FOR CONF. PROCEEDINGS (COMPACT) *18TH MAY 2007 REV*

PRESENTING AT *ICENES 2007* :

13TH INTERNATIONAL CONFERENCE ON EMERGING NUCLEAR ENERGY SYSTEMS:

3-8 JUNE, 2007, ISTANBUL, TURKEY

A Road Map for the Realization of Global-scale Thorium Breeding Fuel Cycle by Single Molten-Fluoride Flow

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ABSTRACT

For global survival, we need to launch a rapid regeneration of the nuclear power industry. The replacement of the present fossil fuel industry requires a doubling–time for alternative energy sources of 5-7 years and only nuclear energy has this possibility. The liquid metal cooled fast breeder reactors (LMFBR) have the best breeding criteria but the doubling time exceeds 20 years. Further, the use of plutonium in these systems has the potential of nuclear proliferation. The Thorium Molten-Salt Nuclear Energy Synergetic System [THORIMS-NES], described here is a symbiotic system, based on the Thorium-Uranium-233 cycle. The production of trans-uranium elements is essentially absent in Th-U system, giving nuclear proliferation resistance. The energy is produced in molten salt reactors (FUJI) and fissile ^{233}U is produced by spallation in an Accelerator Molten-Salt Breeders (AMSB). This system uses the multi-functional “single-phase molten-fluoride” circulation system for all operations. There are no difficulties relating to “radiation-damage”, “heat-removal” and “chemical processing” owing to the simple “idealistic ionic liquid” character of the fuel. FUJI is size-flexible, and can use all kinds of fissile material achieving a nearly fuel self-sustaining condition without a continuous chemical processing of fuel salt and without core-graphite replacement for the life of the reactor. The AMSB is based on a single-fluid molten-salt target/blanket concept. Several AMSBs can be accommodated in regional centers for the production of fissile ^{233}U, with batch chemical processing, including radio-waste management. FUJI reactor and the AMSB can also be used for the transmutation of long-lived radioactive elements in the wastes, and has a high potential for producing hydrogen-fuel in molten salt reactors. The development and launching of THORIMS-NES requires the following three programs during the next three decades**:** (A) pilot plant: **miniFUJI (7-10 MWe)**: (B) small power reactor: **FUJI-Pu (100-300MWe)**. (C) fissile producer: **AMSB** for globally deploying **THORIMS-NES**.

Keywords: thorium, fission energy, molten-salt reactor, fluorides, spallation reaction, accelerator breeder

1. INTRODUCTION

In the 21st century the stress due to environmental issues like Greenhouse effect, pollution, desertification, and local climate abnormality, as well as social issues like population explosion (100 M per year), poverty and starvation, may become intolerable, leading to large scale social disorder. However, it seems that there are no effective measures for averting such disorder outside from ensuring adequate supply of clean energy.

In principle solar-based technology could provide clean energy, as it will not cause global warming or localized abnormal weather patterns. But solar energy is low in energy density, irregular in output and currently uneconomical and impractical for a large industrial scale. Even with a concentrated effort, the first industrial scale solar energy plant may come on line only after a few decades and large scale deployment to meet projected demand would take more than 50 years after that [cf. **Fig. 1A**]. Therefore, in the intervening time there is no other choice but to rely on nuclear energy, although other efforts such as energy saving, solar energy use etc. are essential still, as shown in **Fig.1C**.

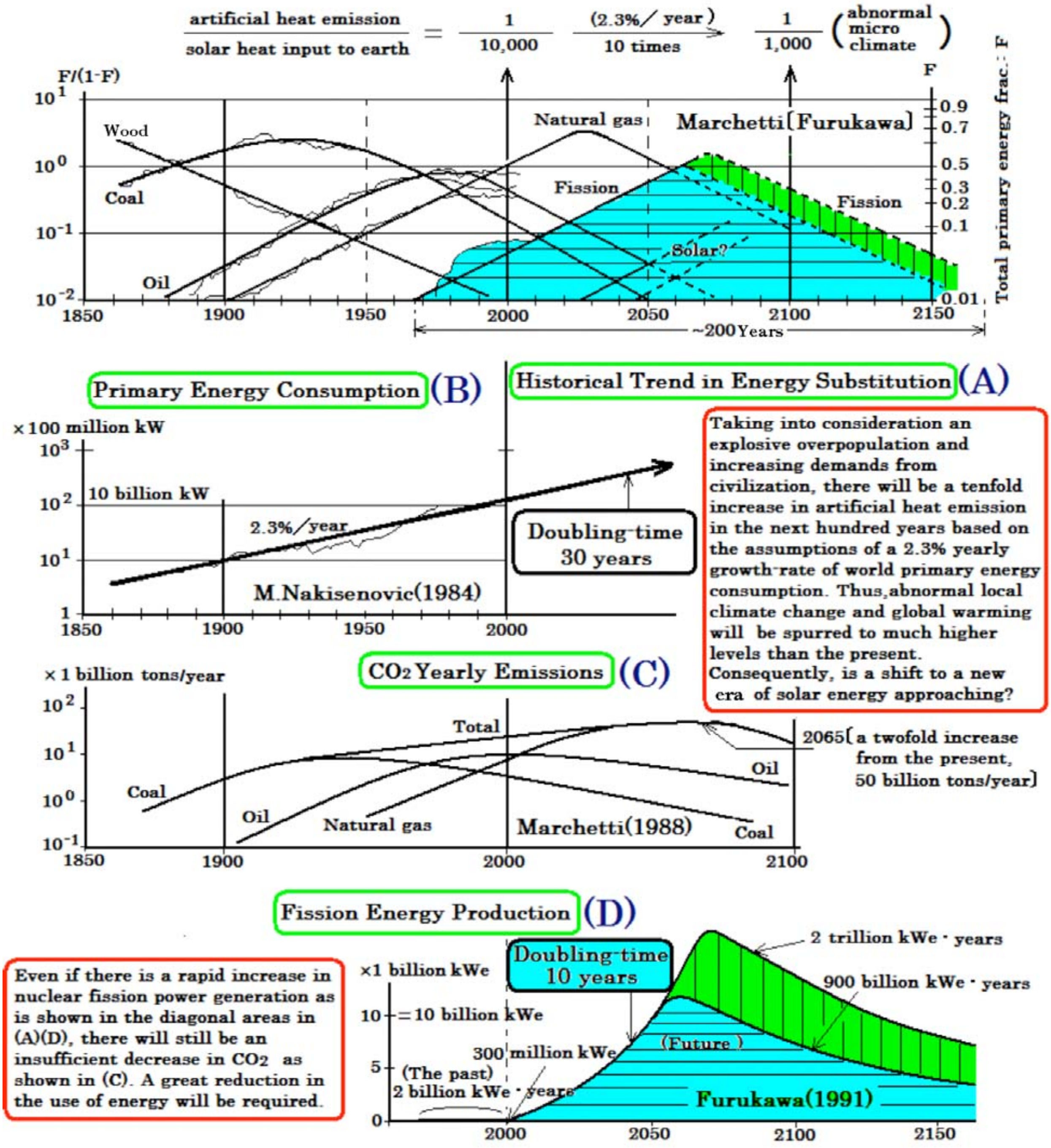
In principle, it is impossible to predict the future. However, a hypothetical prediction--a scenario--based on reliable principles, can be quite useful. A future energy scenario based on initial work of Marchetti (1985)**[1],** and later modified by the members of the Thorium Molten-Salt Forum**[2]** is shown in **Fig. 1A** to **1D**. In **Fig. 1A**, the historical/predicted fractional contribution F from prominent sources is shown as a function of time. In the figure the “logistic function” logarithm F/(1-F) is plotted against the calendar year. The main sources of energy shown are wood in the past, coal, oil and natural gas at present and nuclear and solar for the future. For the solar energy two graphs are shown in view of the uncertainty in the introduction of this source for large-scale deployment. For nuclear energy two scenarios are shown, one with a total nuclear energy production measured in power times years of 900 TWe・year and the other with 2000 TWe・year.

In the past 30 years the market share of usages of all main sources of energy (coal, oil, natural gas and fission) have been surprisingly constant as can be seen from **Fig. 1A** This logistic function analysis suggests that political or financial influences on the energy market have been stronger than market mechanism. A revolution in the global energy strategy is called for by increasing the investment for fission-energy systems so that we return to rising fission use while the market share of other energy sources falls as shown by the curves in **Fig. 1A**.

2. REQUIREMENTS ON NEW NUCLEAR ENERGY (cf. Fig.1)

2.1. Necessity of New Strategy (Brief Summary)

The replacement of the present fossil fuel industry by a fission industry needs to be achieved in the next 30 to 50 years. As shown in **Fig. 1D**, it is essential that the fission industry should grow with less than 10 years doubling–time, for which the practical system performance should be much higher than the above, meaning 5-7 years doubling time. Such a growth rate will never be achieved by any kind of classical **"Fission Breeding Power Station" concept**. Now a symbiotic system coupling with fission and spallation (or D/T fusion, but not yet proven) facilities should be considered, because fission is energy–rich but neutron-poor, and spallation is energy-poor but neutron-rich.**[3]**



Taking into consideration an explosive overpopulation and increasing demands from civilization, there will be a tenfold increase in artificial heat emission in the next hundred years based on the assumptions of a 2.3% yearly growth-rate of world primary energy consumption. Thus, abnormal local climate change and global warming will be spurred to much higher levels than the present. Consequently, is a shift to a new era of solar energy approaching?

Even if there is a rapid increase in nuclear fission power generation as is shown in the diagonal areas in (A)(D), there will still be an insufficient decrease in CO2 as shown in (C). A great reduction in the use of energy will be required.

Fig.1. Prediction of Essential Nuclear Fission Energy Production Scale for the 21st Century

The new Fission-Spallation coupled energy technology should be sufficiently safe eliminating a “severe accident” (cf. Sec.4.4). Radio-waste management should be put in place within one hundred years (cf. Sec.4.6.). Nuclear proliferation resistance should be significantly improved (cf. Sec.4.5). And economy is the most important issue for effective implementation of new huge-size industry, which means that the growth rate should be about 10 years doubling time, and its peak output about 10 TWe (30 times the present) to be achieved by 2065, considering factors such as population and economical growth (cf. **Fig.1**).

2.2. New Technological Requirements.

For the realization of such a global strategy it is essential to have a renewed strong public acceptance of the fission-energy industry; this has yet to be established.

The largest amount of investment in energy resources in the past 60 years has been in the nuclear power. A sound industrial infrastructure for nuclear power has already been established. However, some of the problems for which the technological community has been seriously seeking solutions are:

(A) Safety: improved recently, but doubtful in preventing severe accidents such as “Chernobyl” in the case of a huge earthquake, military or terrorist attack and sabotage.

(B) Reliability: Simplifications in design that result in high reliability and easier operations and maintenance will aid worldwide deployment.

(C) Economy: better economics than the other energy technologies is needed.

(D) Environmental acceptance: public acceptance of nuclear power is based on climate change and pollution. Radio-waste management should be significantly improved by changing the character of the nuclear fuel-cycle to include economical nuclear transmutation.

(E) Social acceptance: it should meet several local district demands such as power size flexibility, nuclear material transportation, electric power transmission, failure and accident support, etc.. The most important is the next issue.

(F) Nuclear proliferation resistance: the world situation is becoming worse due to the confusion of NPT regime, the weak consensus on the human/national “right”, etc.. The military benefit character of U-Pu fuel-cycle worsens proliferation, whereas the Th-U fuel cycle increases proliferation resistance.

(G) Resource problem: it will become much important in the future utilizing the huge size nuclear industry.

Many countries are somewhat reluctant to fully accept nuclear power and some are even planning a phase out of the existing nuclear power reactors. Even Germany in recent reconfirmed the non-nuclear energy way. This reluctance to fully accept nuclear power comes from the lack of solutions to the problems just listed, (A)- (G). The international efforts for the development of advanced reactor systems to address these issues in the Generation IV International Forum (GIF) guided by USA and the IAEA-INPRO is getting nowhere.

But a completely new approach is called for to meet the future energy challenges. As an example, one of the most popular magazine, “Newsweek”, presented an article in the new Year 2007 edition**[4]** titled “The Lost Chance” insisting that “the most promising path towards proliferation-resistant fuels is to return to the road not taken 50 years ago—thorium fuel cycle---“.

3. REEXAMINATION OF NUCLEAR FISSION TECHNOLOGY AND FUEL CYCLE

3.1.The present situation

All current nuclear power plants use “solid” uranium (and plutonium) fuel. This is related to the needs of nuclear armament. However, the current anxiety about nuclear proliferation in the world is leading to their phasing out without replacement. A serious consequence of the U-Pu cycle dominance is that over the last 30 years, almost all textbooks on Nuclear Engineering have ignored the Thorium Reactor issue and the fluid-fuel reactors including MSR. Therefore, the present nuclear engineers have little knowledge of and hesitate to think about thorium and fluid-fuel reactors.

Most of the difficulties relating to safety and economy could be solved by the application of a “fluid” fuel concept; this was recommended by Wigner on 1943**[6]** (cf, Sec.6). Historically there have been many unsuccessful fluid-fuel reactors. On the basis of this, many people think that MSR also might have unknown technical difficulties. (This was partly caused by the discovery of the Te-attack phenomena on Hastelloy N after dismantling of MSRE on 1970.) This was solved nicely during the final R&D stage (1972-76) in ORNL**[7].** USSR research group of Kurchatov Inst. reconfirmed it getting better results**[8].** However, nobody seems to refer on these works beyond 1970**[9].** The situation is much worse owing to the followings fact: among the several fluid-fuel concepts the most successful one is the molten fluoride salt fuel, which was developed by the Oak Ridge National Laboratory (ORNL), USA through the Molten-Salt Reactor Program (MSRP) during 1957 to 1976**[7].**

The excellent simplicity and rationality of the technological principle probably resulted in the “technological **non-popularity**” with the abandonment of further development after its termination at ORNL. The reasons are i) relatively few people are interested on the technology, ii) little outside contact was made due to isolated site, iii) almost no news came out due to the “no accident: full success”, iv) low budget, v) no publicity for work, secret due to military purpose initially, and small funding afterward.

Such R&D works including MSR were terminated more than 30 years ago owing to the apparent success of solid-fuel reactors; however the U-Pu breeding fuel cycle after spending 60 years is still not established.

3.2. Thorium Fuel-Cycle.

Naturally occurring thorium (^{232}Th) is used as a fertile material in a reactor. The following nuclear reaction occurs in this case:

$$^{232}\text{Th} + \text{n} \dashrightarrow {}^{233}\text{Th} \xrightarrow[22\text{ m}]{\text{beta}} {}^{233}\text{Pa} \xrightarrow[27\text{ d}]{\text{beta}} {}^{233}\text{U}$$

Uranium-233 (^{233}U) is a nuclear fuel capable of sustaining a fission chain reaction in a nuclear reactors or a nuclear weapon. It is practically impossible, or at least very difficult, to use reactor produced ^{233}U for making nuclear weapons. It would also be very difficult to hide because of the ^{232}U contamination. The half-life of ^{232}U is 69 years, which is short enough to rapidly yield highly radioactive daughter products, but long enough to ensure that it is present along with ^{233}U for a long time. Thus a reactor system that uses ^{233}U-^{232}Th based fuel cycle, instead of ^{239}Pu-^{238}U fuel cycle, would minimize the risk of nuclear proliferation.

^{233}U is suitable for thermal reactors, but ^{233}U fuel is accompanied with strong gamma activity requiring a fluid-type fuel technology. In addition, the use of thorium, which is 3 to 4 times more abundant than uranium in the earth's crust, would ensure a sustainable supply of energy for a longer period**[5]**. From the nuclear waste point of view a ^{233}U-^{232}Th system would produce hardly any trans-uranium elements (TRU), which are a cause of serious concern in ^{239}Pu-^{238}U based systems, and can dominate waste management.

3.3. Molten Fluoride Salt Fuel Application.

In a molten salt reactor (MSR) the fuel is uranium fluoride UF_4 (uranium as ^{233}U or enriched uranium) dissolved in a molten fluoride salt. Plutonium as PuF_3 can also be used a fuel, and ThF_4, thorium being the fertile material for conversion to ^{233}U. The solvent salt is a mixture of ^{7}LiF and BeF_2, has low thermal-neutron cross-section material and is a good solvent of fissile and fertile material fluorides. This liquid is **multi-functional** not only as nuclear reaction medium useful for fuel, target or blanket, but also as heat-transfer and chemical-processing mediums, which were essentially verified by ORNL[7].

The fuel salt is contained in a nickel alloy vessel with the bulk of the space being occupied by moderator graphite. A stream of fuel salt is pumped to an external heat exchanger and cooled by a coolant salt. The fuel outlet and inlet temperatures are about 700°C and 550°C, respectively. As the fuel salt boiling temperature is about 1400°C there is no need to pressurize the system. Gaseous fission products xenon and krypton are continuously removed by sparging the salt with helium gas. There is no need to have an excess quantity of fuel, required to run the reactor for an extended period, since fuel can be added continuously to the salt while the reactor is operating. These Characteristics give many advantageous features to the MSR as shown in **Table 1**.

Table 1. Main Advantages of MSR compared with Proven Solid-Fuel Reactors

	Solid-Fuel Reactors.	New system: MSR	Advantages of MSR
Fertile fuel	^{238}U	^{232}Th	few Trans-U produc.
Fissile fuel	^{235}U, ^{239}Pu, ^{241}Pu	^{233}U(^{235}U,^{239}Pu,^{241}Pu)	high fission-n yield
Fuel form	solid	liquid :molten-salt	easy fuel management
Fuel material	oxide, alloy, carbide, nitride	fluoride-melt	no radi.damage, inert high heat cap.;low pres.
Moderator	H_2O, D_2O, Be, graphite	graphite	high melting temp., high radi. resistivity
Coolant	H_2O, D_2O, He, Na	fuel-salt	multi functional
Elect. generat.	lower temp. steam	supercritical steam	high therm. efficiency
Fissile breeding	fission breeder (low performance)	simple near breeder +accel. breeder	short doubling time, flexible power-size
Safety	high excess reac. Core melt.	very low excess react. Fuel isolat. & glassifi.	easy criticality cont. no severe accident
Nucl. proliferat.	Pu:weak gamma-ray	^{233}U: strong gamma	easy safeguards

Some of these are shown in the following items, even more detailed explanations are given the following sections:

a) Unlike the conventional systems there is no scenario called 'fuel melt down'.

b) The fuel inventory in the reactor is small which brings down cost and has favorable implications for safeguards.

c) Excess reactivity is small since there is no need to provide for xenon over-ride, and with online refueling no need to make provision for fuel consumption. Thus, there is no chance for large power surges, an important safety concern in conventional reactors.

d) Most gaseous fission products (xenon, krypton etc.) are continuously removed so there is no danger of release of these radioactive products if there is a sudden rise in the fuel temperature.

e) Molten fluorides are stable to the reactor irradiation, because they are simple ionic liquids.

f) Molten fluorides do not undergo any violent chemical reactions with air or water.

g) Reactors have full passive safety. Under accident conditions the fuel is automatically drained into passively cooled critically safe storage tanks.

h) The reactor can use a variety of fuels (^{233}U, Enriched uranium, plutonium) and even TRU can be served as supplementary fuel.

i) No fuel fabrication is required and this is advantageous when you have feed materials with a widely varying isotopic composition. This also makes transmutation of TRU easy in these reactors.

j) High temperature of the fuel salt permits higher conversion efficiency and even holds promise for other heat based applications e.g. hydrogen production.

k) There are no limitations on the fuel burn up.

l) Depending on the fuel used, the conversion ratio in the reactor can range from 0.8 to 1.0. This implies that the reactor would essentially be using in-situ produced ^{233}U as fuel and only a small external input is required.

m) Several non-proliferation advantages of the system are given in the Sec.4.5.

n) The necessary thorium resources will be 2-3 M-tones to produce 900 TWe・y (cf. Fig. 1D.), if the breeding fuel-cycle is established.

Historical unhappiness in the Seventies: The success of MSRE operation and MSBR design study of 1968-70 was significant, and really several countries and groups of USA, France, EC, India, Japan, etc. were aiming to work with ORNL. US-Congress cut its budget once in 1971 due to the non-interest of major plant-makers due to the plant simplicity (no expectation to get a profit from that construction, as you know the makers are enjoying the solid fuel-assembly fabrication profit still.) and their enjoyment of LMFBR jobs at that time. The next year MSR had been restarted, (and in 1977 President Carter had personally recommended MSBR development rather than LMFBR to Japan,) but in 1976 MSR was terminated politically by the "Breeder Moratorium" not depending on the technological reasons**[10].**

Now many aspects have changed worldwide relative to nuclear fission. The MSR reactor concept has been included as a potential system for the Generation IV reactors with a very small research effort. In

Japan the members of the Thorium Molten Salt Forum getting the cooperation of many foreigners have been trying to advance the concept developed at ORNL. These researchers have proposed a Thorium Molten-Salt Nuclear Synergetic System (THORIMS-NES)**[11,12],** which attempts to address nuclear energy issue with a long-term perspective (cf. Sec.4.1).

It will be briefly summarized in the next Sec.4.

4. THORIUM MOLTEN-SALT NUCLEAR ENERGY SYNERGETICS [THORIMS-NES]

4.1. Basic Concept

THORIMS-NES depends on the following three principles**[11,12]:**

[I]Thorium utilization: Natural thorium has only one isotope, ^{232}Th, which can be converted to the fissile ^{233}U. However, ^{233}U fuel is accompanied with strong gamma activity. This strong gamma activity is difficult to handle with solid fuel but is not with a fluid-type fuel technology.

[II]Application of molten-fluoride fuel technology: The molten salt ^{7}LiF-BeF$_2$ (Flibe--named by ORNL) is the best solvent of fissile and fertile materials and has the required low thermal-neutron cross-section. This liquid is **multi-functional** being not only the nuclear reaction medium useful for fuel, target or blanket, but also as heat-transfer and chemical-processing media. This functionality has been verified by ORNL**[7].**

[III]Separation of fissile-producing breeders (process plants--AMSB: Accelerator Molten-Salt Breeder) and power generating fission-reactors (utility facilities--MSR: Molten-Salt Reactor): This separation will be essential for the global establishment of the breeding-cycle, which is required if the doubling time of 10 years or less as mentioned in Sec.2 is to be achieved. The power stations should be simple, safe, economic and flexible in applications as "utility facilities".

Our concept is composed of **simple power-stations** MSR named **FUJI- series**, **fissile-producers AMSB**, and **batch-type process-plants** establishing a symbiotic Th breeding fuel-cycle system [THORIMS-NES], which has a high public acceptability.

Its general characteristics are given in **Table 2.**

Molten-Salt Power Reactor FUJI

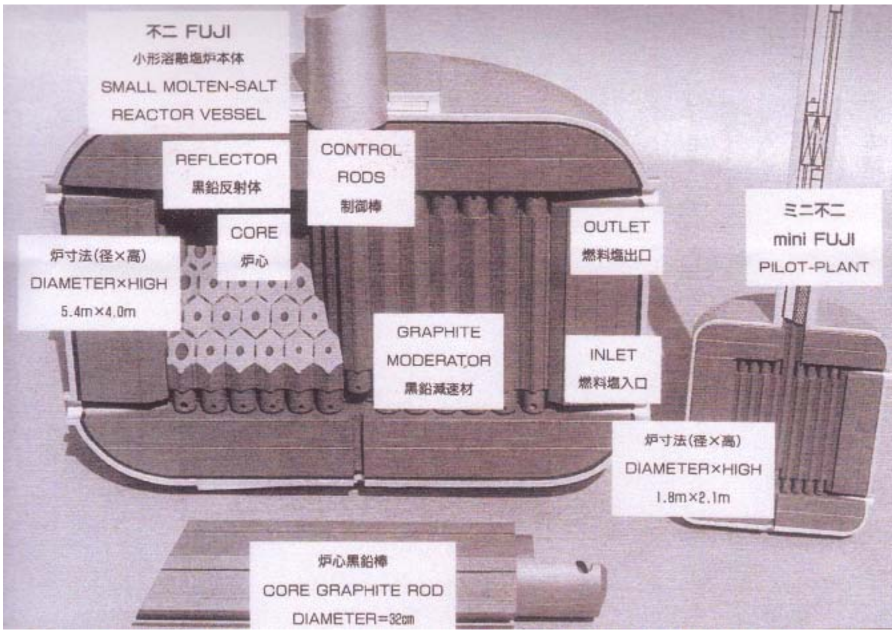
The basic conceptual design of FUJI was established in 1985**[13]** based on the ORNL studies. This design has a simplified structure and is easy to operate and maintain, compared with the ORNL proposed Molten Salt Breeder Reactor （MSBR） of the 1970s. In FUJI the conversion ratio approaches unity and, therefore, it is almost self-sustaining in nuclear fuel reproduction. Construction and operation of a FUJI reactor would herald the first step toward a nuclear proliferation resistant nuclear energy system. A schematic of FUJI reactor is shown in **Fig. 2** and **3**.

FUJI is size-flexible, but typical values are 150 MWe for FUJI-II**[13]**, and 200 MWe for FUJI-U3**[14].** In initial stage Pu burner version, FUJI-Pu, will be operated aiming at the elimination of plutonium though its use for production of energy as well as ^{233}U **[15].**

The reactor vessel is a weld-sealed simple tank, which contains molten-salts with low pressure and unclad graphite. The graphite occupies 90% of the volume and moderates the neutrons. The fuel salt flows upwards at about 1 m/sec. and then goes to an external heat exchanger for transfer of heat to a coolant salt. If the fuel salt leaks, the nuclear reaction will automatically stop, preventing re-criticality. There is no possibility of an extremely dangerous explosive accident in which radioactive substances are released into the atmosphere like that which occurred in Chernobyl.

Table 2. Global Energy/Environment Problems and Achievable Solutions by THORIMS-NES[Thorium Molten-Salt Nuclear Energy Synergetics]

	TECH. PROBLEMS	***ACHIEVEMENTS***	**NEW FISSION TECH.**
RESOURCE	***U*:localized, monopolized**	***Th*: non-localized, popular**	^{232}Th + n ↑ ^{233}U
ENVIRONMENTAL ADAPTABILITY (FOSSIL FUEL)	**thermal pollution** **acid rain** **Greenhouse effect**	**low: high therm.efficiency** **no NOx, SOx** **no CO_2, CH_4**	
RADIO-WASTES	***Trans-U [Pu, Am, Cm]*** **Kr, Xe, T release** **low-level waste(mainte.)**	***negligible production*** **always isolated from core** **minimize by few mainte.**	***Th - ^{233}U*** **CYCLE**
NUCLEAR -PROLIFERAT. & -TERRORISM	**military diversion** **Plutonium(weak gamma)** **safeguard difficulty**	**no Pu-produc. ,*Pu-burnable*** **^{233}U*(highgamma from ^{232}U)*** **easy safeguard**	
SAFETY FUNDAMENTAL	**chemical reactive** **mechanical failure** **nucl. excess reactivity**	**chemical inert** **low pressure, low flow** **very low, *fuel self-sustain*.**	***MOLTEN-*** **FLUORIDE FUEL**
ENGINEERING	**SOLID-FUEL ASSEMB.** **configuration, operation, transport, reprocessing** **core-melt, re-criticality**	***LIQUID FUEL*** **(fuel :*no radi. damage*)** **all simpler & fewer** **NO SEVERE ACCIDENT**	***triple functional:*** **nuclear reaction** **heat transfer** **chem. processing**
BREEDING FUEL-CYCLE	**completion difficulty** **doubling time: too long**	**Simple:Molten-Salt Fuel-cy.** **short: 5 〜 10 years by *AMSB***	
SOCIAL ADAPTABILITY POWER-STATION	**siting difficulty** **large power size** **process-heat : not easy**	**easy : near to utility** **smaller : size flexible** **easy:industrial, district heat**	**SEPARATION of *BREEDING* & *POWER GENE*.**
ECONOMY	**safety, nucl.prolif., rad-waste**	**large improvement**	



[Left]Standard FUJI reactor vessel model (5.4m diameter x 4m height x 150 MWe). Inner part is 90% graphite with fuel salts flowing upward channels at 1m/second.

[Right] miniFUJI reactor vessel model (1.8 m diameter x 2.1m height x 7 MWe).

Fig. 2. Cross-section View of FUJI and miniFUJI Reactor Vessel Models

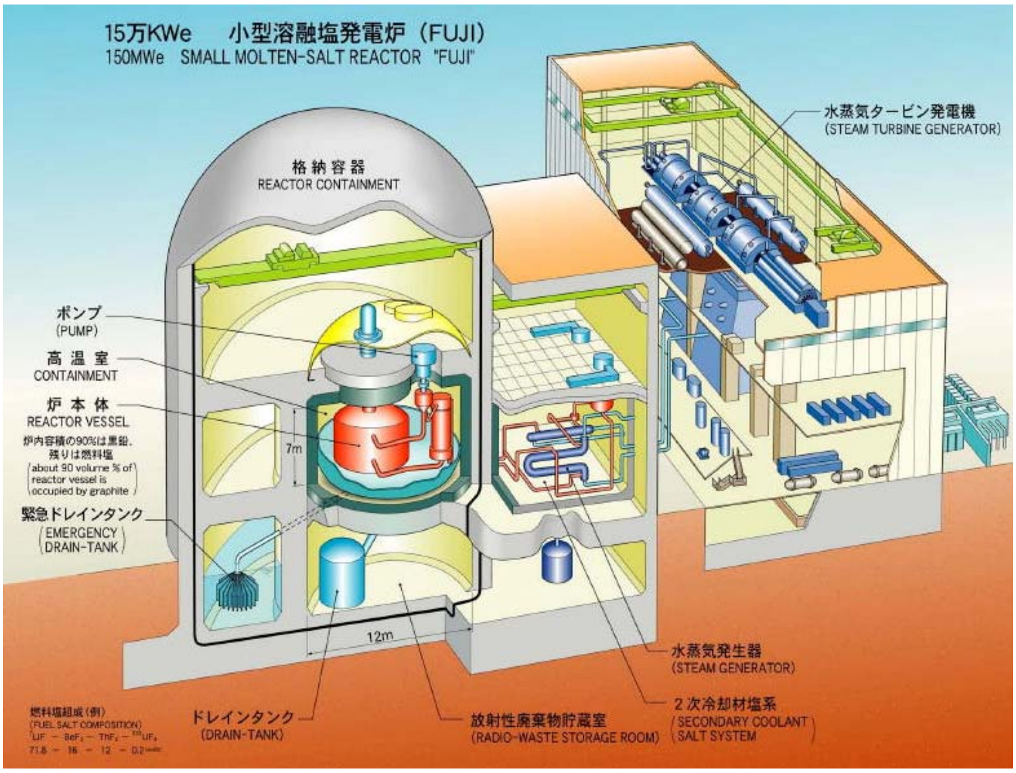


Fig. 3. Full View of FUJI Molten-Salt Reactor

The graphite moderator does not require replacement during the reactor's lifetime unlike, in the MSBR design. This results from using a lower neutron flux and higher graphite volume-ratio in the core, and gives a higher conversion ratio (CR) due to the improved neutron moderation and the lower neutron absorption by ^{233}Pa before its transmutation to ^{233}U.

The reactor vessel is a weld-sealed simple tank, which contains molten-salts with low pressure and unclad graphite. The graphite occupies 90% of the volume and moderates the neutrons. The fuel salt flows upwards at about 1 m/sec. and then goes to an external heat exchanger for transfer of heat to a coolant salt. If the fuel salt leaks, the nuclear reaction will automatically stop, preventing re-criticality. There is no possibility of an extremely dangerous explosive accident in which radioactive substances are released into the atmosphere like that which occurred in Chernobyl.

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Continuous chemical treatment of the fuel salt is not envisaged, therefore, the reactor can operate continuously without shut down. Radioactive Krypton (Kr), Xenon (Xe) and Tritium (T) are constantly removed from the reactor not only to improve the conversion ratio (neutron economy) but also to prevent the accumulation of these gaseous radioactive products and their leakage in case of containment break accident, and thus enhancing safety.

As the operation of FUJI has been greatly simplified, it has a good fuel cycle economy. Since the conversion ratio is high, the annual supply of the fissile material is very small. For the case of FUJI-U3, the initial inventory of fissile material is 0.83 ton, and totally supplied fissile is 0.63 ton for 30 years operation at 75% average load factor. As for the supply of fertile material of thorium, the initial inventory is 41 ton, and totally supplied fertile material is 4.7 ton for the same condition. One of the benefits of MSR is a very small amount of production of Pu and MA (Minor Actinides). For the case of FUJI-U3, total production of Pu in final is only 1.6 kg, and MA (mostly Neptunium) is also only 5.4 kg, for the same condition.

Fissile material must be added to the fuel a few times per year in order to compensate for a small shortfall in breeding. This is estimated to be equivalent to about 400 g per day of thorium salt.

Recent studies by one of the authors indicates that FUJI can achieve CR=1.0 during its full life. This optimized design for 200 MWe sized FUJI can operate for up to 30 years with the initial fissile inventory of 1.6 ton only. The residual 1.6 ton fissile ^{233}U after 30 years operation can be used for the next reactor**[16].**

Conversion efficiency for thermal to electrical power is 44 % as compared with 33 % for the current LWRs. The reactor can also be flexibly operated in a load-following mode by using the movement of a graphite rod, which slightly changes the neutron moderation in the core. One of the authors recently showed two other possibilities, (i) to change the core flow rate, which is a proven technology in BWR**[17]**, and (ii) to use a turbine/master–reactor/slave control, which is also proven in PWR**[18]**. Therefore, FUJI has three different control measures that make FUJI easy to operate in a load-following mode.

The intrinsic safety of FUJI means it can be built relatively near industrial parks or urban areas, making it possible to reduce the need for long distance electric transport networks, and simplifying and extending their application worldwide.

Fig. 4 shows a sectional view of miniFUJI**[19]**, a reactor of 7 MWe, which should be built first to renew experience in operating a molten salt reactor. This has a similar size to the Molten-Salt Reactor

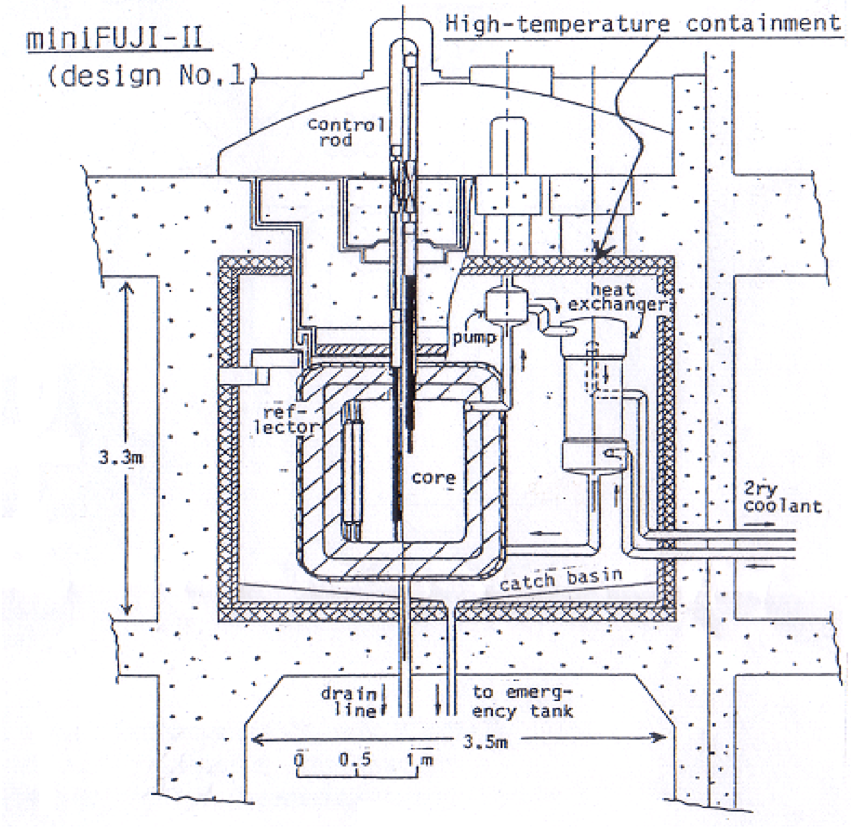


Fig. 4. miniFUJI Concept blueprint [main piping: 8 cm in diameter]

Experiment, MSRE, in ORNL. The miniFUJI vessel would be 1.8 m diameter and 2.1 m height, and the main pipe work 8 cm in diameter resulting in much easier construction than MSRE with its 15 cm piping due to the bigger temperature difference between the inlet and outlet of the reactor. The first aim is to recover basic MSR technology that existed at ORNL 30 years ago. However, miniFUJI is also to demonstrate reactor integrity including the electric generation function and the high temperature containment of the primary system. MSRE is shown in **Fig.5.,** which was successfully operated 17,655 hrs without any accident.

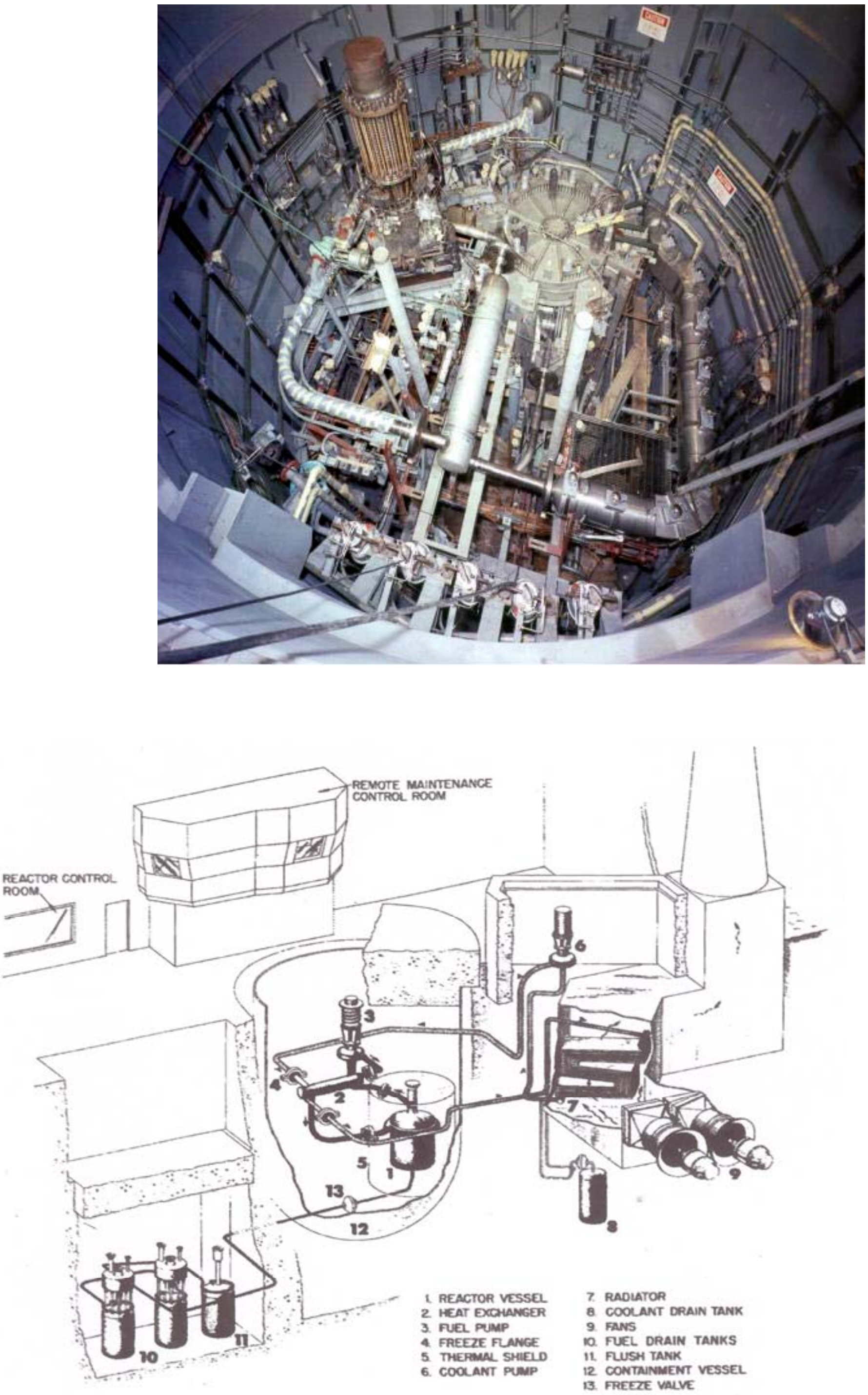


Fig.5. Molten-Salt Reactor Experiment (MSRE) operated from 1965-69 at Oak Ridge National Laboratory, USA

4.3. Accelerator Based Nuclear Fuel Breeding Facility AMSB

During the 1980's, the technical feasibility of AMSB**[20,21]** was established based on a "single-fluid target/blanket concept" using the same kind of molten-salts as FUJI, except with a higher ThF_4 content to establish an idealistic single-phase molten fluoride fuel-cycle.

AMSB is composed of three parts: (1) 1 GeV and 200-300 mA proton accelerator, (2) single-fluid molten fluoride target/blanket system and (3) heat transfer and electric power recovery system. The diagram of the system is shown in **Fig. 6**. The size of target/blanket salt bath is 4.5 m in diameter and 7 m in depth. The modified Hastelloy N vessel is protected by the graphite reflector. The salt is introduced at the top forming a vortex of about 1m in depth. The proton beam is injected in an off-centered position near the bottom of vortex, to minimize the neutron leakage and improve the generated heat dissipation.

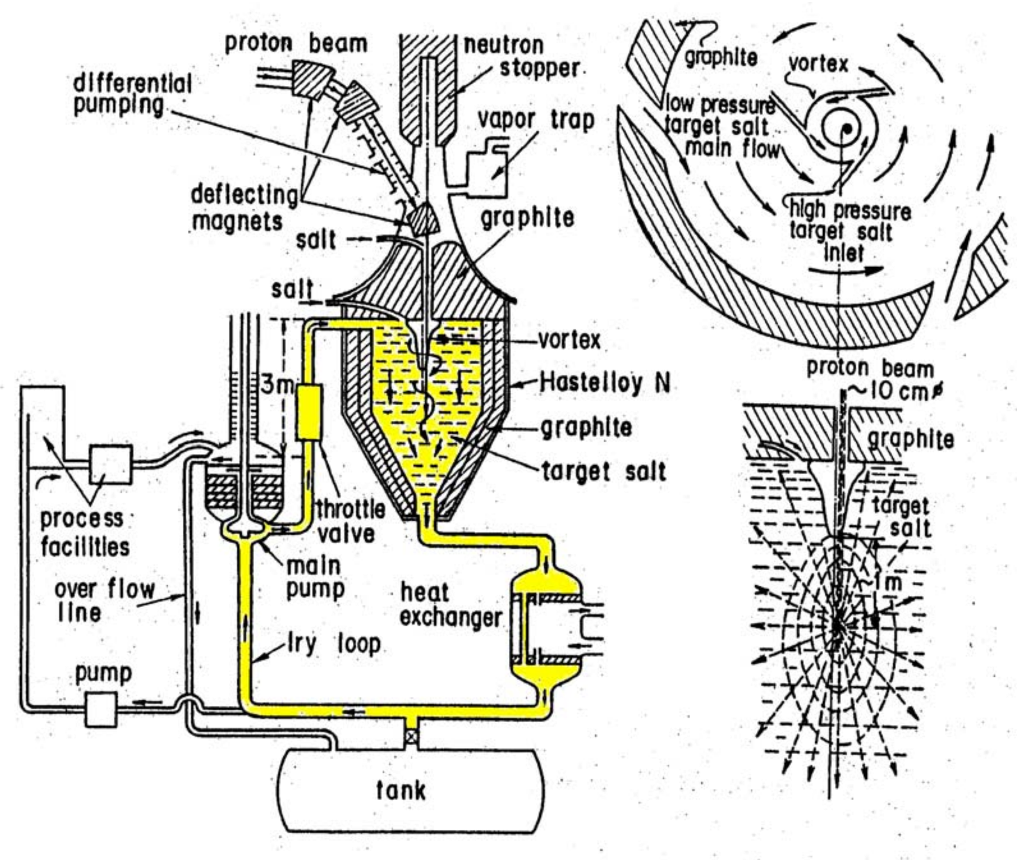


Fig.6. Schematic Figure of Single-Fluid Molten-Salt Target/Blanket System in Accelerator Molten-Salt Breeder (AMSB).

This target/blanket molten-salt system is sub-critical, not affected by radiation, makes heat removal easy, and doesn't need target shuffling. The design of the beam injection port will be aided by improved gas-curtain technology. Engineering this simple configuration, based on the MSR technology, will be manageable. The high proton current accelerator will utilize multi-beam funneling.

The spallation neutrons transmute Th to ^{233}U and also cause fission in the target. The following two items need to be considered. i) Suppression of the fission of produced ^{233}U, ii) Utilization of the fission energy in the target/blanket salt for energy feedback for the operation of AMSB. A heat output power of about 1400 MWth is required to achieve the power for the accelerator proton beam of 1 GeV, 300 mA.

The above two requirements will be satisfied by adding Pu to the flowing target salt7s composition: $LiF-BeF_2-ThF_4-233UF_4-{}^{239}PuF_3$**:** 64-18-17.15-0.3-0.55 mol% for example. The role of Pu component is the same as FUJI-Pu, that is, burning itself and increasing the net production rate of ^{233}U. The annual net production rate of ^{233}U is about 700 kg/y in this case under the following beam and target conditions**[22].**

Proton beam : (1 GeV, 300 mA); Target/blanket size: (4.5m in diameter, 6m in depth),
Initial fissile/fertile inventory: (^{233}U: 2240 kg), (^{239}Pu: 4200 kg), (^{232}Th: 28 Mg)

Power recuperation in the AMSB is desirable, but not essential. It will be one of the functions determining the total efficiency of the electric power network, AMSB and FUJI reactors.

4.4. Safety **[22,23]**

In general, both the FUJI and AMSB systems have no intrinsic features capable of causing severe nuclear accidents and are therefore very safe to operate.

The primary and secondary loops operated at very low pressure (0.5 MPa). Therefore, MSR will have a very low possibility of a destruction of the system or a large salt leakage caused by a pipe break. There is no danger of fire because the molten salt is chemically inert. The low thermal shock in the molten-salt system, in general, represents an advantage over the liquid-metal system.

Because the boiling point of fuel-salt is high (about 1,700 K) compared to the operating temperature (about 970 K), the primary loop pressure remains low under realistic accident scenarios. In addition, a pressure increase from steam/gas generation cannot occur in the containment system due to lack of water or hydrogen generation.

Leakage of fuel-salt from anywhere in the circuit is collected into a drain-tank by gravity. In the absence of moderator graphite the fuel-salt is sub-critical, therefore, leaked fuel-salt will not induce a criticality accident, and can be frozen as a stable glass. Essentially as there is **no chance of "severe accidents"**, the MSR system will always be safer than any other nuclear reactor even under military attack or internal sabotage.

In the case of an intermediate heat-exchanger break, coolant-salt ($NaBF_4$-NaF) will be mixed with fuel-salt. This means the boron introduction will induce reactor-shutdown without any severe chemical heat generation. In the case of a steam-generator break, coolant-salt is nearly inert to the leaked steam and the pressure surge can be mitigated by a rupture-disk design.

The MSR has a large negative temperature coefficient, and can suppress an abnormal reactor power excursion. Because the heat capacity of graphite is large, resulting only in a slow temperature increase, it is possible to control the reactivity even though the temperature coefficient of graphite is positive.

The gaseous fission-products such as Kr, Xe, and tritium, mostly produced from ^{7}Li, can be continuously removed from the fuel-salt during reactor operation. Therefore, the possibility of an environmental release of radioactivity can be significantly decreased in an accident. Daily tritium release could be reduced to less than 3×10^{10} Bq (1 curie) per day in the FUJI**[7].**

As part of the stripping system to remove fission gases, small He bubbles circulate in the fuel salt loop. If primary loop integrity is lost, the pressure may reduce and the bubbles expand. Since the void reactivity coefficient of FUJI is positive, the incident could result in a reactivity insertion accident. The depressurization accident without scram in the FUJI has been analyzed in the case of one version, FUJI-12. The maximum inlet fuel temperature was 920 K in the event of a break at the outlet of the core. The maximum outlet temperature was 1160 K in the event of a break near the inlet of the core. Thus the depressurization accident without scram can be stabilized within the safety limit**[24].**

Since the composition of fuel-salt can be adjusted any time, the excess reactivity is very small. Therefore, the reactivity control required from the control-rods becomes very small. This means that failures in the control-rod system will not lead to severe reactivity changes. A preliminary analysis of reactivity insertion accident has been reported in this Conference separately**[25]**.

Since the delayed-neutron fraction of ^{233}U is smaller than that of ^{235}U, and in addition half of the delayed-neutrons are generated outside the core, the effective delayed-neutron fraction becomes smaller. However, it is possible to control the reactor safely owing to a large negative temperature coefficient of the fuel-salt.

The MSR has three containment barriers (same as the LWR). The first one is the primary system of reactor vessel and primary loop pipes, which contain the fuel. The second one is a high temperature containment round the primary system. The third is the reactor building, which contains all radioactive constituents. These three barriers are all strong and extremely reliable.

These facts attest that THORIMS-NES technologies possess superior safety characteristics.

4.5. Proliferation Resistance and Safeguards[22]

In terms of proliferation resistance ^{233}U is much better than Pu, because it is always contaminated with inseparable ^{232}U. The radioactivity due to daughter nuclides of ^{232}U, e.g. ^{212}Bi and ^{208}Tl, can be cleaned by chemical processing but it rapidly builds up again within days. This radioactivity makes the diversion of ^{233}U difficult and safeguards relatively easy. Th-U fuel cycle produce only a small amount of fissile TRU nuclides including Pu. This will greatly contribute to improving the global implementation of nuclear non-proliferation and lowering safeguard expenses. Some details are given below:

4.5.1. Macroscopic View in Global Fuel Cycles

The amount of Pu in spent fuel from various thermal reactors is steadily increasing in the world. Expansion of nuclear power based on the U-fueled LWRs or HWRs will accelerate this increase. Pu brings proliferation risks even when it remains in spent fuels and should be subjected to more stringent safeguards as compared to that for fresh low enriched U fuel. Even if spent LWR/HWR fuels are deposited in deep geological stratum, it would form a potential future “Pu-mine”, as the radioactivity of fission products decays in 200-300 years.

However, when spent LWR/HWR fuel is reprocessed for waste volume reduction, or for conservation of energy resources, proliferation risks will increase unless there is a good scheme to utilize separated Pu. When the Pu is recycled in LWRs, i.e. LWR-MOX cycle, the problem will not be much improved from the usual LWR cycle. On the other hand, if the Pu is used in FBR cycle other issues arise as discussed in section 4.5.2. Therefore, Thorium fuel cycle development through Pu incineration by THORIMS-NES is the best scheme for enhancing the share of nuclear in electricity production. This aims at i) producing nuclear energy, ii) utilizing the energy potential of Pu in the spent fuel without generating material desirable for weapons use, and iii) generating ^{233}U which can eventually lead to near elimination of proliferation concerns in nuclear energy production.

4.5.2. Pu vs ^{233}U (FBR vs FUJI)

Significant quantity (SQ) in nuclear safeguards is 8 kg for Pu and also 8 kg for ^{233}U, but diversion of ^{233}U for a weapons program will be significantly difficult if not impossible. One core fuel-assembly of an FBR, which is rather small in size and easy to handle and conceal for the diversion or theft, usually contains about 1 SQ of Pu. One blanket fuel-assembly for an FBR has lower Pu concentration than the core assembly, and several blanket assemblies are required to get 1 SQ of Pu. But plutonium in the blanket is close to the weapons grade and attractive to potential diverters. On the other hand, fissile material concentration in FUJI fuel is very low (≅0.1-0.2 mol %), and would require diversion of 1-2 tons of salt to get 1 SQ. Moreover, Pu in FUJI-Pu fuel would usually contain significant concentration of higher isotopes of Pu making it less attractive for weapon use.

Uranium-233 in FUJI usually contains more than 500 ppm **^{232}U** and its daughter nuclides **[13]**, some of which emit strong high energy (^{208}Tl, 2.6 MeV) gamma rays. They bring lethal dose of 1-2 Sv/hr at 50 cm distance from 1 SQ (8 kg) of ^{233}U. More than 20 cm thick lead or 1 m concrete is necessary to shield personnel from this radiation. This makes it impossible or at least very difficult to steal and fabricate nuclear explosives using ^{233}U. In FUJI the ^{232}U content is 20-30 times higher than MSBR due to the retention of ^{232}Pa by the continuous chemical processing **[13].**

In theory it is possible to prepare pure ^{233}U in an MSR and this was, in fact, proposed in the MSBR concept of ORNL. This can be done by continuously separating traces of ^{233}Pa from the fuel salt before it decays to ^{233}U. Once outside the reactor ^{233}Pa can be allowed to decay ($t_{1/2}$ 27 days) and yield pure ^{233}U. However, this technology is yet to be developed and in any case would require setting up a reactor with a dedicated and elaborate continuous chemical processing facility. A clandestine facility of this nature would be very difficult to hide and would violate the IAEA safeguards. Further, it would be necessary to treat a full core of fuel-salt to get 1 SQ pure ^{233}U in FUJI.

Pu inventory in an FBR ranges between 3 to 5 kg/MWe; so a 1000 MWe FBR will have several tones of Pu, and a hold to a few SQs, so can easily go undetected. Also, large quantities of Pu will be shipped between the reactor, reprocessing plant and fuel fabrication plant, which would enhance proliferation risk. The situation in FUJI/THORIMS-NES is much easier, because the ^{233}U inventory is small 0.55 ton in FUJI (0.15 GWe) and 0.53 ton in FUJI-Pu (0.11GWe). Also since the reactor is nearly self-sustaining in terms of fissile material, transportation of only small quantities of fissile material is required.

4.5.3. Microscopic View at Reactor Site

Fissile material concentration in molten-salt fuel is low (about 1 weight %) for both FUJI-Pu and FUJI-^{233}U. Therefore, the fuel salt containing 1 SQ (8 kg) of Pu or ^{233}U weights 800 kg with the volume of about 250 liters. This makes the theft effectively impossible.

FUJI does not have large excess reactivity, and even if the operator diverts fissile material, the safeguards inspectors can easily detect this fact. This will act as a deterrent to diversion. FUJI has a further merit that only small additive quantities of make up fuel are required and also the quantity of spent fuel on site is small. High gamma dose level of ^{233}U (due to ^{232}U daughter products) in the Th fuel cycle also makes detection of any irregular transfers, in and out of the normal fuel-handling route, quite easy.

Reprocessing and reconstitution of fuel-salt in the regional centers is simpler and easier whereas, the product is difficult to handle because of the attendant gamma radiation. These advantages of MSR are also valid for an AMSB. AMSB and the fuel-salt processing facilities will be non-utility/process plants, and will be accommodated inside the Regional Centers, which are heavily safeguarded. This separation plan of the breeding facilities from the very little fissile consuming power stations FUJI-^{233}U is a good management scheme of nuclear materials, which will be effective for the prevention of diversion within states as well as trans-border illicit trafficking (the theft and smuggling of nuclear materials).

Under intense globalization of the Nuclear-energy industry, the complete implementation of an NPT regime is not easy including not only technical but also budgetary problems, which will be improved by application of “remote inspection” technology depending on the high penetration gamma rays of ^{233}U fuels.

To summarize above, it should be strongly recommended to convert Pu to "**the hardest and least desirable fissile material for weapon -- ^{233}U**" through FUJI-Pu and gradually to shift to FUJI-^{233}U fuel cycle on a global scale. In the long range THORIMS-NES can usher in a safer world with ^{233}U, rather than Pu for nuclear energy production. If states having nuclear weapons agree, Pu in the weapons could also be converted to ^{233}U leading to nuclear disarmament.

4.6. Radio Waste Management including Economical Nuclear Transmutation

Some advantages of THORIMS-NES in the field of radioactive waste management are given below:

- In an MSR there is no fuel-assembly fabrication, and chemical processing is a not carried out very frequently. Further, the reactor design is such that there is very little maintenance required. These three factors would result in generation of very small quantities of low/intermediate level waste.
- The fuel-salt can accommodate fairly large amount of fission-products, which will either decay or be destroyed by neutron capture while circulating in the reactor system.
- As mentioned earlier there is practically **no TRU production** in a ^{233}U fueled MSR. On average the production of Pu and Am+Cm in FUJI-^{233}U are respectively 0.5 kg and 0.3 g for each GWe・y of energy production. The corresponding figures for an LWR are 230 kg and 25 kg.
- Initial operation of the MSR with Pu fuel would produce significant quantities of TRU elements. However, these can be readily transmuted to harmless nuclides by keeping them within the reactor. Effective nuclear transmutation of long-life radioisotopes can also be carried out inside an AMSB where high-energy neutrons are present.
- An economical nuclear transmutation (incineration) work of all Radio-wastes including the legacy of U-Pu cycle reactors such as TRU and FP elements could be preformed in this fuel-cycle by using the plentiful low-cost **excess-neutrons** coming from excess fissile material (fuel materials should be diminished as an essential duty) in the “recession age (after about 2065 or later)” of Thorium ERA as shown in Fig.1. In this age not only FUJI but also AMSB will be converted to the most effective incinerators.

With the elimination of TRU elements **radio-waste management** issue will become a “**Hundred Years**” problem from a “**Million Years**” problem allowing the incineration in the fuel-cycle after temporary storage of radio-wastes for several decades. The molten-fuel-salt medium and facilities of THORIMS-NES are the best for such work due to the high solubility of reactants and products, no radiation damage of salt, easy chemical processing, etc

4.7. Economy

4.7.1. Economy of FUJI

The economy is not a simple issue owing to depending on the social/district requirements too. The flexible characteristics of FUJI such as simple operation and maintenance including load-following and utility-near-site characters will be a big economic advantage.

However, the general feature of economy in THORIMS-NES compared with the conventional LWR system will be excellent for the following technological reasons:

(1) **Capital cost** of MSR is almost similar to LWR. There are many pro and cons between these two reactors. MSR has three fluid loops as in an FBR. The thermal efficiency of FUJI is 30% higher than a

PWR, the reactor-vessel is a simple low pressure tank and reactor internals are very simple. The safety system is simplified resulting in a smaller building without the fuel-handling facilities. Preliminary examinations by ORNL**[26]** and LLNL**[27]** have estimated costs equal or lower than PWR by 10 %.

(2) **Fuel cycle cost** is lower than LWR. This is because MSR requires a smaller amounts of thorium and ^{233}U (fissile) for plant lifetime, meanwhile LWR requires much larger amounts of natural uranium and large amounts of ^{235}U (fissile). Besides that, MSR is a liquid fuel, and does not need fuel fabrication process as LWR.

(3) **Operation and Maintenance cost** of MSR is almost similar or less than LWR due to the no fuel-assembly exchange/shuffling work, although MSR needs remote maintenance, because molten fuel salt of high radioactivity circulates outside the reactor vessel. Meanwhile, MSR can operate longer than LWR, and the MSR can save downtime.

The FUJI-series reactor has a simpler infrastructure including almost no fuel fabrication, less fuel transportation, short electric transportation distance, small land area, etc. Therefore, the total cost of FUJI for consumers is estimated to be even less by 10 % compared to a LWR mentioned above.

4.7.2. Economy of THORIMS-NES

The cost of fissile ^{233}U is fairly high due to the higher capital cost of AMSB. However, the final electric power cost produced in THORIMS-NES would not increase so much due to the following reasons:

a) The net ^{233}U consumed by fission is only about 0-5 % due to the high conversion ratio of 100-95 %.

b) The maintenance and operation cost of fuel-cycling composed of a simple fluid fuel salt flow is very low, and needs only simple dry chemical processing not requiring an expensive reprocess plant and Radio-waste management. AMSB is supported by its own electricity.

c) The following items in the U-Pu cycle system will be eliminated: i) U enrichment work, ii) residual depleted U, and iii) TRU.

5. DEVELOPMENTAL STRATEGY

5.1. Basic Strategy in brief

The basic elements of THORIMS-NES developmental strategy are as follows:

- **Installation and Operation of miniFUJI (7-10 MWe):** This would help in laying afresh the foundation for the MSR technology with a view to improving upon the successful 4 years (17,655 hrs) operational experience of Molten-Salt Reactor Experiment at ORNL and building a core team of specialists. The status of MSR development and what remains to be done has recently been discussed by Forsberg**[28]** and recommendations for a restart of MSR development is discussed by Moir **[29].** As adequate information exists to design this reactor, its operation should start about 7 years after the start of the program **[19].**
- **Installation and Operation of FUJI-Pu (100-300MWe)**: In parallel with miniFUJI the design work should be initiated on a larger FUJI demonstration plant of 100-300 MWe capacity. The work on the preparation of Pu containing molten salt-fuel by dry processing (simplified FREGATE process depending on the direct fluorination) of spent-fuels from existing nuclear power stations should also be started so that it can be used as fuel in FUJI reactors to produce energy and ^{233}U. FUJI-Pu is expected to start operation about twelve years after start of the program**[13,15]**. As sufficient quantities of ^{233}U are built up over time only ^{233}U fuelled FUJI reactors should be set up.

This step would permit gradual and smooth transition from the present U-Pu cycle era to Th-U Era.

- **Development and Installation of AMSB** : The development of high energy (1 GeV) high current (300 mA) proton accelerators for AMSB and the associated spallation reactor can proceed over the next two to three decades**[20,21]**. As Pu available in the existing spent fuel would provide fuel for FUJI reactors for several decades there is ample time to develop a spallation reactor.
- **THORIMS-NES**: Eventually THORIMS-NES should be globally deployed in several regional centers to meet the energy needs of mankind with greatly reduced proliferation and environmental concerns. This would open the new THORIUM ERA under international cooperation. This strategy has been supported at the MSR Specialists' Meeting in 1997, USA.

The brief time schedule of THORIMS-NES development is shown in **Fig. 7**.

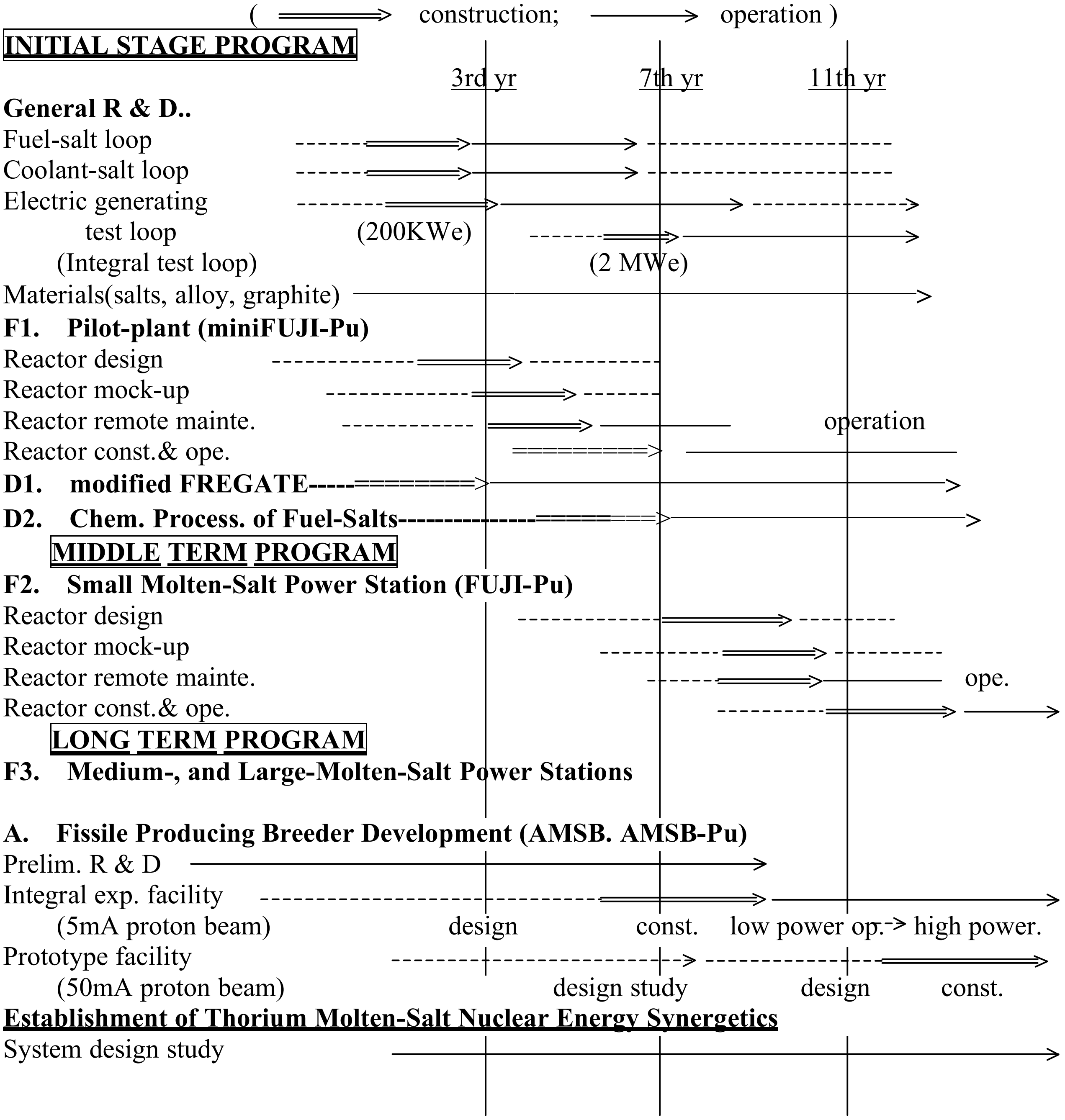


Fig.7. Developmental schedule of Thorium Molten-Salt Nuclear Energy Synergetic System (THORIMS-NES).

5.2. THORIMS-NES Plans

The basic program for developing THORIMS-NES is composed of three plans:

F-plan: Fission reactor development including miniFUJI, FUJI in several versions.

D-plan: Dry-processing of spent fuel and target/blanket salts including not only molten salt but also solid fuels of ordinary reactors such as LWR, FBR, HWR etc. for getting molten fluoride fuel salt for FUJI. or target salt for AMSB.

A-plan: Accelerator Molten-Salt Breeder development in several versions.

Some details regarding these plans are given below:

5.2.1, The F-plan:

A medium range program for achieving a mature F-plan is as follows:

- Install and operate several molten salt test loops along with machinery (pumps etc) /instruments for education and training of project staffs.
- Finalize specifications of materials used for various systems in the reactor, get industry to manufacture these materials and carry out high temperature mechanical properties, compatibility and irradiation tests. High temperature molten-material reactor technology developed for at ORNL, as well as for Na-cooled FBR worldwide with huge investment, can be helpful for the development of the FUJI's supporting facilities.
- Finalize the design of miniFUJI (7-10 MWe, **Fig.2, 4**.) including the electric generation system. Based on information from the MSRE (7.4 MWth), this design should be completed within 4 years. The construction of miniFUJI is expected to be finished 6-7 years after start of the program. After charging salts and doing several preliminary tests miniFUJI will become critical after the seven years from the start.
- In parallel develop remote maintenance technology and carry out mock up exercises to get experience on handling problems during reactor operations.
- In view of the wealth of information available on MSRE from ORNL work, the R&D and construction expenses for miniFUJI are expected to be 300-400 million US dollars.
- The 4-year fuel-burning experience of MSRE is approximately equivalent to that of nuclear fuel burning 10 years for FUJI due to the lower power-density (lower burning rate). Therefore, no serious problems are anticipated.
- After getting significant experience from miniFUJI operation and combining this with MSRE/MSBR data, carry out detailed design and related R&D work for FUJI, in several innovative variants, in the next 6-9 years.
- Simultaneously focus on a conservative design, such as FUJI-U3, optimize the design in terms of the flexibility of reactor operation, core configuration, and the like and recommend its construction as the first prototype power station. It should be planned that FUJI achieves criticality in 12-15 years.
- As there are almost no trans-uranium elements in the nuclear waste from FUJI, there is only a little work required for operation and maintenance of the reactor. The amount of nuclear waste produced is very small.

5.2.2. The D-plan

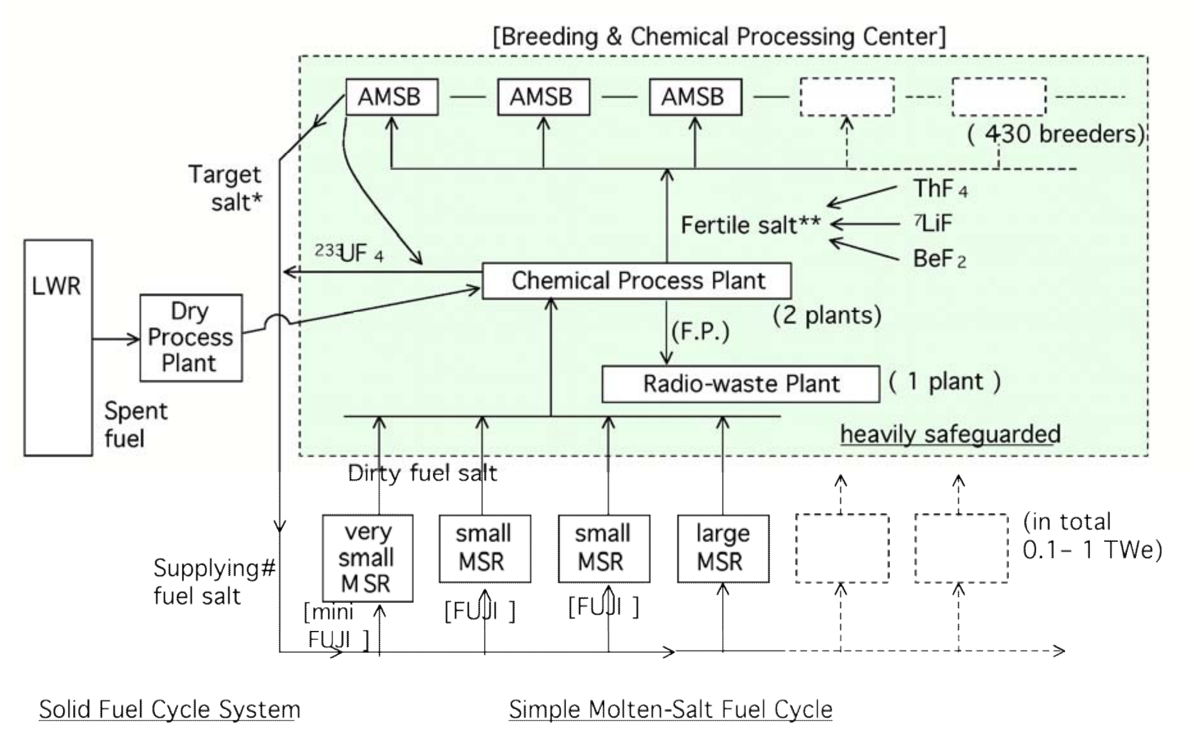
For the realization of this new Th system, it is necessary to develop a simple dry process (non-aqueous), which can convert fissile plutonium from the spent fuel to a fluoride suitable for dissolution in molten fluoride salt. This fluorination is an industrial technology and used extensively for enrichment of uranium. Basic elements of technology for spent fuels were developed under the FREGATE project by French, Russian and Czech scientists**[28]**. The first step in the D-Plan would be to study transfer of plutonium from a simulated fuel rod/bundle to a molten salt. Simultaneously, development of remotely operable process equipment for hot cell use has to be developed. Once these two steps are established treatment of spent fuel from LWRs/HWRs should be carried out to prepare plutonium containing molten salt suitable for use in FUJI reactors. Pu from the spent fuel can then be routinely used to prepare molten salt fuel for new reactors as well as to provide makeup fuel for the operating reactors.

5.2.3. The A-plan

In the long range AMSB is required for a successful operation of THORIMS-NES. Currently there are accelerators that can produce proton beam having 1 GeV energy, but the current in these systems is very small and not easy to increase up to 200-300 mA, although the related R&D effort is progressing in USA (SNS project) and Japan (J-PARC project). Simultaneously the spallation system required for the AMSB has to be developed and work on this facility has also to start in earnest.

Regarding the time frame for these developments it can be said that with a successful D-Plan the stocks of Pu in the spent fuel are large and can easily support an expanding FUJI program for a few decades. So there is plenty of time to complete the development of an AMSB. Once developed, the AMSB, along with a chemical treatment plant and nuclear waste disposal plant, should be built in the specially planned 20-30 bases of "**Regional Centers**" heavily safeguarded under international supervision throughout the world. After spent nuclear fuel salts are treated in the chemical treatment plant and nuclear waste disposal plant, they are transformed into nuclear target/blanket salts in the AMSB and then utilized as fuel in the FUJI by making up the chemical composition (cf. **Fig. 8**).

Regional Center



(*)^{7}LiF -BeF$_2$-ThF$_4$-^{233}UF$_4$ (**)^{7}LiF -BeF$_2$-ThF$_4$ (#)target salt* + additive ^{233}UF$_4$

Fig. 8 Thorium molten-salt breeding fuel-cycle system

Regional Center accommodating AMSB, Chemical-Process & Radio-Waste Facility, and Molten-Salt Power Reactors are coupled by MS Fuel. The connection with U-Pu Cycle System is shown in the transient stage.

5.2.4. Plan Integration

The three plans listed above should eventually lead to commercialization of the FUJI power stations of small as well as large size. Completion of the development of AMSB would herald a new era in thorium based nuclear energy. The use of FUJI nuclear power stations will reach a peak around the year 2070 in our scenario (**Fig.1**). Afterward TORIMS-NES can work for solving the problem of nuclear waste in parallel with energy production (cf.Sec.4.6.).

5.3. Future advanced program

As a future ambitious program the followings will be examined for further improvement:

(a) ***Core graphite development:*** The development of higher radiation resistant form of graphite will allow a higher power density, resulting in a smaller core vessel, or operation for a longer time. This will lower the capital and electric generation cost. The improved irradiation and sealing characteristics should be developed by a well-qualified graphite manufacturer. The irradiation test should be performed using a powerful irradiation-test reactor, such as the MS-4 at Demitrovgrad, Russia, for example. In addition, the basic research on the developed materials by irradiation with energetic particles including carbon ions and high-energy electrons should also be performed in order to understand the mechanism of the damage more precisely and develop better materials.

(b) ***No core-graphite reactors:*** It is useful if epithermal or fast reactors are developed eliminating core-graphite moderator. There are several studies already, but generally their engineering feasibility is unclear, and they appear to require a larger and longer R&D effort than required for the thermal MSR.

(c) ***Stirling engine application:*** The outlet temperature of coolant-salt is very high, and its utilization in electric generation technology should be pursued. Stirling engines are known as the most efficient devices for converting heat into electric current. They operate quietly based on the principle of closed operating chambers, and hold the promise of long-life designs with minimum maintenance and high temperature for high efficiency. Further improvement of the Stirling engines should be undertaken for achieving less weight, more compactness, longer life, higher power level and efficiency**[31].**

(d) ***High temperature application including hydrogen generation:*** FUJI is also very promising for the supply of high temperature heat for industrial use. The pipes and other related parts used in this type of reactor are primarily made of nickel alloys, which can safely withstand more than 900°C. Carbon composites are not yet practical to be used to build FUJI today but R&D is advancing rapidly and may make its use in the future possible, in which case temperature well over 1000°C might become practical**[32]**. Research is ongoing to make hydrogen using heat at 900°C and above, for use in a thermo chemical cycle or high temperature electrolysis. Of course hydrogen can be made with ordinary electrolysis, and high temperature is advantageous to making electricity more efficiently. Therefore, there is also great expectation for FUJI to be utilized as a hydrogen production reactor.

(e) ***Further development on fissile-producers including AMSB:*** Not only the improvements of AMSB by the new compact and high efficiency accelerators, etc., but also the study of new type fissile producers including DT-fusion facilities should be pursued applying i) inertial confinement fusion**[33]**, ii) magnetic fusion, etc., although the other exotic technologies such as plasma-focus, impact fusion**[34]**, or in-lattice confinement fusion**[35],** if a technological break through occurs.

The molten-salt applications similar to AMSB have been examined preliminarily on these concepts expecting the break through among the next 20 years even the spallation reaction is the best for breeding at present.

6. DOMESTIC AND INTERNATIONAL SUPPORT ON NEW THORIUM STRATEGY

While many persons may never have heard of, or believe in, the above mentioned strategy, or not be convinced, the following points have been raised in the hope of gaining some understanding.

Almost all information regarding thorium has been eliminated from the current nuclear engineering textbooks. Hence, the present-day nuclear energy technology specialists dealing with (uranium) nuclear reactors are specialized only in the field of uranium. They are unfamiliar with the knowledge of nuclear science held by the nuclear specialists in the 1950's or '60's, who have studied the principles of both the uranium and the thorium fuel cycles.

There was a great amount of examination regarding the principles of Thorium in the textbooks written more than 30 years ago**.**

E. Fermi succeeded in operating the first nuclear reactor: Chicago Pile-1 in 1942. Soon after that the New Pile Seminar was held in Chicago under the leadership of Nobel Prize Winners: E.P. Wigner, Harold C.Urey et al. At this seminar Wigner highly praised liquid molten fluoride salt as a fuel. Wigner and one of his very trusted students, Alvin Weinberg, went on to expand and improve the facilities at ORNL while leading the development of MSR at ORNL**[6]**(cf.Sec.3.2.1). A great deal of R&D on fluid fuelled nuclear reactors performed by many countries revealed that the MSR concept was overwhelmingly successful compared to other types. However, in 1976 the MSR budget was cut for various political reasons. There was also great success achieved with the basic physics of the accelerator breeder at Chalk River Nuclear Laboratories (CRNL) in Canada but that budget was also cut around the same period.

The THORIMS-NES consisting of "FUJI" (1985) and "AMSB" (1980-83) had greatly increased the possibilities for practical use of the MSR and accelerator breeder**[11,12]**. Although this research has not been in the mainstream yet, this system concept has almost been established owing to the cooperation of researchers around the world, and support and recommendations from the leaders in the field,

The details of this development process are already written in various scientific papers in this field. In 1981, the Academic Committee of Thorium Energy was established in Japan. This committee consists of prominent professors such as S. Kaya**,** E. Nishibori**,** K. Husimi**,** N. Saito, E.Takeda and H.Yamamoto as well as others. The efforts of a group of Diet members from various factions of the Liberal Democratic Party, the Federation of Economic Organization and Management leader Mr. T. Dokou and others also encouraged the research.

At the end of 1987 Electricite de France (EdF) completed their first Fast Breeder Reactor "Superphenix" with the effort of Commissariat a l'Energie Atomique (CEA). However, if a second breeder were to be built the country would suffer economic loss, and EdF then invited Furukawa to discuss the possibility of a joint research project for MSR, but gave up due to political problems. It was finally decided in 1998 that the Superphenix would be disposed off. If such a decision had been taken 10 years earlier the joint research project might have taken off.

Kurchatov Institute, Soviet Union, approached the Furukawa Group in 1983 regarding joint MSR development project. However, as the system was still in the research stages at that time, several research organizations and scientists of Japan, Soviet Union (Russia), France, Belarus, Czech, Turkey and others, carried out a large amount of cooperative research. In 1995, the Russian Federal Institute of Technical Physics (ITP, Snezhinsk, the west end of Siberia), proposed the joint construction of a miniFUJI. Then, in a meeting for the trilateral joint development plan, people from Japan, the US and Russia decided to construct miniFUJI on the grounds of the ITP. The Russian government also acknowledged this.

A MSR joint research work between Japan and the U.S. was started around 1974. The directors and researchers of ORNL and other places contributed a great deal to the work、 including Drs. Alvin Weinberg, H. MacPherson, A.W. Trivelpiece, ORNL and Mr. L. Reicle, Dr. D. deBoisblanc, Ebasco. In 1992 the advisor to the US President for science and technology, Dr. Alan Bromley, highly praised the MSR and THORIMS-NES system. In 1997 the next advisor Dr. John Gibbons also praised the Trilateral Cooperation Development Program. The MSR was among the 6 reactors chosen by the 4th Generation Reactor International Forum (GIF). Leading nuclear physicist Edward Teller and Ralph Moir who belonged to the Lawrence Livermore National Laboratory (LLNL) published a scientific paper praising the MSR system such as FUJI**[36].**

Our strategy, this system including FUJI developmental program, has been unanimously recognized by all 24 Conferees (participants from Japan, the U.S, Russia, Belarus, Czech, France, India, Turkey and IAEA) at the MSR specialists' meeting: "International Conf. on Th Molten-Salt Reactor Development", held on April 8-11, 1997 at RAND Headquarter, Santa Monica, California, USA.

From results of the joint inspection of the OECD/IEA, /NEA and IAEA the MSR-FUJI system was chosen by the international joint development recommendation plan in 2002**[37]**. Brazil, China, Indonesia, South Korea , Australia and other countries are also showing interest in this MSR system. Successively, IAEA is publishing "Status of Small Reactor Designs without On-site Refueling: 2007" including THORIMS-NES**[38]**.

Furthermore, in August 2001 the book: **"The Revolution in Nuclear Power Plants"** by K.Furukawa was successfully published in Japanese**[39]**, and the MSR system began to be recognized by the public more. Due to the recent confusion regarding international nuclear policies, fear against nuclear terrorism and sudden rise in price of oil, a number of countries have finally taken an interest in Thorium. In the 22nd Eisaku Sato Memorial Prize Essay Contest [Nuclear Non-proliferation] the Furukawa's essay was the recipient of the Award of Excellence (Grand Prize) from the foundation established on the dying wishes of Nobel Peace Prize Winner Eisaku Sato (the former Japanese prime minister) on 30th June, 2006**[2]**.

The message of Thorium Power Ltd presented in the New-year issue of Newsweek is also a big encouragement for us to open the Thorium ERA**[4]**. The utilization of Thorium solid fuels in the several modified reactors of LWR**[40]**, HWR**[41]** or High Temperature Gas-cooled Reactors will be useful for opening the Thorium Era in its initial stage.

7. CONCLUSIONS

One of the most promising philosophical and technical strategies for the survival of the world in this century has been presented. Although many more detailed design and optimization studies are needed and should proceed with international cooperation, we have to start from the simple pilot-plant, miniFUJI, to demonstrate the rational technological integrity of THORIMS-NES and to make the initial step into the Thorium era.

We hope that our work will be valuable as a reply to the sincere wish of David E. Lilienthal**[42],** the most significant American/Human of the 20th century, given on the final sentence of his last book **"Atomic Energy: A New Start"**: **"What I have reflected upon and written about is not merely a new source of electrical energy, nor energy as an economic statistic. My theme has been our contemporary equivalent of the greatest of all moral and cultural concerns --- fairness among men and the endless search for a pathway to peace."**

For such purpose, **"I have proposed that we make a new start toward a safer peaceful atom, using a technology that will not, as the present technology does, produce bomb material in the process of creating the peaceful atom."** And he recommended to us that **"We need to back away from our present nuclear state in order to find a better way, a route less hazardous to human health and to the peace of the world and its very survival."**

One of the authors (K.F.) deeply benefited from the strong support of J. D. Bernal**[43]** in his early scientific work on inorganic liquid structure chemistry as a base of this work. Bernal was also one of the scientists who was most concerned to achieve a **"World without War"[44]**, and was the first to use the phrase "weapons of mass destruction". On his birthday towards the end of his life he wrote: **"I am sure that you share my hope that in the not too distant future science may come to be used for the benefit of all mankind"**.

At the Pugwash Conference on "A New Design toward Complete Nuclear Disarmament" held at Kyoto, Japan, 1975, the Japanese Nobel laureates in physics, H. Yukawa and S. Tomonaga**[45]** presented the following Statement on "Beyond Nuclear Deterrence" (signed by 28 scientists): **"Scientists ask for help in persuading all governments to renounce without conditions the use of nuclear weapons"**. THORIMS-NES offers a chance to the countries having nuclear weapons to renounce their use and to use the fissile material released for providing energy to mankind.

Acknowledgements:

In order to create this work we received a lot of cooperation, support and encouragement from a large number of people worldwide in the past 40 years. While I cannot mention all the names, I would like to express sincere and deep thanks for all their help, partially presenting some names eliminating the title as the followings:

Japan: E. Nishibori, S. Kaya, K. Kamei, E. Takeda, T. Mukaibo, N. Husimi, N. Saito, T. Ishino, N. Watanabe, T. Fujinaga, T. Matsumae, S. Nasu, K. Tsukada, Y. Nakahara, A. Furuhashi, H. Tago, K. Minami, Y. Kojima; K. Ikuta, Y. Kawarasaki ***USA:*** A.M. Weinberg, H.G. MacPherson, L Lidsky, M.W. Rosenthal, A.W. Trivelpiece, W.R. Grimes, F.C. Reicle, D.R. deBoisblanc, J.R. Engel, U. Gat, R.E. Thoma, J.H. DeVan, P.R. Kasten, P. Grand, A. Bromley, J. Gibbons, L. Dodds, C.W. Forsberg; ***France :*** C. Bienvenu, M. Chemla, R. Romano, M. Israel, M. Gaune- Escard; ***USSR, Russia:*** V.N. Novikov, E.P. Velikov, I.V. Chuvillo, G.V. Kiselev, Y. Korovin, V.N. Prusakov, L.V. Konstantinov, D.A. Semenov, E.N. Avrorin, V.M. Mourogov, K.F. Grevionkin; ***Belarus:*** S. Chigrinov, A. Kievitskaya, S. Shuskevich; ***Czech:*** I. Peka, M. Hron, P. Hosnedl, O. Matal, M. Fiala; ***India:*** P.K.

Iyengar, M. Srinivasan, R. Chidambaram, A.K. Kakodkar; ***Switzland:*** F. Atchison; ***Brazil:*** C.W. Urban; ***Canada:*** A.A. Harms, G.A. Bartholomew; etc.

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