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A road map for the realization of global-scale thorium breeding fuel cycle by single molten-fluoride flow

Kazuo Furukawa [a,*], Kazuto Arakawa [b], L. Berrin Erbay [c], Yasuhiko Ito [d], Yoshio Kato [a], Hanna Kiyavitskaya [e], Alfred Lecocq [f], Koshi Mitachi [g], Ralph Moir [h], Hiroo Numata [i], J. Paul Pleasant [j], Yuzuru Sato [k], Yoichiro Shimazu [l], Vadim A. Simonenco [m], Din Dayal Sood [n], Carlos Urban [o], Ritsuo Yoshioka [p]

[a] *International Thorium Molten-Salt Forum, 1029-5 Oiso, Kanagawa 255-0003, Japan*
[b] *Research Center for Ultra-High Voltage Electron Microscopy, Osaka University, Osaka 567-0047, Japan*
[c] *Mechanical Engineering Department, Eskisehir Osmangazi University, 26480 Bati Meselik, Eskisehir, Turkey*
[d] *Department of Environmental Systems Science, Doshisha University, Kyoto 610-0321, Japan*
[e] *Joint Institute for Power & Nuclear Research – Sosny, Krasin Street, 99 220109 Minsk, Belarus*
[f] *ITMSF 91400 Orsay, France*
[g] *Department of Mechanical Engineering, Toyohashi University of Technology, Toyohashi, 441-8580, Japan*
[h] *Vallecitos Molten Salt Research Association, 607 E. Vallecitos Road, Livermore, CA 94550, USA*
[i] *Graduate School of Metallurgy & Ceramic Science, Tokyo Institute of Technology, Tokyo 152-8552, Japan*
[j] *Energy Frontiers International, 11472 Ehren Street, Lake View Terrace, CA 91342, USA*
[k] *Department of Metallurgy, Tohoku University, Sendai 980-8579, Japan*
[l] *Department of Environmental Systems, Hokkaido University, Sapporo 060-0808, Japan*
[m] *Fed. Inst. of Tech. Physics, Snezhinsk, Russia*
[n] *Sector 15, Sanpada, Navi Mumbai 400705, India*
[o] *Thorium Group, Engineering School, Federal University of Minas Gerais and National Nuclear Energy Commission, Brazil*
[p] *Japan Functional Safety Laboratory, 3-17-24, Hino-chuo, Konan, Yokohama 234-0053, Japan*

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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 the capability to achieve this. 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, which simplifies the issue of nuclear waste management. The use of ^{233}U contaminated with ^{232}U as fissile material, instead of plutonium/^{235}U makes this system nuclear proliferation resistant. The energy is produced in molten-salt reactors (FUJI) and fissile ^{233}U is produced by spallation in 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 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:

* Corresponding author. Tel./fax: +81 463 61 3088.
E-mail address: QYT00127@nifty.ne.jp (K. Furukawa).

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(A) pilot-plant: miniFUJI (7–10 MWe), (B) small power reactor: FUJI-Pu (100–300 MWe), (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 disorder. However, it seems that there are no effective measures for averting such disorder outside from ensuring an 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 large industrial scale power plants. 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 also necessary, as shown in Fig. 1C.

In principle, it is impossible to predict the future. However, a hypothetical prediction based on reliable principles, can be quite useful. A future energy scenario based on initial work of Marchetti [1], and later modified by the members of the Thorium Molten-Salt Forum [2] is shown in Fig. 1A–D. 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 mechanisms. 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. Reexamination of nuclear fission technology and fuel cycle

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 30–50 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 fission with spallation (or D/T fusion, but not yet proven) should be considered, because fission is energy-rich but neutron-poor, and spallation is energy-poor but neutron-rich [3].

The new Fission–Spallation coupled energy technology should be sufficiently safe eliminating a "severe accident" (cf. Section 3.4). Radio-waste management should be put in place within one hundred years (cf. Section 3.6.). Nuclear proliferation resistance should be significantly improved (cf. Section 3.5). 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 bigger than the present) to be achieved by 2065, considering factors such as population and economical growth (cf. Fig. 1).

2.2. Thorium fuel cycle

The largest amount of investment in energy resources in the past 60 years has been in 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 seeking solutions include: (a) nuclear proliferation (b) safety (c) nuclear waste disposal, (d) economics and (e) resources. Because of these, many countries are somewhat reluctant to fully accept nuclear power and some are even planning a phase out of the existing nuclear power reactors. International effort for the development of advanced reactor systems to address these issues is underway, (Generation IV International Forum (GIF) guided by USA and the IAEA-INPRO), but a completely new approach is called for to meet the future energy challenges. Recently, a popular

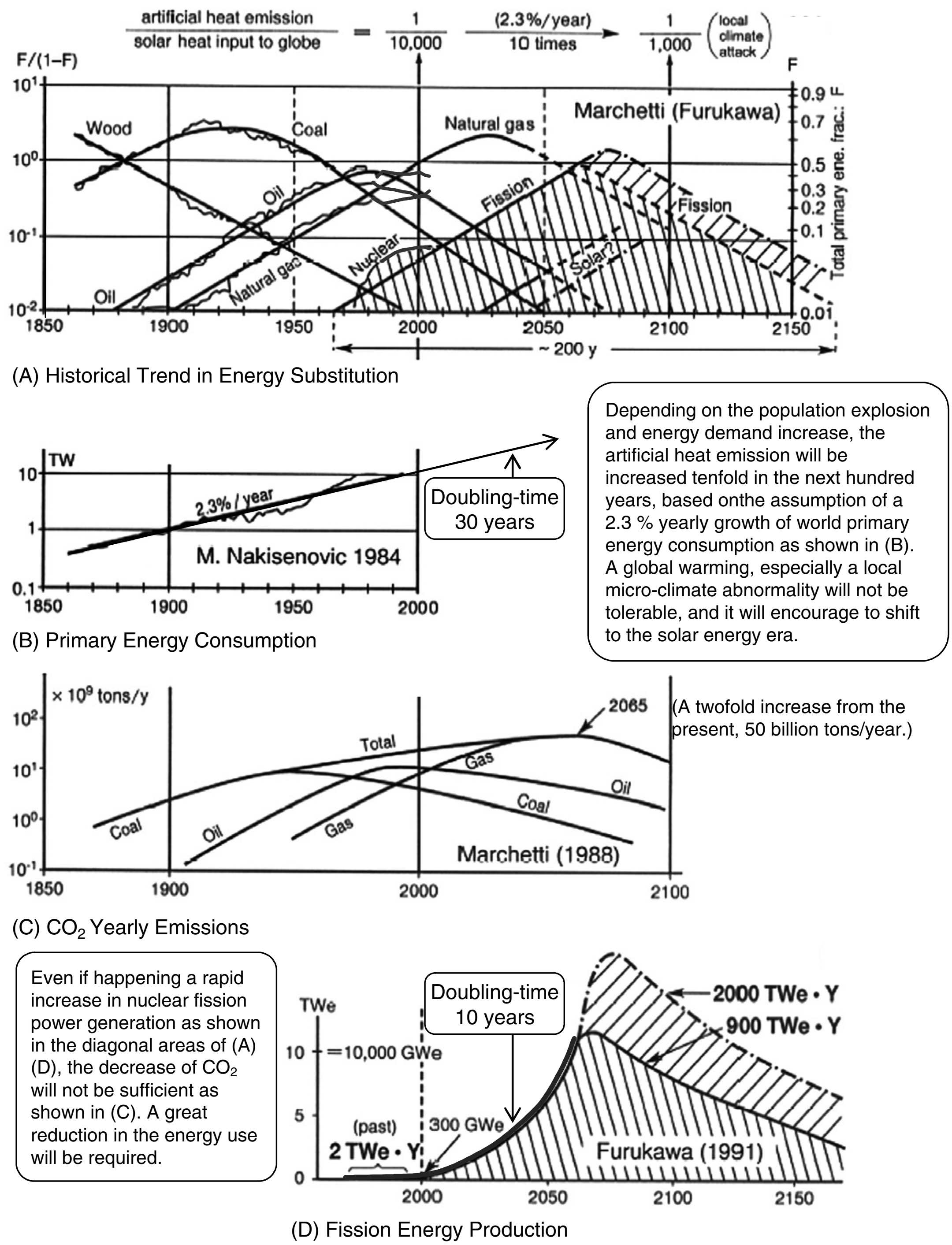

Fig. 1. Prediction of essential nuclear fission-energy production scale for the 21st century.

magazine, ‘Newsweek’ [4] presented an article entitled “The Lost Chance” postulating that “the most promising path towards proliferation-resistant fuels is to return to the road not taken 50 years ago—thorium fuel cycle”.

All the current nuclear power reactor systems are based on the use of uranium as the “solid” fuel, in which the production of plutonium is one of the main concerns for nuclear non-proliferation. To eliminate this risk fortunately, there is an option based on the use of naturally occurring thorium (^{232}Th) as a fertile material in a reactor. The following nuclear reaction occurs in this case:

$$^{232}\mathrm{Th} + \mathrm{n} \rightarrow {}^{233}\mathrm{Th} \underset{22\,\mathrm{m}}{\overset{\mathrm{beta}}{\rightarrow}} {}^{233}\mathrm{Pa} \underset{27\,\mathrm{d}}{\overset{\mathrm{beta}}{\rightarrow}} {}^{233}\mathrm{U}$$

Uranium-233 (^{233}U) produced in this reaction is also a nuclear fuel. From the non-proliferation point of view, it is fortunate that due to other nuclear side reactions occurring in a reactor, ^{233}U is contaminated with traces (a few hundred ppm) of highly radioactive ^{232}U, which cannot be separated. The daughter products of ^{232}U are highly radioactive and emit strong gamma rays such as 2.6 MeV of ^{208}Tl. Concrete walls of 1 m thickness or 25 cm of lead are necessary to shield personnel from ^{233}U fuel containing ^{232}U, otherwise just a few hours of exposure is lethal to humans. It is practically impossible, or at least very difficult, to use reactor produced ^{233}U for making nuclear weapons and also to hide them. 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 3–4 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 hardly produce any trans-uranium elements (TRU), which are a cause of serious concern in ^{239}Pu–^{238}U based systems, and can dominate waste management.

2.3. Molten-fluoride salt fuel application

2.3.1. Advantages

All current nuclear power plants use "solid" (U and Pu) fuel. This is the origin of several difficulties relating to safety and economy. This problem could be solved by the application of "fluid" fuel concept, which was recommended by Wigner in 1943 [6] (cf. Section 5). 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 1957–1976 [7].

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 as 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 and is a good solvent for fissile and fertile material fluorides. This liquid is multi-functional not only as nuclear reaction medium, but also as heat-transfer and chemical-processing medium, the characteristics that 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 unclad 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. Many advantageous features of the MSR are shown in the following summary:

(a) Unlike the conventional systems there is no scenario called 'fuel melt down'.
(b) 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.
(c) Most gaseous fission products (Xe, Kr etc.) are continuously removed so there is no danger of release of these radioactive products, even under accident conditions.
(d) Molten fluorides are stable to the reactor irradiation, because they are simple ionic liquids, and do not undergo any violent chemical reactions with air or water.
(e) Reactors have full passive safety. Under accident conditions the fuel is automatically drained into passively cooled critically safe storage tanks.
(f) The reactor can use a variety of fuels (^{233}U, Enriched uranium, plutonium) and even TRU can serve as supplementary fuel.
(g) 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.
(h) High temperature of the fuel salt permits higher conversion efficiency and even holds promise for other heat based applications e.g. hydrogen production.
(i) Several non-proliferation advantages of the system are given in the Section 3.5.
(j) The thorium resources necessary to produce 900 TWe y (cf. Fig. 1D) will be only 2–3 M-tones, if the breeding fuel cycle is established.

2.3.2. Handicaps

The above advantages of this concept are so significant that it is pertinent to surmise on the reasons for a lack of interest in molten-salt reactors in the nuclear community and decision makers. Some conjectures on this issue are given, although almost all of them seem to be "aberrations".

(a) *Non-popularity of fluid-fuel reactor concept itself*: All power reactors so far are solid-fuel reactors and a fluid-fuel concept looks alien.
(b) *Non-success of fluid-fuel reactors other than MSR*: Historically there were many unsuccessful fluid-fuel reactors with MSR being an exception. In analogy

with other fluid-fuel reactors, many people imagined that MSR also might have difficulty in its container materials. The discovery of Te-attack phenomena on Hastelloy N after dismantling of Molten-Salt Reactor Experiment (MSRE) in 1970 exaggerated this belief. This small problem was readily solved during the final R&D stage (1972–1976) at ORNL [7]. USSR research group of Kurchatov Institute reconfirmed it getting better results [8]. However, results of this R&D are never quoted beyond 1970 [9].

(c) *Non-existence of fissile isotope in thorium*: Whereas natural uranium can be used to build a nuclear reactor because of the presence of fissile ^{235}U (0.72%), it is not the case with thorium. Thorium can only act as a fertile material and fissile content in thorium reactors has to be supplied externally. Further, a number of power reactors in the early stages doubled as plutonium factories for weapons programs.

(d) *Historical development in the Seventies*: The success of MSRE operation and MSBR design study in the years 1968–1970 was significant, and several groups in the USA, France, EC, India, Japan, etc. were aiming to work with ORNL But in 1976 MSR program was terminated, not due to any technological reasons but because of a political decision to enforce a "Breeder Moratorium" [10].

Now the perspective of the world has changed on the nuclear fission issue. The MSR concept has been included as a potential system for the Generation IV reactors. In Japan the members of the Thorium Molten-Salt Forum are getting cooperation from many foreigners and have been trying to advance the concept developed at ORNL. These researchers have proposed a Thorium Molten-Salt Nuclear Energy Synergetic System (THORIMS-NES) [11,12] with a long-term perspective.

3. Thorium molten-salt nuclear energy synergetics [THORIMS-NES]

3.1. Basic concept

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

(I) Thorium utilization (cf. Section 2.2).

(II) Application of molten-fluoride fuel technology (cf. Section 2.3).

(III) Separation of fissile-producing breeders process plants—AMSB: Accelerator Molten-Salt Breeder) and power generating fission-reactors (utility facilities—MSR: Molten-Salt Reactor): It will be essential for the global establishment of breeding-cycle applicable over the world. This separation comes from the need for a doubling time of fission industry growth to be 10 years or less as mentioned in Section 2, which means that ordinary "Fission Breeding Power Station" concept even MSBR proposed by ORNL is not acceptable.

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 Fig. 2.

3.2. Molten-salt power reactor FUJI

The basic conceptual design of FUJI was established in 1985 [13] based on ORNL studies. This design has a simplified structure and is easy to operate and maintain, compared with the ORNL's proposed Molten-Salt Breeder Reactor (MSBR) of the 1970s. In FUJI the conversion ratio (CR) 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 a FUJI reactor is shown in Figs. 3 and 4.

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. The unclad graphite occupies 90% of the volume. The fuel salt flows upwards at about 1 m/s and then goes to an external heat exchanger for transfer of heat to a coolant salt.

The graphite moderator does not require replacement during the reactor's lifetime unlike an MSBR. This is achieved by a lower neutron flux and a higher graphite volume-ratio in core. This also results in a higher conversion ratio (CR) owing to the lower neutron absorption by ^{233}Pa before its transmutation to ^{233}U.

Continuous chemical treatment of the fuel salt is not envisaged. But radioactive Kr, Xe and Tritium (T) are continuously removed from the reactor not only to improve the CR but also to prevent their release in a pipe-line break accident enhancing safety.

As FUJI has a high CR, the required annual supply of the fissile material is very small. Also the production of Pu and MA (Minor Actinides) is very small. For the case of FUJI-U3, the total production of Pu is only 1.6 kg, and MA is also only 5.4 kg for example.

Fissile material must be added to the fuel a few times per year in order to compensate for a small shortfall in breeding. It is estimated that about 400 g thorium is used up per day for conversion to ^{233}U and make up salt for this purpose has to be supplied.

Recent study by one of the authors indicates that FUJI can achieve CR = 1.0 during its full life. This optimized design for a 200 MWe sized FUJI can operate for up to 30 years with the initial fissile inventory of 1.6 ton only.

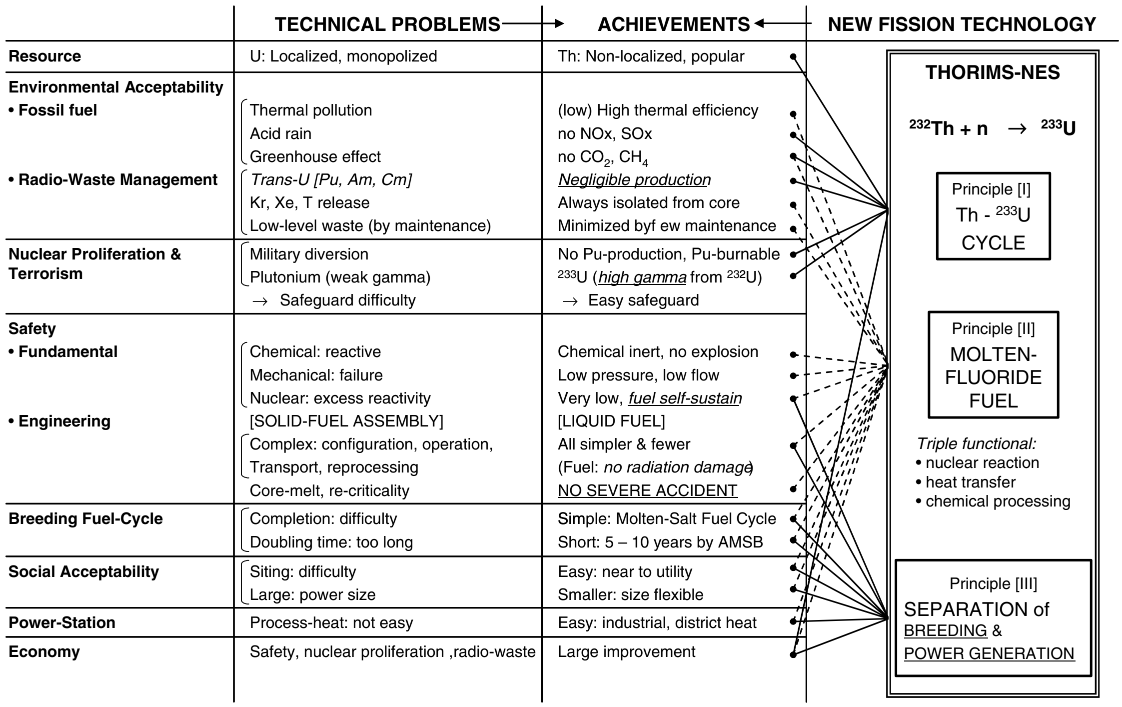

Fig. 2. Global energy/environment problems and achievable solutions by THORIMS-NES [thorium molten-salt nuclear energy synergetics].

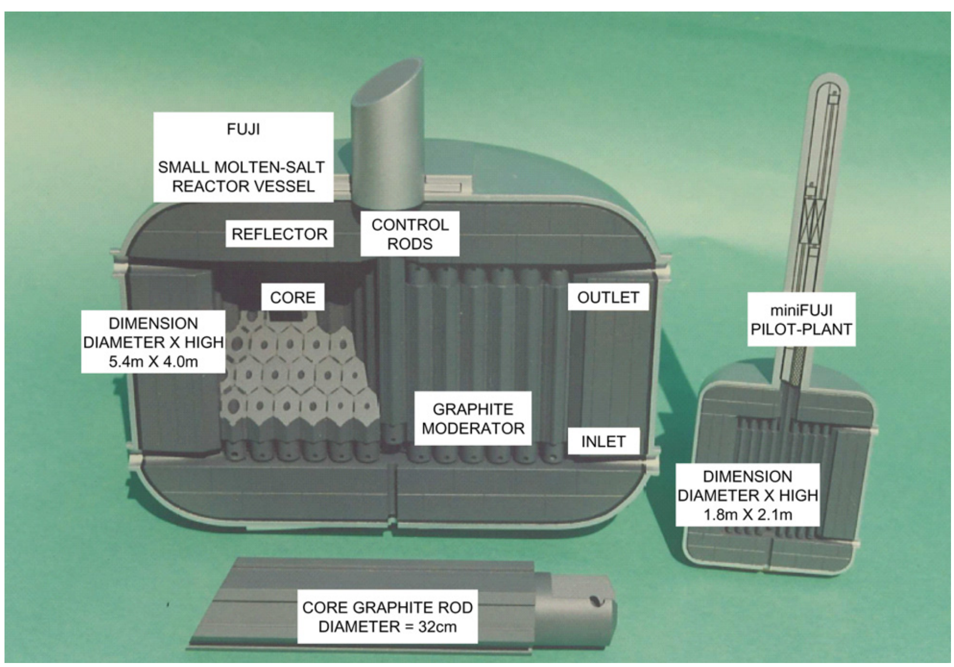

Fig. 3. Cross-sectional view of FUJI and miniFUJI reactor vessel models. [Left] Standard FUJI reactor vessel model (5.4 m diameter × 4 m height × 150 MWe). Inner part is 90% graphite with fuel salts flowing in an upward cycle through remainder of space at 1 m/second. [Right] miniFUJI reactor vessel model (1.8 m diameter × 2.1 m height × 7 MWe).

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 electric 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 has shown 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.

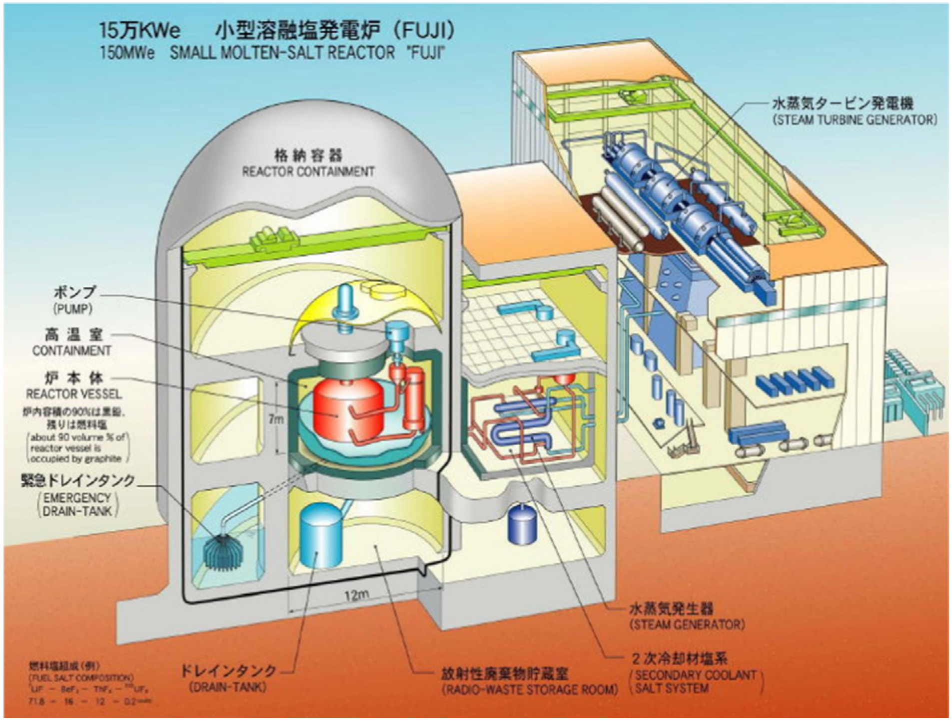

Fig. 4. General view of FUJI molten-salt power station.

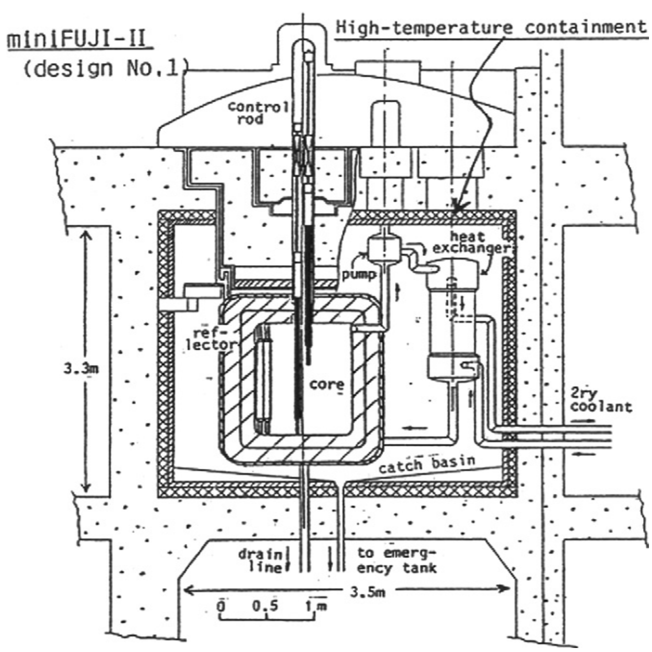

Fig. 5. miniFUJI concept blueprint [main piping: 8 cm in diameter].

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. 5 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. Its size is similar to the Molten-Salt Reactor Experiment (MSRE) at ORNL. The miniFUJI vessel would be 1.8 m diameter and 2.1 m height, and a main pipe line is only 8 cm in diameter resulting in much easier construction than MSRE with its 15 cm piping. The first aim is to recover the basic MSR technology that existed at ORNL 37 years ago. The 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. 6, which was successfully operated for 17,655 h without an accident.

3.3. Accelerator based nuclear fuel breeding facility AMSB

During the 1980s, 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. A diagram of the system is shown in Fig. 7. The size of target/blanket salt bath is 4.5 m in diameter and 7 m in depth. The Hastelloy N vessel is protected by the graphite reflector. The salt is introduced at the top forming a vortex of about 1 m 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.

This target/blanket molten-salt system is sub-critical, is not affected by radiation unlike similar systems based on

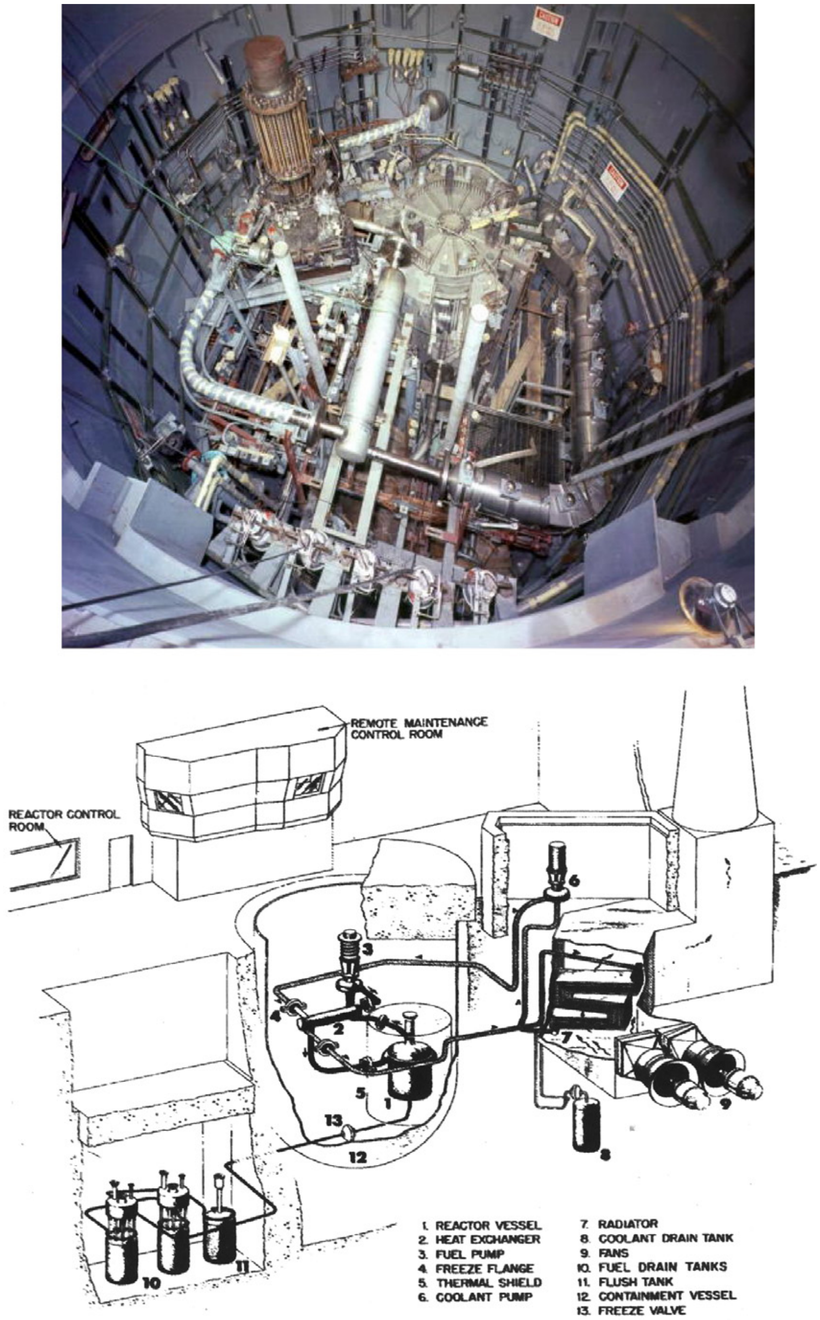

Fig. 6. Molten-salt reactor experiment (MSRE) operated from 1965 to 1969 at Oak Ridge National Laboratory, USA.

solid target, makes heat removal easy, and does not 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 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 target salt composition: $LiF–BeF_2–ThF_4–^{233}UF_4–^{239}PuF_3$: 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]:

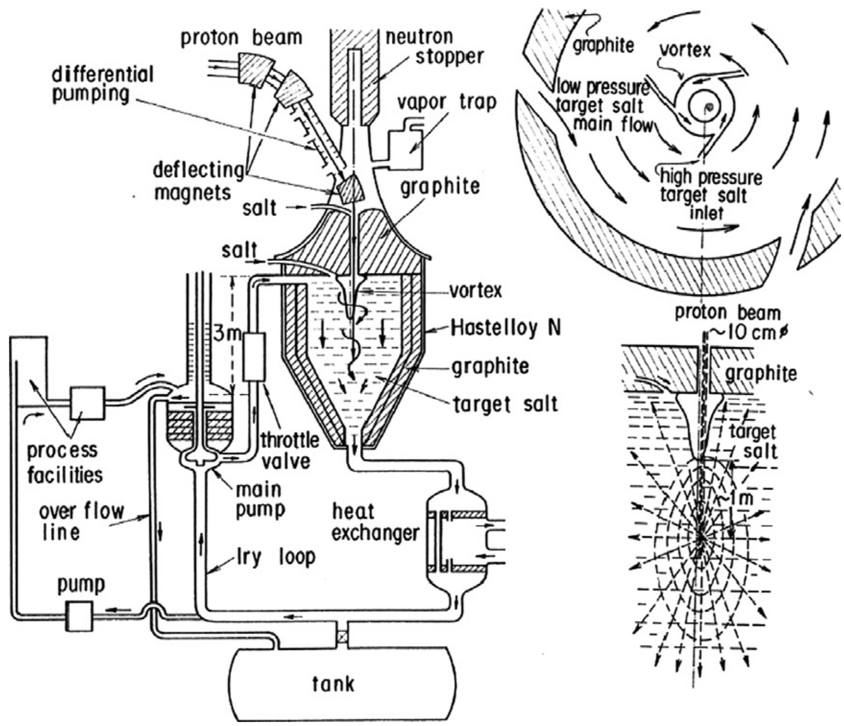

Fig. 7. Schematic figure of single-fluid molten-salt target/blanket system in accelerator molten-salt breeder (AMSB).

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

3.4. Safety [22,23]

The designs of FUJI and the AMSB systems are aimed specifically at addressing at least the first three of the problematic areas of nuclear power discussed in Section 2.2; nuclear proliferation, safety and waste. The intrinsic advantages of these systems in this area are discussed in general terms in Section 2.3; here we present specific features concerned with safety. In general, both the FUJI and AMSB systems have essentially no possibility of severe accidents, which might cause core meltdown and/or large radioactivity release. The details are shown in TECDOC-1536. 2007. Anex XXX [23], for example.

FUJI has three containment barriers (same as for a LWR). The first is the primary system of reactor vessel and primary loop pipes, which contain the fuel. The second 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 are reinforced by intrinsic safety features of the system that reduce the risk of a primary release:

- The molten-salt fuel may be removed from the reactor at any time using passive methods (gravity):
  - (i) the salt fuel is only critical when in the graphite moderator assembly,
  - (ii) a dump tank with a passive cooling system will be able to freeze the molten-salt fuel (m.p. 773 K) into a stable glass.
- The excess reactivity and the reactivity margin that need to be compensated by control rods are small:
  - (i) the fuel composition is continuously adjusted outside the critical region,
  - (ii) poisoning gasses (Xe, Kr and tritium) are continuously removed. Such systems keep the radioactive inventory as low as possible; daily tritium release could be reduced to less than 3×10^{10} Bq (1 curie) per day [7]. The reactivity requirements for the control rods are small, which 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 [25].
- The MSR has a large negative reactivity coefficient on fuel salt temperature that can suppress an abnormal change of the reactor power. For example, the temperature coefficient of reactivity is -2.7×10^{-5} 1/K for FUJI-U3 [23].
- The temperature coefficient of the graphite is positive but as the heat capacity of graphite is large, temperature rise rates will be slow.
- The system eliminates features that could lead to rupture of the containment:
  - (i) the primary and secondary cooling loops operate at a very low pressure (0.5 MPa); this allows large mechanical safety margins to be used;

(ii) because the boiling point of the fuel salt is much higher than the operating temperature (about 1700 K compared with 970 K) and in addition, the high temperature containment has no water inside, pressure increases due to flash boiling in the primary system are eliminated;
(iii) the molten-salt coolant is chemically inert and inflammable;
(iv) in the case of a failure of the primary cooling system, the graphite in the core will not be set on fire as there will be no heat source (the fuel salt will have been drained into an emergency tank).

Since the void reactivity coefficient of FUJI is positive, the primary system break could result in a reactivity insertion accident due to the increase of the bubble volume. The depressurization accident without scram has been analyzed for one typical FUJI design (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].

The above safety features of FUJI will also contribute to the safeguards against military attack or internal sabotage. As a conclusion, these facts attest that THORIMS-NES technologies possess superior safety characteristics compared with any other nuclear reactor systems.

3.5. 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 within days. This radioactivity makes the diversion of ^{233}U difficult and safeguards 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.

3.5.1. 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 strata, it would form a potential future “Pu-mine”, as the radioactivity of fission products decays in 200–300 years.

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.

3.5.2. 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. Fissile material concentration in FUJI fuel is very low ($\cong$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/h at 50 cm distance from 1 SQ (8 kg) of ^{233}U. More than 25 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, in which ^{232}Pa is removed 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. This can be done by continuously separating traces of ^{233}Pa (half-life: 27 days) from the fuel salt before it decays to ^{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. Further, it would be necessary to treat a full core of fuel salt to get 1 SQ pure ^{233}U in FUJI.

3.5.3. 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 l. 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.

Reprocessing and reconstitution of fuel salt in heavily safeguarded regional centers is simpler and easier. 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, it is strongly recommended to convert Pu to “the hardest and least desirable fissile material for weapons: ^{233}U" through FUJI-Pu and gradually to shift to FUJI-^{233}U 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.

3.6. Radio-waste management including economical nuclear transmutation

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

- In an MSR there is no fuel-assembly fabrication, chemical processing is not carried out very frequently, and very little maintenance work is required. These factors would result in very small quantities of low/intermediate level waste.
- The fuel salt can accommodate fairly large amount of FP, which will either decay or be destroyed by neutron capture while circulating in the reactor system.
- There is practically no TRU production in MSR. On an 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. The corresponding figures for an LWR are 230 kg and 25 kg.
- An economical nuclear transmutation work of all Radio-wastes including the legacy of U–Pu cycle reactors such as TRU and FP elements could be preformed 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 step by step.

With the elimination of TRU elements the radio-waste management issue will become a "Hundred Years" problem from a "Million Years" problem allowing the incineration 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.

3.7. Economy

3.7.1. Economy of FUJI

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 estimated to be almost similar to LWR. There are many pros and cons between these two reactors. MSR has three fluid loops as is the case with an FBR. The thermal efficiency of FUJI is 30% higher than a PWR, the reactor vessel is a simple low pressure tank with simple reactor internals, and 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 that the cost of an MSR would be equal to or lower than PWR by 10%.

(2) *Fuel-cycle cost* is lower than LWR. This is because MSR requires smaller amounts of thorium and ^{233}U (fissile) for plant lifetime, meanwhile LWR requires much larger amounts of natural U and ^{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 saving downtime.

The FUJI 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 less by 10% compared to an LWR.

3.7.2. 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 CR of 100–95%, (b) the maintenance and operation cost of a simple fuel cycle is very low, and needs only simple dry chemical processing and Radio-waste management. AMSB is supported by its own electricity, and (c) the following items in the U–Pu cycle system will be almost eliminated: (i) U enrichment work, (ii) residual depleted U, and (iii) TRU management.

4. Developmental strategy

4.1. 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 operational experience of MSRE 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* (1000–300 MWe): 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]. When 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], because Pu available in the existing spent fuel would provide fuel for FUJI reactors for several decades.
- *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. 8.

4.2. 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:

4.2.1. 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 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, Figs. 3, 5) 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 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, 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 TRU elements in the nuclear waste from FUJI, there is only a little work required for operation and maintenance of the reactor.

4.2.2. 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 fuels (and hopefully also from weapons) 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 [30]. Plutonium containing molten salt suitable for use in FUJI reactors can be routinely used to prepare molten-salt fuel for new reactors as well as to provide makeup fuel for the operating reactors.

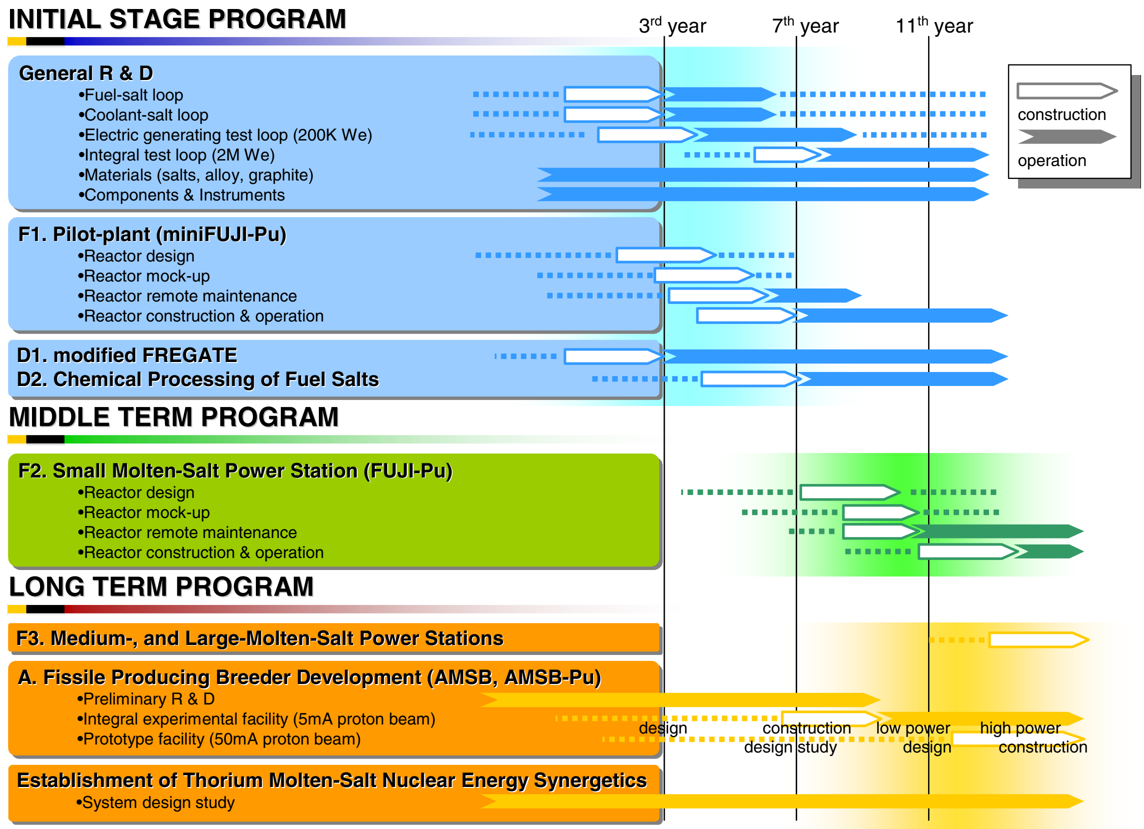

Fig. 8. Developmental schedule of thorium molten-salt nuclear energy synergetic system (THORIMS-NES).

4.2.3. 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 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 handled 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. 9).

4.2.4. 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 will reach a peak around the year 2070 in our scenario (Fig. 1). Afterward THORIMS-NES can also work for solving the problem of nuclear waste with energy production (cf. Section 3.6).

4.3. Future advanced program

As a future ambitious program the further improvements will be examined:

(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. Such development will be done 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 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.

(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

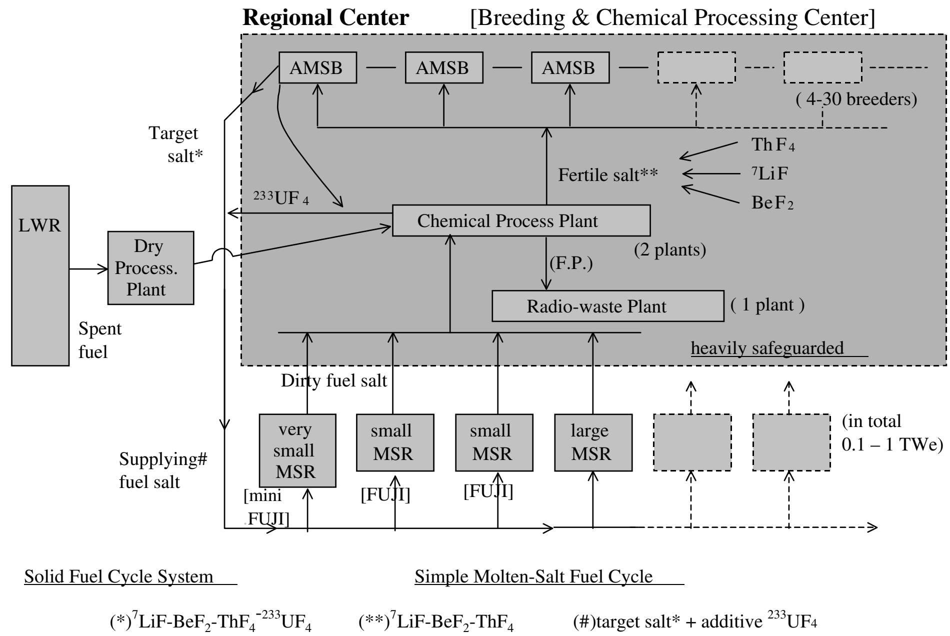

Fig. 9. Thorium molten-salt breeding fuel-cycle system. Regional Center accommodating AMSB, chemical-process and radio-waste facility, and molten-salt power reactors are coupled by ms fuel. The connection with U–Pu cycle system is shown in the transient stage.

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 energy. 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 more compact light weight engines, with 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 thermochemical 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], and (ii) magnetic fusion. Other exotic technologies such as plasma-focus, impact fusion [34], or in-lattice confinement fusion [35], may also be explored if a technological break through occurs. The molten-salt applications similar to AMSB have been examined preliminarily on these concepts expecting the break through during the next 20 years. Currently, the spallation reaction is the best for breeding ^{233}U.

5. 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 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 1950s or 1960s, 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 Laureates: 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]. 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. The reason for shutting-off MSRE in 1969 was the satisfactory completion of all experimental programs, and ORNL planned to shift to the next program of "Molten-Salt Breeder Experiment". However, in 1976, such a new program proposal was refused "for budgetary reasons", because by then the LMFBR program had been spending "copious government development funds" [10].

There was also great success achieved with the basic physics of the accelerator breeder at Chalk River Nuclear Laboratories (CRNL) in Canada, stimulating a number of R&D programs from the early 1950s [36], through the Intense Neutron Generator (ING) study of the 1960s [37] and the Advanced System research till 1981 [38]. However, this research budget was also cut around the same time as the MSR program of ORNL, because Canada had no more interest in new nuclear systems due to her rich energy resources, including hydro-electricity.

The THORIMS-NES consisting of "FUJI" (1985) and "AMSB" (1980–1983) 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 the 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 Fast Breeder Reactor "Superphenix" with the effort of Commissariat a l'Energie Atomique (CEA). However, if a second breeder were to be built, France would suffer economic loss, and EdF invited Furukawa to discuss the possibility of a joint research 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 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 US 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 six 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 [39].

Our strategy of THORIMS-NES developmental program, has been unanimously recognized by all 24 Conferees (participants from Japan, the US, Russia, Belarus, Czech, France, India, Turkey and IAEA) at the MSR specialists' meeting: "International Conference 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 FUJI system was chosen by the international joint development recommendation plan in 2002 [40]. Brazil, China, Indonesia, South Korea, Australia etc. 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 [41].

Furthermore, in 2001 the book: "The Revolution in Nuclear Power Plants" by Furukawa was successfully published in Japanese [42], and the MSR system began to be recognized by the public in Japan. Due to the recent confusion regarding international nuclear policies, fear against nuclear terrorism and price rise of oil, many countries have 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 from the foundation established on the dying wishes of Nobel Peace Prize Laureate

Winner Eisaku Sato (the former Japanese prime minister) on June, 2006 [2].

The message of Thorium Power Ltd presented in the New-year issue of Newsweek is a encouragement for us to open the Thorium ERA [4]. The utilization of Thorium solid fuels in the several modified reactors of LWR [43], HWR [44] or High Temperature Gas-cooled Reactors will be useful for opening the Thorium Era in its initial stage.

6. Conclusions

One of the most promising philosophical and technical strategies for the world survival 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 Lilienthal [45], a 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 Bernal [46] 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" [47], 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, Yukawa and Tomonaga [48] 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.

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