Future of Nuclear Power

2018-12-2. ImPACT Conference

Former Executive Director, IEA
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WEO2017

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Tipping the energy world off its axis

- Four large-scale upheavals/revolutions in global energy set the scene for the new *Outlook*:
  - The United States is turning into the undisputed global leader for oil & gas
  - Solar PV is on track to be the cheapest source of new electricity in many countries
  - China is switching to a new economic model & a cleaner energy mix
  - Electricity is broadening its horizon, spurred by cooling, electric vehicles & digitalisation

China

- These changes brighten the prospects for affordable, sustainable energy & require a **reappraisal of approaches to energy security.**
- There are many possible pathways ahead & many potential pitfalls if governments or industry misread the signs of change

The *new* geography of energy

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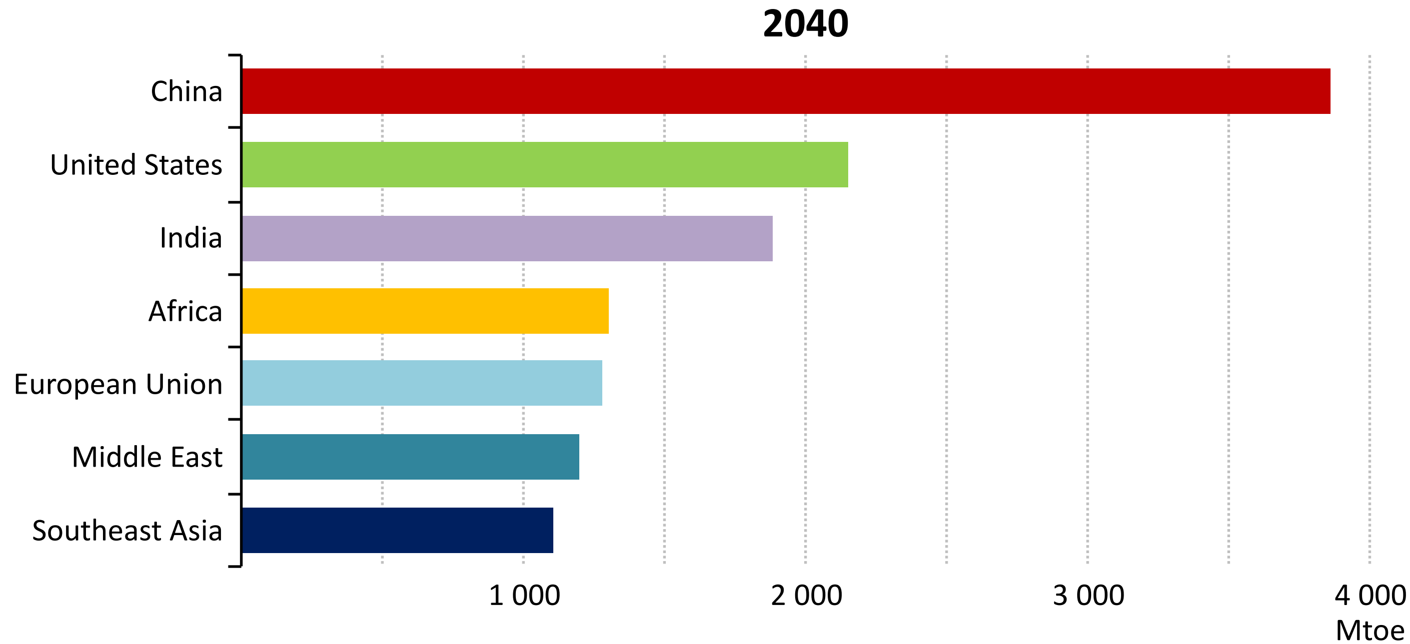
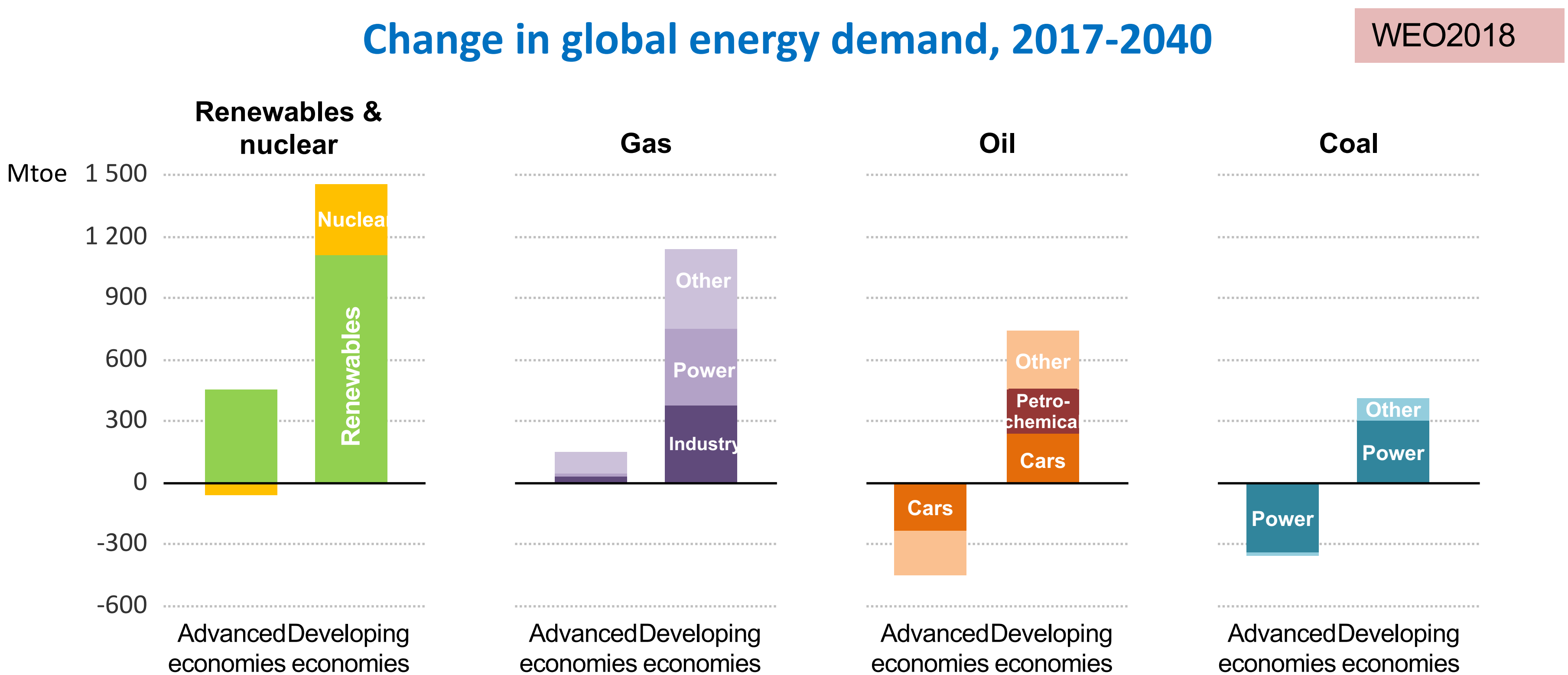
Energy demand



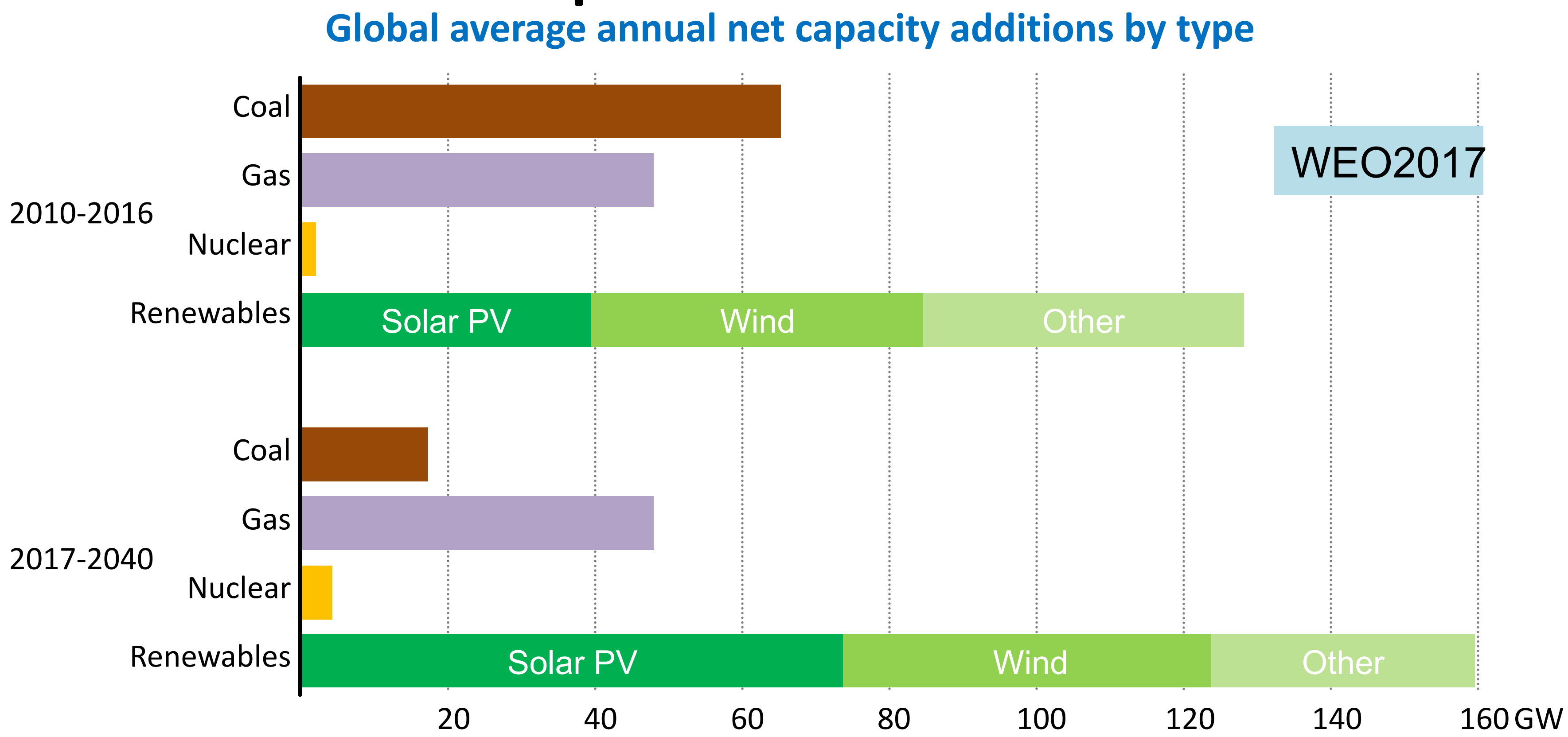
In 2000, more than 40% of global demand was in Europe & North America and some 20% in developing economies in Asia. By 2040, this situation is completely reversed.

Fuelling the demand for energy



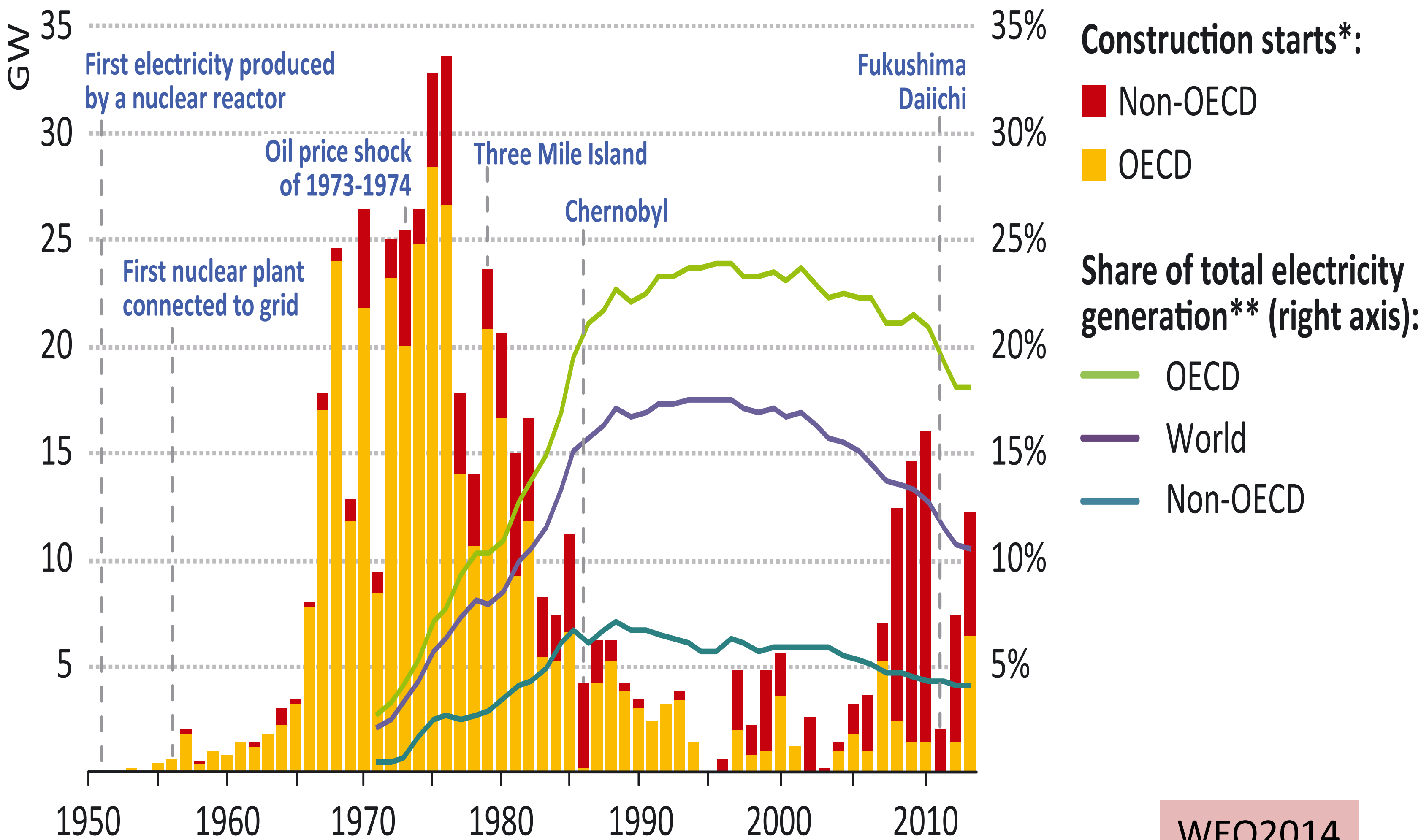
The increase in demand would be twice as large without continued improvements in energy efficiency, a powerful tool to address energy security & sustainability concerns

Solar PV forges ahead in the global power mix



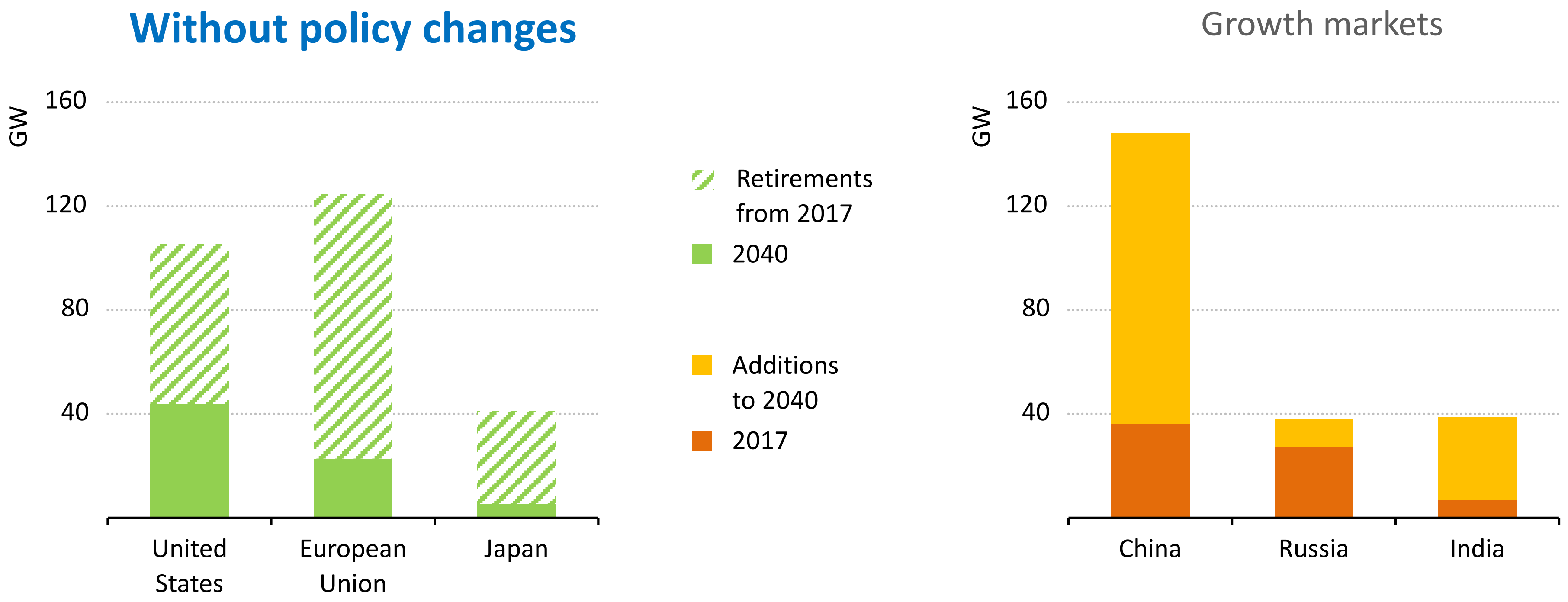
China, India & the US lead the charge for solar PV, while the EU is a frontrunner for onshore & offshore wind: rising shares of solar & wind require more flexibility to match power demand & supply

History of Construction of Nuclear Reactors



WEO2014

Two directions for nuclear power



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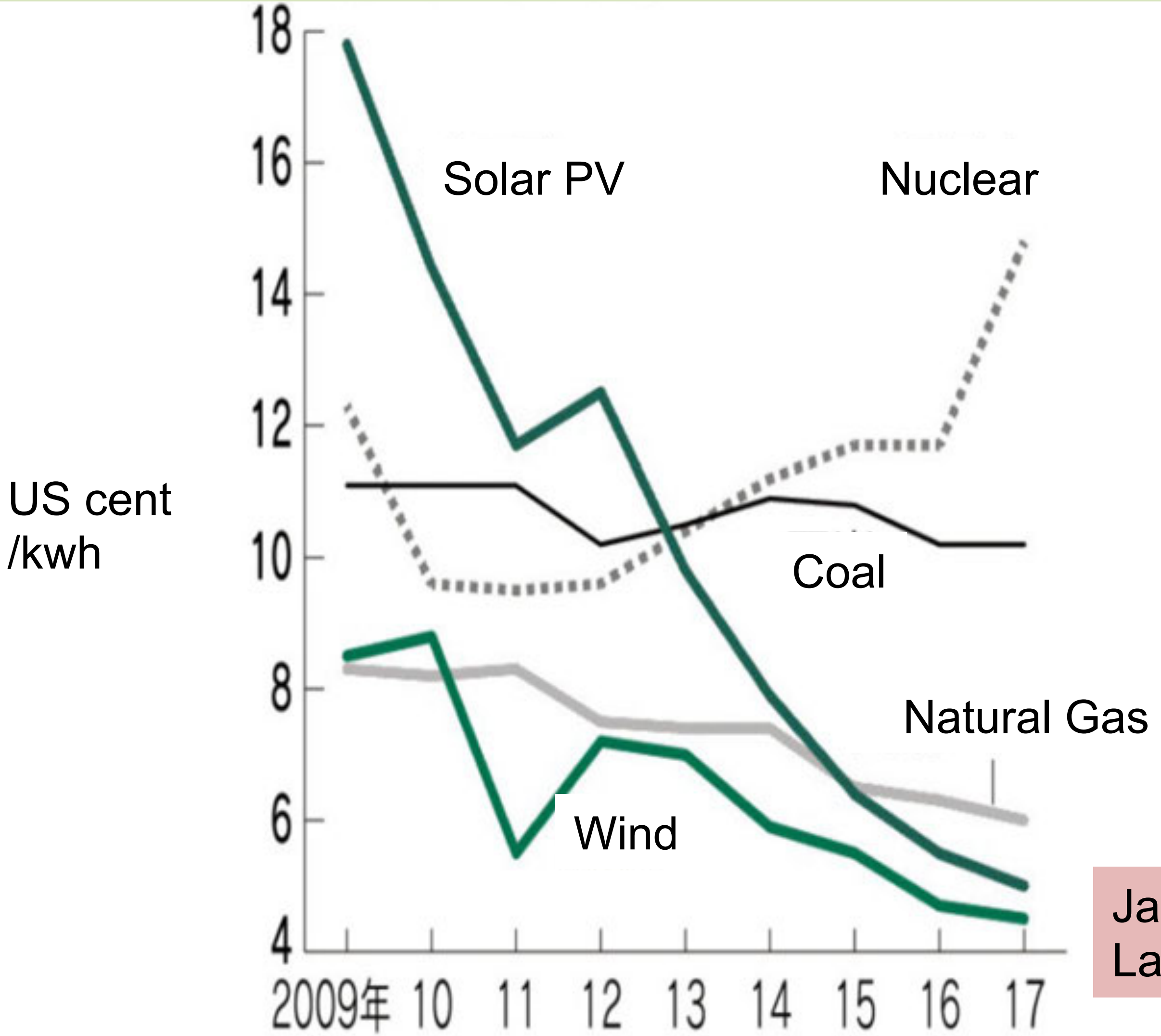
The contribution of nuclear power could decline substantially in leading markets, while large growth is coming, as China takes first position within a decade

Renewables vs other powers
Cost competitiveness structure is changing rapidly



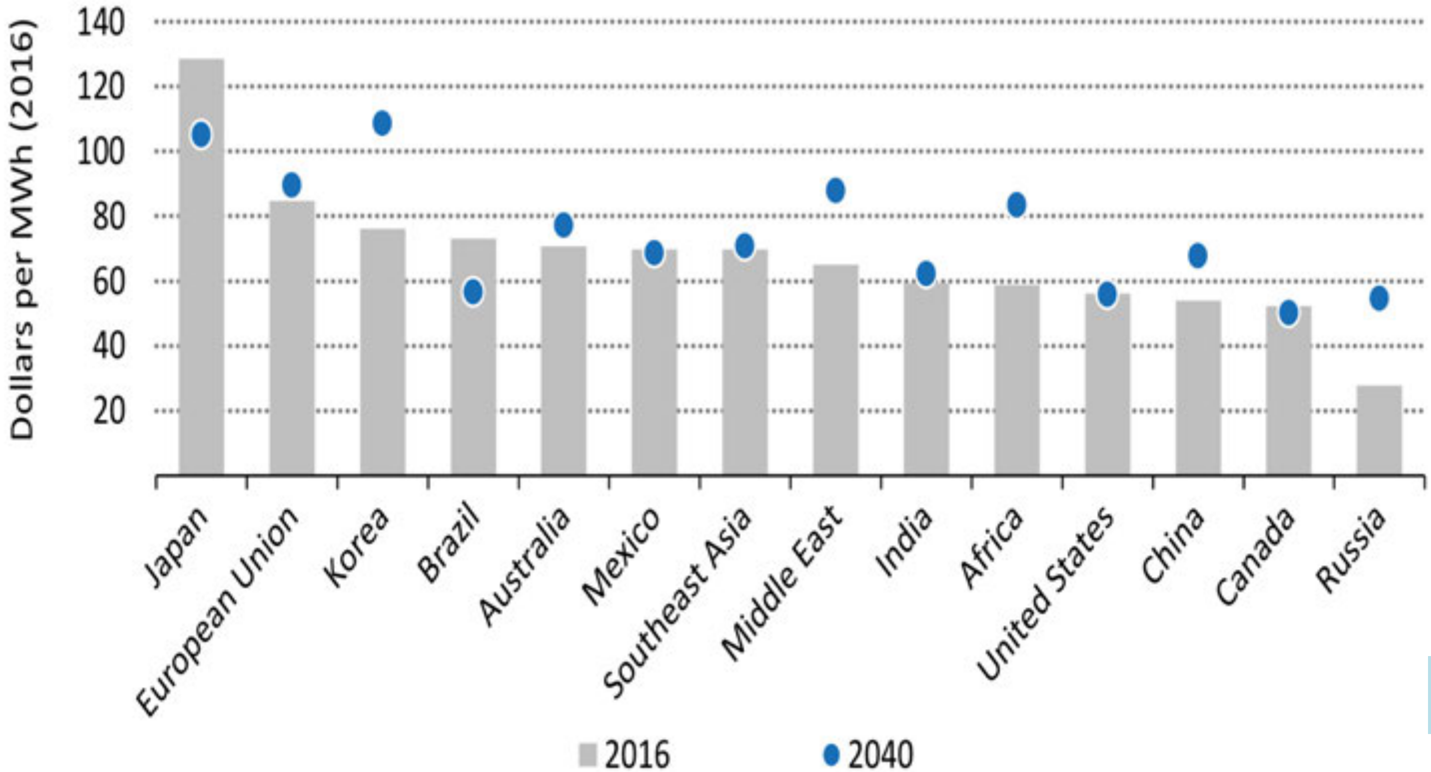
Japan Economic Journal
Lazard Asset Management

Construction cost of New power plants in China (1000yen/kw)

	2013	2014	2015	2016
Coal (USC)	53	55	61	52
hydro	154	198	219	179
nuclear	241	209	351	313
wind	123	128	147	126
solar	145	148	166	137

JEPIC/ China Federation of Power Company

Average Costs of Power Generation



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Average power generation costs are $50-80/MWh in most regions today, and most increase over time in the New Policies Scenario

Nuclear power: public concerns must be heard and addressed

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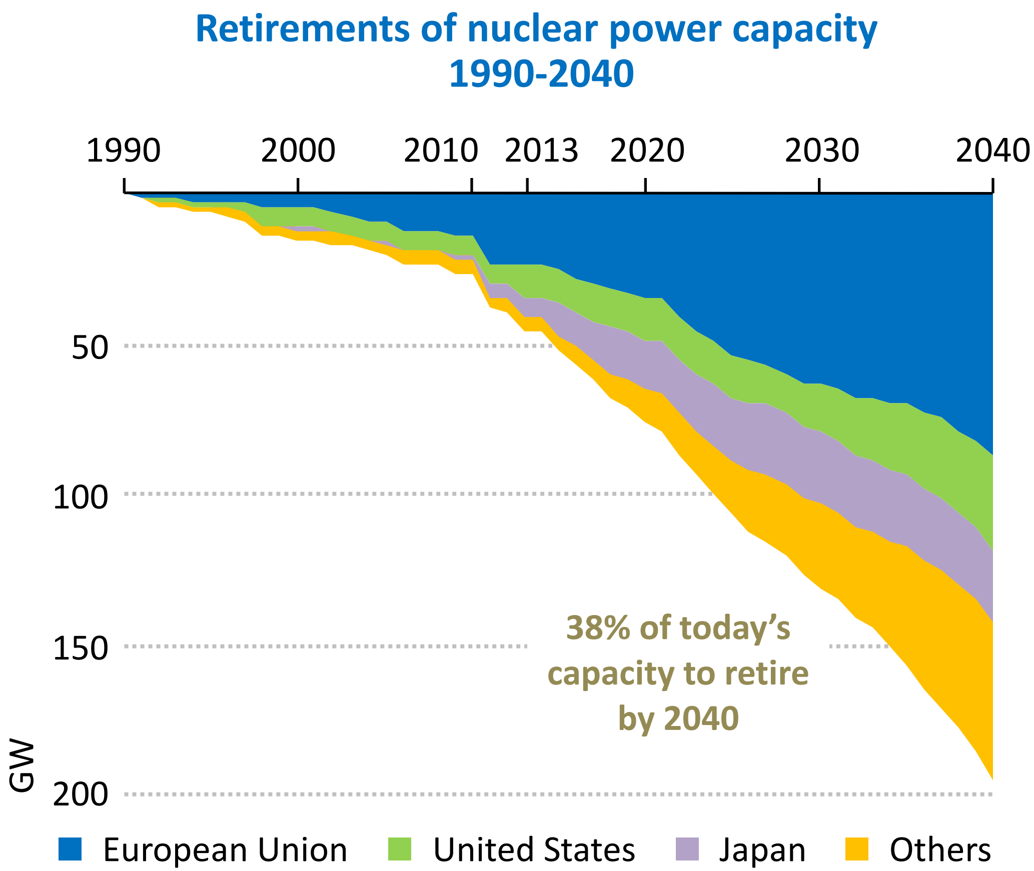
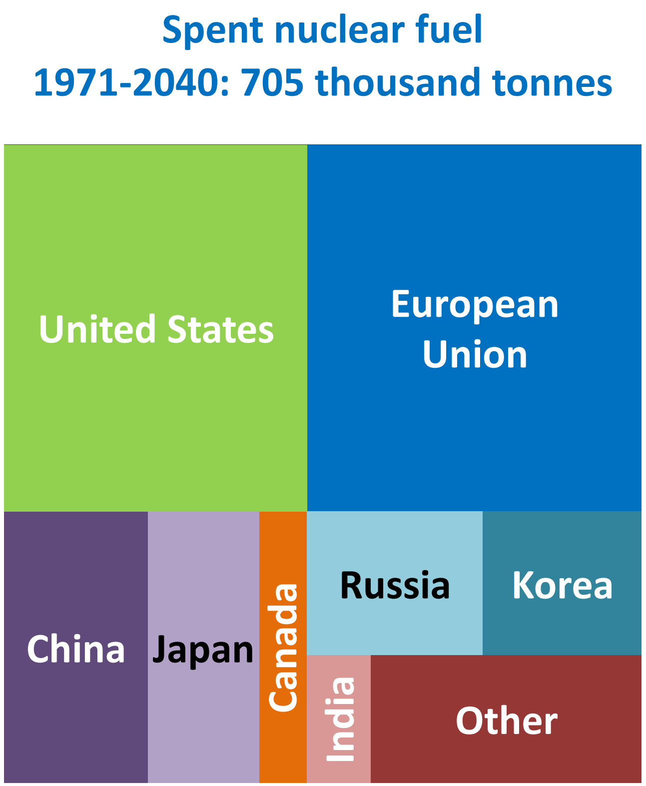




Key public concerns include plant operation, decommissioning & waste management; By 2040, almost 200 reactors are retired & the amount of spent fuel doubles

Generations of Nuclear Energy

Generation I

Early Prototypes

- Shippingport
- Dresden
- Magnox

Generation II

Commercial Power

- PWRs
- BWRs
- CANDU

Generation III

Advanced LWRs

- CANDU 6
- System 80+
- AP600

Generation III+

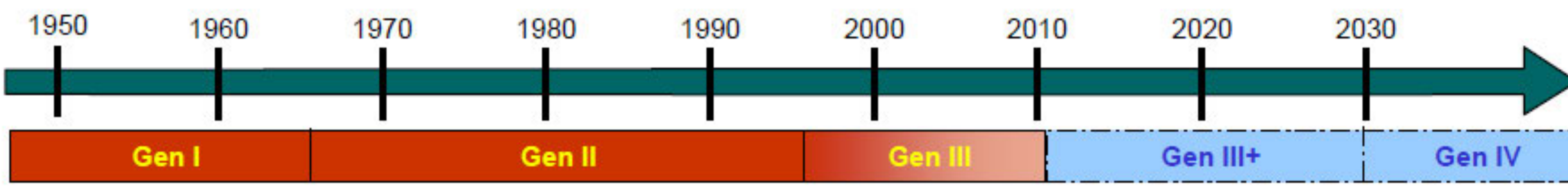
Evolutionary Designs

- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR

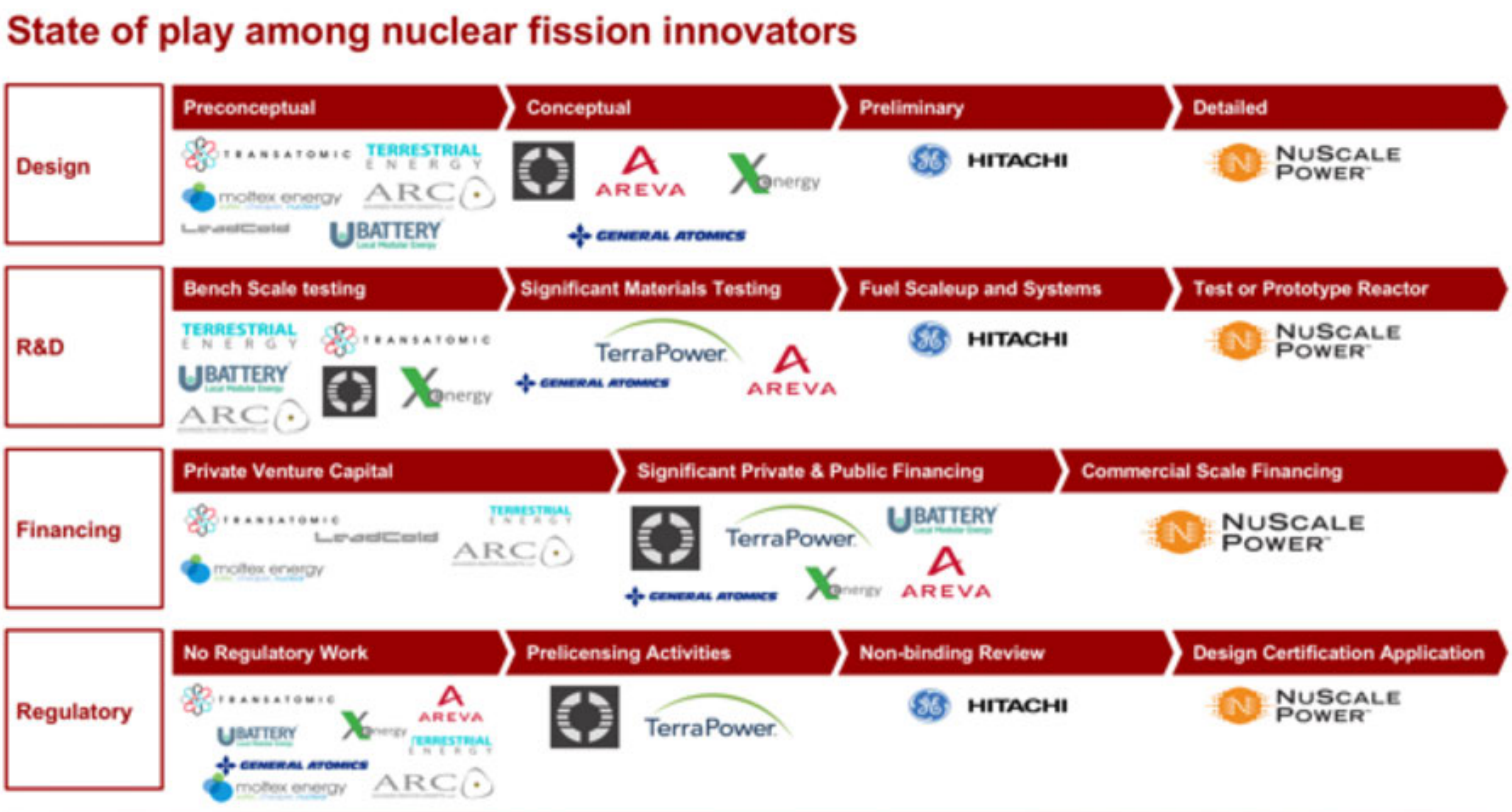
Generation IV

Revolutionary Designs

- Safe
- Sustainable
- Economical
- Proliferation Resistant and Physically Secure



Ventures for Small Modular Reactors



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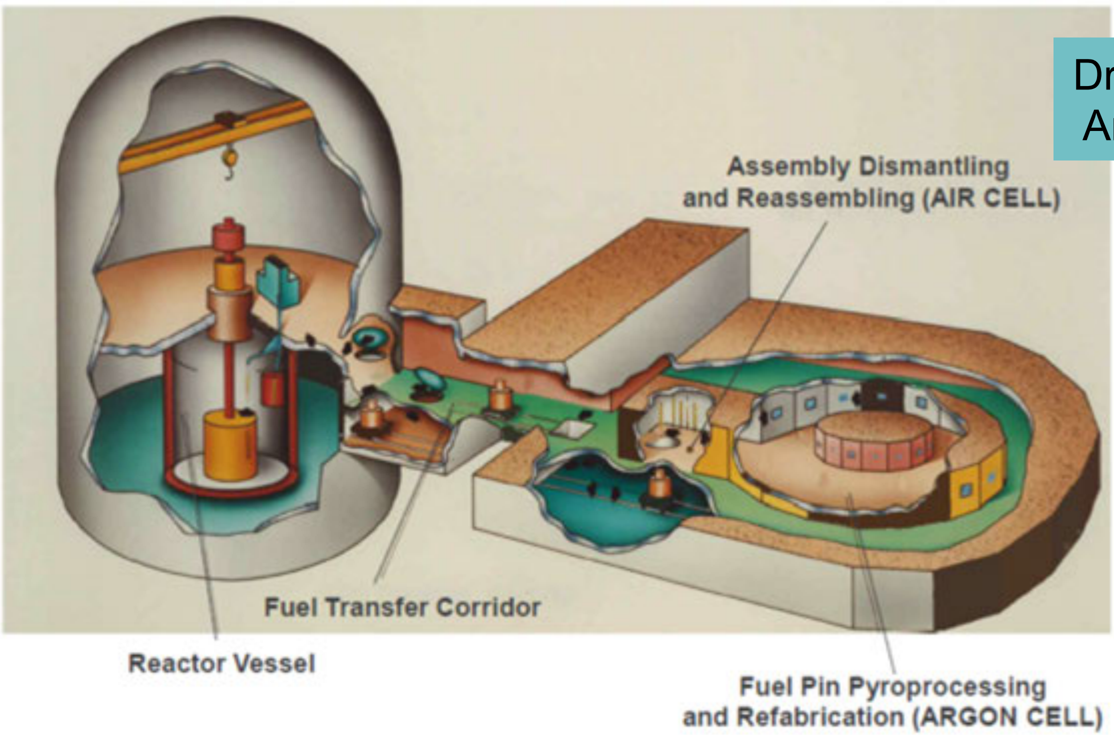
Time for Safer, Proliferation resistant and Easier Waste Management Paradigm: Integral Fast Reactor and Pyroprocessing

Pyroprocessing was used to demonstrate the EBR-II fuel cycle closure during 1964-69

Dr. YOON IL CHANG
Argonne National Laboratory



IFR has features as Inexhaustible Energy Supply ,Inherent Passive Safety ,Long-term Waste Management Solution , Proliferation-Resistance , Economic Fuel Cycle Closure.
High level waste reduces radioactivity in 300 years while LWR spent fuel takes 100,000 years.

Technical Rationale for the IFR

✓ Revolutionary improvements as a next generation nuclear concept:

- Inexhaustible Energy Supply
- Inherent Passive Safety
- Long-term Waste Management Solution
- Proliferation-Resistance
- Economic Fuel Cycle Closure

✓Metal fuel and pyroprocessing are key to achieving these revolutionary improvements.

✓Implications on LWR spent fuel management

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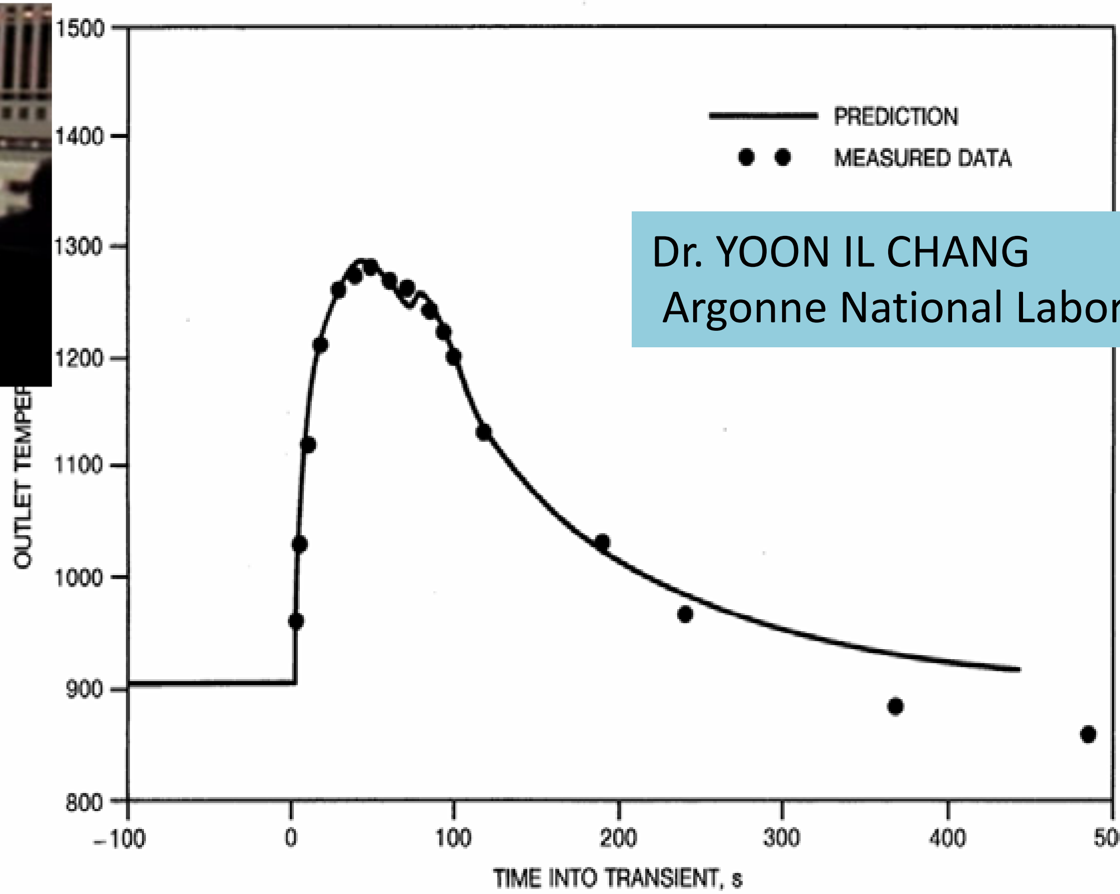
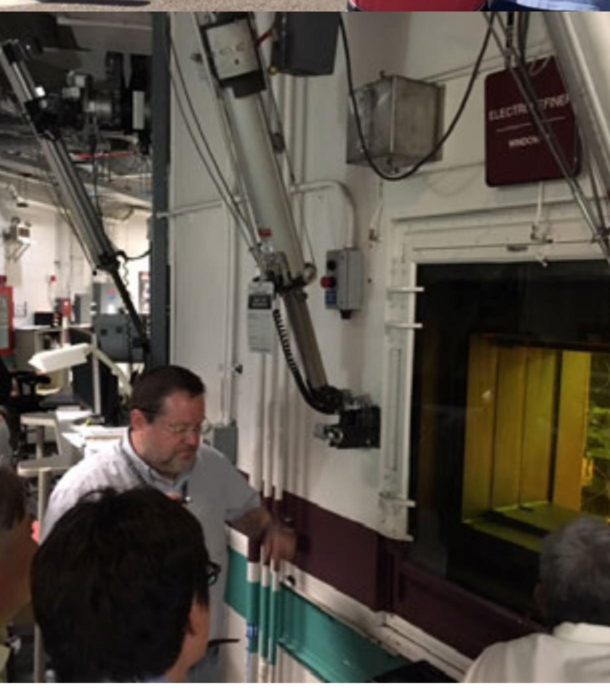
Passive Safety was proven by the 1986 Severe Accident Experiment very similar to the Fukushima event.

Loss-of-Flow without Scram Test in EBR-II



Dr. YOON IL CHANG
Argonne National Laboratory

Idaho National Laboratory 201



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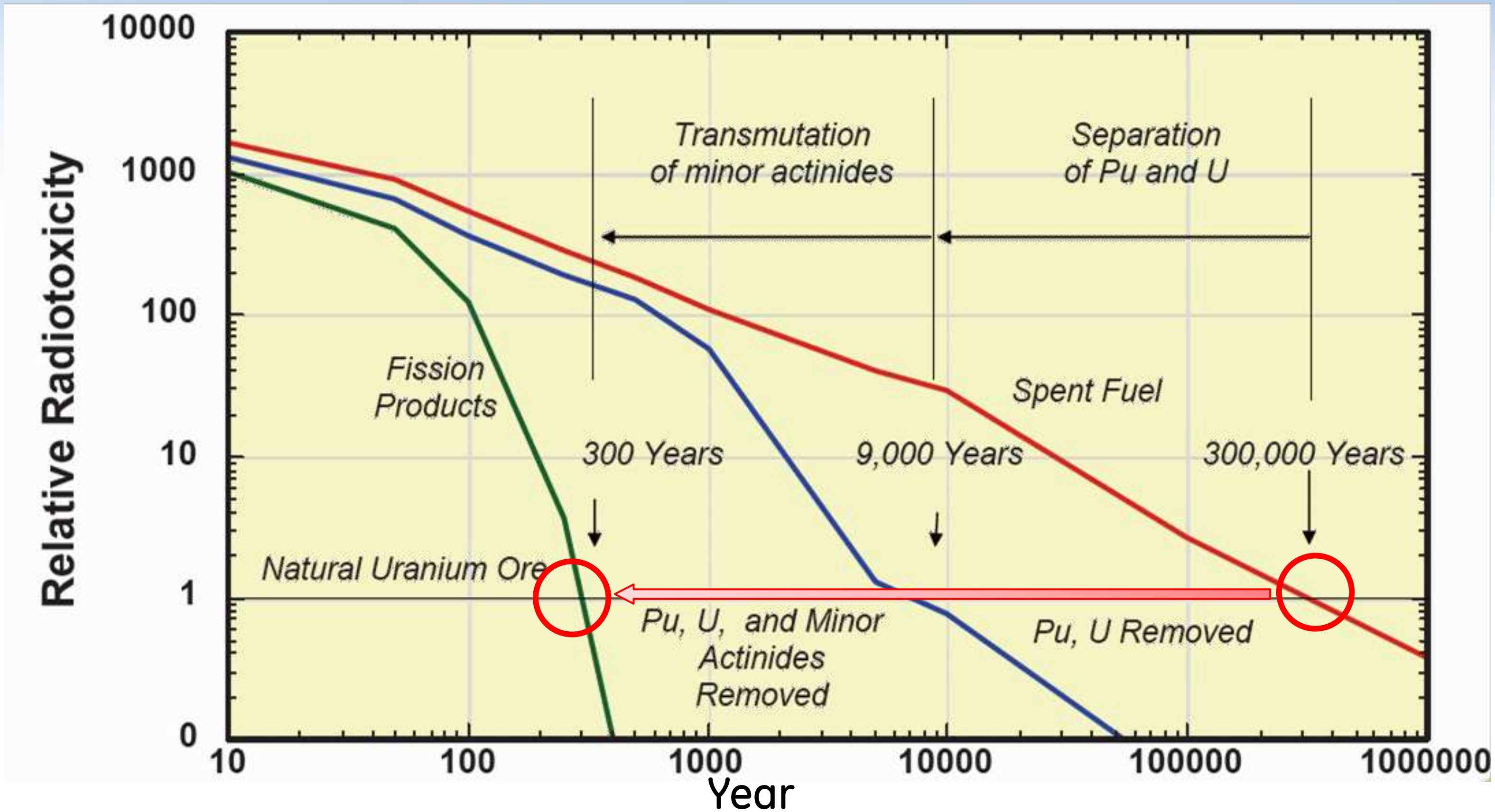
Transuranic disposal issues

The 1% transuranic (TRU) content of nuclear fuel is responsible for 99.9% of the disposal time requirement and policy issues



Removal of uranium, plutonium, and transuranics makes a 300,000 year problem a 300 year problem

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Proposal to Demonstrate IFR and Pyroprocessing at Fukushima

- Melt downed fuel debris and contaminated equipments will likely stay in Fukushima, though nobody admits so.
- Pyroprocessing is the most appropriate method for treating melt-downed debris.
- Pu and MA from Debris and Spent fuels be burned in IFR. Electricity is generated as by-product.
- High level waste of 300 years be easily stored or disposed geologically while decommissioning of units be cemented for tens of million years.
- Fukushima Daini (Second) Nuclear Plant of TEPCO is best located to demonstrate GE's extended S-PRISM.
- Provides ground for the extended Japan-US 1-2-3 Agreement by demonstrating complemental fuel cycle options.
- International joint project of Japan-US-Korea will provide an alternative for global non-proliferation regime (NPT).

International Conference on “Sustainability of Nuclear Power and the Possibilities of New Technology”
organized by the Sasakawa Peace Foundation (SPF) on November 18, 2016.

Technical Feasibility of an Integral Fast Reactor (IFR) as a Future Option for Fast Reactor Cycles

-Integrate a small Metal-Fueled Fast Reactor with Pyroprocessing Facilities -

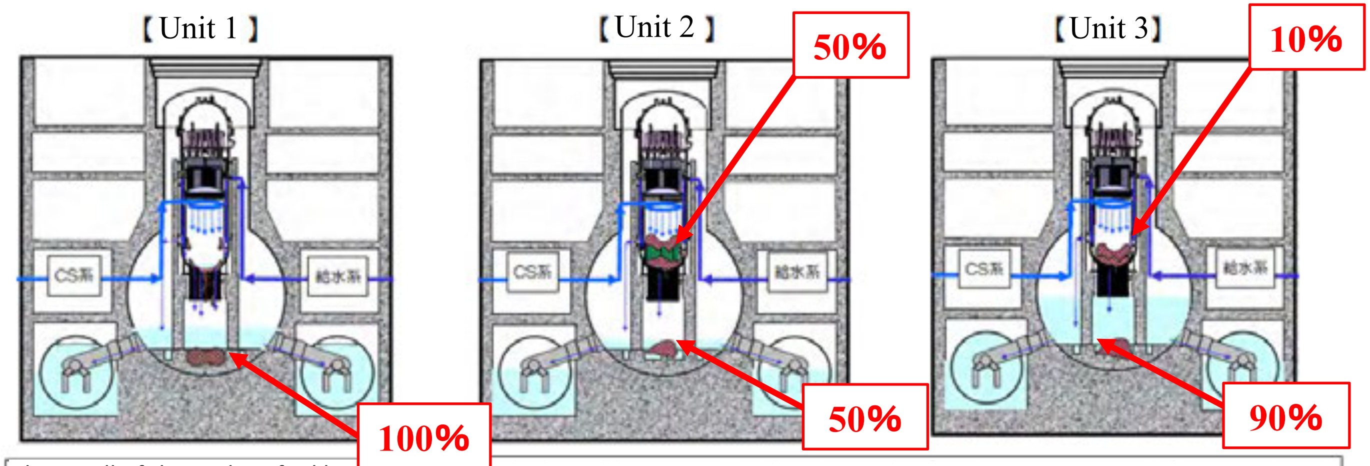
November 18, 2016

Nuclear Salon / the Sasakawa Peace Foundation

5. Research Results

Amounts of fuel debris and nuclear materials from the TEPCO Fukushima Daiichi NPS (estimated)

The distribution fraction of heavy metals (TRU+U+FP) is estimated to be as shown by the numbers to the right in red based on analyses using the SAMPSON code[*2]



Almost all of the molten fuel has fallen to the bottom of the RPV plenum and almost none of the fuel is left in the core.

-Some of the molten fuel has fallen to the bottom of the RPV plenum or to the PCV pedestal, and some fuel still remains in the core.
-It is estimated that more fuel than originally thought has fallen to the bottom of the PCV at Unit 3

Assumed states of the Unit 1~3 cores/containment vessels[*1]

The amount of debris and primary composition has been estimated as follows based upon the amount of fuel, number of control rods, and the remaining amount[*3] of structural material in each reactor.

	[Unit 1]	**[Unit 2]**	**[Unit 3]**
Amount of core region debris (Approx. 120 tons):	0	Approx. 100 tons	Approx. 20 tons
Amount of MCCI debris (740 tons):	Approx. 260 tons	Approx. 170 tons	Approx. 310 tons

- Main composition of core region debris that fused/mixed with core structure material (SUS, Zry): $(U,Zr)O_2$, SUS-Zry alloy
- Main composition of MCCI debris that fused/mixed with concrete outside the pressure vessel: $(Zr,U)SiO_4$, $CaAl_2Si_2O_8$, etc.

- As the average fuel composition for debris in Units 1~3, we used the composition at the time when void reactivity is the most severe, a maximum minor actinide ((MA) neptunium, americium, etc.) content rate and the largest number of years since the disaster within the published data.

⇒Transuranium element（TRU：Pu+MA) mass is 1.94 tons, and heavy metal (HM) mass is 251 tons

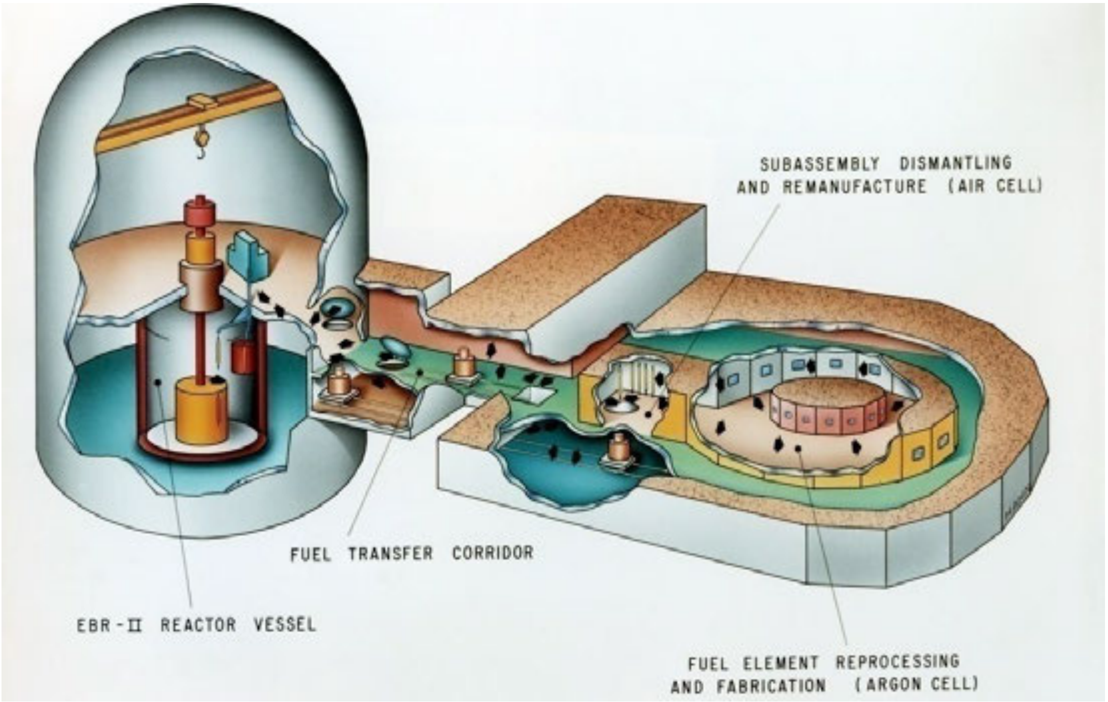
＊1：Excerpt from 1st Progress Report on the Estimate of the Status of the Fukushima Daiichi Nuclear Power Station Units 1~3 Core/Containment Vessels and the Deliberation of Unsolved Issues,"from TEPCO website.
＊2：Masanori Naito, "Analyzing Accident Event Escalation using the SAMPSON Code," Atomic Energy Society of Japan Fall Symposium, September 11, 2015.
＊3：T. Washiya et.al, Study of treatment scenarios for fuel debris removed from Fukushima Daiichi NPS, Proc. of ICONE-23, May 17-21, 2015, Chiba, Japan

Technical Feasibility of an Integral Fast Reactor (IFR)

- ✓ The concept of an integral fast reactor (IFR) consists of reprocessing the fuel debris, fabricating TRU fuel, burning it in a small MF-SFR and recycling the spent fuel by reprocessing

- ✓ Amount of heavy metals (HM), such as uranium, present in fuel debris: Approx. 250tons and **TRU elements account for approximately 1.9tons**.

- ✓ Configuration
  - A MF-SFR with inherent safety features (reactor output: 190MWt)
  - Application of a metallic fuel pyro-processing method that makes debris processing possible.

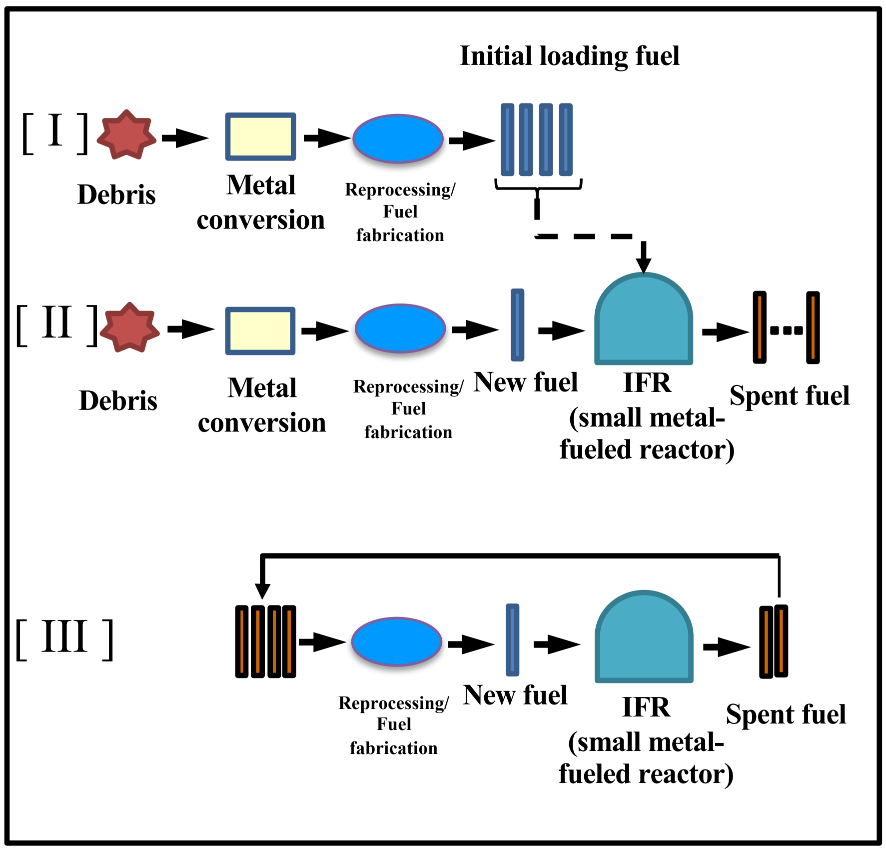


Concept diagram of an IFR that combines a fast reactor with a fuel recycling facility
(Example: Argonne National Laboratory Experimental-Breeder Reactor EBR-II and fuel cycle facility (FCF))

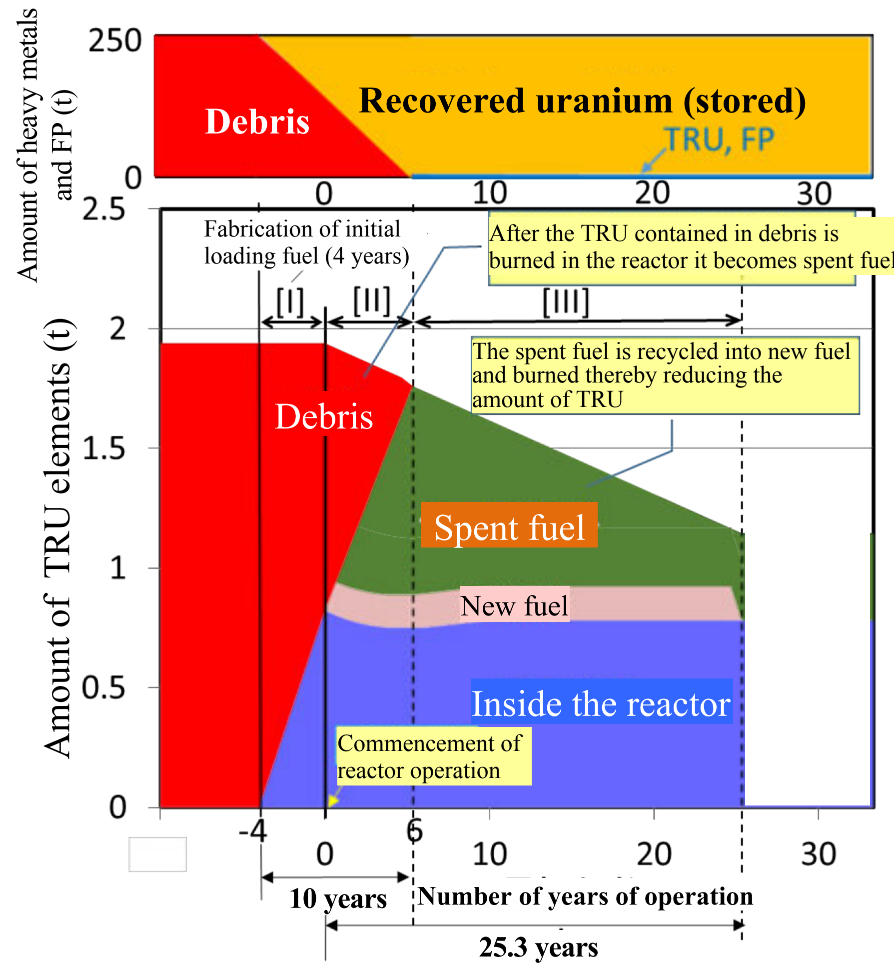
(Source : Y. I. Chang, "Integral fast reactor – a next-generation reactor concept," in Panel on future of nuclear Great Lakes symposium on smart grid and the new energy economy, Sept. 24-26, 2012.)

Debris Processing Scheme and TRU Reductions

- An assessment of TRU burn-up performances showed the originally estimated debris processing period of 15 years could be shortened to 10 years.
- The 1.9 tons of TRU present in the debris will be reduced to a total of 1.2 tons in 25 years after the launching the IFR including that remaining in the reactor and that existing in the spent fuel. Since the amount of TRU required to constantly fabricate fuel after this point will be insufficient, it will be necessary to procure TRU from external sources in order to continue continuous operation of the reactor.



Concept diagram of debris processing scheme



IFR operation and TRU reductions

Evaluation of Construction Costs for Reactor and Fuel Cycle Facilities

[Reactor]

- A small MF-SFR with the **thermal output of 190MWt** (**electrical output: 70MWe**) was estimated:
  - Decision on the major plant specifications, created general main-circuit system schematics, conceptual diagrams for reactor structures, and conceptual diagrams for the reactor building layout
  - Estimated plant commodity with referencing commodity data from past designs.
  - JAEA's evaluation code for construction cost is adopted.
- Results: **Approx. 110 billion yen** (construction unit cost: Approx. **1.6 million yen/kWe**) (However, there is much uncertainty in these values since the system design has not yet been performed.)

[Fuel Cycle]

- A tentative assessment of the overall construction costs of pyroprocessing facilities capable of **reprocessing 30tHM/y** and **fuel fabricating 0.72tHM/y** was done as follows:
  - The number of pieces of primary equipment were estimated based upon the processing capacity of primary equipment after determining a general process flow and material balance.
  - A general assessment was made by referencing recycle plant cell volume and building volume from past researches
- Assessment result: Whereas the construction cost of these facilities may be able to be kept at approximately **several tens of billions of yen**, there is much uncertainty in regards to reprocessing facilities and since design aspects have not been examined, it is necessary to refer to assessment values made during other design research into facilities with similar processing capabilities.

Statement by Dr. Takashi NAGAI after Nagasaki atomic bomb. "How to turn the devil to the fortune."

Dr. Takashi Nagai, a Professor at Nagasaki University in 1945 when the atomic bomb was dropped, exemplifies the resilience, courage and believe in science of the Japanese people. Despite having a severed temporal artery as a result of the bomb, he went to help the victims even before going home. Once he got home, he found his house destroyed and his wife dead. He spent weeks in the hospital where he nearly died from his injuries. But just months after the atom bomb dropped, he said:

"Everything was finished. Our mother land was defeated. Our university had collapsed and classrooms were reduced to ashes. We, one by one, were wounded and fell. The houses we lived in were burned down, the clothes we wore were blown up, and our families were either dead or injured. What are we going to say? We only wish to never repeat this tragedy with the human race. We should utilize the principle of the atomic bomb. Go forward in the research of atomic energy contributing to the progress of civilization. Devil will then be transformed to fortune.(Wazawai tenjite Fukutonasu) The world civilization will change with the utilization of atomic energy. If a new and fortunate world can be made, the souls of so many victims will rest in peace."