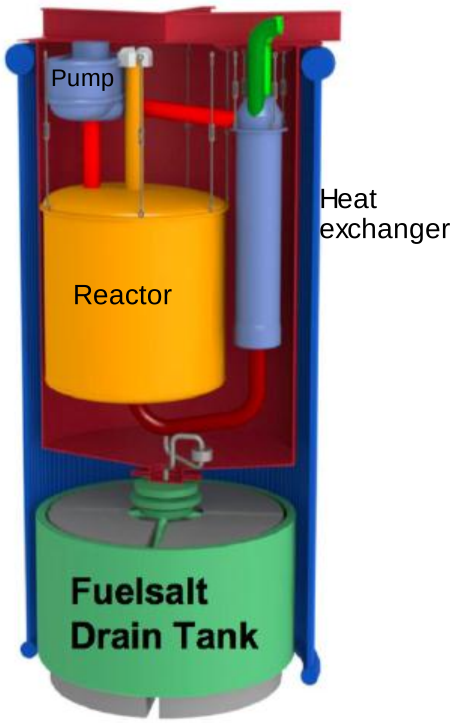


Fig.2 Configuration of primary circuit of ThorCon.

ThorCon is a scale-up design of MSRE which as operated in 1960's. Prototype of ThorCon's output power is 550MWth and 250MWe [22]. Its pilot plant will be similar to miniFUJI, which was proposed by Furukawa in 1980, where reactor vessel, primary circuit (pipes, heat exchanger and pump) and drain tank are contained in a shroud. Furukawa named this idea as "high temperature containment vessel" and he applied it for his FUJI-series including miniFUJI [23] where the purpose of this idea is to keep fuel salt at higher temperature than melting point and to catch leaked salt from primary circuit. The central point of this design of FUJI-series is not to replace main component including graphite moderator during whole lifetime of about 30 years [24].

No replacement of graphite moderator in FUJI was achieved by adopting low power density of 7.3 MW/m^3 which gives smaller irradiation damage. On the contrary to FUJI, ThorCon uses also graphite as moderator material, and it has higher power density of 16 MW/m^3. Because of this high power density, ThorCon can replace the whole part of containment vessel in every 4 years as shown in Fig. 2. Power density of MSBR (Molten salt breeder reactor) was as high as 22.2 MW/m^3, therefore, its design policy was to replace graphite moderator in the central region of reactor core in every 4 years [24]. Thus ThorCon might determine their replacement interval considering both on MSBR's design and MSRE's operation experience being about three and half years. ThorCon's intermittent replacement of primary circuit may contribute to avoid tube failure of primary heat exchanger. But possibility of occurrence of tube failure of secondary heat exchanger, which is in reality steam generator, will still happen during its lifetime. As mentioned above, MSR's high economy will be achieved by no replacement of key instruments. Thus detailed evaluation will be needed whether such design and operation policy requiring replacement enables high economy.

3.2.2 DFR

DFR (Dual Fluid Reactor) is a German design proposed by Huke *et al.* [25] Its power output is 3 GWth and 1.5 GWe. DFR's design is largely different from other ordinary MSRs. In the core of DFR, many tubes in which fuel salt flows are equipped and liquid lead flows around these tubes to remove fission heat. Core configuration of DFR and total heat removal system are shown in Fig. 3 and Fig. 4, respectively.

A similar configuration that fuel salt flows in core by using tube was experimentally examined during ARE (Aircraft Reactor Experiment) in 1950's [12].

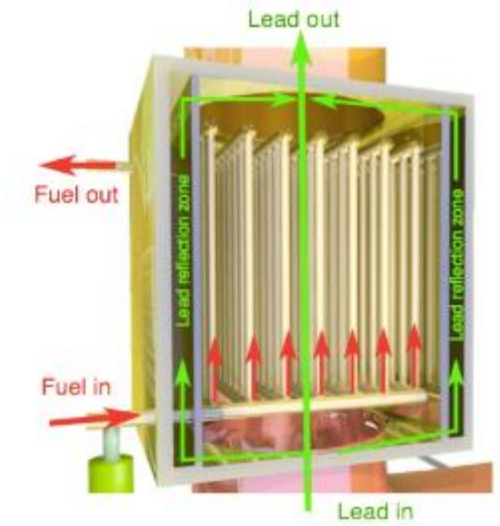


Fig.3 Core configuration of DFR.

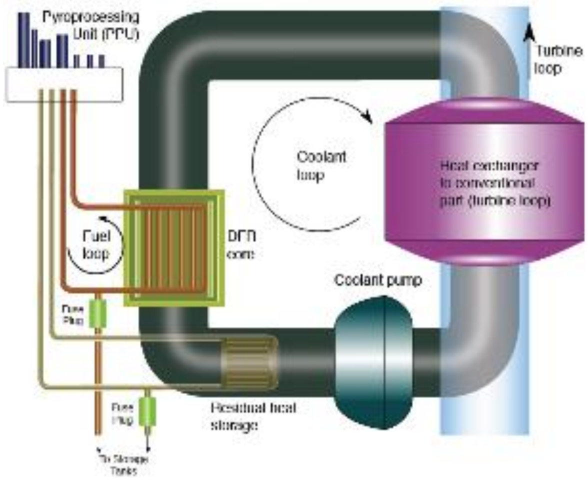


Fig.4 Heat removal system of DFR.

During this experiment, it was found that the tubes located in core were easily damaged by several reasons such as (i)salt is corrosive, (ii) metallic tube is irradiated by high neutron flux, (iii) temperature is high, and (iv) flow rate is high. The factors (ii), (iii) and (iv) are especially enhanced at the center of core region. Based on those ideas, the design of MSRE adopted holes made in the graphite moderator as flowing channel of fuel salt in core region. Then corrosion and irradiation of metallic part were completely eliminated and this design policy was followed by most of successive MSR concepts. There may be some change in the detailed design in future for DFR, not only corrosion by chemical reaction of fuel salt but also erosion by fluid dynamics of the coolant will easily happen especially at the elbow of tubes as long as the configuration indicated in Fig. 3 is adopted.

3.2.3 Simple MSR

UK's Scott proposed his own new design named "Simple MSR" having power output ranging from 1.5 GMth to 2 GWth [26]. He and his colleagues have already established a venture company named "Moltex" to promote his reactor concept. Configuration of "Simple MSR" is shown in Fig. 5. As same as DFR, Simple MSR utilizes tubes in its core, in which fuel salt consists. Difference from DFR is that there is no elbow in the flowing region. In addition, fuel salt in the tube is not circulated by external pump. Diameter of the tube is about 40 mm and fuel salt circulates by natural convection because of the heat removal from outside of the tube. However, as same as the case of DFR, these fuel salt tubes are irradiated to high neutron flux. Moreover, thickness of the wall of these tubes must be thin for enhancing thermal conduction as same as LWR's fuel rods. As a result, such an effect of neutron irradiation becomes to occur apparently. In addition, thermal-hydraulic effects such as erosion and fluttering become more explicit due to its high thermal output power of 2 GWth, which needs large flow velocity at a few m/s. Therefore, Simple MSR will need detailed engineering evaluation. Anyway, it should be remarked that UK is considering SMR where MSR is also included [27] [28].

3.2.4 WAMSR

WAMSR is a proposal from Transatomic Power, a venture company of MIT (Massachusetts Institute of Technology) [29]. WAMSR's output power is 1.25 GWth and 520 MWe. They say that WAMSR's power density is 83 MW/m^3, which is very large as compared with other concepts. It is not obvious but reactor height will be about 3 m and radius will be about 1.3 m. Reactor configuration is shown in Fig. 6.

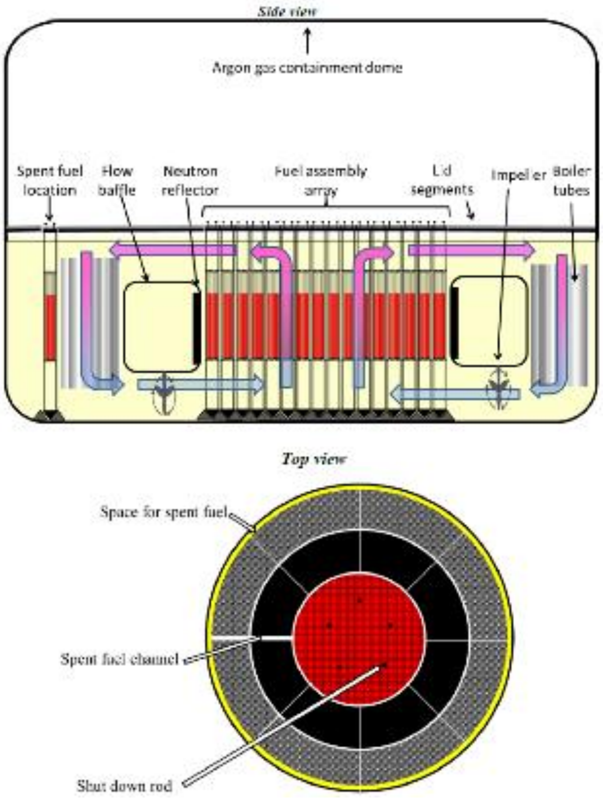


Fig.5 Schematic of reactor configuration of "Simple MSR".

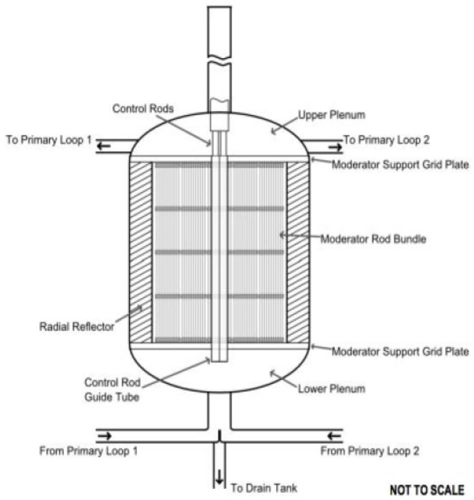


Fig.6 Reactor core of WAMSR.

They claim that the very high power density enables very compact reactor even though its output power is large. Such compactness also enables easy fabrication in factory and shipment directly from factory to site. As explained above, even though MSBR's power density is kept at 22.2 MW/m^3, it is necessary to replace graphite moderator in every four years. Because of this strong damage of high neutron flux, WAMSR uses $ZrH_{1.8}$ (Zirconium hydride) as moderator material instead of graphite. The reasons to apply this material are $ZrH_{1.8}$'s high resistance against neutron irradiation and good moderation ability of fast neutron. They estimated that reactor vessel becomes more compact because moderator occupies only 50% of reactor volume and more fuel salt can exist in the core.

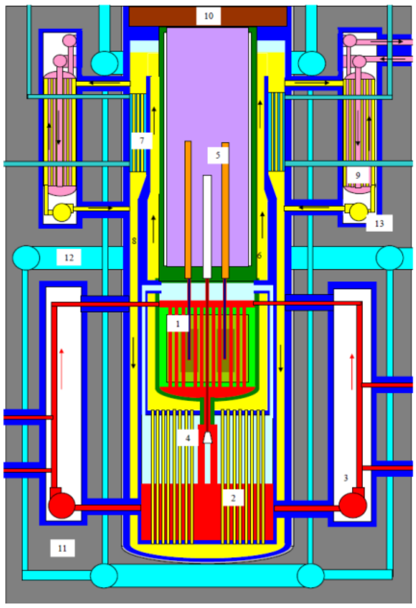
$ZrH_{1.8}$ is a rod-shape and for improving its resistance against corrosion of fuel salt, the $ZrH_{1.8}$ rod is equipped in a crud. Thus, engineering feasibility depends on the resistivity of this crud against irradiation of neutron and corrosion of fuel salt. Since the power density is extremely large, flow rate in the core must be very large for effectively removal of heat. However, such large flow rate finally enhances erosion and corrosion of the crud. By considering these disadvantage, they also consider to apply modified Hastelloy N instead of commercially sold Hastelloy N. Since modified Hastelloy N has not yet contained in the ASME (American Society of Mechanical Engineers) code, it will need much longer years to accept NRC's (Nuclear Regulatory Commission) approval.

Though large power density is attractive both to achieve large output power and compactness of reactor size, it always accompanies with other engineering difficulties. Especially for such an extremely large density adopted in WAMSR, lots of experimental test results for confirmation will be needed.

3.2.5 IMSR^1

This is a design proposed by Harto, Indonesia in 2011 [30]. The name "IMSR" is well-known by LeBlanc's design [31] but these two are different. The former is "Innovative MSR" and the latter is "Integral MSR". In this paper, Harto's proposal is identified by using superscript "1" and LeBlanc's is by "2". System configuration of Harto's IMSR is shown in Fig. 7.

IMSR^1's output power is 450 MWth and 250 MWe. IMSR^1's original idea is to locate primary heat exchanger at the bottom of reactor vessel. This idea is common with the past proposed concept by Nishibori *et al.* [12], which packs primary circuit including reactor vessel in one containment vessel. However, Harto's design cannot contain all part of the primary circuit such as pumps in one vessel because of its slightly large output power. Nishibori recommended that thermal output power should be less than 100 MW enabling to pack all part in one vessel.



REMARKS :

1. Reactor (Core and Blanket)
2. Primary Heat Exchanger
3. Fuel Pump
4. Flow Regulator Valve
5. Control Rods
6. Primary Coolant Riser
7. Post Shutdown Heat Exchanger
8. Primary Coolant Down Comer
9. Intermediate Heat Exchanger
10. Reactor System Plug
11. Concrete Containment
12. Concrete Containment Cooling Duct
13. Primary Coolant Pump

Fig.7 Schematic of IMSR[1]'s primary circuit.

3.2.6 IMSR[2]

This is another design named "IMSR" by David LeBlanc. In this design, primary heat exchanger is located above reactor vessel, which is opposite to Harto's design. Schematic of LeBalnc's design is shown in Fig. 8.

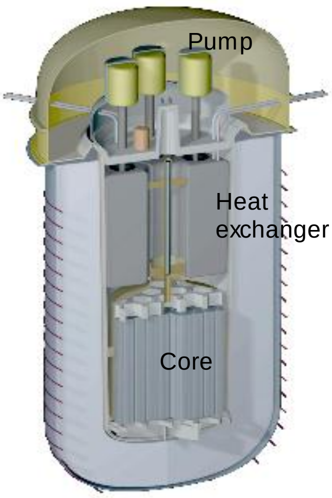


Fig.8 Schematic of primary circuit of LeBlanc's IMSR[2].

LeBlanc's IMSR[2] has several line-ups having output power of 80 MWth (30 MWe), 600 MWth (300 MWe), and so on. For example, the type of 400 MWth has 3.5 m of outer diameter and 7 m height of reactor vessel. Thus power density will be about 6 MW/m^3 which is rational value as compared with the value of MSBR and FUJI. Therefore, IMSR[2] can use graphite which is widely confirmed material in nuclear application on the contrary to WAMSR. But the graphite moderator is planned to be replaced in every 7 years for avoiding risk of damage by neutron irradiation.

3.2.7 Wasteburner[1]

There are two different proposals from Denmark. But both of them call their reactor as "Wasteburner". One of the design is proposed by Copenhagen Atomics. Configuration of the core is not publicly opened thus only image of placement of the reactor is shown in Fig. 9. Based on their whitepaper [32], it is written that their design is similar to MSRE, therefore Wasteburner may be thermal-spectrum reactor using graphite moderator, and fuel salt will be circulated outside the reactor vessel. It must use external heat exchanger because their prototype has 50 MWth in output power.

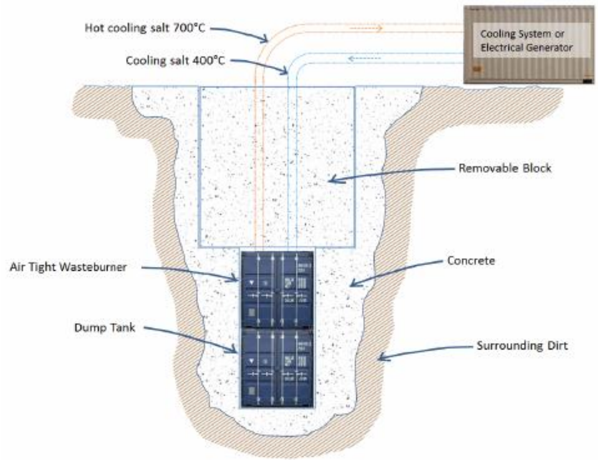


Fig.9 Image of Wasteburner by Copenhagen Atomics.

3.2.8 Wasteburner[2]

There is another MSR in Denmark and it is proposed by Seaborg. They also calls their reactor as "SWaB (Seaborg Technologies Wasteburner)" in their whitepaper [33]. Cross-sectional view of SWaB's reactor core is indicated in Fig. 10.

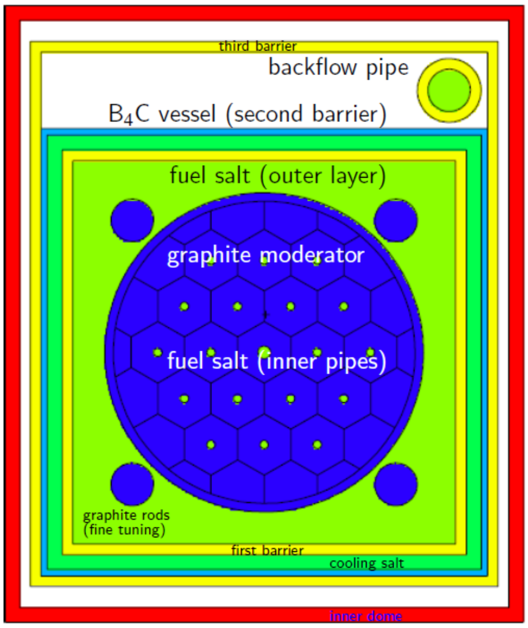


Fig.10 Cross-sectional view of SWaB's reactor core.

SWaB uses graphite moderator by the same way as in MSRE. Output power of its prototype is 50 MWth as the same as Copenhagen Atomics' design. However, the difference between those two Danish companies is that SWaB is targeting up to 250 MWth. Moderator's radius is 1.4 m and height is 2.4 m. SWaB also replaces its graphite moderator in every 4 years as the same way as ThorCon. Heat removal system is following the orthodox configuration of adopting primary circuit, secondary circuit and steam circuit which was proposed in the MSBR. But this reveals that the essential engineering problem relating to MSR for heat exchange still remains in SWaB.

3.2.9 RTMSR

There are many ventures established recently to promote MSR. Most of them do not reveal their idea at first for intellectual property's reason. WAMSR was one of such examples. WAMSR reviewed in 2013 [12] has also less open nformation. Now their idea is opened and technical challenges become also clear. Thoreact is a venture from US Utah Valley University and they are promoting RTMSR [34]. At the moment, reactor configuration is completely unclear due to patent pending. Only the known information is their output power ranging from 2.5 MWth to 1 GWth. If one reactor generate 1 GWth, orthodox configuration of heat removal system of MSBR has to be used. If the same configuration is simply applied for the case of 2.5 MWth, the cost of total system will be very expensive. Thus the author of this paper will re-evaluate the system of RTMSR in near future once it is opened.

In the former part of this section, recently proposed designs of MSR were reviewed from the viewpoint of weakness of heat transfer system especially in heat exchanger of primary circuit. The results unfortunately show that most of the proposals are based on the assumption that "there is no technical remaining problem because MSRE was successfully operated". Though it is not the prime theme in this paper, it should be noticed that primary circuit of MSR also brings another essential subject of difficulty caused by loss of delayed neutron outside of reactor core. This tendency appears more apparent in thorium fuel cycle because uranium-233 generated from thorium-232 has less delayed neutron [13].

4 UNOMI as small MSR

By considering previously mentioned inherent subjects of MSR, the author of this paper has already proposed a small-sized small capacity MSR utilizing thorium named UNOMI (Universally operatable molten-salt reactor integrated) since 2012 [13] in order to reduce extremely the possibility of failure of primary circuit and irradiation damage of moderator. The system configuration of UNOMI is shown in Fig. 11.

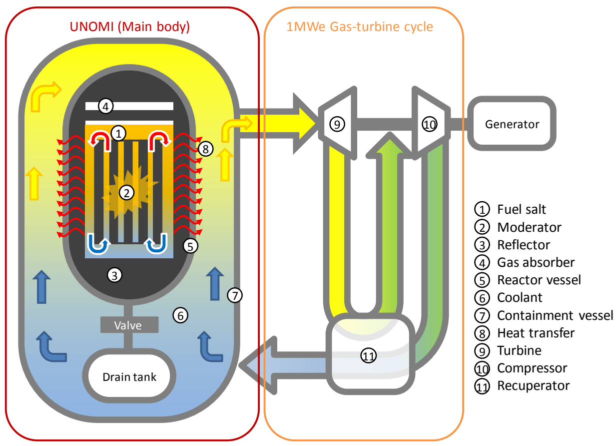


Fig.11 System configuration of UNOMI.

UNOMI'S thermal output is 4 MW for prototype. This may also be a commercial type. Electricity output is targeting to be 1 MWe by gas-turbine generator. Radius and height of the core is 0.7 m and 1.6 m, respectively. Commercially and technically available graphite will be used as moderator. Since there is no direct contact of fuel salt to reactor vessel, UNOMI can apply commercially sold Hastelloy N. Fuel salt flows among the gap which is formed by moderator and reflector only inside the reactor vessel. As can be seen from Fig. 11, there is no pipe which penetrates through the reactor vessel wall. Thus the reactor vessel is merely a closed tank. Preliminary calculation shows that upward velocity of fuel salt in the center of core around 1 cm/s by natural convection. Thus there is no need of pump for forced convection. This slow movement of fuel salt enables most of delayed neutron being released in the core region while it moves from bottom to top of the core. Gaseous FP such as Xe and Kr are naturally separated at the liquid surface. These gaseous FP are absorbed in the activated carbon locating upside of upper reflector.

UNOMI's power density is 1.6 MW/m^3 being 1/14 of MSBR, 1/4 of FUJI and 1/51 of WAMSR, respectively. The small power density is applied to avoid irradiation damage of graphite moderator. Life time of graphite will be 50 years under above power density (UNOMI's design life time will be much shorter being less than 30 years).

UNOMI's most remarkable feature is to remove fission heat only by the radiation from reactor vessel surface. As it is easily imagined, reactor output power increases by a cube of the size but surface area only increases by a square of the size, which determines radiation amount. Therefore, output power exceeds radiation amount for a large reactor. This relation is shown in Fig. 12.

Horizontal axis is radius of UNOMI and vertical axis is thermal energy. Reactor output power is indicated by blue line. Orange line shows upper limit of removal heat from reactor vessel for a smooth surface. Heat flux for calculating removal heat is 157 kW/m^2. This value is smaller than that of heat exchanger of MSBR of 430 kW/m^2. This is because (i) UNOMI's flow velocity of fuel salt is slow enough to achieve large Nusselt number, (ii) wall thickness of reactor vessel is 2 cm increasing thermal resistance. Wall thickness of tube in heat exchanger of MSBR is about 1mm. Figure 12 apparently shows that output power becomes larger than heat removal while output power is larger than 4 MW. Grey line shows a case of heat removal for a rough surface. In this case, heat flux is set to be twice larger than that of smooth surface. The rough surface can remove heat up to about 14 MW. Yellow circles are output powers of other MSRs introduced in this paper. It means that any other designs cannot remove its fission heat by surface radiation from reactor vessel thus they need to use heat exchanger.

Though details are not described in this paper, UNOMI's system configuration having no primary instruments (pipes, pump and heat exchanger) and secondary circuits enables no intermittent replacement of main structure as different from WAMSR, ThorCon, SWaB and IMSR^2. As a result, high economy of energy production can be achieved even by UNOMI having small-sized capacity.

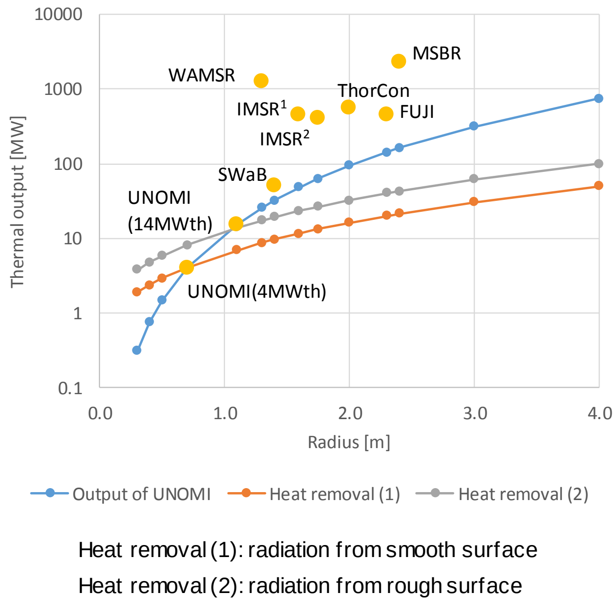


Fig.12 Thermal energy vs. radius of UNOMI.

5 Summary

Recent trend of R&D of MSR was reviewed from a view of small modular reactor. MSR is remarked by its high safety and more than 10 new design concepts have been proposed only in these few years. Even many ventures have been established. Most of those proposals are based on a story that "molten salt reactor is liquid fueled reactor and therefore there is little irradiation damage enabling high power density and compact size with large power output". However, MSR has quite limited, or it should be said that there had only one real experience of existed reactor as compared with LWR. It is concerned that nearly no new designers pay attention to the remaining engineering subjects which have been pointed out since 1970's. However MSR is attractive as small reactor. Therefore, its trend should be paid attention.

Nomenclature

CR Conversion Ratio
DFR Dual Fluid Reactor
FHR Fluoride salt-cooled High-temperature Reactor
FP Fission Products
IMSR[1] Innovative Molten-Salt Reactor
IMSR[2] Integral Molten-Salt Reactor
LWR Light-Water Reactor
MSBR Molten-Salt Breeder Reactor
MSR Molten-Salt Reactor
MSRE Molten-Salt Reactor Experiment
ORNL Oak-Ridge National Laboratory
R&D Research and Development
SMR Small Modular Reactor
SWaB Seaborg Technologies Wasteburner
UNOMI UNiversally Operatable Molten-salt reactor Integrated
WAMSR Waste-Annihilating Molten Salt Reactor

References

[1] International Energy Agency: CO_2 Emissions from fuel combustion highlights, 2015.
[2] International Energy Agency: World Energy Outlook 2015, 2015.
[3] KAMEI, T.: Symbiotic energy demand and supply system based on collaboration between rare-earth and thorium utilization, Nuclear Safety and Simulation, 2011, 2 (2): 178-190.
[4] KAMEI, T.: A study of functions of "The Bank (Thorium Energy Bank)", Nuclear Safety and Simulation, 2013, 4 (1): 67-71.
[5] KAMEI, T.: Preliminary Study of Development of the Organization of Rare-Earth Exportation Countries (OREEC), Journal of Sustainable Development of Energy, Water and Environment Systems, 2013, 1 (1): 1-13.
[6] Nuclear Energy Agency: Introduction of Thorium in the Nuclear Fuel Cycle, 2015.
[7] International Atomic Energy Agency: Status of Small Reactor Designs Without On-Site Refueling (IAEA-TECDOC-1536), 2007.
[8] KAMEI, T.: Thorium MSR as a small-scale energy source - opportunities for Japan, SMR 2011, (2011).
[9] HARTO, A. W. and IMARDJOKO, Y.: Innovative molten salt reactor (IMSR) design, SMR 2011, (2011).
[10] SABHARWALL, P., KIM, E. S., MCKELLER, M. and PATTERSON, M.: Small modular molten salt reactor (SM-MSR), SMR 2011, (2011).
[11] HOLCOLM, D. E., FLANAGAN, G. F., PATTON, B. W., GEHIN, J. C., HOWARD, R. L. and HARRISON, T. J.: Fast Spectrum Molten Salt Reactor Options, ORNL/TM-2011/105, (2011).
[12] KAMEI, T.: R&D of thorium molten-salt reactor (MSR), Nuclear Safety and Simulation, 2013, 4 (2): 80-96.
[13] KAMEI, T.: Recent Research of Thorium Molten-Salt Reactor from a Sustainability Viewpoint, Sustainability, 2012, 4: 2399-2418.
[14] KAMEI, T.: Study of nuclear environment & material strategy, Nuclear Safety and Simulation, 2011, 2 (4): 338-348.
[15] KAMEI, T.: A newly developed accelerator to convert thorium to uranium-233, International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle (URAM-2014) June 23–27, 2014, Vienna, Austria.
[16] ENGEL, J. R. *et.al*: Conceptual Design Characteristics of a Denatured Molten-Salt Reactor with Once through Fueling, ORNL/TM-7207, 1980.
[17] MOIR, R. W.: Cost of Electricity from Molten Salt Reactors, Nuclear Technology, 2002, 138 (1): 93-95.
[18] International Atomic Energy Agency: Assessment and management of ageing of major nuclear power plant components important to safety: Steam generators (IAEA-TECDOC-981), 1997.
[19] MCDONALD, P. E., SHAH, V. N., WARD, L. W. and ELLISON, P. G.: Steam generator tube failures, NUREG/CR-6365, 1996.
[20] http://thorconpower.com/ - Accessed Dec. 14, 2015
[21] http://www.prweb.com/releases/2015/12/prweb13110710.htm - Accessed Dec. 14, 2015
[22] Martingale Inc.: ThorCon The Do-able Molten Salt Reactor, 5 Sep. 2015.
[23] FURUKAWA, K., ARAKAWA, K., ERBAY, L. B., ITO Y., KATO Y., KIYAVITSKAYA H., LECOCQ A., MITACHI K., MOIR R., NUMATA H., PLEASANT J. P., SATO Y., SHIMAZU Y., SIMONENCO V.A., SOOD D. D., URBAN C., and YOSHIOKA, R.: A road map for the realization of global-scale thorium breeding fuel cycle by single molten-fluoride flow, Energy Conversion and Management, 2008, 49: 1832-1848.
[24] Ebasco: 1000 MWe MSBR conceptual design study Final report – Task I, TID-26156, 1972.
[25] HUKE, A., RUPRECHT, G., WEIßBACH, D., GOTTLIEB, S., HUSSEIN, A., and CZERSKI, K.: The Dual Fluid Reactor - a new concept for a highly effective fast reactor, FR13_T1-CN-199-481, 2013.

[26] SCOTT, I. R.: The simple molten salt reactor – safe, cheap nuclear energy at last?, Molten Salt Discussion Group 2013 Christmas Research Meeting, Dec. 16, 2013, London, United Kingdom.
[27] House of Commons Energy and Climate Change Committee: Small nuclear power Fourth Report of Session 2014–15, 17 Dec. 2014.
[28] Energy Process Developments Ltd, MSR Review Feasibility of Developing a Pilot Scale Molten Salt Reactor in the UK, Jul. 2015.
[29] Transatomic Power: Technical white paper, Mar., 2014.
[30] HARTO, A. W.: Reaktor innovative molten salt (IMSR) dengan sistem keselamatan pasif menyeluruh, J. Tek. Reaktor. Nukl., 2011, 13(1): 10-20.
[31] Copenhagen Atomics: White Paper, Affordable Sustainable Clean Energy, Nov., 2014.
[32] LEBLANC, D.: The Integral Molten Salt Reactor (IMSR), 3rd International Technical Meeting on Small Reactors, Ottawa, Ontario, Nov. 5-7, 2014.
[33] Copenhagen Atomics: White Paper, Affordable Sustainable Clean Energy, Nov., 2014.
[34] Seaborg Technologies: Whitepaper, Seaborg Wasteburner Molten Salt Reactor, Mar., 2015.
[35] https://www.ideaconnection.com/new-inventions/portable-molten-salt-thermal-reactor-07234.html - Accessed Dec. 14, 2015