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

By
K Furukawa*, K Arakawa, L.B Erbay（Turkey),
Y Ito, Y Kato, H Kiyavitskaya(Belarus),
A Lecocq(France), K Mitachi, R Moir(USA),
H Numata, J. P Pleasant(USA), Y Sato,
Y Shimazu, V A.Simonenco(Russia),
D D Sood(India), C Urban(Brazil), R Yoshioka

International Thorium Molten-Salt Forum, JAPAN

INTRODUCTION

In the 21st century, the *globe will seriously be attacked* by the *social/environmental disorder:*

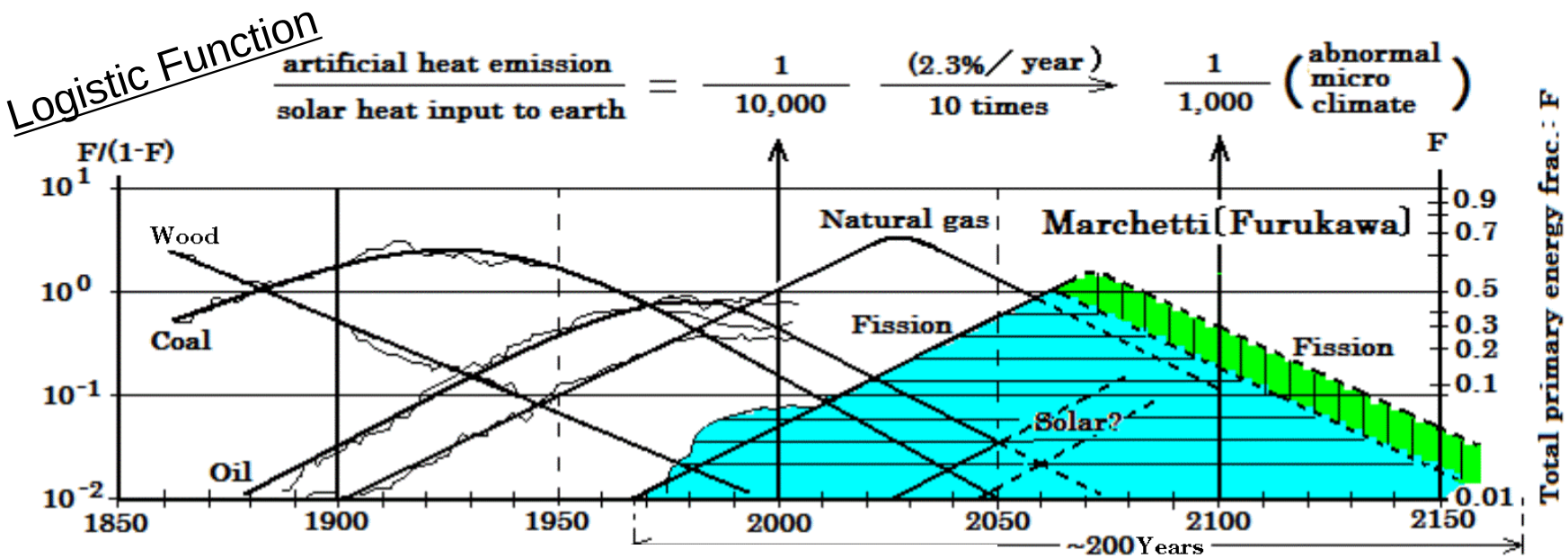
- ✓**population explosion, consuming energy**
- ✓**poverty, & starvation,**
- ✓**Greenhouse effect,**
- ✓**Chemical pollution,**
- ✓**desertification, etc.,**

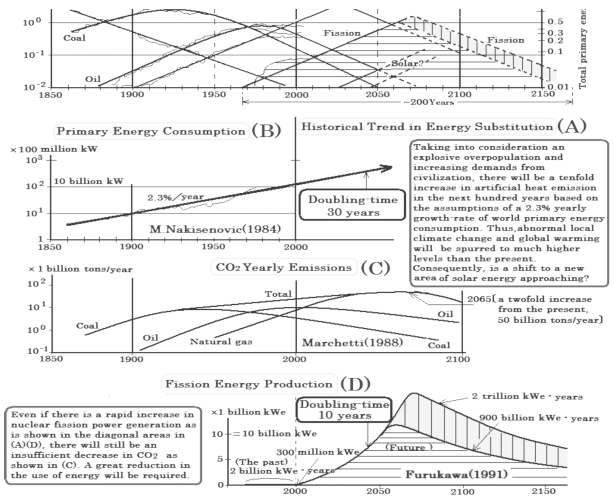
and such situation will become intolerable by human inducing *riot* or *terrorism*.

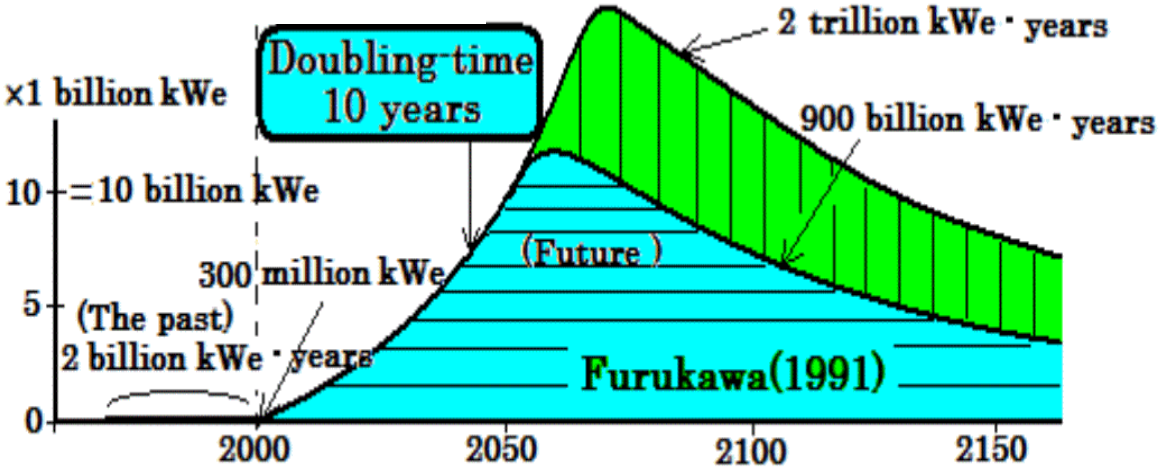
"How to solve" such disorder ? among 20-30 years

“Global Future Energy Prediction”

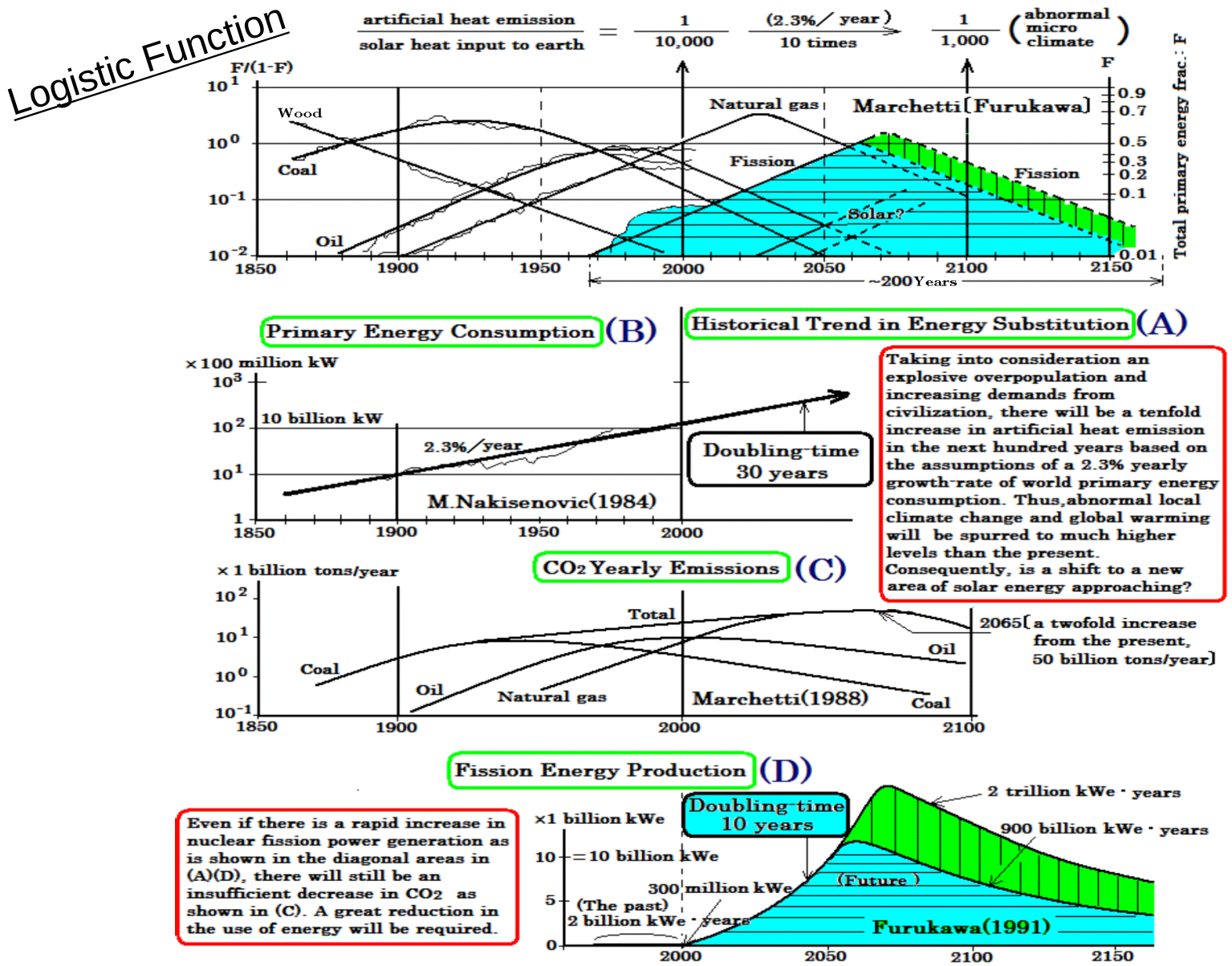
The basic problem: ***disordering of major energy technology***,
Application of **solar-based technology**: Needs more than 100 years







“Global Future Energy Prediction”



REQUIREMENTS ON *NEW NUCLEAR ENERGY(1)*

--- Necessity of New Strategy :*revolution*---

Fossil fuel cannot be used as a major energy source even using *natural gas* in the first half of 21st century.

- **Achieve in the next 30 to 50** years at least
- Total Peak output about **10TWe** at 2065
  (30 times bigger than the present)
- **doubling–time: 5-7 years**
- **SAFETY: No severe accident**
- **RADIO-WASTE** management by *transmutation*
  (among **100 years)** *no Million years*
- **NUCLEAR PROLIFERATION** resist. &
  NUCLEAR TERRORISM protection.

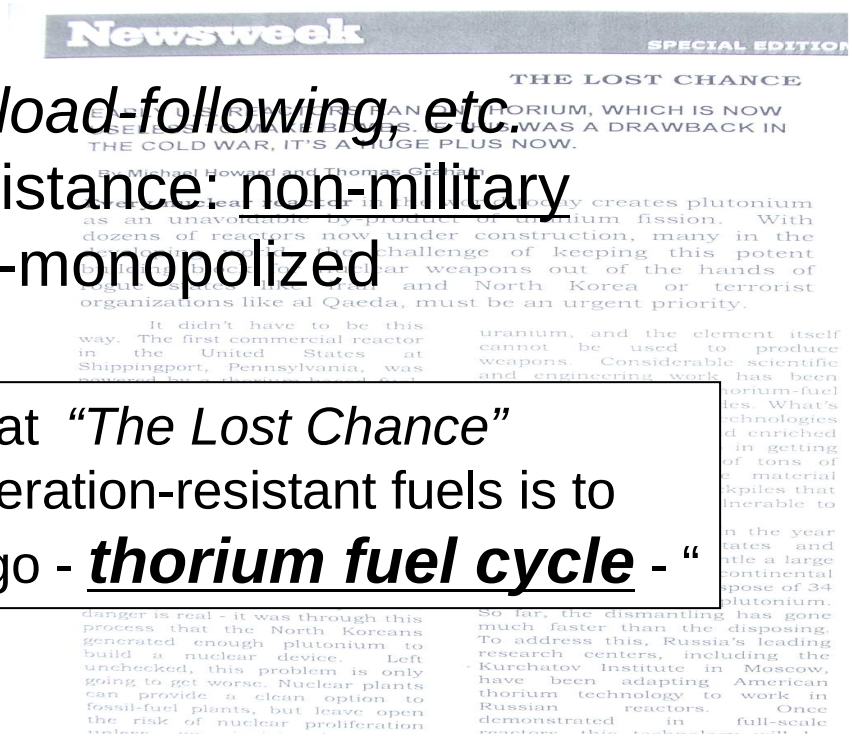
- **ECONOMY** is the most important issue:
  "***SIMPLICITY***" in Integrated FUEL-CYCLE SYSTEM

REQUIREMENTS ON NEW NUCLEAR ENERGY(2)

--- New Technological Requirements ---

A strong ***public acceptance*** is needed for fission-energy.
Problems remaining are:

A) Safety
B) Reliability ---- "*SIMPLICITY*" in all aspect
C) Economy
D) Environmental acceptance: RADIOWASTE
E) Social acceptance
--flexible in *site, size, load-following, etc.*
F) Nuclear proliferation resistance: non-military
G) Resource problem: non-monopolized


Newsweek
SPECIAL EDITION
THE LOST CHANCE
THE COLD WAR, IT'S A HUGE PLUS NOW.

"Newsweek", 2007 New Year issue: at *"The Lost Chance"*
"the most promising path towards proliferation-resistant fuels is to return to the road not taken 50 years ago - ***thorium fuel cycle*** - "

- ***"Thorium"*** **Fuel Cycle** -

- **^{232}Th** (fertile) + n → ^{233}Th → ^{233}Pa → ***^{233}U*** (fissile)
- ***Trans-U elem.***(Pu, Am, Cm): **negligible** production
- accompanied with ***strong gamma activity:***
  10^2-10^3 ppm ***^{232}U*** ------→ ^{208}Tl : 2.6 MeV gamma
- requiring ***"fluid-fuel"*** technology : **MOLTEN-SALT**
- suitable for ***"thermal"*** neutron reactors

- **Th** resource: 3 to 4 times more abundant than **U**
  popular, non-monopolized

Molten Fluoride Salt **Fuel Application**

- Molten salt solvent: $^{7}LiF\text{-}BeF_2$ ("***Flibe***" named by ORNL)
- *Low thermal-neutron cross-section* material
- ***Best solvent*** of fissile and fertile materials, & fission-products.
- ***Multi-functional*** medium:

i) *NUCLEAR* REACTION,
ii) *HEAT*-TRANSFER, iii) *CHEMICAL*-PROCESSING
by a Single-Fluid Phase

Advantages

a) Fuel : no fuel fabrication; no replacement; small inventory
no radiation-damage; no melt down; glassy material
no violent chemical reactions with air or water
fully passive safety

b) Excess reactivity : very small

c) Xe, Kr, T : continuously removed--- few trouble
high conversion-ratio : near breeder (best for power-st.)

d) Usable any fissile materials: ***^{233}U, ^{235}U, ^{239}Pu, $^{241}Pu***

Molten Fluoride Salt Fuel Application(B)

Handicaps

(1)Non-popularity of ***fluid-fuel reactor*** concept itself

(2)Non-success of the fluid-fuel reactors *except MSR*

(3)No descrip. on “Thorium Reactor” issue in recent Textbooks

(4)No existence of fissile isotope in Th resource

(5)Few people/fund for MSR-devel. at isolated site: still “enough” and “no accident” ------- ”few news”

(6)Historical unhappiness in the Seventies : political

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**.

T H O R I M S - N E S

THORIUM **M**OLTEN-**S**ALT
NUCLEAR **E**NERGY **S**YNERGETIC System

Basic Concept depends on *three principles*:

[I] *Thorium* utilization

[II] Application of

***Molten-Fluoride Fuel* technology**

[III] Separation of

Fissile-Producing Accele.Breeders: *process-plant*

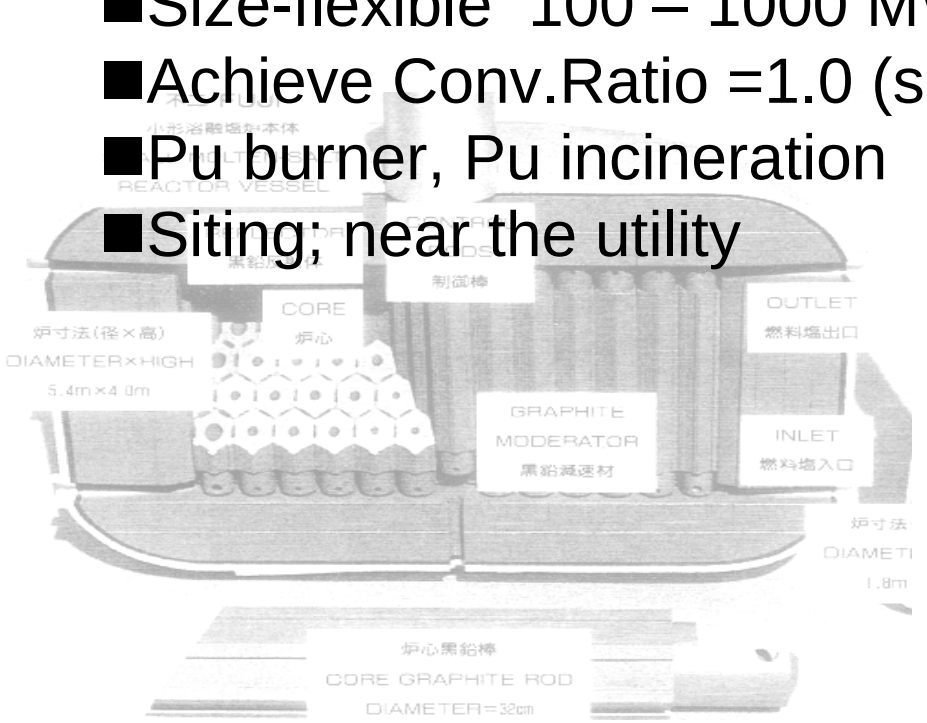
& Power Gene. Fission-Reactors: *power plant*

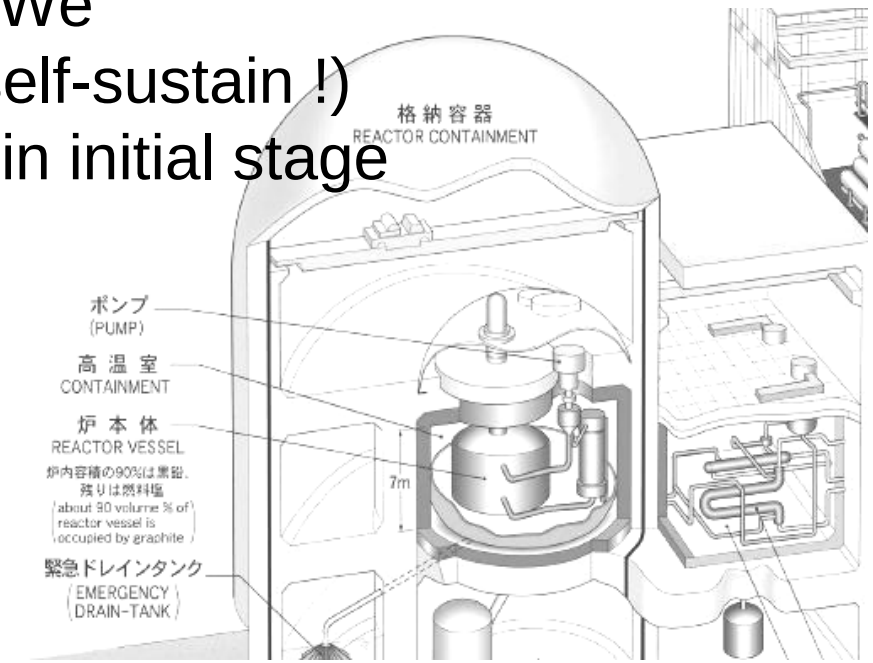
Refusing "Fission Breeding Power Station" concept.

Complex ! Bigger ! Non-economical !
Weak breeding (too longer doubling time>>5-7 y) !
(no LMFBR even MSBR)

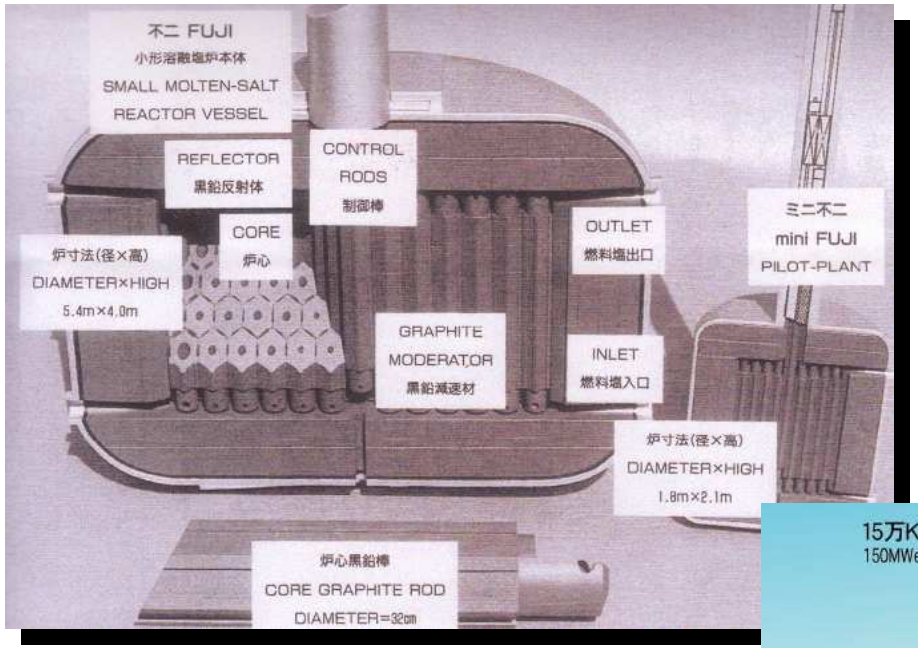
Molten-Salt Power Reactor : *FUJI*

- Fuel-self-sustainable (no continuous chem. processing)
- Small amount of production of Pu and MA
- Simple structure and easy oper,/mainte. than MSBR : closed vessel (no big flange); no graphite replacement; no solid-fuel handling; nearly no control-rod and few safety/safeguards facility; load-following operation
- Size-flexible 100 – 1000 MWe
- Achieve Conv.Ratio =1.0 (self-sustain !)
- Pu burner, Pu incineration in initial stage
- Siting; near the utility





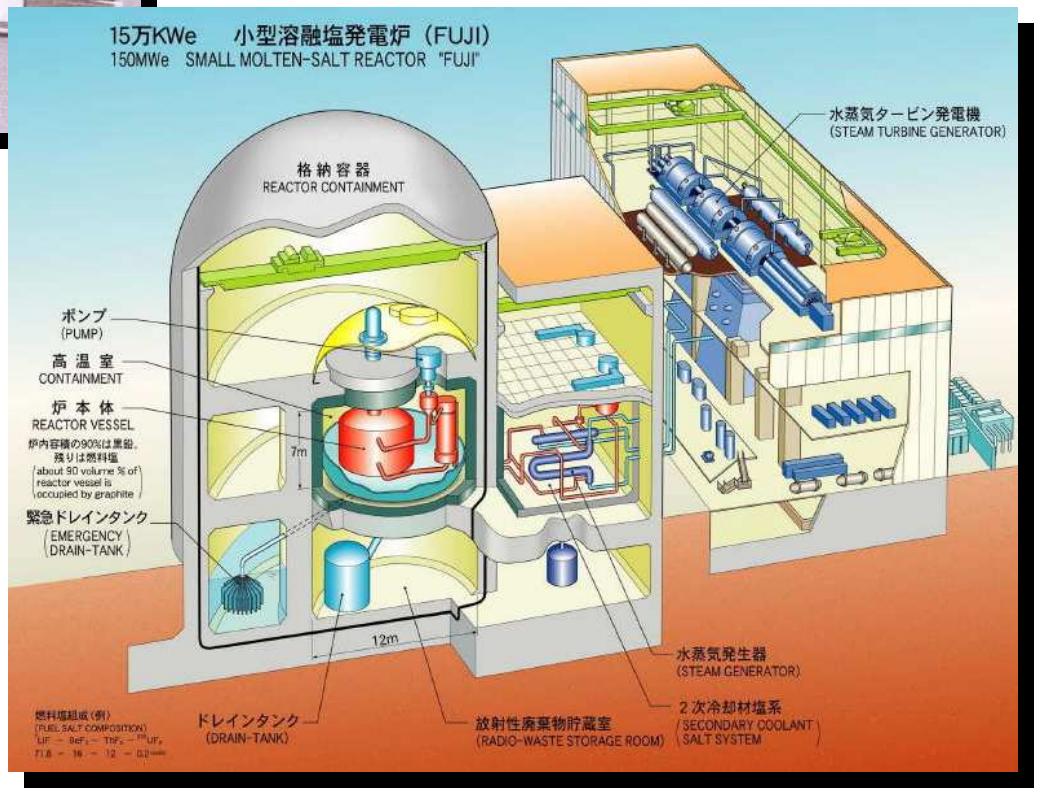
Molten-Salt Power Reactor :



FUJI

Cross-section View of FUJI and miniFUJI Reactor Vessel Models

Full View of FUJI Molten-Salt Reactor



Accelerator Molten-Salt Breeding Facility:

AMSB

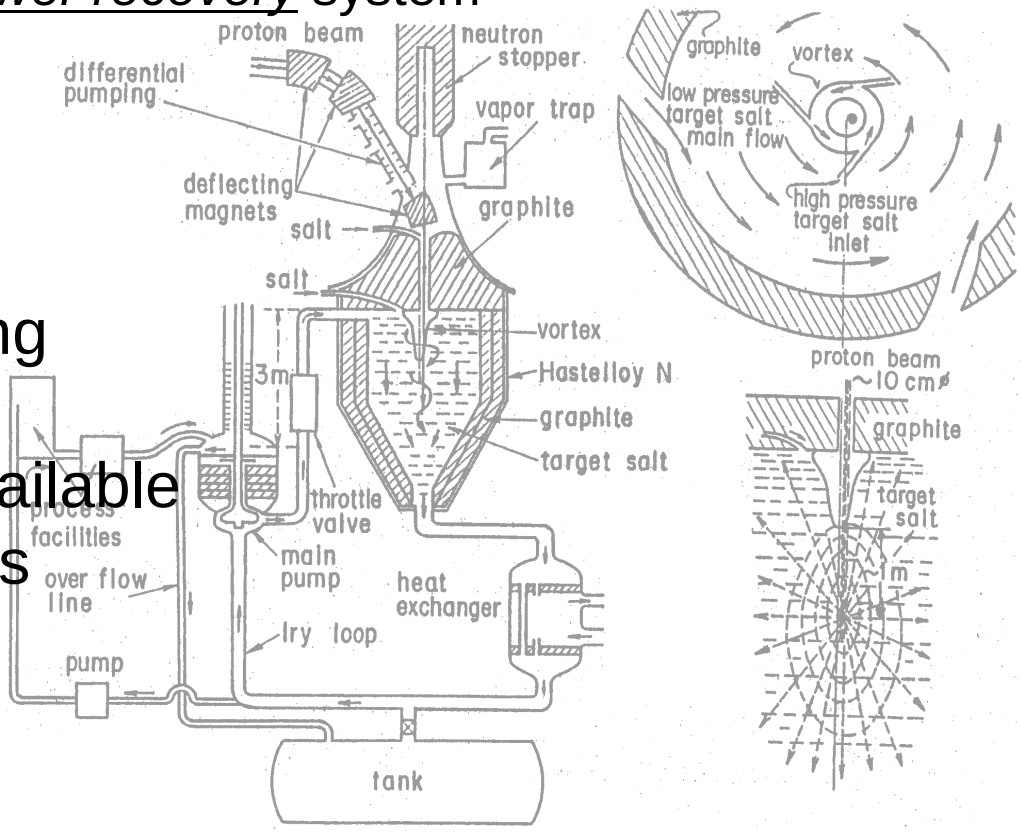
Composed of *three parts*:

(1) 1GeV and 200-300 mA *proton accelerator*

(2) Single-fluid molten fluoride *target/blanket* system

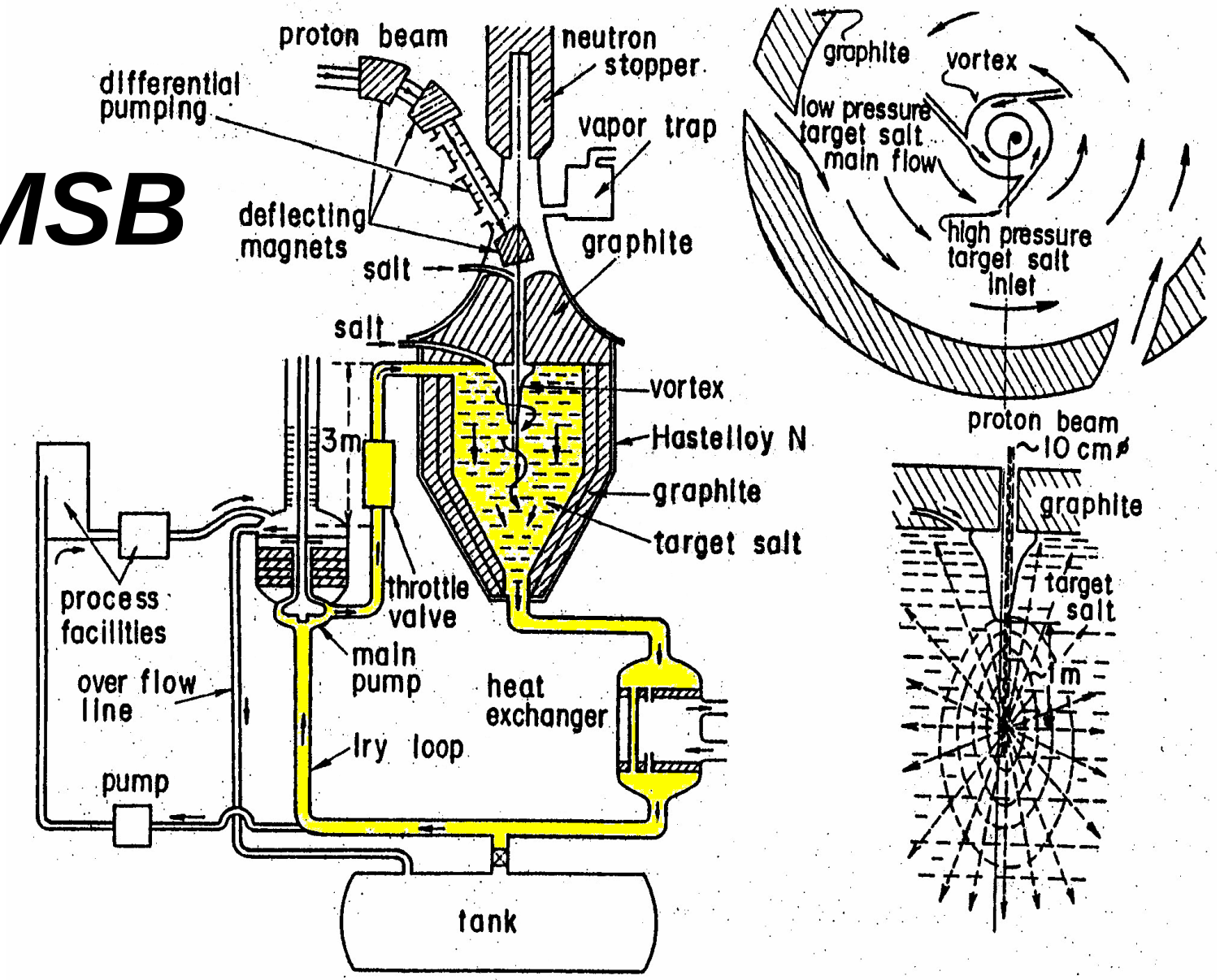
(3) Heat transfer and electric *power recovery* system

- sub-critical
- no radiation damage
- easy heat removal
- no target/blanket shuffling
- Gas-curtain window
- multi-beam funneling available
- simpler chemical aspects



Accelerator Molten-Salt Breeding Facility:

AMSB



Safety

FUJI and AMSB have many advantages.

- very low pressure (0.5 MPa)
- no chemical activity
- no radiation damage in core
  except graphite : high melting point 4000K.
- Xe, Kr, T : always removed from the system :
  few release to PUBLIC
- prompt negative temperature coefficient
- very low excess-reactivity, or subcritical (AMSB).
- leaked fuel-salt :<u>no re-criticality accident</u>
  and frozen as <u>*stable glass*</u>.
- <u>no chance of “severe accidents”</u>.
- mostly safer even under
  <u>military attack</u> or <u>internal sabotage</u>.

Proliferation Resistance and Safeguards

■**^{233}U : better *proliferation resistance than Pu***

< Strong 2.6 MeV gamma emission >

More than **20 cm thick Pb** or ***1 m thick concrete*** is required for biological **shielding** and the **^{233}U detection is easy.**

1) Macroscopic View in Global Fuel Cycles

Pu in spent fuel from various thermal reactors is steadily increasing.

THORIMS-NES is the best scheme for *Pu incineration*.

2) Pu vs ^{233}U (FBR vs FUJI)

SQ in nuclear safeguards is 8 kg for Pu also 8 kg for ^{233}U.

But the ^{233}U for a weapons program will be significantly difficult.

3) Microscopic View at Reactor Site

a) Fissile inventory in MSR is low and just critical(no excess fissile)

b) Fissile material concentration in molten-salt fuel is low enough.

Then the theft will be impossible.

Radio Waste Management

including *Economical Nuclear Transmutation*

i. very **few "low-level radio-waste" production:**
few works on chemical process & maintenance

ii. practically **no Trans-U production** : few Minor Acti.
Pu & (Am+Cm): 0.5kg & 0.3g per 1 GWe・y in FUJI
230kg & 25kg in LWR

iii. fuel-salt : include fairly much ***fission-products***,
decay/destroy in the "***molten-salt fuel cycle***"

iv. economical nuclear **transmutation** in the ***fuel-cycle***
by huge low-cost excess-neutrons (fissiles)
in the *recession age* of **Thorium ERA (Fig.1)**

Now the **"high-level radio-waste management"** issue:
"*One Hundred Years*" problem. "No Million Years!"

ECONOMY

- **Capital cost of FUJI** is almost similar to LWR.
- **Fuel cycle cost** is lower than LWR (No solid-fuel assemb.)
- **Operat./Mainte.cost of FUJI:** similar or less than LWR.

- The final **electric power cost** in **THORIMS-NES** would not increase so much

  1. The net ^{233}**U** consumed by fission : only **about 0-5 %**
  2. The mainte./operation cost of fuel-cycling : very low
  3. No or few
     - i) U-enrichment work,
     - ii) fuel handling (fabrication, transport, storage),
     - iii) residual dep.U, TRU & Radio-wastes management

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	$^{232}Th + n \rightarrow {}^{233}U$
ENVIRONMENT 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(*high gamma from* ^{232}U) easy safeguard	

SAFETY FUNDAMENTAL ENGINEERING	chemical reactive mechanical failure nucl. excess reactivity SOLID-FUEL ASSEMB. configuration, operation, transport, reprocessing core-melt, re-criticality	chemical inert low pressure, low flow very low, *fuel self-sustain*. *LIQUID FUEL* (fuel :*no radi. damage*) all simpler & fewer NO SEVERE ACCIDENT	*MOLTEN-* FLUORIDE FUEL *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 ECONOMY	siting difficulty large power size process-heat : not easy safety, nucl.prolif., rad-waste	easy : near to utility smaller : size flexible easy:industrial, district heat large improvement	SEPARATION of *BREEDING* & *POWER GENE.*

DEVELOPMENTAL STRATEGY

■**Installation/Operation of <u>miniFUJI</u> (7-10 MWe)** : 7 years later

successful 4 years operation(1965-69) of experi.reactor: *MSRE* in ORNL

(NEXT PAGE)

■**Installation/Operation of <u>FUJI-Pu</u> (100-300MWe)** : 12 years later

Pu fuel-salt from the existing spent-fuels : *<u>using and eliminating Pu</u>*

Depending on such MSR-technology development,

■**Development and Installation of <u>AMSB</u>** : 20-30 years later

■**<u>THORIMS-NES</u>** of real Th-U breeding Fuel-Cycle: **<u>AMSB/FUJI</u>**

globally deployed in the *<u>regional centers</u>* (AMSB & chem.Process)

to open the *<u>new THORIUM ERA</u>*

***supported* by the all 24 Conferees at the MSR specialists' meeting:**

"International Conf. on Th Molten-Salt Reactor Development",

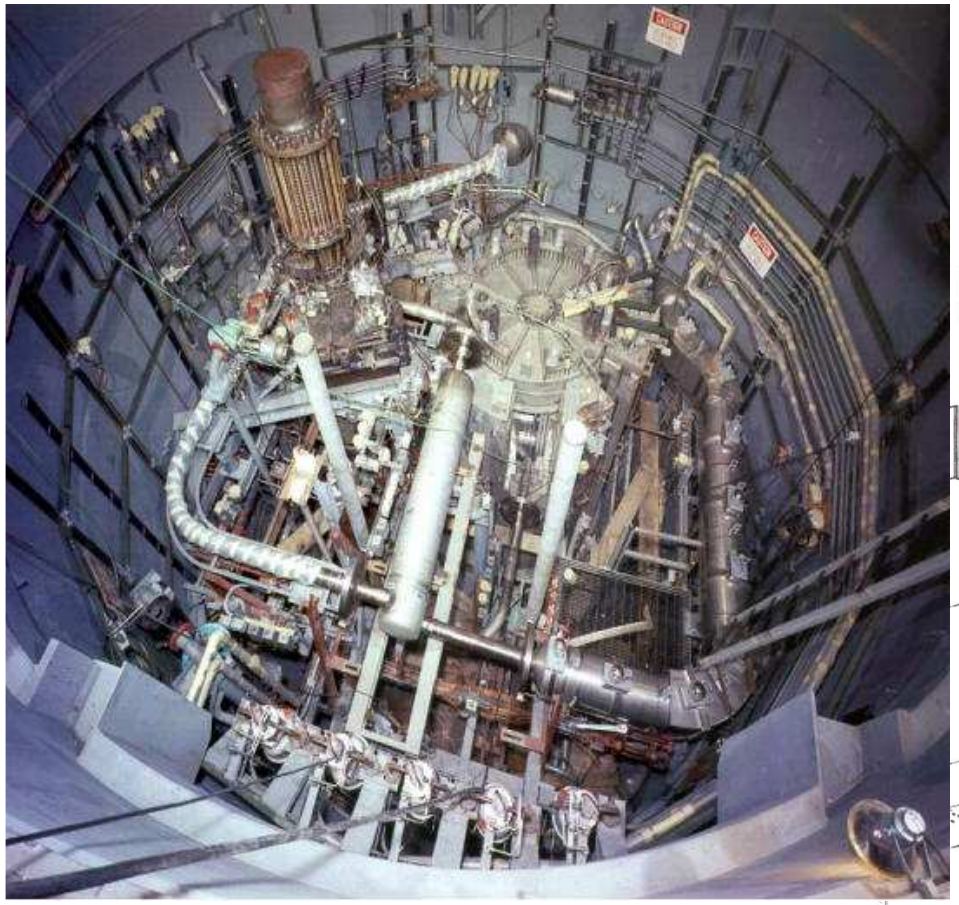
April 8-11, 1997 at RAND, Santa Monica, California, USA.

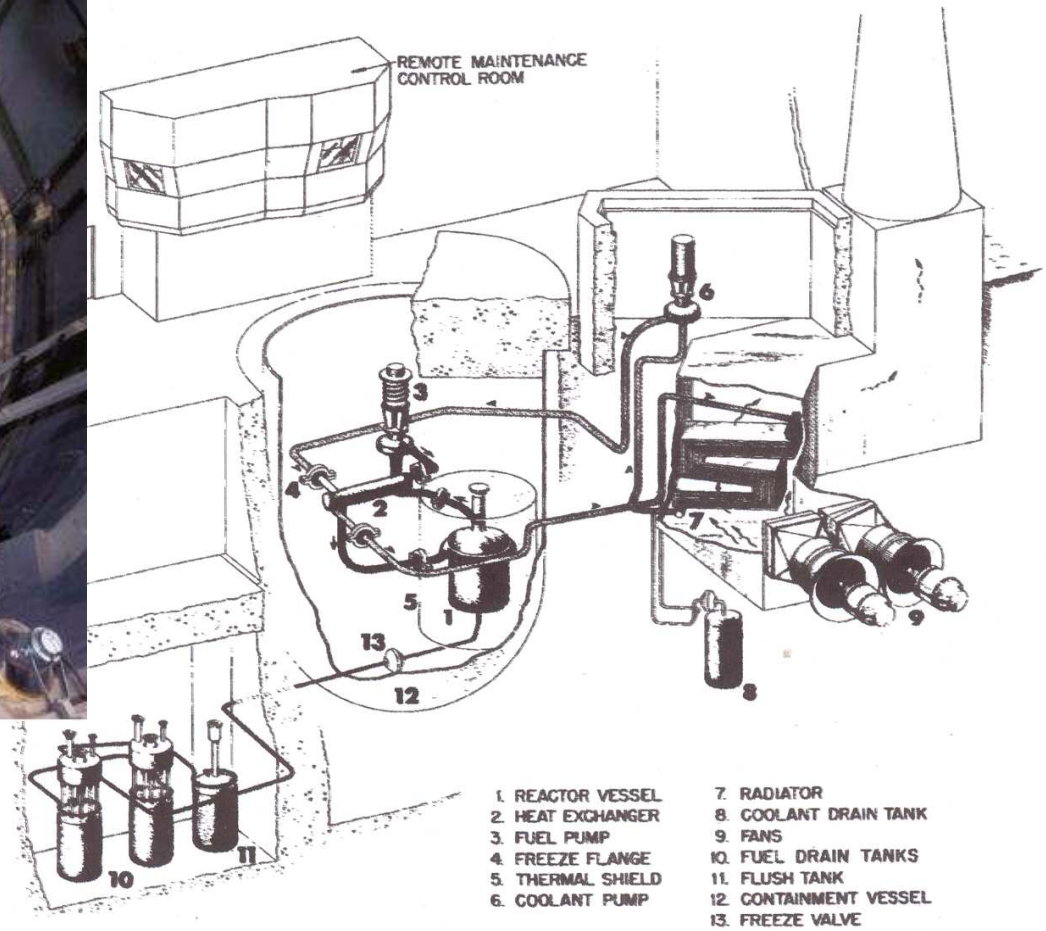
Japan, the U.S., Russia, Belarus, Czech, France, India, Turkey & IAEA

MSRE operated on 1965-69 at ORNL, USA

(without accidents)

Reactor operation: 17,655 hrs
Loop operation: 26,076 hrs





MSRE

Molten-Salt Reactor Experiment

THORIMS-NES Deployment Plans

■**F-plan:** Fission reactor development:
miniFUJI, FUJI in several versions.
FUJI power stations of *smaller* as well as *larger* size.

■**D-plan:** Dry-processing of spent fuel salt and target/blanket salts

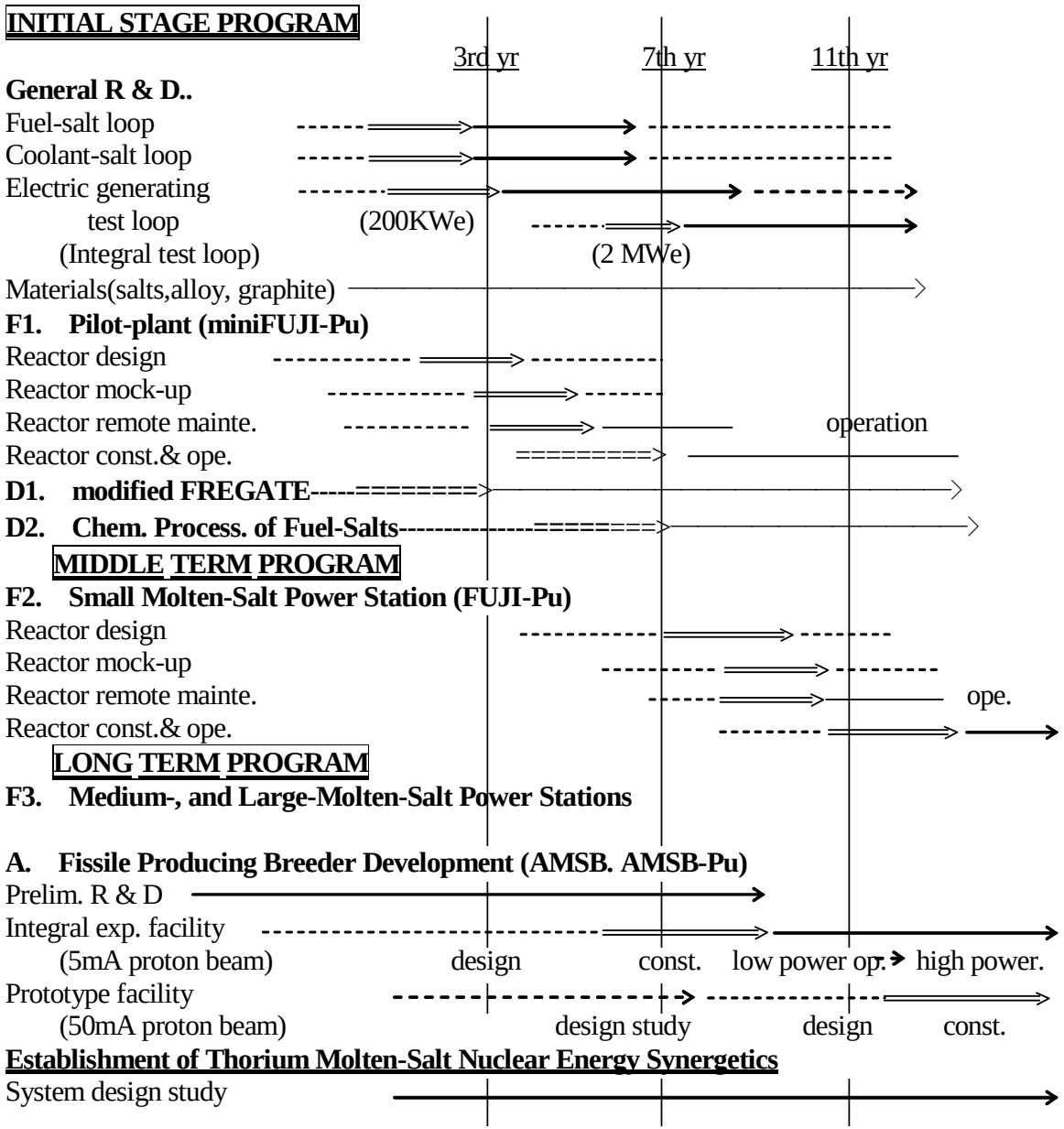
Pu including fuel salt preparation from "spent solid fuels"
of ordinary reactors such as LWR, FBR, HWR etc.

■**A-plan:** Accelerator Molten-Salt Breeder （AMSB) development
Experimental, Prototype, & commercial facilities

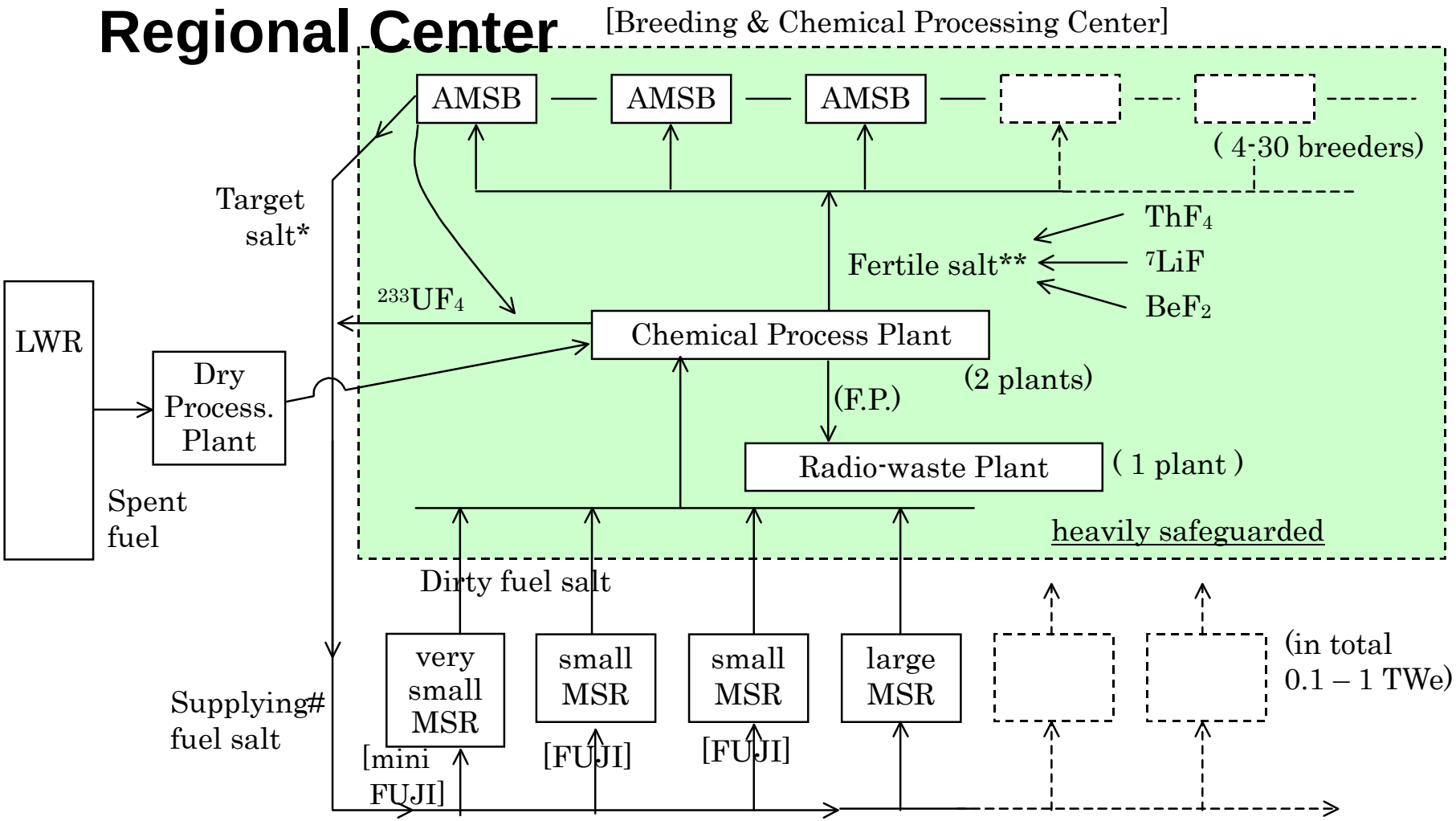
■**Regional Centers Deployment plan:** (cf. the later Figure)
Chemical processing & Radio-waste management plants

Developmental schedule of THORIMS-NES

(⟹ construction; → operation)



Thorium molten-salt breeding fuel-cycle system



Solid Fuel Cycle System

Simple Molten-Salt Fuel Cycle

(*)^{7}LiF-BeF_2-ThF_4-$^{233}UF_4$ (**)^{7}LiF-BeF_2-ThF_4 (#)target salt* + additive $^{233}UF_4$

DOMESTIC AND INTERNATIONAL SUPPORT ON NEW THORIUM STRATEGY

- Our strategy has been unanimously recognized
  by the all 24 Conferees in 1997 at ***"Intl Conf. MSR Develop."*** RAND, USA
  Japan(5), USA(5), Russia(4), Belarus(2), India, France, Turkey, Czech & IAEA

JAPAN: Academ. Asoc. "Th-Energy Research"

CONCLUSIONS

- One of the most promising philosophy and strategies for the global survival in this century has been presented in "**THORIMS-NES**": very simple new "Th-U Breeding Fuel-Cycle System"

- Although many more detailed design and optimization studies are needed and should proceed with international cooperation,

- As the initial step for ***opening the Thorium era***, we have to restart the demonstration of *MSR* ***technological integrity*** by simple pilot-plant **miniFUJI**

“Atomic Energy: A New Start”

by David E. Lilienthal

[former TVA President, the 1st Chairman of USAEC]

We hope that our work will be valuable
as a reply to the sincere wish of* David E. Lilienthal*,
the most significant American/Human of the 20th century,
given on the following final sentence in his last book,

“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*.”

Replying him, we proposed “*THORIMS-NES*”,
Promising to *industrialize 20 years later* from now
in order to solve a *global Energy/Environmental disorder*.

“GLOBAL SURVIVAL”.

THORIMS-NES will be a hope of Scientists

Professor <u>John D.Bernal</u> (the teacher of K.F.) [1901-1971]
had strongly hoped to achieve a **"World without War"**
and that in the not too distant future
"*Science* may come to be used *for the benefit of all mankind*".
(He was the first to use the phrase
"weapons of mass destruction".)

Professors <u>H. Yukawa</u> & <u>S. Tomonaga</u>
Pugwash Conference on "A New Design toward Complete Nuclear Disarmament" held at Kyoto, Japan, 1975,
Statement on "Beyond Nuclear Deterrence"
(signed by 28 scientists):
"all governments should renounce without conditions the use of nuclear weapons"

Scientists should fight
for Technology Revolution for Human.
<u>THORIMS-NES</u> will offer a chance to promote such wishes.