THE INTEGRAL FAST REACTOR

By Dr Clarence Hardy
Secretary, Australian Nuclear Association
Managing Director, Nuclear Fuel Australia Ltd

Presentation to Engineers Australia,
Southern Highlands & Tablelands Regional Group,
RSL Club, Mittagong, NSW, 29 April 2010

What is an Integral Fast Reactor?

Accepted definition: An Integral Fast Reactor is a liquid metal-cooled fast reactor using metal fuel and integrated with an on-site fuel recycling plant.

There are currently 438 nuclear power plants operating in 30 countries and **only 1 of these is a Fast Reactor**. However, 20 fast reactors have operated in the 50 years 1959-2009 with 390 reactor-years operating experience.

What is the difference between the majority of NPPs and Fast Reactors and why are there so few FRs?

FACT: Fast Reactors are in the minority –
Thermal Reactors are in the majority

Basic Principles of Fission Reactors (1)

The generation of nuclear power from fissile elements can be achieved with fast neutrons or thermal neutrons which are neutrons that have been slowed down by passing them through a moderating medium, eg, water, heavy water, graphite, etc.

The most common fissile elements are:

uranium-233, uranium-235, plutonium-239

In contrast, uranium-238 and thorium-232 are not fissile.

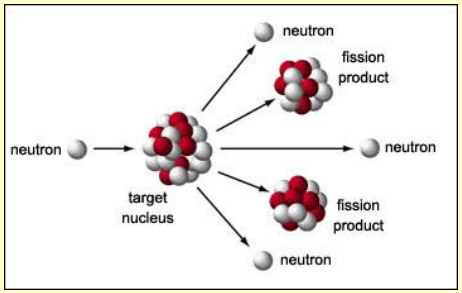
Basic Principles of Fission Reactors (2)

1. When a **neutron** (n) passes near a heavy element nucleus, the neutron may be **captured** by the nucleus and this may or may not result in **fission** of the heavy nucleus.
2. The probability that fission will occur is described by the **cross section** for that reaction. The cross section can be imagined as an area or target which the neutron must hit or pass close to for it to be captured.

3. The fission cross section increases greatly as the neutron velocity decreases. **Fast neutrons** travel at 7% of the speed of light (21,000 km/s cf. *300,000 km/s*). Slow or **thermal neutrons** at about eight times the speed of sound (2,700 m/s cf. *343 m/s*). A thermal neutron is in thermal equilibrium with its surroundings.
4. **The most common fissile nuclei: U-233, U-235 and Pu-239**.

Basic Principles of Fission Reactors (3)

4. In a THERMAL REACTOR, **U-235 fissions** to give two fragments of about equal mass plus 2-3 neutrons. About 85% of the energy released is in the kinetic energy of the fission fragments and the neutrons. This energy is converted into heat.



5. The total binding energy released is **200MeV** compared with 4eV released per molecule of CO_2 in combustion **($50x10^6$ greater).**

6. Neutrons can also be **captured** by non-fissile nuclei, eg. U-238. This is important in a thermal reactor, because **U-238 + n** becomes **U-239** which quickly emits an electron (beta-particle) to become **Np-239** and this also emits a beta to become **Pu-239** which is relatively stable with a half life is 24,200 years. **Pu-239 is fissile** and can contribute one-third of the energy produced in the fuel over a period of three years.

Basic Principles of Fast Fission Reactors (1)

1. In a typical **fast reactor**, the main fissile element is **Pu-239**, often mixed with **U-238** either in the fuel or in a blanket .
2. The fuel elements are submerged in a **liquid metal coolant**, eg. **sodium** or a lead/bismuth alloy and operated at above the m.pt., eg >**500°C.** Water is not used because it would slow down the neutrons and also would need to be at high pressure to operate at 500°C. [Na, mpt 98°C, bpt 883°C]
3. A fast reactor can be up to 100 times more efficient than a thermal reactor at converting fertile nuclei (eg. **U-238**) into fissile material (**Pu-239**).
4. However, a fast reactor can be designed to **breed** plutonium or to **burn** plutonium (and unwanted materials) as an alternative to disposing of spent fuel deep underground.

Historical Applications of Fast Reactors

The first nuclear reactor to produce electricity was the Experimental Breeder Reactor (EBR I) operated at the Idaho National Laboratory in the USA from 1951-1963. It produced electricity to run its own building. It was followed (1963-94) by EBR II producing 62.5MWth and 19MWe. The IFR was also developed at Dounreay in the UK from 1959 !!

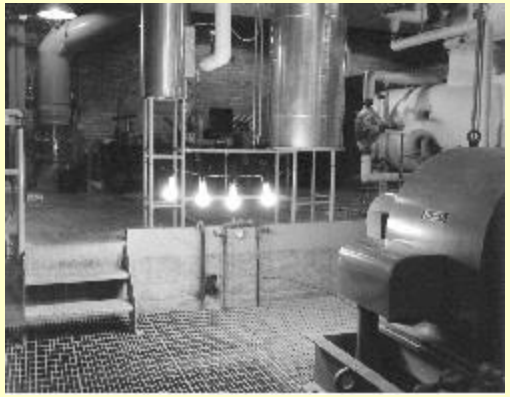
EBR I was the basic concept for the Integral Fast Reactor with an on-site pyro-reprocessing plant to recycle the metal fuel. This was strongly supported by the US National Academy of Sciences but opposed politically by US administrations and advisers seeking to minimise proliferation but not understanding the complex issues involved. Congress under the Clinton administration shut down EBR II in 1994.

The IFR is now being "reinvented" under the US Advanced Fuel Cycle Initiative. GE-Hitachi's PRISM modular design is one present concept in a number of projects worldwide. But several new FRs are not IFRs.

EBR I Historical Views

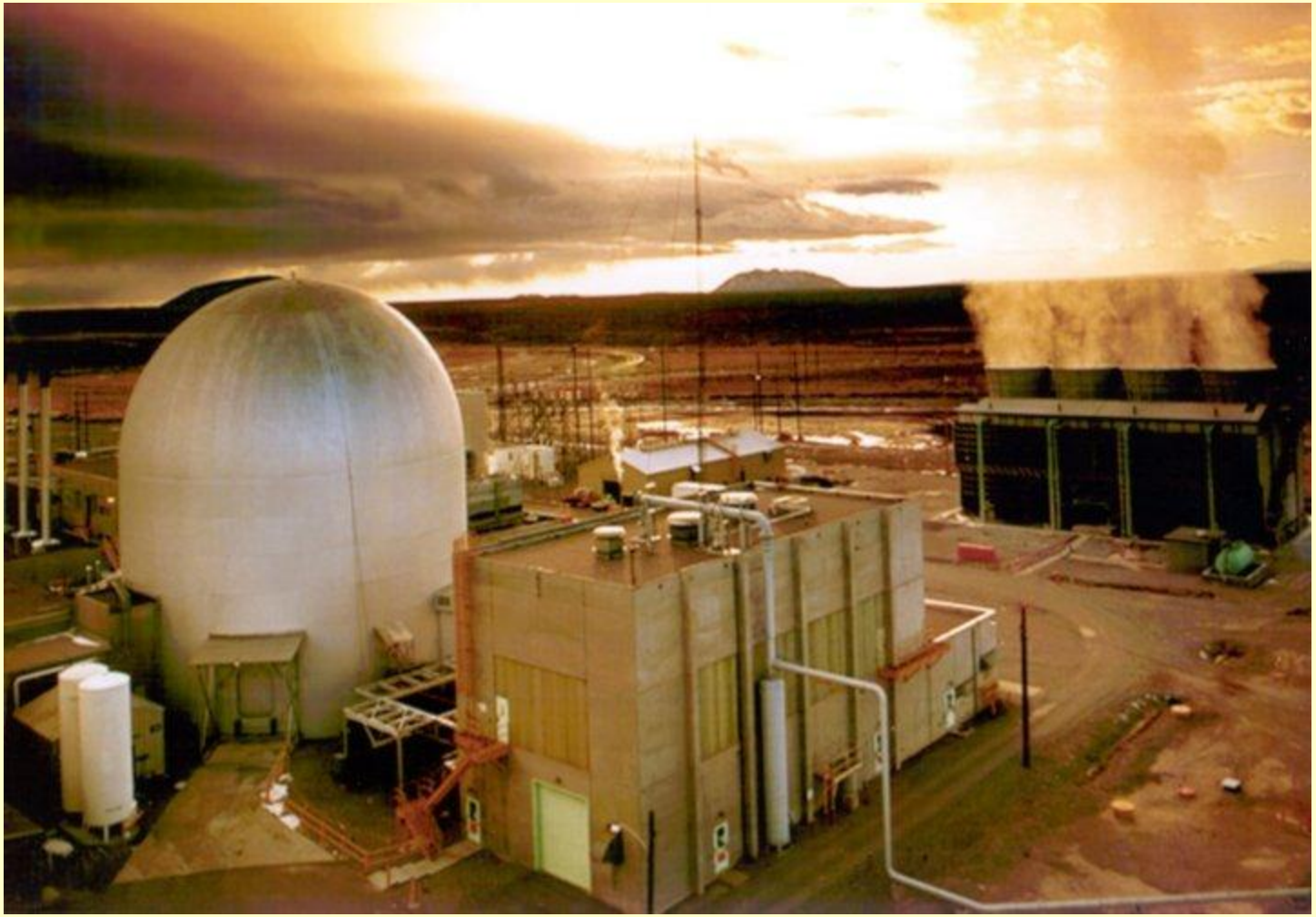
Lowering the EBR I core into its containment vessel, 1951

EBR I is in the large building at Idaho National Lab. Historical Centre



The four famous light bulbs

The EBR II Fast Reactor, Idaho, USA
1963-94, 62.5MWth, 19MWe

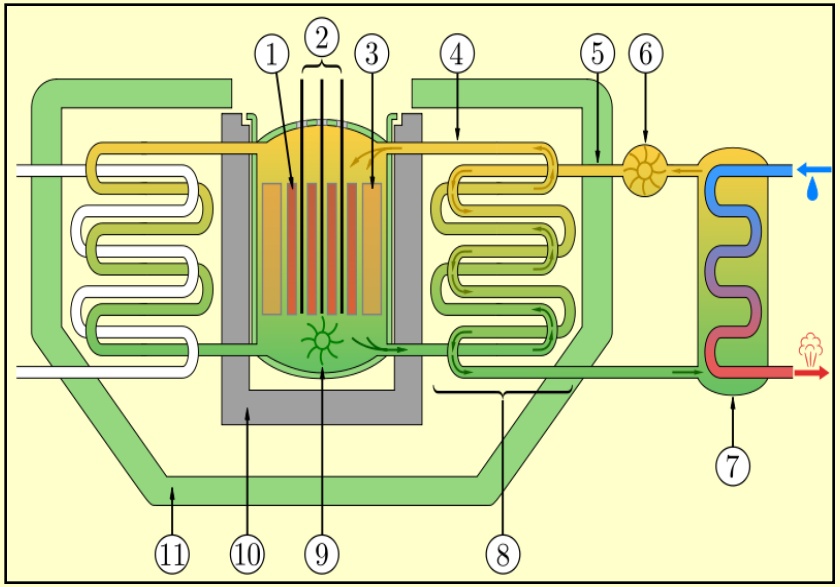


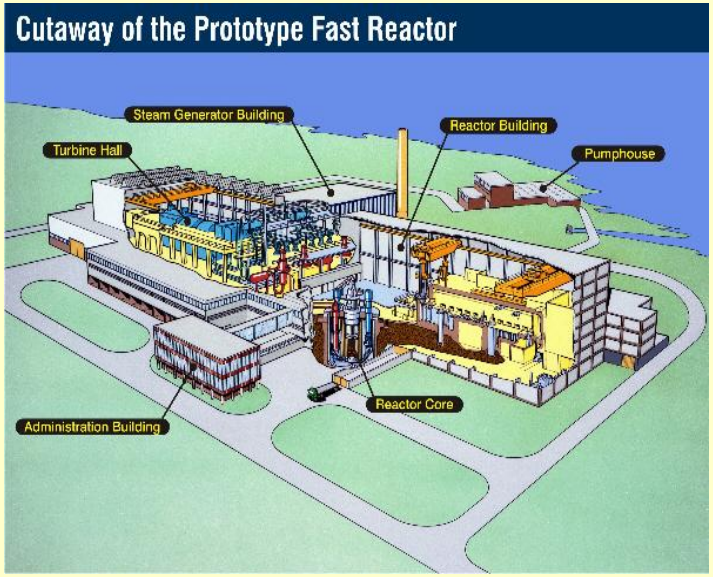
How safe was EBR II ?

In April 1986, two tests were performed on the EBR-II. In the first, the main primary cooling pumps were shut off with the reactor at full power. Without allowing the normal shutdown systems to interfere, the reactor power dropped to near zero within about five minutes. No damage to the fuel or the reactor resulted.

The second test was again with the reactor at full power, and the flow in the secondary cooling system was stopped. This caused the reactor temperature to increase, and as the fuel, primary sodium coolant and structure expanded, the reactor shut down on its own. No damage resulted.

The Dounreay Fast Reactor (DFR), 1959-77, and the Prototype Fast Reactor, PFR, 1974-1994, were prototype IFRs with reprocessing and fuel fabrication plants on the Dounreay site, N. Scotland





DFR design, 24 loop type, NaK, 14MWe Enriched U metal + Mo fuel clad in Nb.

PFR design, pool type, Na, 250MWe, MOX fuel first tested in DFR.

Why were Fast Reactors not developed more rapidly ?

1. In the decade after World War 2 the development of US nuclear technology based on its PWR and BWR designs was dominated by its control of uranium enrichment and reprocessing and its military ship propulsion technology. US companies aggressively marketed their designs.
2. Early fast reactors were mainly designed to **breed Pu** (Fast Breeders) but from the 1970s were thought to be a risk for **proliferation** rather than for the sustainable use of uranium resources. President Carter and others tried to ban FBRs and civil reprocessing, but France, Japan, Russia and UK did not.
3. Fast reactors were **more expensive** at a time of **relatively low uranium prices**. Large scale use of liquid sodium had to be developed at a high R&D cost.

The Basic Concepts of IFRs and Non-IFRs

Fast Reactor

Pool-type **Loop-type**

Metal Fuel + Liquid Metal Cooling

Oxide Fuel + Liquid Metal Cooling

(Variants are Nitride Fuel and Gas Cooling)

IFR

On-site reprocessing and refabrication

Non-IFR

Off-site reprocessing and refabrication

Examples

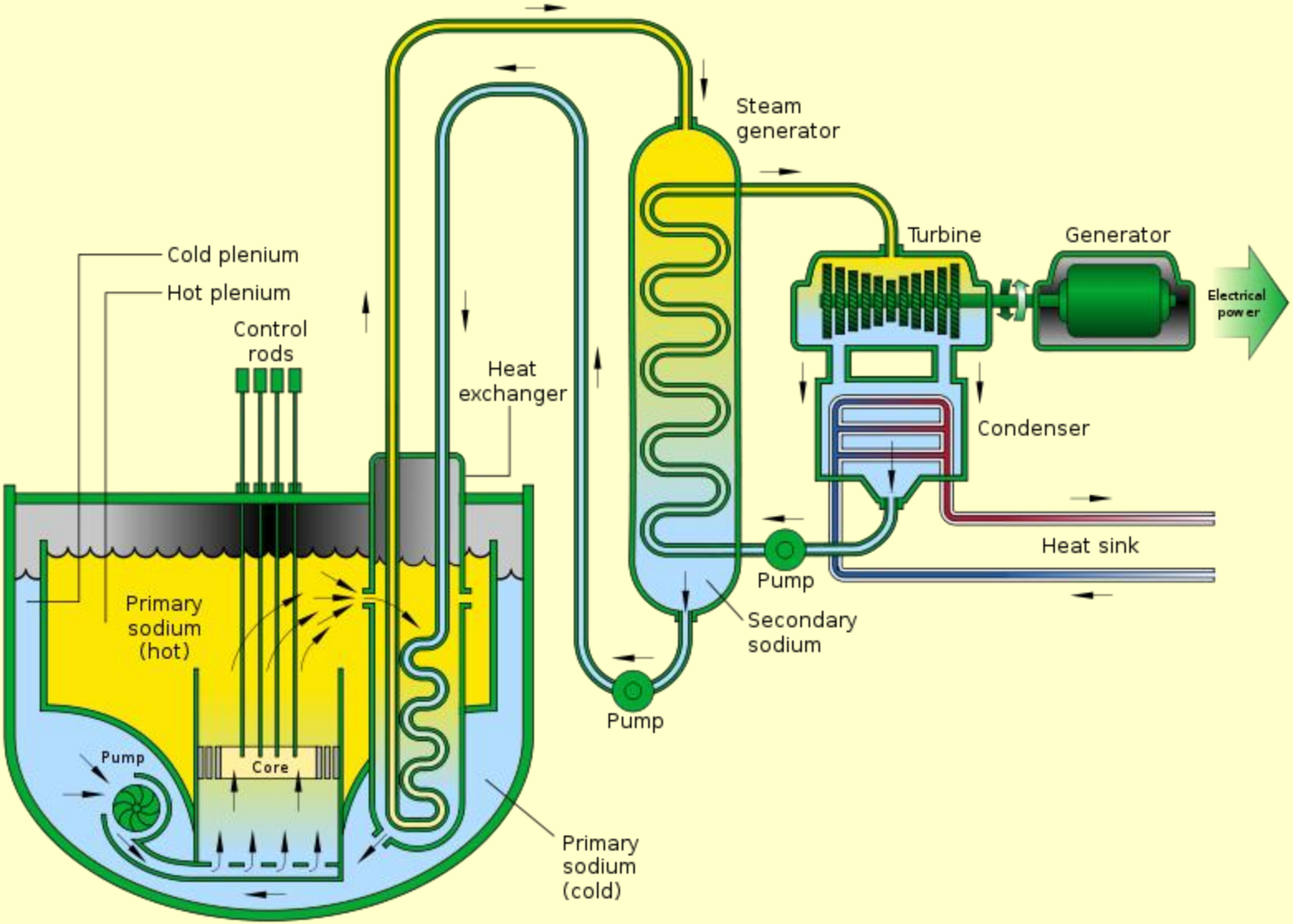
EBR I &EBR II (USA)

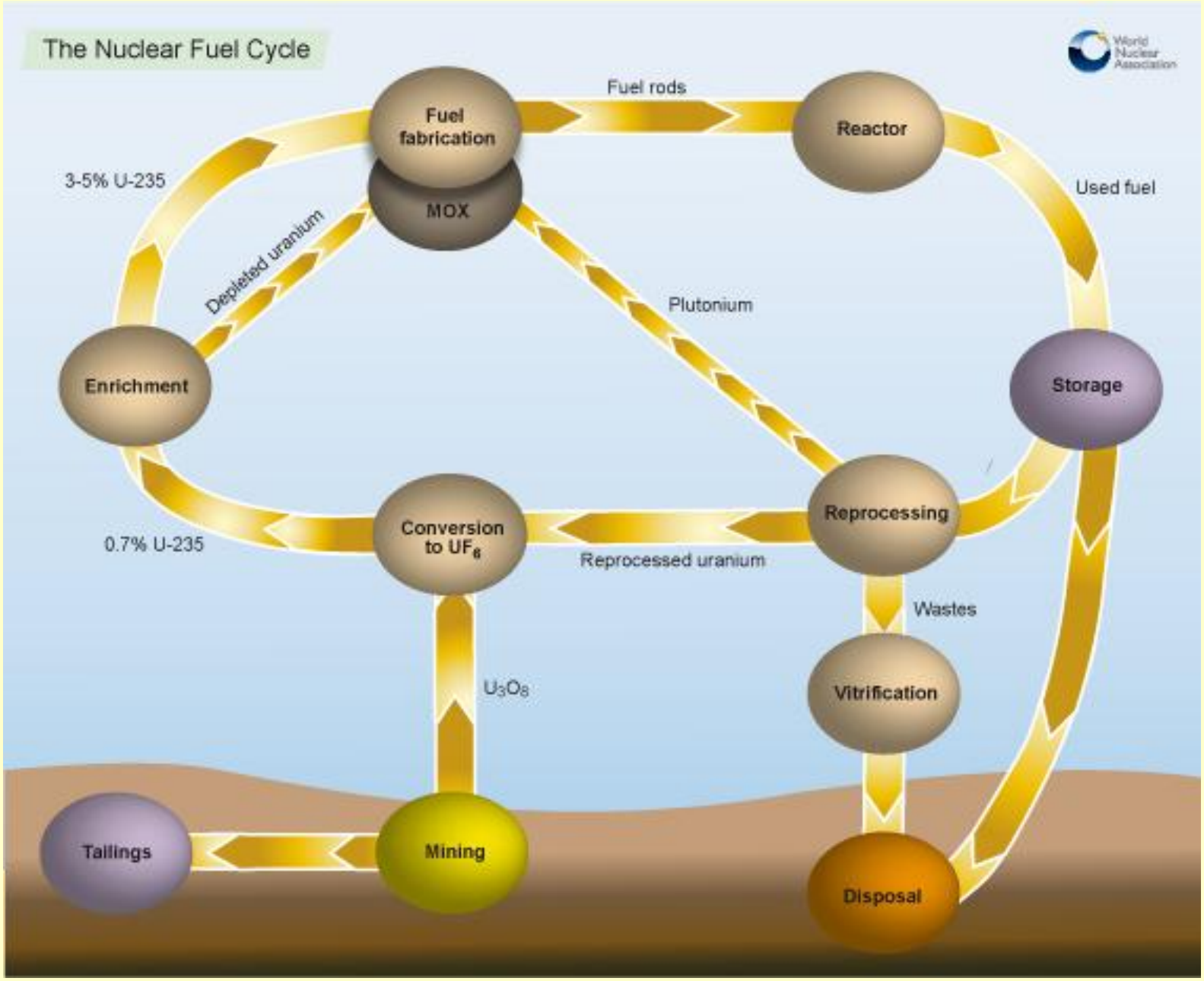
DFR &PFR (UK)

Examples

FRs and Reprocessing Plants in UK, France, Japan, Russia

Basic design of a Liquid Sodium Cooled Fast Reactor




The Nuclear Fuel Cycle
World Nuclear Association
Fuel fabrication
Fuel rods
Reactor
3-5% U-235
MOX
Used fuel
Depleted uranium
Plutonium
Enrichment
Storage
Reprocessing
Conversion to UF_6
0.7% U-235
Reprocessed uranium
Wastes
U_3O_8
Vitrification
Tailings
Mining
Disposal

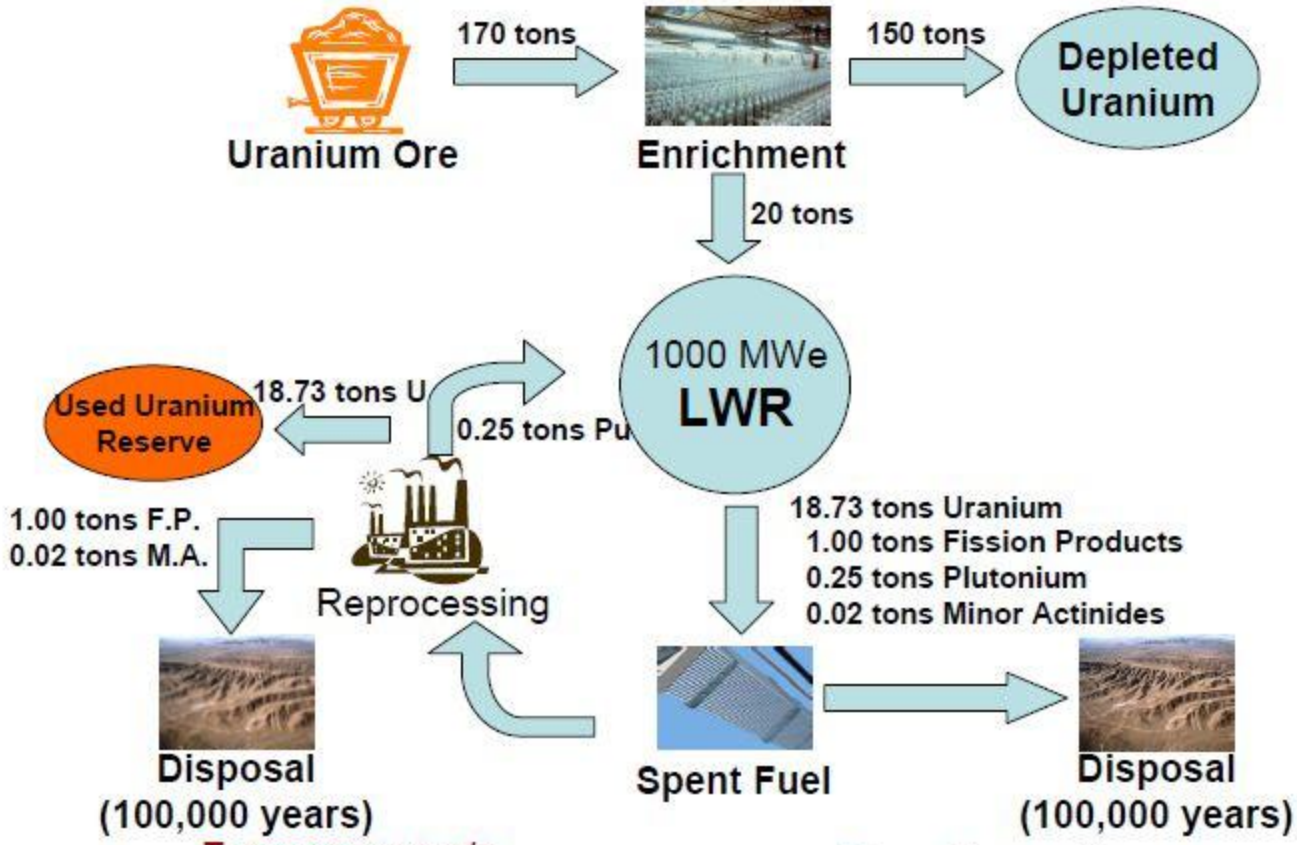
Historically, a Reprocessing Plant has been Large and Expensive to Serve a Number of NPPs

The Sellafield site in the United Kingdom.

<< Old Reprocessing Plant, Sellafield, UK, with 2 old NPPs and MOX Plant

New Reprocessing & Fuel Centre >> Aomori, Japan, with Enrichment Plant, Reprocessing Plant, Vitrification Plant, MOX Plant and LLW Storage ($25B)

Annual Mass Flow for LWR



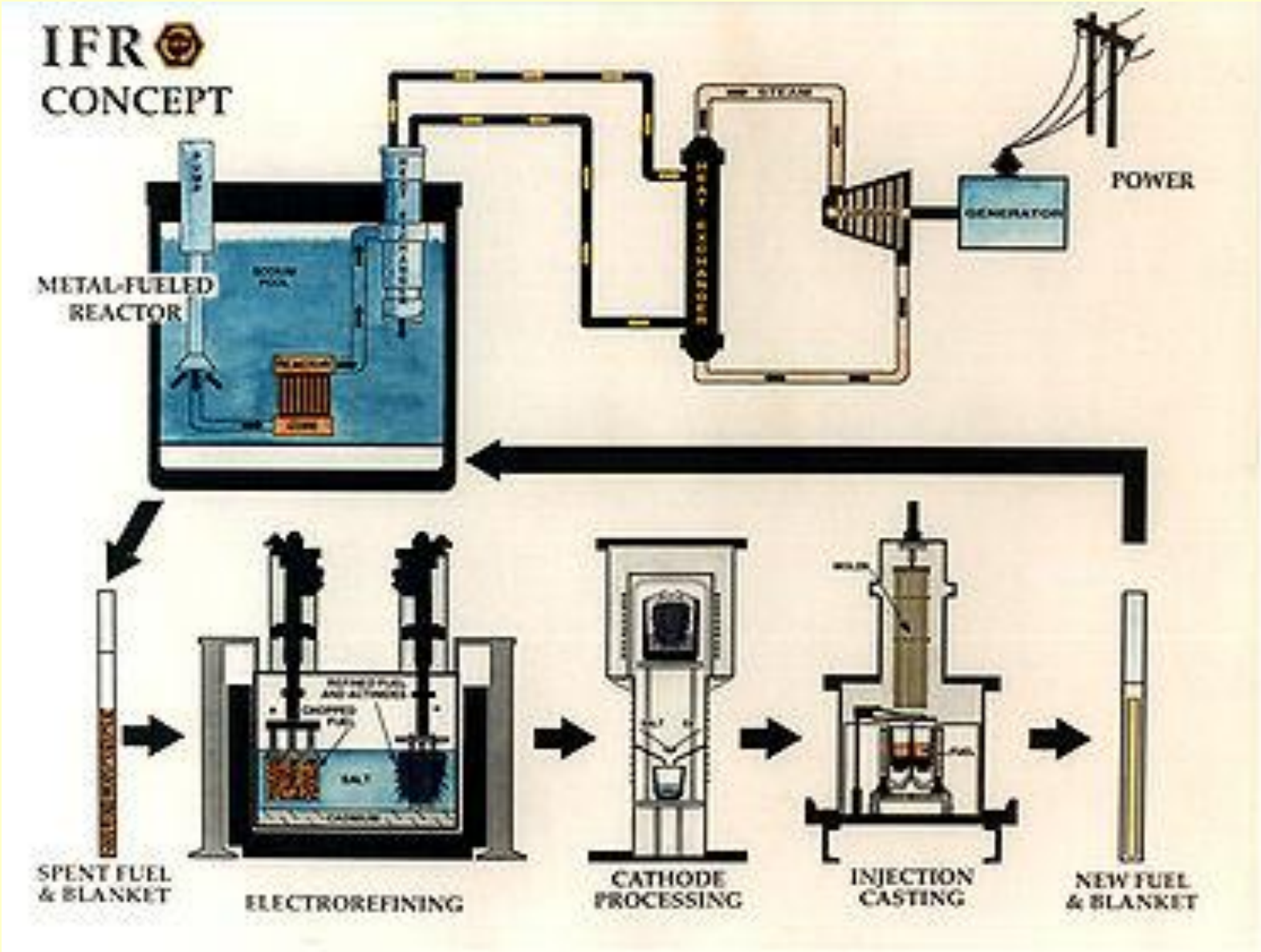
European recycle
- Saves 15% uranium
- But no reduction in waste life

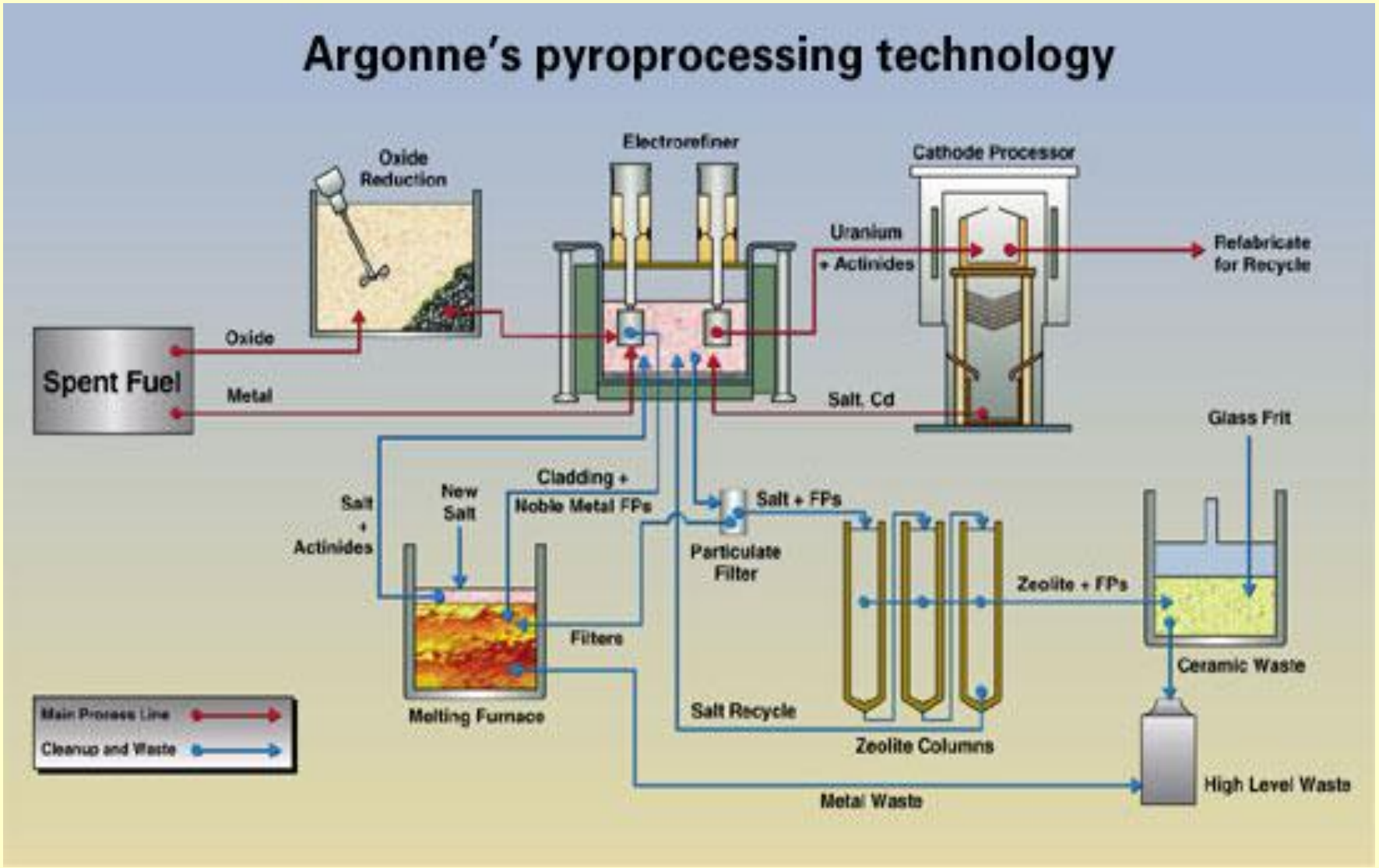
Direct disposal is
the current U.S. policy

Nine Selected Non-IFRs

1. Phenix, France, 250MWe, 1973-2009, MOX fuel
2. Super Phenix, France, 1240 MWe, 1985-98, MOX fuel
3. KNK2, Germany, 21MWe, 1977-91
4. FBTR, India, 40MWt, 1985-
5. Joyo, Japan, 140MWt, 1978-, MOX fuel
6. Monju, Japan, 280MWe, 1994-96, MOX fuel (lost 5te Na)
7. BN-350, Kazakhstan, 135MWe, 1972-99, MOX fuel
8. BN-600, Russia, 600MWe, 1980-, MOX fuel
9. BN-800, Russia, 800 MWe, under construction 2010

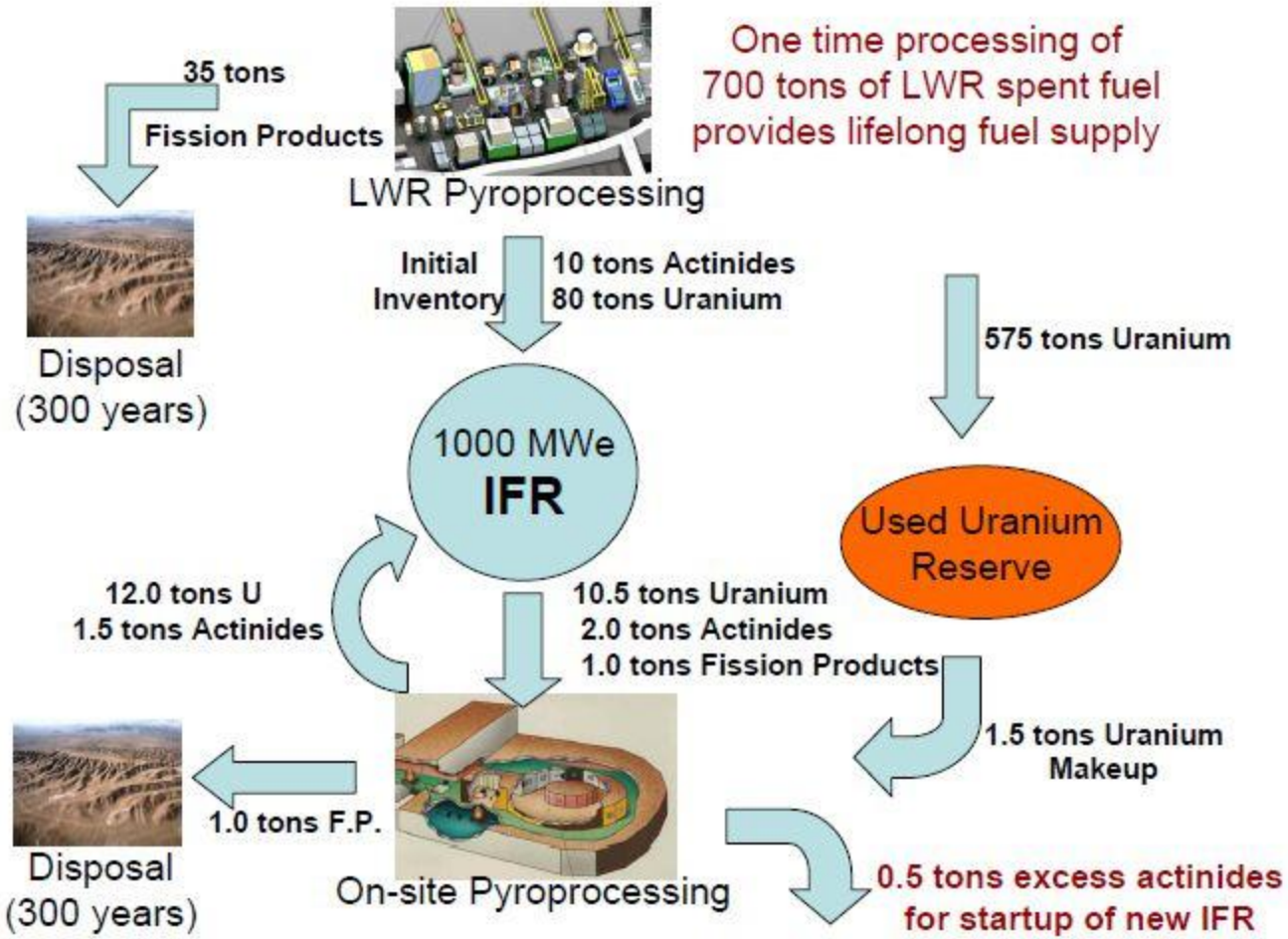
All of these were supplied with Pu/MOX from **off-site** plants but far more Pu has been recycled into Thermal Reactors.


IFR
CONCEPT
POWER
GENERATOR
METAL-FUELED
REACTOR
SPENT FUEL
& BLANKET
ELECTROREFINING
CATHODE
PROCESSING
INJECTION
CASTING
NEW FUEL
& BLANKET



Problem: Only tested on small scale decades ago

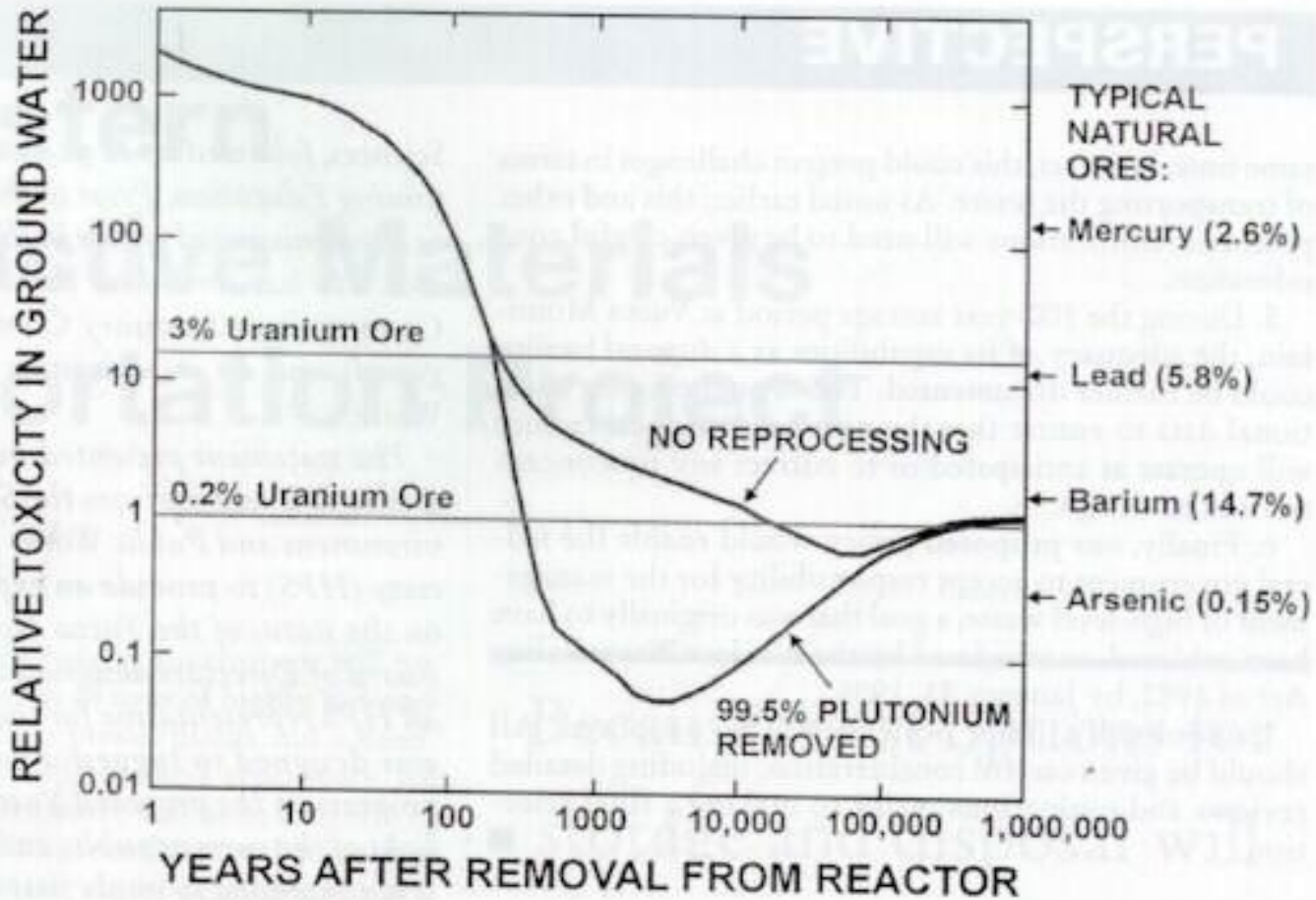
Annual Mass Flow for IFR



Advantages claimed for the IFR

1. **Efficiency:** Up to100 times greater than conventional LWRs as it uses up to 100% of energy in uranium compared with about 1% in LWRs.
2. **Unlimited long term power:** Power the USA for 1500 years with DU in store or indefinitely with known U resources. Energy in stored DU is greater than all known US coal resources.
3. **Safety:** The IFR is even safer than present advanced NPPs.
4. **Proliferation resistant:** The pyro-process cannot produce Pu with the purity required for a weapon. If all NPPs were IFRs there is no need for sensitive enriched U plants or separate reprocessing plants.
5. **Consumes existing waste** from current NPPs and decomm. weapons.
6. **Minimal waste:** A 1GWe IFR produces 1 te waste/a needing 300 years storage. A conventional NPP produces 100 te "waste" needing up to one million years storage under present US repository requirements.
7. **Nuclear material security:** The material in the IFR or pyro-processing plant would be too hot to handle by a terrorist and the fission products leaving the site are also too hot and cannot make a bomb.

High Level Radioactive Waste – How long is it toxic?



Source: J. Boulton, Ed., "Management of Radioactive Fuel Wastes: The Canadian Disposal Program", AECL-6314, 1978.

Relative toxicity (in groundwater) of used nuclear fuel and natural ores.

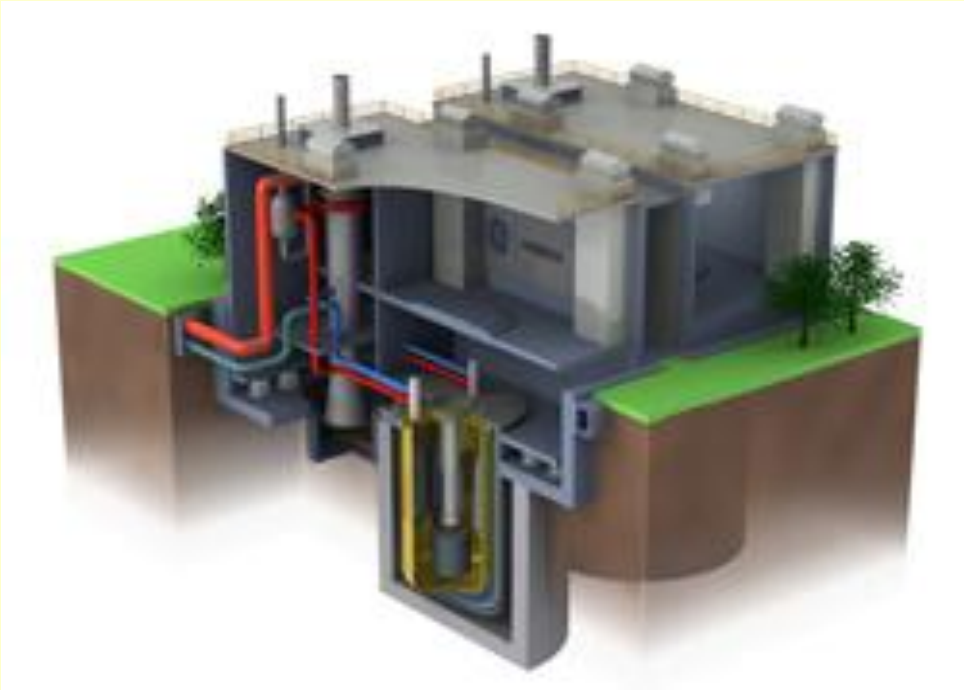
Practical Versions of the IFR

Several versions of an IFR have been designed in recent years:

1. **PRISM, USA** (GE/Hitachi) - 311MWe, Na, 500°C, Pu/DU fuel
2. **STAR, USA** (Argonne) – 300-400MWt, Pb/Bi, U/PuN, 15 yrs
3. **SVBR, Russia** -75-100MWe, Pb/Bi, various fuels
4. **BREST, Russia** - 300MWe, Pb/Bi, U/Pu nitride fuel
5. **BN800, Russia** - 880MWe, Na, 550°C, various fuels (metal)
6. **4S Nuclear Battery, Japan** - Toshiba, 10 & 50 MWe, Na, metal fuels, 30 year operation (L-4S is a Pb/Bi version)
7. **PFBR, India** – 500MWe, U/PuO_2/C, Th blanket (?) (Th R&D)
8. **Astrid, France** – Large, Na, Pu burner; **Allegro**, gas cooled, 50 MWt, MOX core at 560°C/ceramic core at 850°C, recycle fuel

Two types: Less than 100MWe or greater than 300MWe.

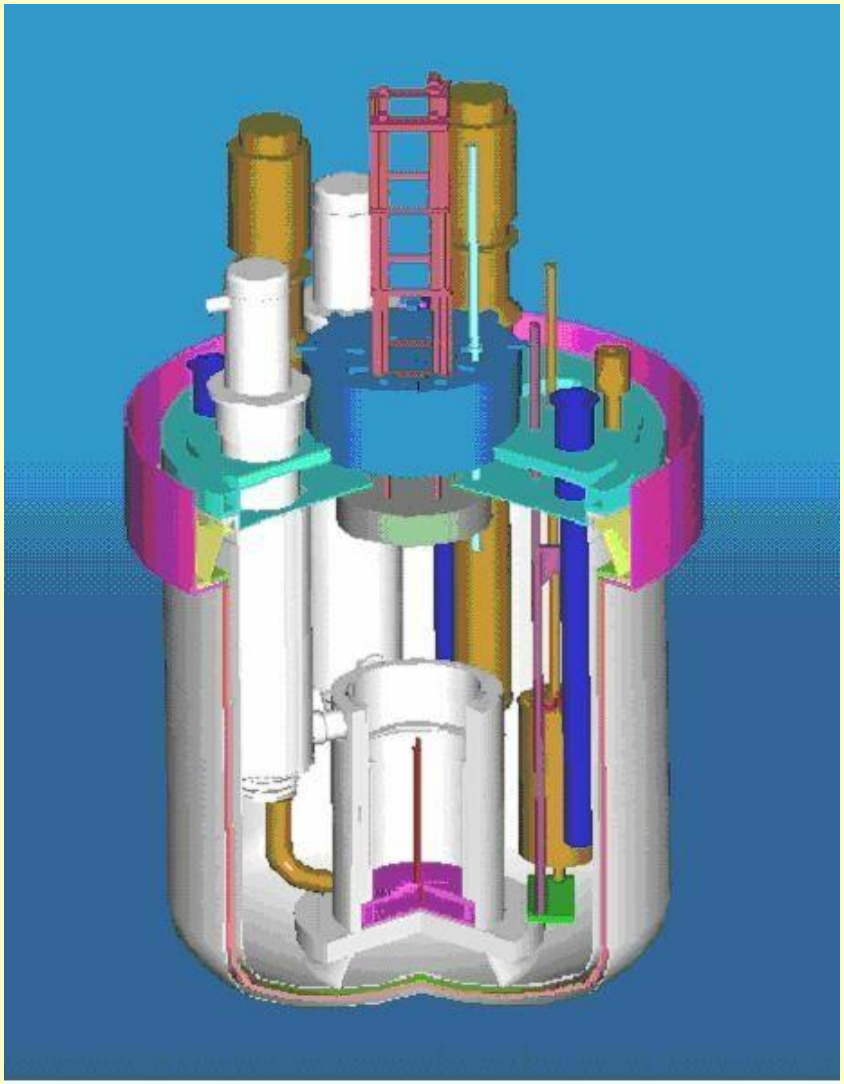
PRISM Fast Reactor, GE-Hitachi



Artist's view of the PRISM Reactor 311MWe, Na, 500°C, Pu/DU fuel, plus closed fuel cycle

Needs the addition of an On-Site PYRO-PROCESSING Plant to Process the Pu/DU spent fuel and recycle Pu in new fuel

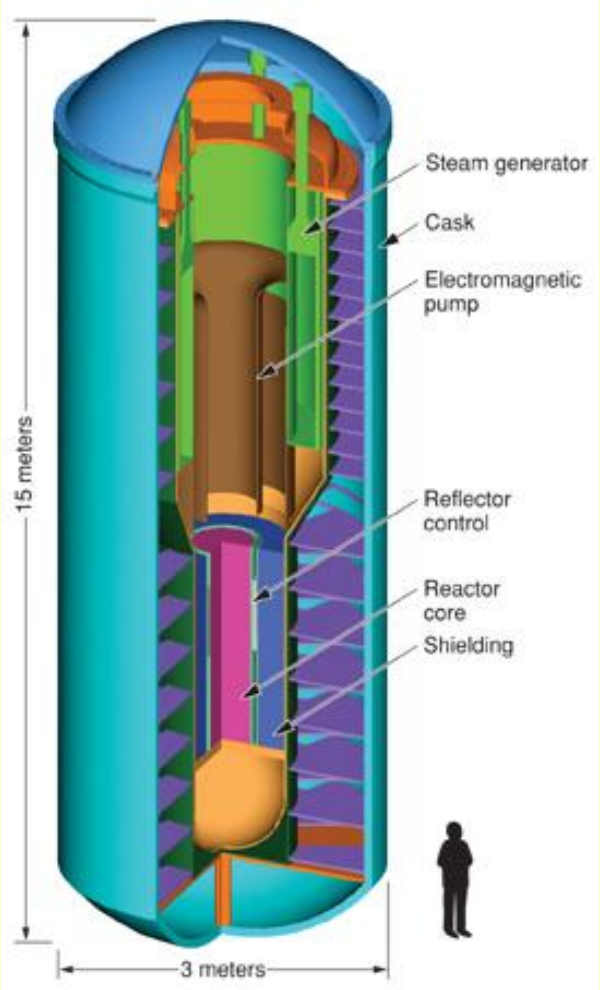
View of Reactor Vessel, Advanced Fast Reactor
Argonne National Lab, USA



Recent development of the ANL EBR II

Needs the addition of an On-Site PYRO-PROCESSING Plant to Process the Pu/DU spent fuel and recycle Pu in new fuel

SSTAR, Lawrence LNL, Modular FR, Lifetime Core
300-400MWt, 100MWe, Pb/Bi, U/PuN, 15 -30 yrs



At End-of-Life the Core would be shipped to a secure PYRO-PROCESSING Plant to process the spent fuel and recycle Pu in new fuel

A small 10MWe version is readily transported but only has 15 year lifetime

CONCLUSIONS

1. There are currently **438 nuclear power plants** operating in 30 countries and **only 1 of these is a Fast Reactor**. However, 20 fast reactors have operated in the 50 years 1959-2009 with 390 reactor-years operating experience. Several new FRs are being built.
2. The difference between conventional NPPs and Fast Reactors is that conventional NPPs use slowed down or **thermal neutrons** and FRs use **fast neutrons**, ie. neutrons travelling very fast (no moderator).
3. Two of the first FRs were EBR I (1951-1963) and EBR II (1963-1994 with 19MWe output) in the USA. These introduced and developed the concept of integrating a reprocessing plant on the same site as the reactor. **This became the Integral FR Concept.**
4. Several FRs were built and operated in France, Japan, Russia and the UK in the following 50 years but most were designed to **breed Pu** and most **used off-site reprocessing**. The only **IFRs** in this period were the UK's DFR and PFR using integral on-site reprocessing and fuel fabrication .

CONCLUSIONS (Continued)

5. **Three Main Factors inhibited the development of FRs and the IFR: POLITICS of Non-Proliferation, Minor Accidents and Economics.**

- **POLITICS** started with the US Carter administration in the 1970s which tried to persuade major nuclear countries like France, Japan, Russia and the UK to stop reprocessing and throw away spent fuel. Of course, these countries refused and planned to recycle Pu **(INFCE).**
- **Minor FR accidents,** usually sodium leaks, and shutdowns did not help.
- **Economics of FRs and reprocessing** were not favourable, cf. cheap U.

6. **The nuclear tests carried out by India in 1974 and Pakistan in 1998** accelerated the belief in the USA and elsewhere that proliferation was a growing problem and FRs and reprocessing should not be encouraged – **The US forgot that enrichment was a bigger problem!**

7. **RESULT – FR R&D and reprocessing were actively discouraged.**

CONCLUSIONS (Continued)

21st Century – The minimisation of carbon emissions and sustainability became more important. Nuclear power became more acceptable. Nuclear scientists and engineers as well as governments began to get interested again in FRs and burning Pu and dangerous Minor Actinides instead of throwing them away.

The Integral Fast Reactor has taken centre stage because of its benefits. However, it still has problems to overcome because it needs more R&D and that costs money. Thorium is a competitor.

The good news is that major companies like GE-Hitachi and Toshiba are investing and so are the Russians and Indians.

I am sure that all of us wish them success.

Useful References

1. "Prescription for the Planet" by Tom Blees
   Soft cover, 405 pps, 2008, ISBN: 1-4196-5582-5
   Publisher not known, available from Amazon Books USA
   at US$25.00 plus postage (?)
2. "Response to an IFR Critique" by Brook, Blees, et al
   http://bravenewclimate.com/2009/02/21
   (Critique was by Jim Green, FOE)

Thank you.