Kjernekraft i Norge?

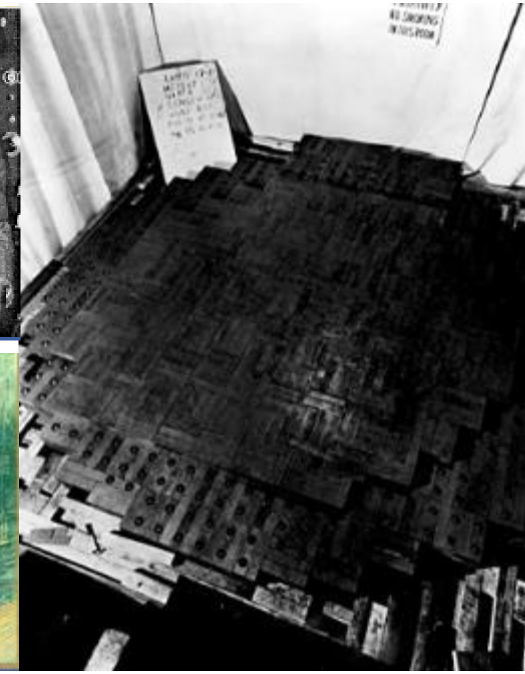
Dieter Roehrich

UiB

Shall Norway invest in nuclear energy and build nuclear reactors?

Nuclear Energy from Fission

History
First reactors
- graphite moderated, natural uranium fuel

1. **E. Fermi, Chicago Pile, USA, Dec. 1942**

2. **I. Kurchatov, Russia, Dec. 1946**


Nuclear Energy from Fission

Controlled chain reaction of neutron induced fission processes of uranium or plutonium nuclei

- **Fuel cycle**
  - **^{235}U** is the only natural fissile material, natural uranium contains 99.3% ^{238}U and 0.7% ^{235}U
  - the other isotopes (**^{233}U** from ^{232}Th), (**^{239}Pu** from ^{238}U) have to be produced in reactors ("breeding").

- **Reactor technology**
  - Reactor design: **thermal reactors** (slow neutrons) or **fast reactors** (fast neutrons)
  - Coolant
    The energy released in the fission process is converted into heat which has to be transferred away from the reactor core by a coolant. Typical coolants for thermal reactors are water or helium gas; fast reactors used liquid metals (sodium or lead)
  - Moderator (only thermal reactors)
    In case of a thermal reactor, the fast neutrons have to be slowed down by a moderator. Moderator and coolant can be identical, but don't have to be. Typical moderators are water (normal or light water), heavy water (made with deuterium) and graphite.

Nuclear Energy from Fission

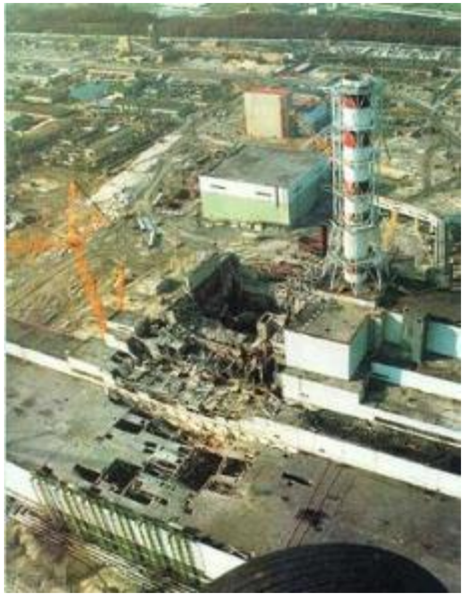
Nuclear energy is a complex technology with many risks

Four key problems:

1. **Operational accidents**
2. **Shortage of ^{235}U fuel / Breeding of ^{233}U from ^{232}Th and ^{239}Pu from ^{238}U?**
3. **Waste management**
4. **Proliferation – nuclear weapons**

Nuclear Energy from Fission

1. **Operational accidents**



- **Criticality accident (Chernobyl)**
  loss of control of reactivity → prompt criticality

- **Loss of coolant (Fukushima)**
  Energy release after shutdown (normal operation: 2700 MW_{th})

  After 1 minute: 150 MW

  After 1 hour: 45 MW

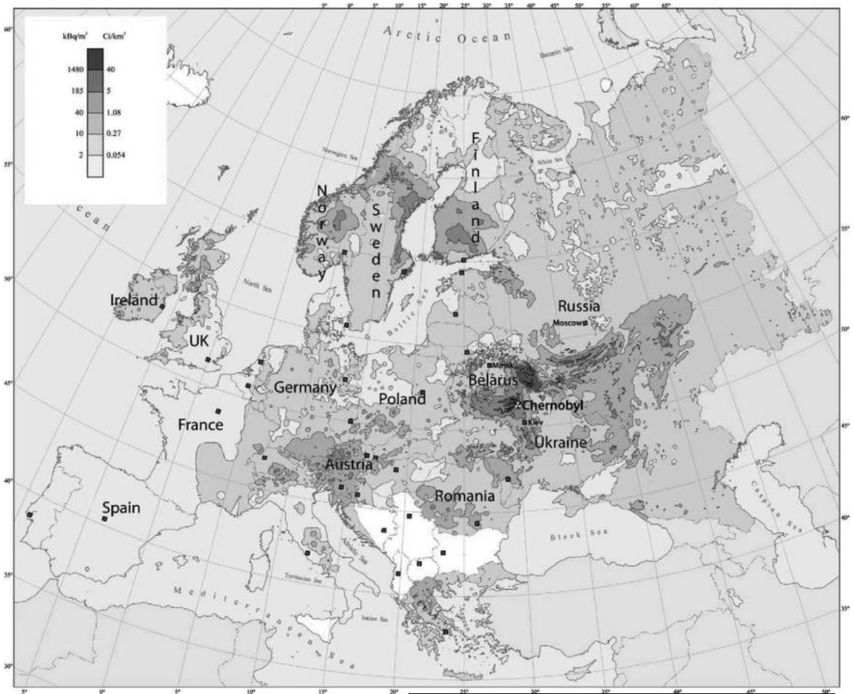
  After 1 day: 15 MW

  Weeks/months: ≈15 MW

  → The heat must be removed from the reactor core after shutdown of the chain reaction. Without cooling, the fuel rods overheat, react with water/steam creating hydrogen and finally melt.

Nuclear Energy from Fission

^{137}Cs contamination



EUR Report 16733; 1998

Criticality accident (Chernobyl) - consequences

- Release of 1-2% of the radioactive inventory into the atmosphere
- Radioactive contamination of central, eastern and northern Europe
- Collective dose in the northern hemisphere: ≈ 600.000 person-Sv

  IAEA-SM-339/185; 1995

- Estimates of excess fatal cancer cases based on the Linear Non-Threshold (LNT) model:

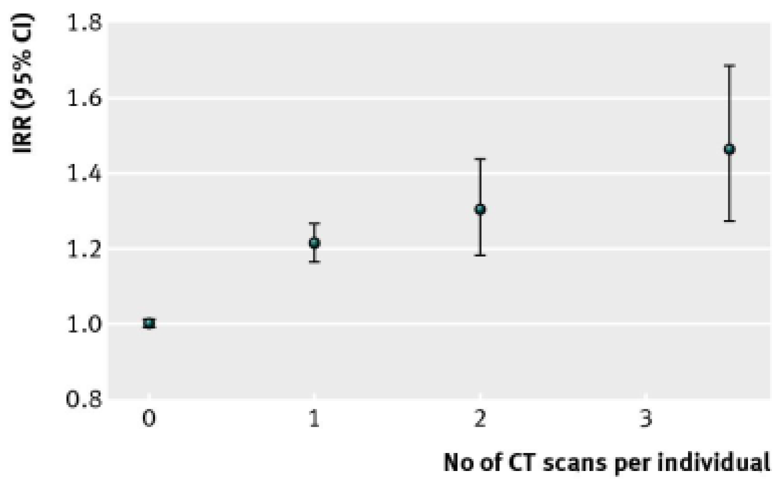
  1. Risk factor per Sv: 1.5% → 17.850 cases
  2. Risk factor per Sv: 5-10% → 30.000-60.000 cases

Int. J. Cancer: 119, 1224-1234; 2006

Medicine, Conflict and Survival, 23:1; 2007

Establishing a dose-response relationship

- **Linear non-threshold dose-response curve: epidemiologic evidence**
  - **Radiation exposure from CT scans in childhood**
    - **Incidence rate ratios (IRR) for all types of cancers in exposed versus unexposed individuals vs the number of CT scans (≈5.7 mSv per scan)**



BMJ 2013;346:f2360 doi: 10.1136/bmj.f2360

Nuclear Energy from Fission

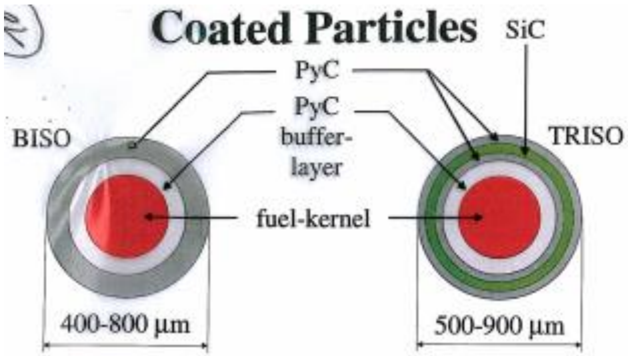
2. **Shortage of ^{235}U fuel - reported uranium reserves last until about 2040**
   Solution to the fuel crisis: breeding of ^{233}U from ^{232}Th and ^{239}Pu from ^{238}U

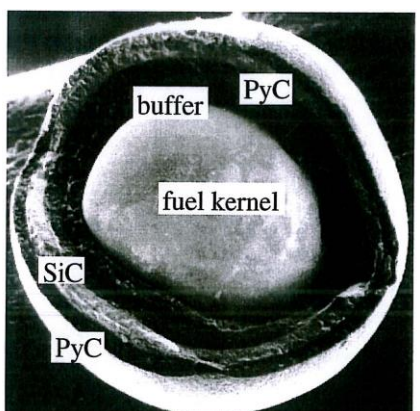
$$^{232}\mathrm{Th} \xrightarrow{(n,\gamma)} {}^{233}\mathrm{Th} \xrightarrow[22.2\mathrm{m}]{\beta^-} {}^{233}\mathrm{Pa} \xrightarrow[27\mathrm{d}]{\beta^-} {}^{233}\mathrm{U} \qquad {}^{238}\mathrm{U} \xrightarrow{(n,\gamma)} {}^{239}\mathrm{U} \xrightarrow[23.5\mathrm{m}]{\beta^-} {}^{239}\mathrm{Np} \xrightarrow[2.35\mathrm{d}]{\beta^-} {}^{239}\mathrm{Pu}$$

– **Thermal Thorium breeder: conversion factor of only 80%, i.e. no breeding**
– **Fast Plutonium breeder: breeding factors higher than one have been achieved**

Compact reactor core – just fissile and fertile fuel rods
→ **high neutron flux → material damage**
→ **highly enriched fuel (^{239}Pu, ^{233}U)**
→ **narrow range of allowed reacticity → criticality accidents**
→ **proliferation**
→ **High energy density – liquid metal coolant (sodium, lead)**
→ **unproven technology (on large scale) → accidents**
→ **Requires reprocessing of spent fuel - closed fuel cycle**
→ **hot chemistry → (criticality) accidents**
→ **proliferation**

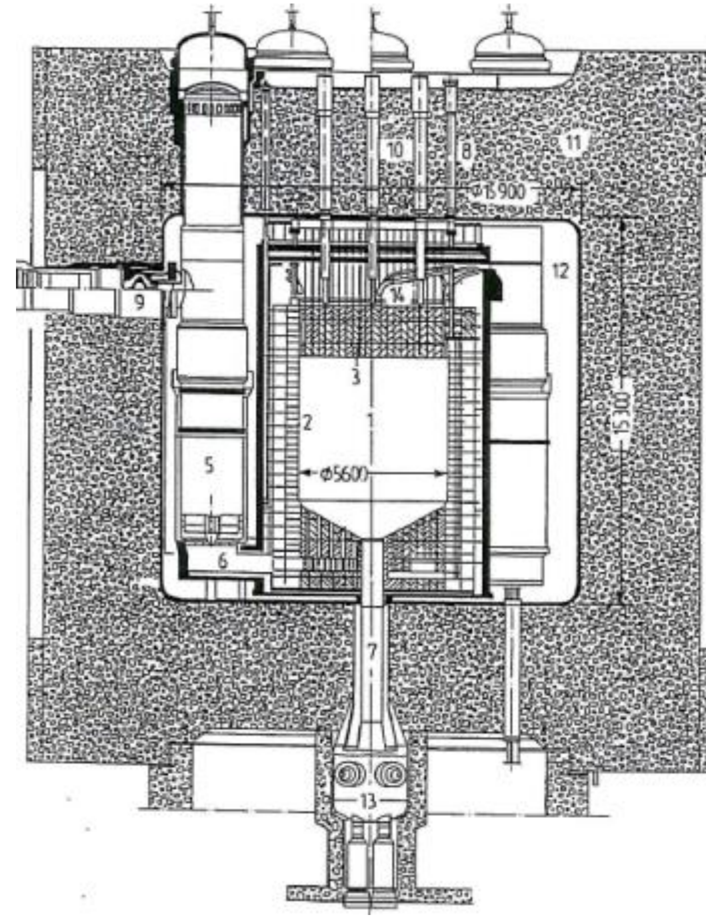
Thorium high temperature reactor





Gas-cooled (He) graphite-moderated reactor

- **Fuel: 675,000 spherical fuel elements**
- **Fuel element: 30,000 coated particles**
- **Fuel elements are continuously loaded during operation**
- **They are recycled several times (about 6) to gain the final burn-up**

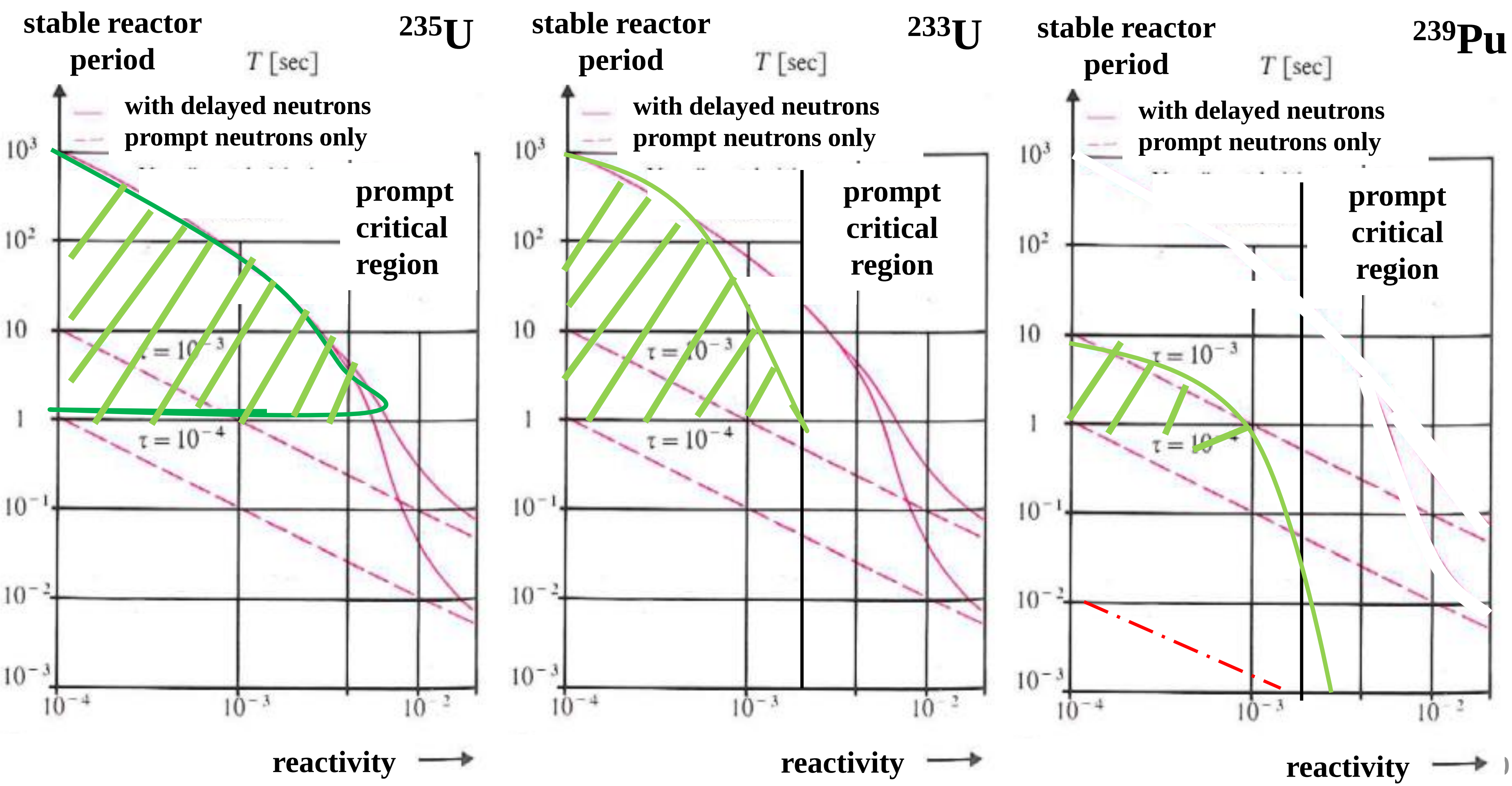


Development costs for the fuel cycle and the reactor technology today: ~ 50 – 100 billion NOK

Nuclear Energy from Fission

Reactor operation diagram: safety margins

Thermal reactors **Fast reactor**



Nuclear Energy from Fission

3. **Waste management**

   Fuel inventory of a typical power reactor (LWR, 1 GW_{el}): 100 tons
   Spent fuel discharge per year: 30 tons containing about 2% unused ^{235}U, plutonium isotopes of breeding process from ^{238}U and fission products:

   600 kg ^{235}U
   285 kg Pu (70% ^{239}Pu)
   450 kg fission products

Fuel cycles

- **Open fuel cycle (once-through)**
  uranium ore -> enrichment -> reactor -> waste storage
  (current reactor technology relies on enriched ^{235}U fuel)
- **Closed fuel cycle**
  ^{238}U - ^{239}Pu or ^{232}Th - ^{233}U cycles, require reprocessing of spent fuel

Nuclear Energy from Fission

Reprocessing of spent fuel - ^{239}Pu/^{233}U extraction

Medium/large-scale chemical plant

- PUREX: various ”hot” chemical processes
  - chopping up spent fuel
  - dissolving the fuel in acid
  - solvent-extracting and ion-exchanging processes
  - converting plutonium to metallic form

- THOREX: similar process for the extraction of ^{233}U

→ accident prone, high maintenance hot chemistry plant (e.g. Sellafield)

Nuclear Energy from Fission

Storage of nuclear waste

- **Waste from LWR (U fuel), with and without reprocessing, and from Thorium reactors (U-Th)**
  - **some differences in toxicity after 200 years**
  - **waste has to be kept away from biosphere and/or safeguarded for about 10^7 years**

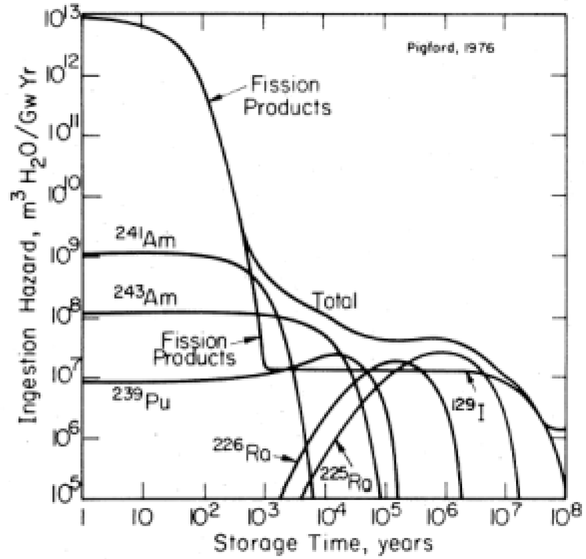


FIG. 7B1. Principal contributions to the ingestion hazard index at HLW from the reprocessing of a uranium fueled LWR as a function of time.

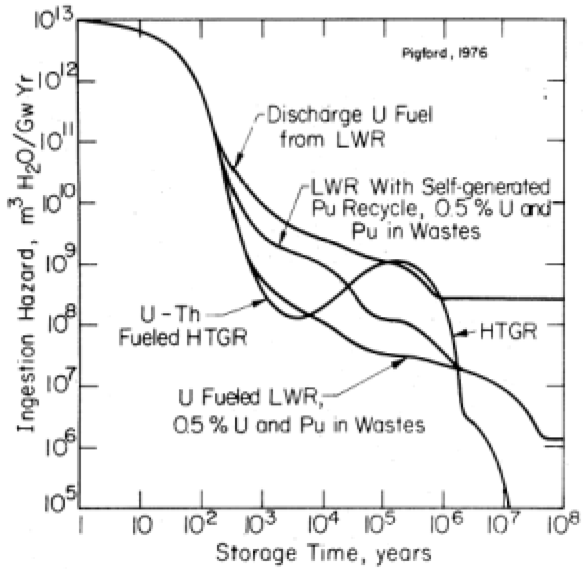


FIG. 7B2. Ingestion hazard index of high-level wastes from LWR, with and without reprocessing, and from HTGR (LWR = Light Water Reactor, HTGR = High-Temperature Gas-Cooled Reactor).

- **Storage in a geologic repository**
  - **no consensus on what is a safe geologic formation**

Nuclear Energy from Fission

4. **Proliferation**
   Any civilian nuclear installation (enrichment plant, reactor, reprocessing plant) can give access to weapons-grade nuclear material

   – **Enrichment plant – no difference in operation for 3% or >80% (weapons-grade) enrichment of ^{235}U**

   – **Reactor operation – short burn-up of fuel gives high yields of weapons-grade isotopes (^{239}Pu and ^{233}U)**

   – **Reprocessing plant – PUREX and THOREX process - extraction of almost pure ^{239}Pu and ^{233}U**

Nuclear Energy from Fission

Nuclear energy is a complex technology with many risks

1. Some experience with thermal reactors and ^{235}U fuel
2. Very limited experience with breeding of ^{233}U from ^{232}Th and operating reactors with ^{233}U

   one large-scale prototype in Germany (1960-86)
   → conversion factor of only 80%, i.e. no breeding
3. Some, mostly negative, experience with fast reactors for breeding of ^{239}Pu from ^{238}U
4. Closed fuel cycle, i.e. chemical reprocessing of spent fuel, is messy
5. Waste storage not solved
6. Norway no longer has expertise in nuclear energy and there is no nuclear industry

→ Instead of spending money on nuclear energy, **Norway should invest in lossless energy transmission and energy storage technologies**

The End