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Lesson 1

A Reactor Physics Perspective

The Nuclear Fuel Cycle
and
the needs of nuclear data

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The Speaker

Oscar Cabellos
(UPM)

- I am Oscar Cabellos, full professor in nuclear engineering at the Polytechnic University of Madrid (UPM).
- I am coordinator of UPM courses on “Introduction on Nuclear Technology”, “*Simulation of Nuclear Power* Plants”, “Nuclear Energy for the Energy Transition” and “Design *and Simulation of PWRs*” which is one of the UPM coursed based on the CDIO (Conceive, Design, Implement and Operate) initiative.
- My background is **reactor physicist**, specifically in PWR simulations where I did my PhD in 1998. Since 2005 I have been involved in EU projects **working on nuclear data activities**: EUROTRANS (2005-2010), ANDES(2010-2013), CHANDA(2013-2018) and SANDA (2019-2023).
- In 2014-2017, I moved to NEA Data Bank as Nuclear Data Scientist working in the development of EXFOR and JEFF databases , and JANIS and NDaST web-tools. Currently, I am actively working in the JEFF project and WPEC activities of the OECD/NEA.
- Member of the JEFF-CG, WPEC (coordinator WPEC/SG46 and monitor of WPEC/SG47), WPNCS (monitor SG12 on Decay Heat). Member of the OECD/NEA - Nuclear Science Committee (NSC) and the Management Board for the Development, Application and Validation of Nuclear Data and Codes (MBDAV).
- Over 40 papers in international scientific journals with reviewers, more than 60 papers/presentations in proceedings of international conferences and more than 100 contributed talks in workshops.

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1. Introduction:
The Nuclear Fuel Cycle (NFC) for LWRs

The nuclear fuel cycle (NFC) is the series of industrial processes which facilitate the production of electricity from uranium in nuclear power reactors.

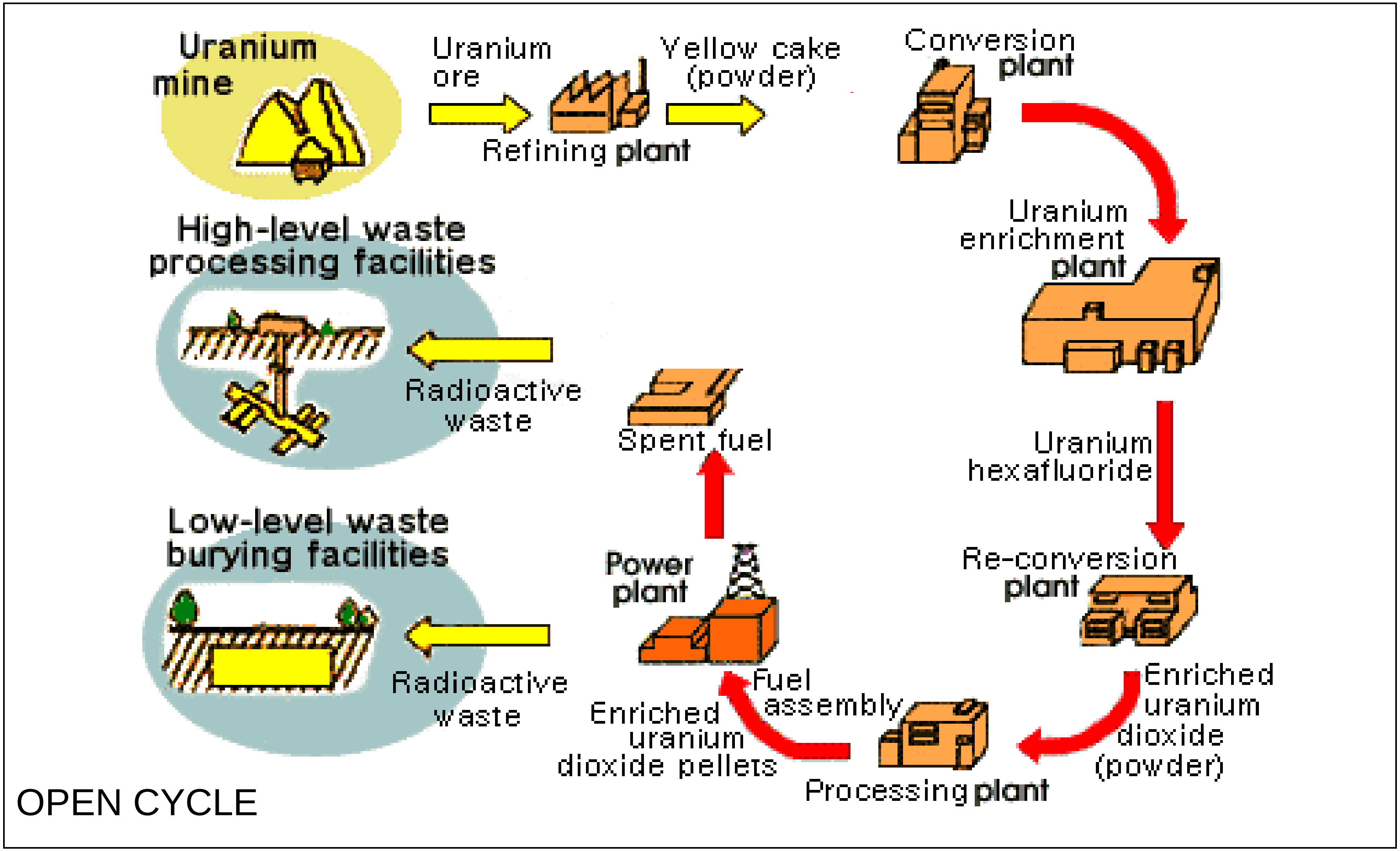
The NFC includes all stages that fuel material goes trough from mining to disposal:

1) **Uranium** is a relatively common element that is found throughout the world. It is mined in a number of countries and must be processed before it can be used as fuel for a nuclear reactor.

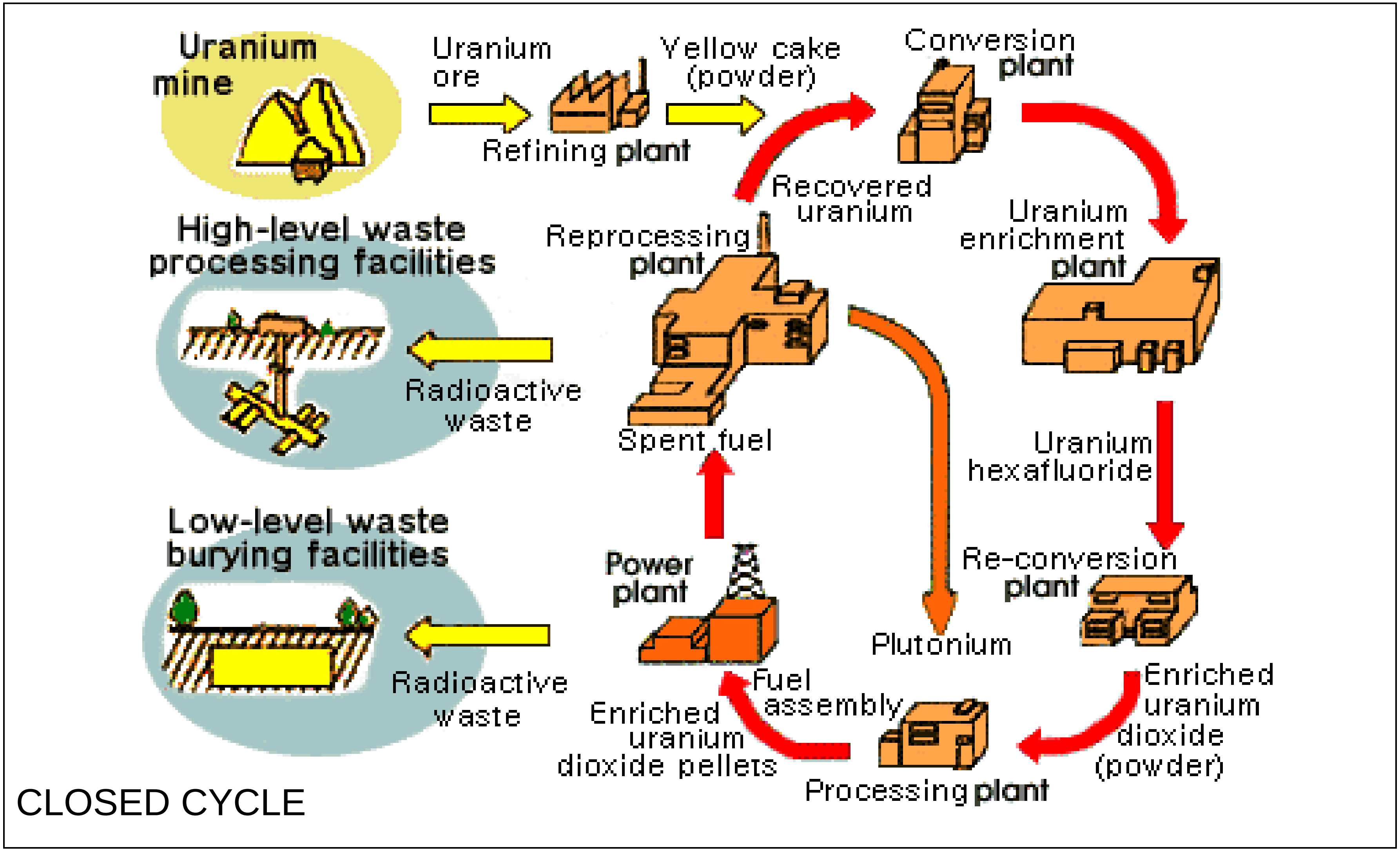
2) **Electricity** is created by using the heat generated in a nuclear reactor to produce steam and drive a turbine connected to a generator.

3) **Fuel must be removed from the reactor**, when the fuel has reached the end of its useful life:
    3.1) It can be stored and disposed as waste
    3.2) It can be reprocessed to produce new fuel

The Nuclear Fuel Cycle Flowchart



The Nuclear Fuel Cycle Flowchart



CLOSED CYCLE

… ND Needs in the Nuclear Fuel Cycle

Fission Reactor

Reactor Core Design

- Criticality, Burnup, Shielding
- Source term prediction (FPs, TRUs)
- Start-up sources

Reactor Core Analysis

- Effective multiplication factor
- Neutron spectrum
- Reactor power distribution
- Reactivity coefficients
- Controls rod worth
- Breading ratio
- Burnup – reactivity swing
- Spent fuel – source term
- Dopped fuel pins

Reactor Shielding

- Neutron and gamma leakage
- Heating
- Damage

Reactor Dynamics

- Reactivity changes

Reactor Safety Analysis

- Heating by decay heat
- Dose rate

Front-end: Nuclear Fuel Cycle

Enrichment, conversion plant, manufacturing

- Criticality
- Dose /radiotoxicity

Back-end: Nuclear Fuel Cycle

Fuel processing

- Criticality safety management (Neutron emission, Decay Heat)
- Dose rate/radiotoxicity

Nuclear Material transport

- Dose rate
- Criticality

Reparocessing

- Criticality: FPs, TRUs

Waste Disposal

- Environmental safety
- Criticality

Decommissioning

Handling remote/no-remote

Activation estimation

- Building
- Reactor structure

Waste disposal options

- Environmental safety

The fuel: Uranium

Uranium is a slightly radioactive (α and γ emitter) metal that occurs throughout the earth's crust about 4 parts per million (ppm)

$\Rightarrow$ about 500 times more abundant than gold

$\Rightarrow$ about as common as tin

It is present in most rocks and soils as well as in many rivers and in sea water.

For example, found in concentrations of about:

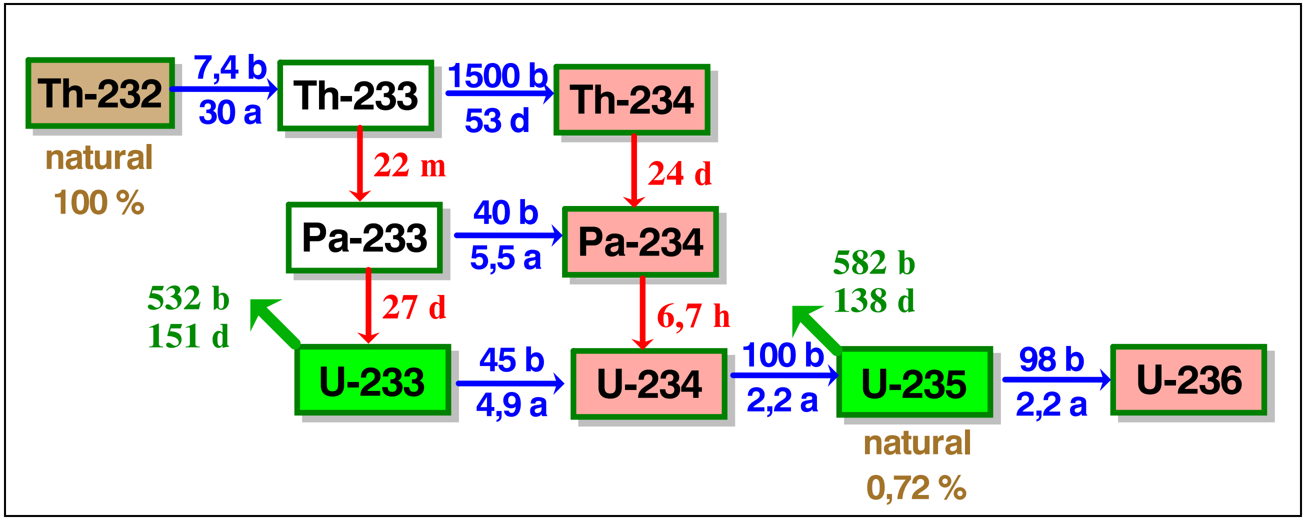
- 4 ppm in granite (60% of the earth's crust)
- 400 ppm (0.04%) in fertilizers
- 100 ppm (0.01%) in coal deposits

	Relative Percentage	*Atomic weight u.m.a.*	*Percentage in weight*
U^{238}	99.2745 %	238.0510	99.28362 %
U^{235}	0.7200 %	235.0440	0.71097 %
U^{234}	0.0055 %	234.0410	0.00541 %
	100.0000 %	238.0291	100.00000 %

U-235 is a major fissile (burnable) material in light water reactor

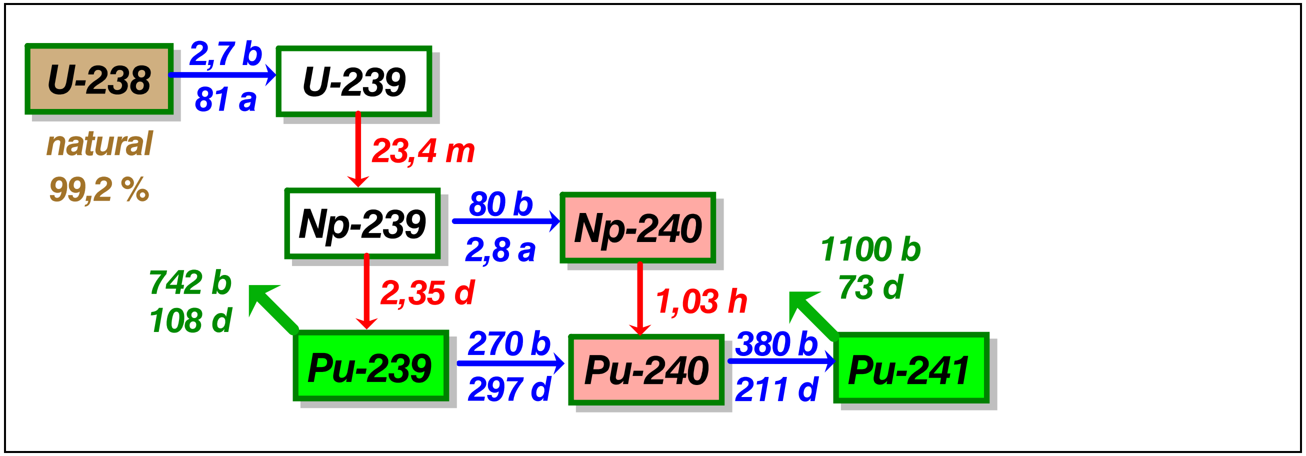
The fuel: Thorium and Plutonium

Thorium Fuel



Th-232
7,4 b
30 a
Th-233
1500 b
53 d
Th-234
natural
100 %
22 m
24 d
Pa-233
40 b
5,5 a
Pa-234
582 b
138 d
532 b
151 d
27 d
6,7 h
U-233
45 b
4,9 a
U-234
100 b
2,2 a
U-235
98 b
2,2 a
U-236
natural
0,72 %

Plutonium Fuel



U-238
2,7 b
81 a
U-239
natural
99,2 %
23,4 m
Np-239
80 b
2,8 a
Np-240
1100 b
73 d
742 b
108 d
2,35 d
1,03 h
Pu-239
270 b
297 d
Pu-240
380 b
211 d
Pu-241

Uranium - MINING

Type of Mining	Deposits	Requirements on the surface	Quantity of material that must be removed in order to access the ore
Open pit	Close to the surface	large openings	large
Underground	deep deposits >120 m deep	relatively small openings	Lower than open pit

The decision as to which mining method to use for a particular deposit is governed by safety, economic and **political** considerations.

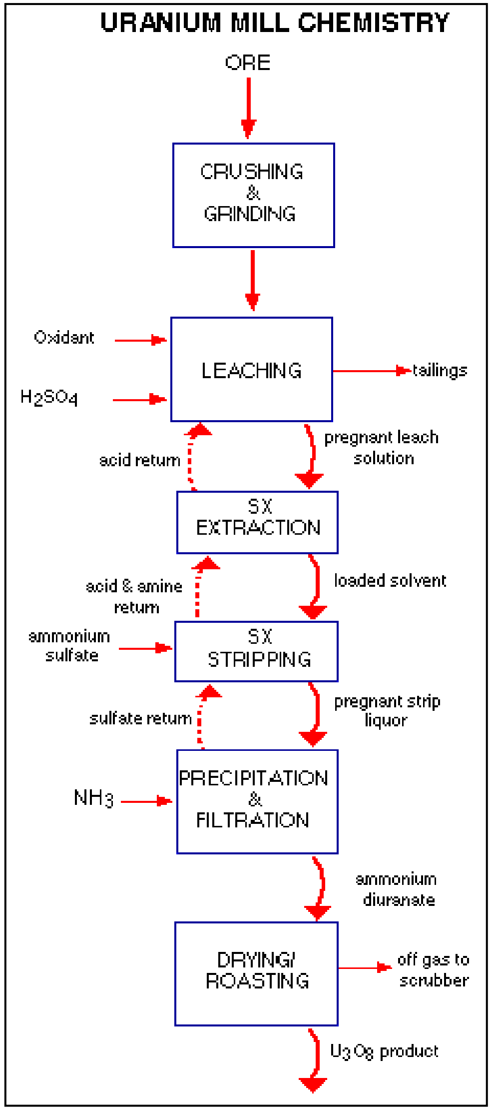
In the case of underground uranium mines special precautions, consisting primarily of increased ventilation, are required to protect against airborne radiation exposure.

Other: in situ leaching of uranium deposits
a chemical solution in which uranium will dissolve is introduced into the ground at or close to a deposit. Ground water is then extracted from the area using a well which has been located such that the uranium solvent is drawn through the ore body.

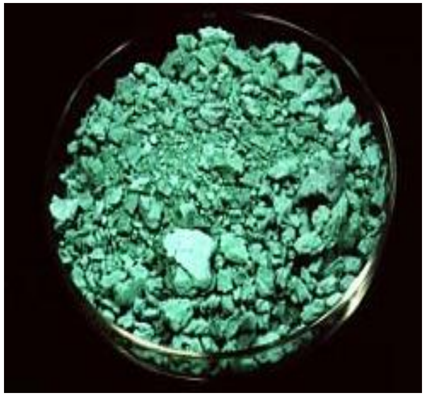
Uranium - MILLING

Milling, which is generally carried out close to a uranium mine, extracts the uranium from the ore and produces a uranium concentrate (“yellowcake”), that has a smaller volume than the ore, and hence is less expensive to ship

- The “yellowcake” (U3O8) contains more than 60% uranium
- The original uranium ore contains typically between 0.1 and 1% uranium



Uranium - CONVERSION

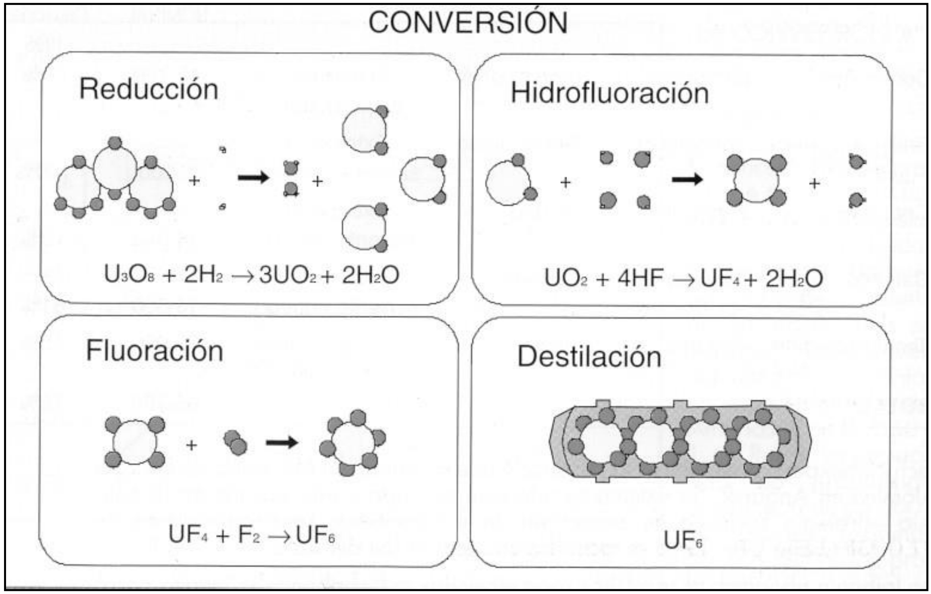


The product of a uranium mill is not directly usable as a fuel for a nuclear reactor. Additional processing, generally referred to as conversion, is required.

At a **conversion facility**, uranium is converted to either uranium dioxide (UO2)

- used as the fuel for those types of reactors that do not require enriched uranium
- enriched to produce fuel for the majority of types of reactors.

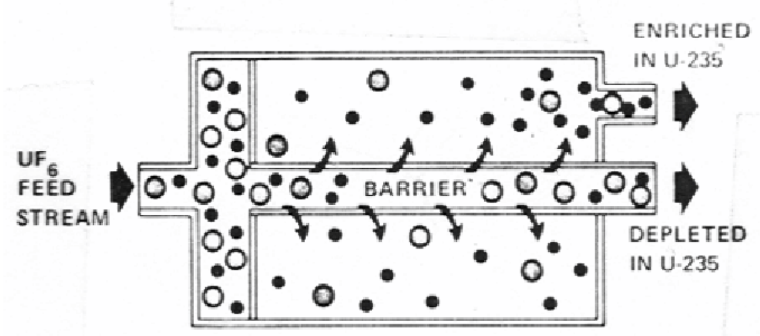
The enrichment process uses uranium hexafluoride (UF6)



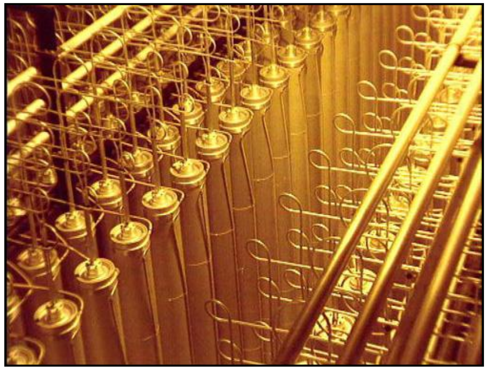
Uranium - ENRICHMENT

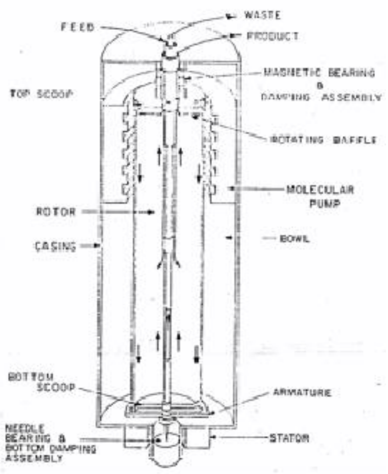
There are two enrichment processes in large scale commercial use, each of which uses uranium hexafluoride (UF6) as feed:

gaseous diffusion stage



gas centrifugation





The enrichment process produces this higher concentration**, typically < 5% U-235**, removing a large part of the U-238 (80% for enrichment to 3.5%) by separating gaseous uranium hexafluoride into two streams.

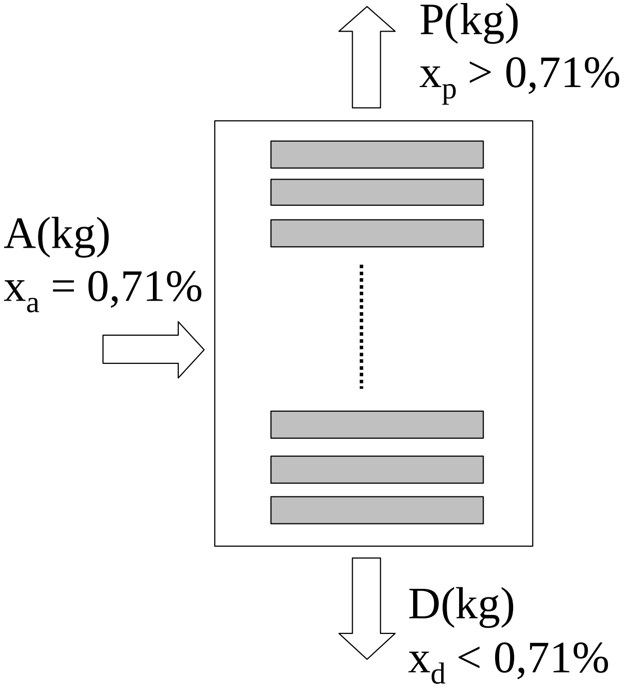
Uranium - ENRICHMENT

Many procedures/stages are required due to only 1.3% weight difference between 235U and 238U.

DEFINITION: SWU (Separation Work Unit)

$$\Delta U = P * V(X_p) + D * V(X_d) - A * V(X_a)$$

$$V(x) = (2 * x - 1) * \ln \frac{x}{1 - x}$$



- U235 Balance:
  $P * x_p + D * x_d = A * x_a$
- Masses Balance:
  $P + D = A$

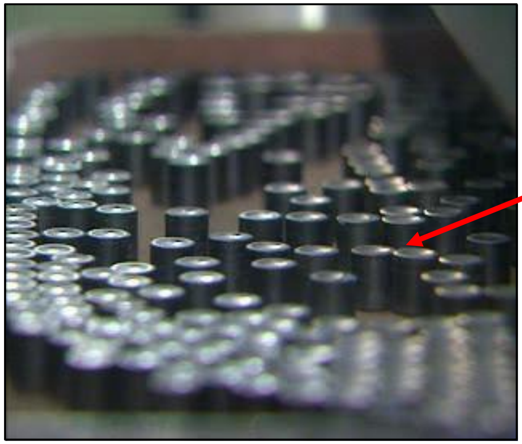
Example:

$x_a = 0.0071$ A=262*P
$x_p = 0.0500$ D=261*P
$x_d = 0.0025$ P= P

The large Tricastin enrichment plant in France

Uranium - FUEL FABRICATION

Enriched UF6 is transported to a fuel fabrication plant where it is converted to uranium dioxide (UO2) powder and pressed into small pellets: **sintering process** for UO2 (high pressure and high temperature ~ 1400 °C)



UO2
pellets

These pellets are inserted into thin tubes, usually of a zirconium alloy (zircalloy) or stainless steel, to form fuel rods.

The rods are then sealed and assembled in clusters to form fuel elements or assemblies for use in the core of the nuclear reactor.

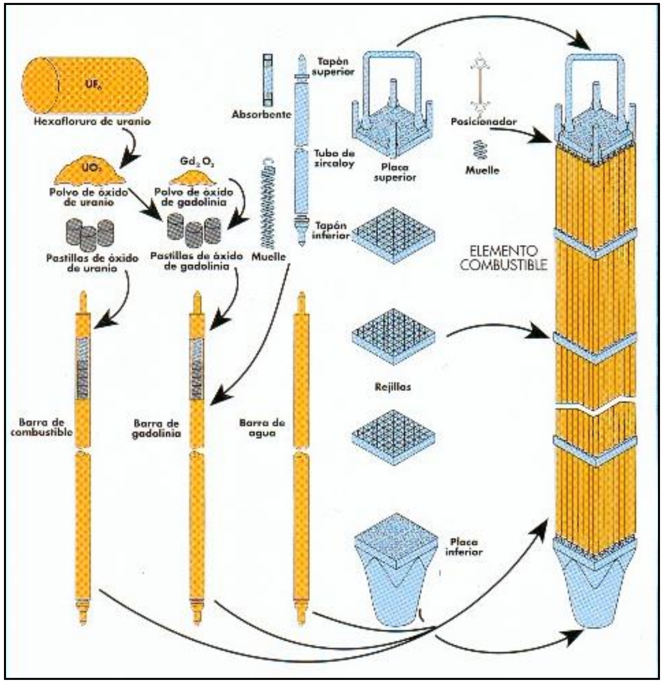
Uranium - FUEL FABRICATION

The two most important characteristics of **fuel** are:

- High melting point
- No fission products should be released

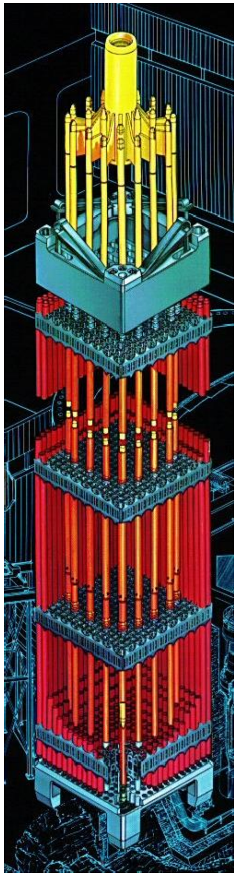
For **cladding** (Zr alloy), we need :

- small thermal cross section
- corrosion resistant
- retain fission products
- allow fuel volume changes
- good heat transfer

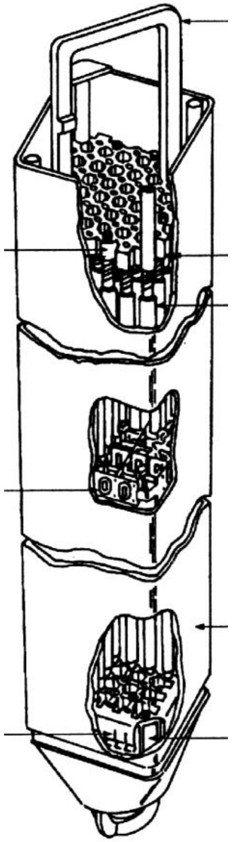


Uranium - TRANSPORT to NNPP

PWR

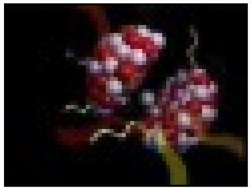


BWR



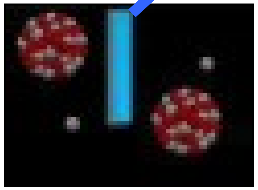
Uranium - POWER GENERATION

In the reactor core the **U-235 isotope fissions** or splits

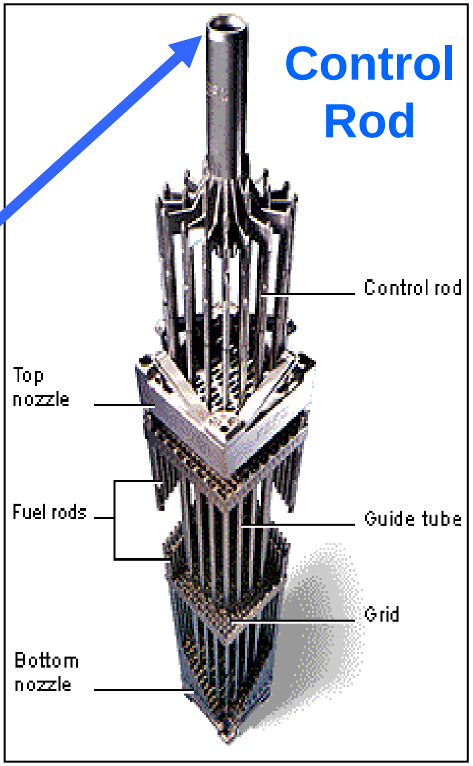


Nuclear Fission

- ❑ Producing heat in a continuous process called a **chain reaction**.
- ❑ The process depends on the presence of a **moderator** such as water or graphite.
- ❑ The process is fully controlled using the **control system.**



Controlled Fission



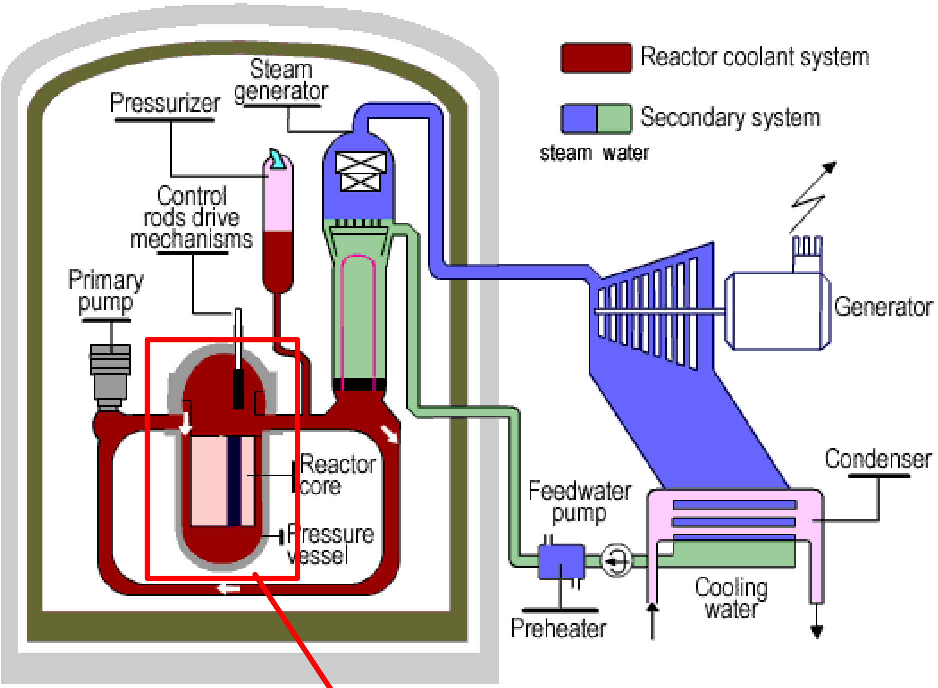
Control Rod

Breeder concept:

Some of the U-238 in the reactor core is turned into plutonium and about half of this is also fissioned, providing about one third of the reactor's energy output

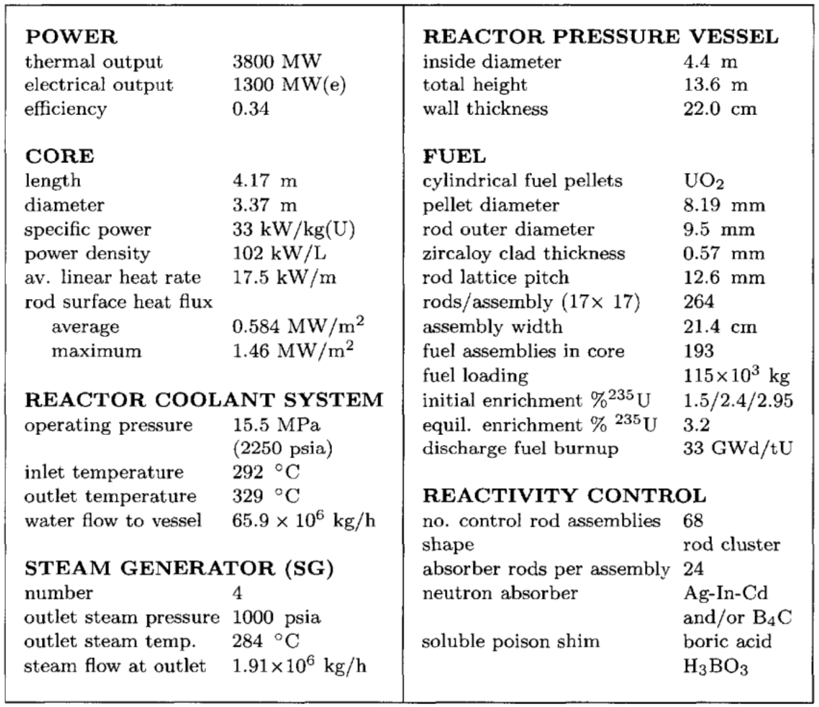
Uranium - The NNPP

Figure. A typical Pressure Water Reactor (PWR)



Reactor core

Table. Parameters for a typical PWR 1300 MWe



POWER	
thermal output	3800 MW
electrical output	1300 MW(e)
efficiency	0.34
CORE	
length	4.17 m
diameter	3.37 m
specific power	33 kW/kg(U)
power density	102 kW/L
av. linear heat rate	17.5 kW/m
rod surface heat flux	
average	0.584 MW/m^2
maximum	1.46 MW/m^2
REACTOR COOLANT SYSTEM	
operating pressure	15.5 MPa (2250 psia)
inlet temperature	292 °C
outlet temperature	329 °C
water flow to vessel	65.9×10^6 kg/h
STEAM GENERATOR (SG)	
number	4
outlet steam pressure	1000 psia
outlet steam temp.	284 °C
steam flow at outlet	1.91×10^6 kg/h

REACTOR PRESSURE VESSEL	
inside diameter	4.4 m
total height	13.6 m
wall thickness	22.0 cm
FUEL	
cylindrical fuel pellets	UO_2
pellet diameter	8.19 mm
rod outer diameter	9.5 mm
zircaloy clad thickness	0.57 mm
rod lattice pitch	12.6 mm
rods/assembly (17× 17)	264
assembly width	21.4 cm
fuel assemblies in core	193
fuel loading	115×10^3 kg
initial enrichment $\%^{235}U$	1.5/2.4/2.95
equil. enrichment $\%\ ^{235}U$	3.2
discharge fuel burnup	33 GWd/tU
REACTIVITY CONTROL	
no. control rod assemblies	68
shape	rod cluster
absorber rods per assembly	24
neutron absorber	Ag-In-Cd and/or B_4C
soluble poison shim	boric acid H_3BO_3

Uranium - The NNPP

Figure. The reactor core in a PWR 1000 MWe/Westinghouse

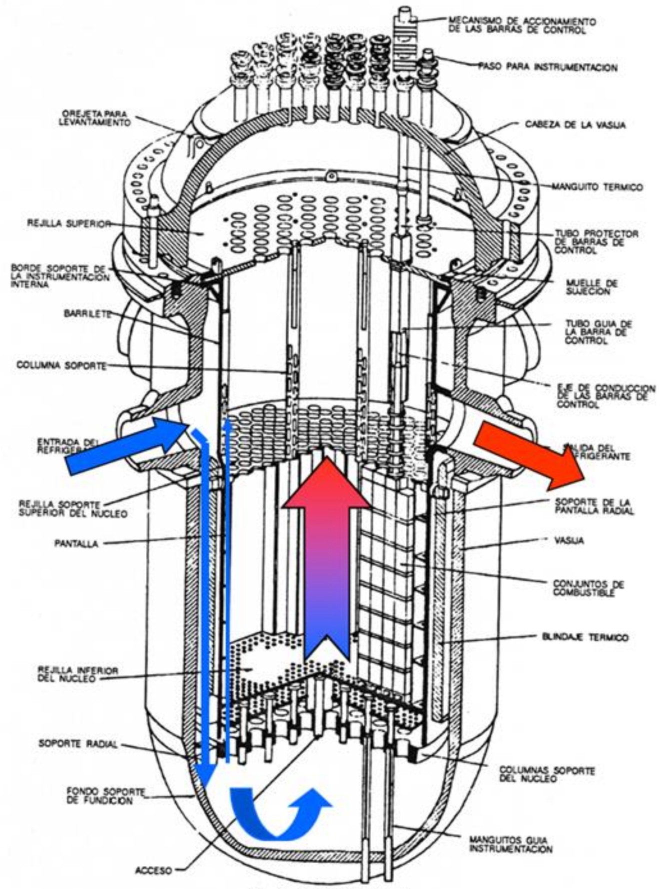
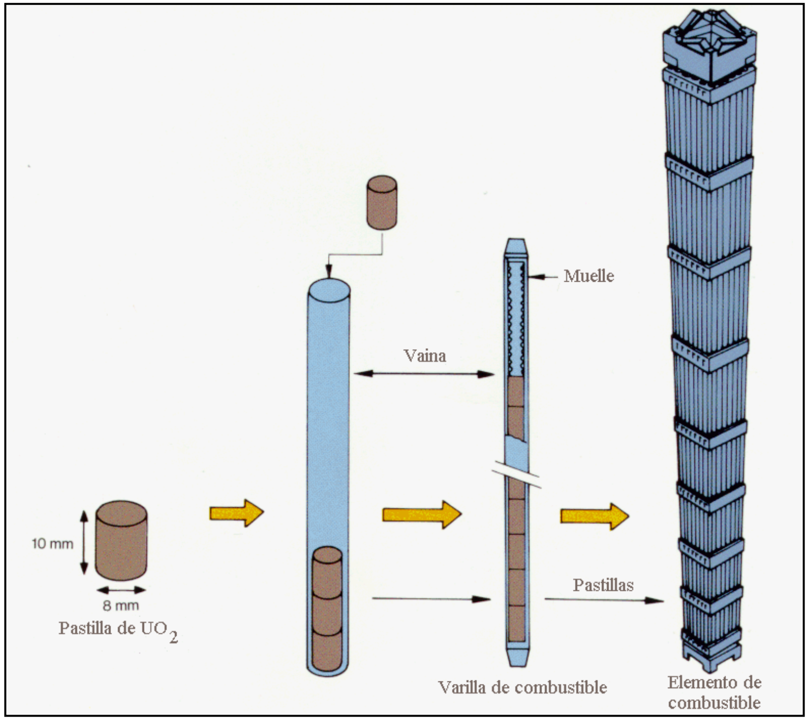


Fig. 7 Reactor de Surry

Figure. A typical 17x17 Fuel Assembly for a PWR/Westinghouse



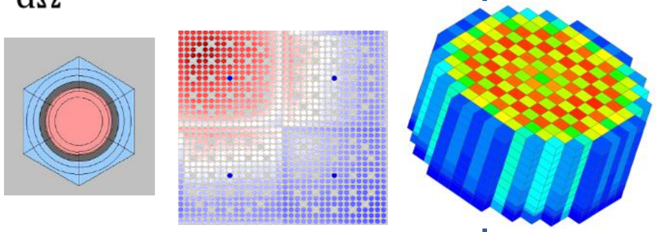
Criticality Calculation

- ❑ A **set of nuclear data** are validated by **simulating** and comparing to **integral experiments**

$$\frac{1}{v}\frac{\partial\Psi}{\partial t} + \Omega\cdot\nabla\Psi + \Sigma_T\Psi = S + \int_E\int_\Omega \Psi(E',\Omega')\cdot\Sigma_s(E'\to E,\Omega'\to\Omega)dE'd\Omega'$$

$$S_{PF} = \sum_i N_i \int dE'\ \phi(E')\cdot\nu_i(E')\cdot\sigma_{F,i}(E')\cdot\chi_{F,i}(E,'E)$$

$$S_{dn} = \sum_k \lambda_k\cdot C_k(r,t)\cdot\chi_{d,k}(E)$$



Neutron transport
Boltzmann equation

$$\Omega\cdot\nabla\Psi(\mathbf{r},E,\Omega) + \Sigma_T(\mathbf{r},E,\Omega)\Psi(\mathbf{r},E,\Omega) = \int_0^\infty\int_{4\pi}\Psi(\mathbf{r},E',\Omega')\cdot\Sigma_s(\mathbf{r},E'\to E,\Omega'\to\Omega)dE'd\Omega'$$
$$+\frac{1}{k_{eff}}\frac{\chi_f(E)}{4\pi}\int_0^\infty\int_{4\pi}\Psi(\mathbf{r},E',\Omega')\cdot\overline{\nu_t}(\mathbf{r},E')\cdot\Sigma_f(\mathbf{r},E'\to E,\Omega'\to\Omega)dE'd\Omega'$$

Responses: *keff, reactivity coefficients, power distribution,… neutron leakage…*

Searching criticality conditions: Boron let down*, control rod position, power level (temperature fuel and moderator)*

Criticality Calculation – Reactivity

- ☐ The multiplication factor: **keff**
- ☐ **Excess multiplication: k_{excess}= k-1 (how much the keff differs from criticality)**
- ☐ Reactivity: ρ= (k-1)/k

UNITS: $\Delta k/k$ or $\%\Delta k/k$
pcm (per cent mille)

BOC: Begin of Cycle
EOC: End of Cycle

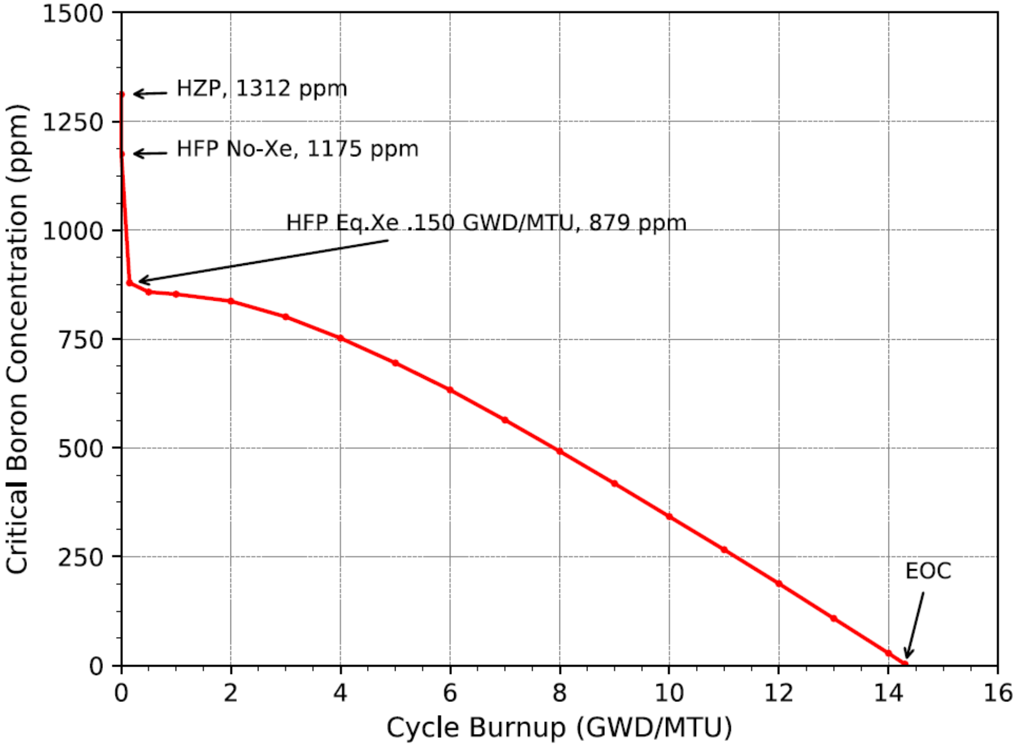
CZP: Cold Zero Power
HZP: Hot Zero Power
HFP: Hot Full Power

Table. Typical ($\Delta k/k$) values in a PWR

Fuel Reactivity Excess ($\Delta k/k$)	
CZP/BOC	**0.293**
HFP, no-Xenon	0.248
HFP, equilibrium Xe+Sm	0.181
Total value control system (ρ_{excess}+ ρ_{sm})	**0.32**
• Control rods	0.07
• Burbable absrobers (Gd, WABAS)	0.08
• Boron dilution	0.17
Shutdown margin (ρ_{sm})	
CZP and BOC	**+0.03**
HFP, eq. Xe+Sm	+0.14

Criticality Calculation –
Boron Let-down in PWRs

Figure. **Critical boron-let down** (HZP and HFP, ARO) as a function of burnup for a typical PWR/Westinghouse - 1000MWe



ppm = parts per million of by weight of boron concentration diluted in the water

HZP = Hot Zero Power
HFP = Hot Full Power
ARO = All Control Rods out

BOC =Begin of Cycle
EOC = End of Cycle

Burnup = Measure of the energy output of the fuel per metric ton of initial uranium metal (GWd/MTU)

Transmutation - Radioactivity Calculation

- ***Transmutation calculations:***

$$\frac{dN_i(t)}{dt} = -(\lambda_i + r_i) \cdot N_i(t) + \sum_{i \neq j} (\lambda_{j \to i} + r_{j \to i}) \cdot N_j(t) + PF_i$$

$$\mathrm{PF}_i = \sum_h N_h \cdot \int_0^\infty dE \cdot \phi(E) \cdot \gamma_{h \to i}(E) \cdot \sigma_{f,h}(E)$$

Bateman transmutation equation

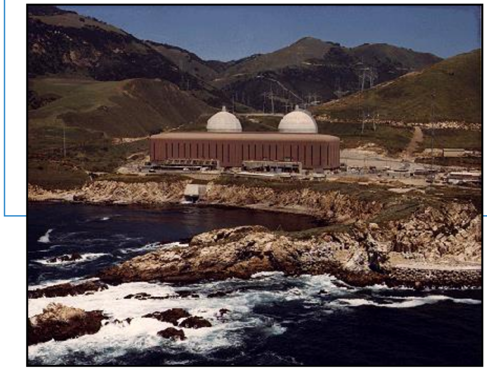
Responses: *Inventory (atoms), Activity (Bq), Dose (Sv), Decay Heat (W), Material damage (gas generation and dpa), neutron/gamma emission,…*

- ***Burnup calculation****: Neutron transport + Transmutation/Depletion*

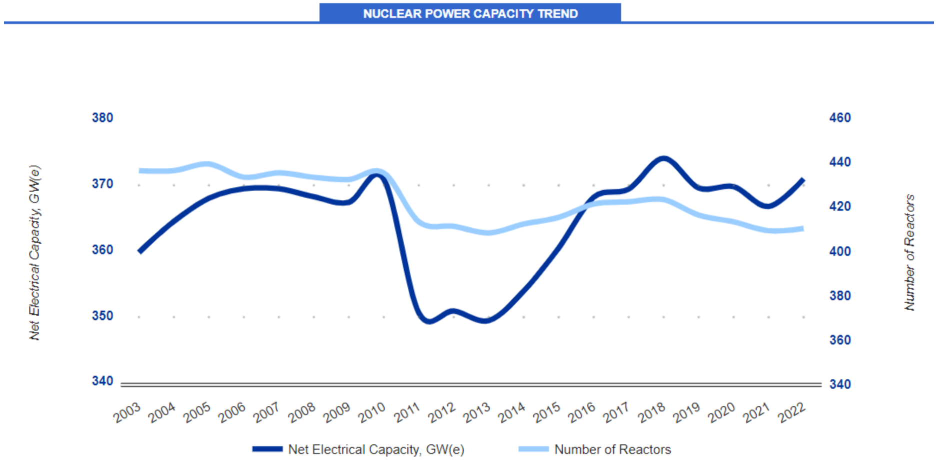
- ***Reactor Safety Analysis****: “Multiphysics” problem*

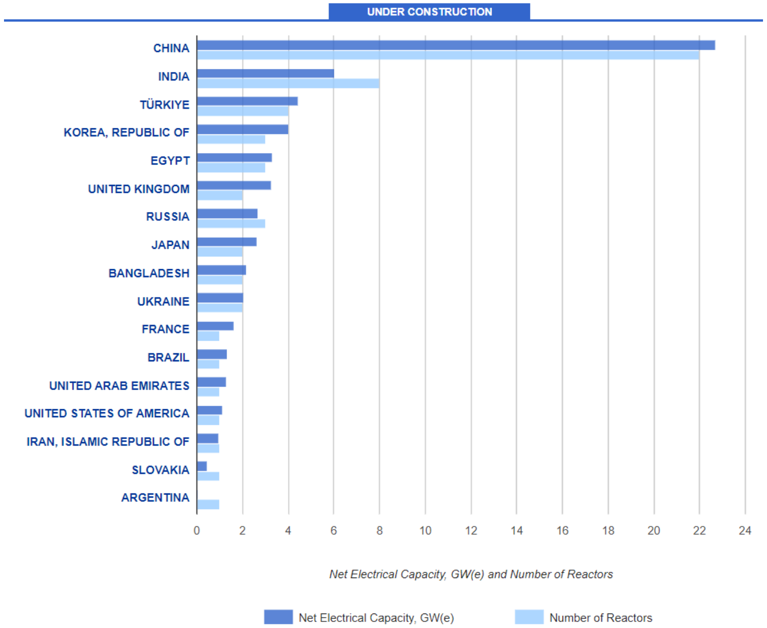
  Neutron transport + Transmutation + Thermo-hydraulic + Fuel performance

Uranium - Current Status of the Existing NPP: Fleet in the World



Diablo Canyon nuclear power plant, USA





Source: IAEA PRIS database: https://pris.iaea.org/pris/home.aspx (Last update on 2023-10-10)

Current status (October 10, 2023)

- 411 NPP in operation -> 369.39 GWe total installed capacity
  10% of the world's electricity
- 26 NPP in suspended operation
- **58 NPP under construction**
- 30 countries with NPPs
- 66 GtCO2 cumulative emissions avoided 1971-2021
  1.6 GtCO2/year avoided by nuclear energy
- 19613 reactor-year of operation

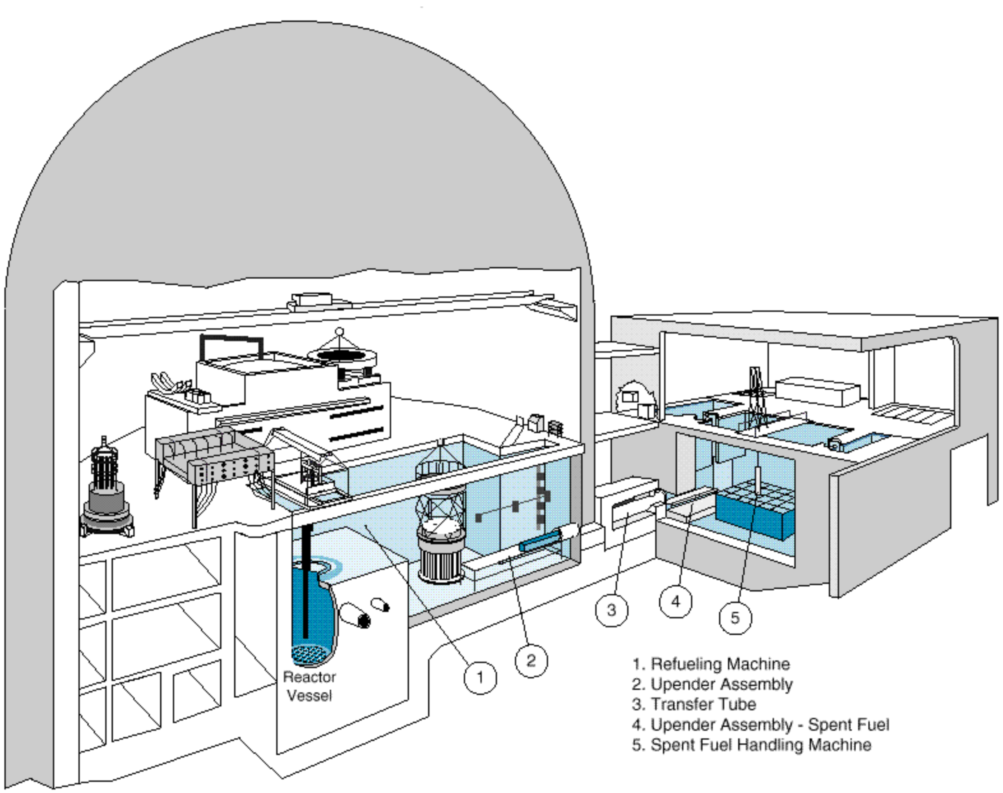
*"In order to limit climate change to 1.5°C by the end of the century, the planet has a **"carbon budget" of 420 GtCO2*** emissions (Raupach et al., 2014), which represents the maximum quantity of carbon dioxide that can be emitted into the atmosphere while still keeping climate change to a maximum of 1.5°C."*

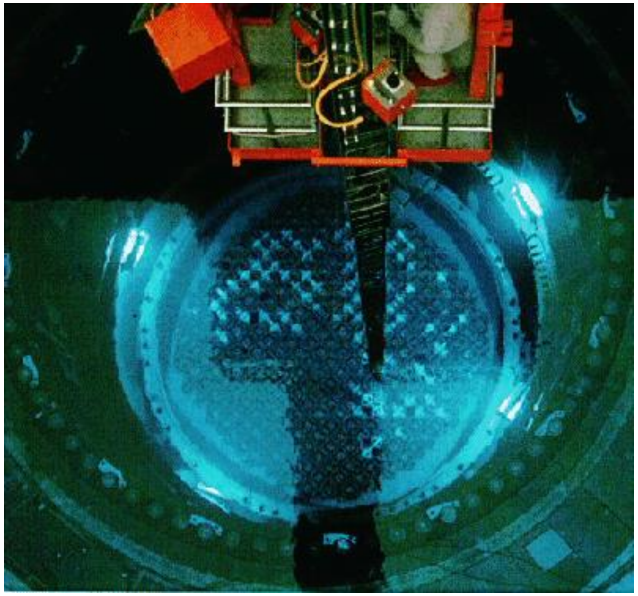
*Note: **The remaining carbon budget is highly uncertain***

Uranium - REFUELING AND LOADING

Loading concept:

To maintain efficient nuclear reactor performance, **about one-third of the spent fuel** is removed every year or so, to be replaced with fresh fuel.





In a PWR-1000MWe, 157/177 fuel assemblies (500kg U/FA) are present in each reactor core

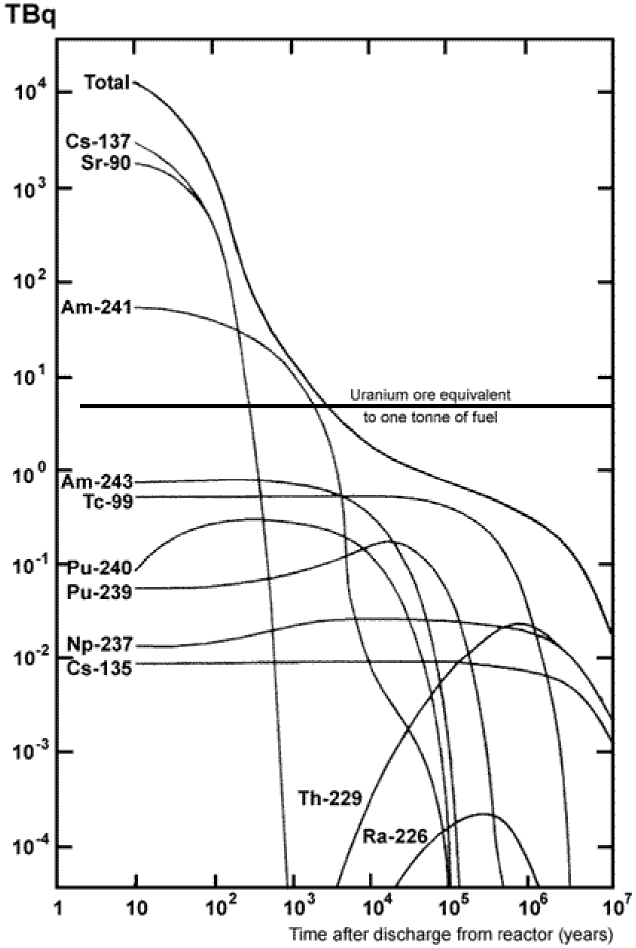
Uranium - SPENT FUEL

With time, the concentration of fission fragments in a fuel bundle will increase to the point where it is no longer practical to continue to use the fuel. At this point the **“spent fuel”** is removed from the reactor.

The amount of energy that is produced from a fuel bundle depends on the type of reactor and the policy of the reactor operator. (**BURNUP=MW·D/tU**)

Decay Heat (in MW) is produced even after shutdown.

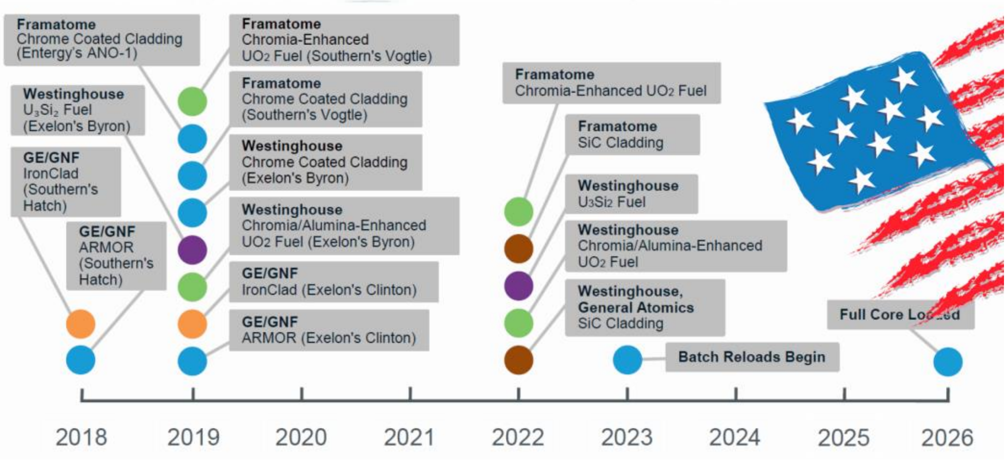
Fuel should keep its integrity during its lifetime to prevent the release of fission products (radiation)



Activity of high-level waste from 1 t. of spent fuel
Source: IAEA, 92- radioactive waste management

Uranium - Accident/Advanced Tolerant Fuels (ATF)

- In 2012, US Congress mandated DOE: *“Develop LWR fuel with* ***Enhanced Accident Tolerance”***



Source: C. Muñoz-Reja, ATF Concepts, ATF Workshop, Seville, June 2019

Current fleet of LWR fuel:

- Fuel : UO2
- Clad: Zircalloy

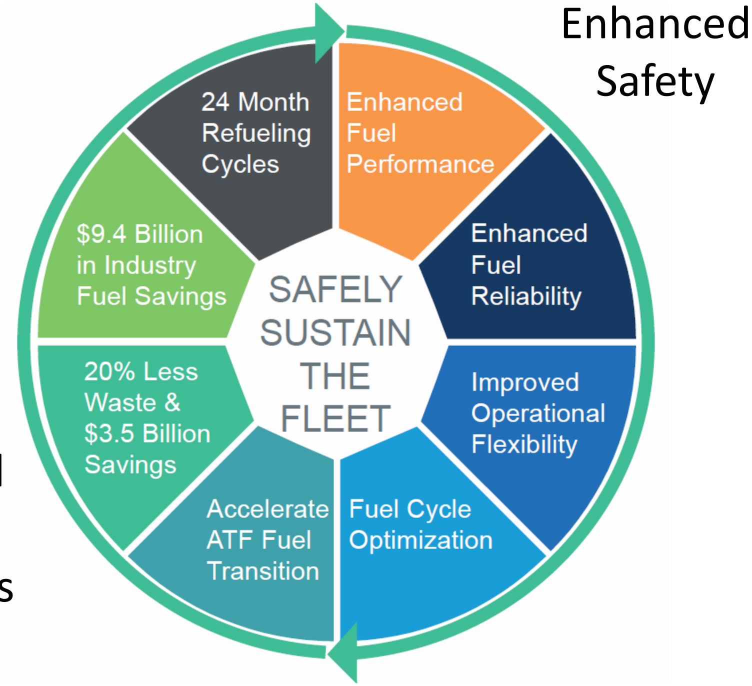
$$Zr + 2H_2O \rightarrow ZrO_2 + \mathbf{2H_2} + \mathbf{586\ kJ/mol}$$

ATF concepts:

- ***Enhancing cladding***
  - Cr-coated. Cr-Al coated
  - FeCrAl
  - SiC
- ***Enhancing fuel***
  - Dopped UO2 with BeO or Cr
  - Nitride Fuel – (U, Pu)N
  - U_3Si_2
  - TRISO

Uranium - Accident Tolerant Fuels (ATF): ATF+ ↑w/o + ↑ Burnup

- In 2012, US Congress mandated DOE: *"Develop LWR fuel with **Enhanced Accident Tolerance**"*
- Enabling Fuel Transition*: **"ATF + increased enrichment (< 10%) + Burnup (~75 GWd/MTU)"***



*"For implementation of the near-term ATF concepts (**chromium-coated cladding, doped pellets, FeCrAl cladding**), fuel vendors and power reactor licensees are exploring the possibility of increasing the maximum enrichment of fuel up to 10%.*

*Currently, **NRC regulations** state that 235U enrichment levels in power reactor fuel may be no more than 5% by weight, unless significant additional restrictions, plant systems, or analyses are implemented."*

Source:
https://www.nrc.gov/reactors/power/atf/technologies/enrichment.html

Source: A. Csontos, The Drive to Deploy ATS, NEI, 2022

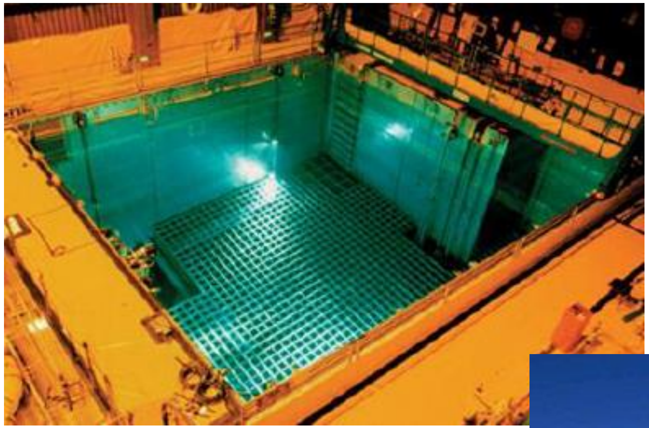
Uranium - SPENT FUEL STORAGE

When removed from a reactor, a fuel bundle will be emitting both radiation, primarily from the fission fragments, and heat.

Spent fuel is unloaded into a storage facility immediately adjacent to the reactor to allow the radiation levels and the quantity of heat being released to decrease.

These facilities are large pools of water; the water acts as both a shield against the radiation and an absorber of the heat released.

Spent fuel is generally held in such pools for a minimum of about five months.

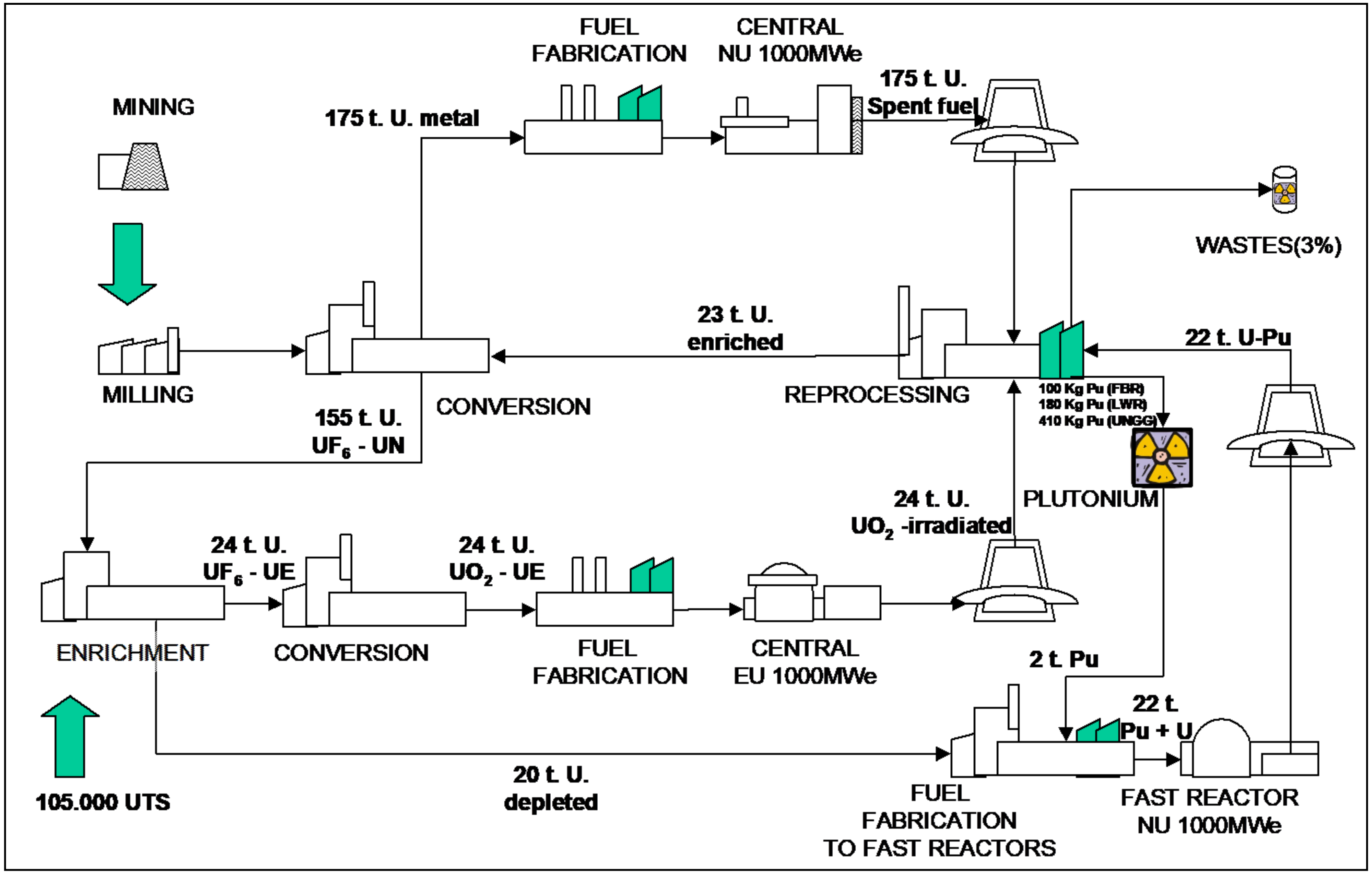


Storage – Spent Fuel Pool

Dry Interim Storage (40/60 years) - Dry Casks

Uranium - SPENT FUEL TRANSPORT

While much of the spent fuel is held at reactor sites beyond the initial storage period, some of it is transferred to interim storage facilities.
Finally, spent fuel must either be reprocessed or sent for permanent disposal.



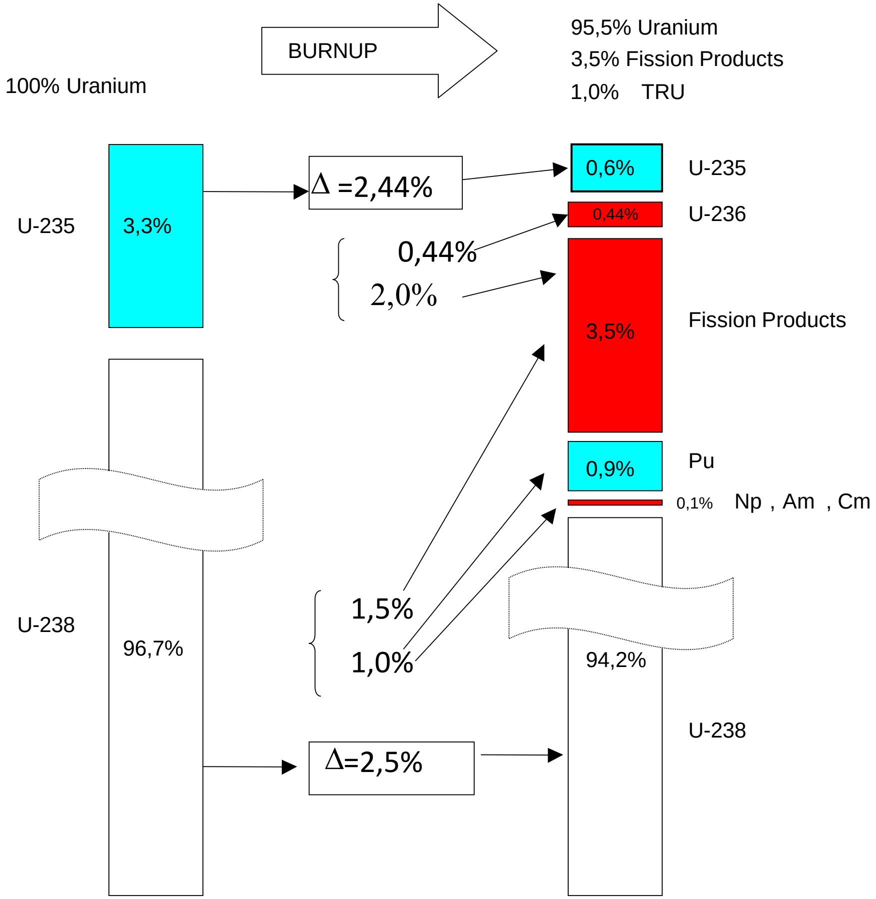
Uranium - REPROCESSING AND WASTE DISPOSAL

There are two options for spent fuel:

- long-term storage and final disposal
- reprocessing to recover the usable portion of it

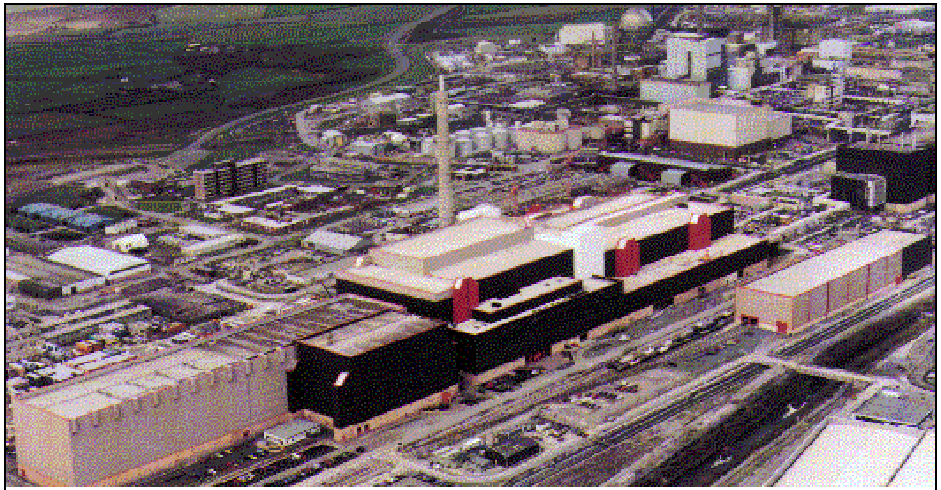
Spent fuel still contains:

- approximately 96% of its original uranium
- the fissionable U-235 content has been reduced to less than 1%
- About 3% of spent fuel comprises:
  - waste products
  - the remaining 1% is plutonium (Pu) produced while the fuel was in the reactor and not “burned”

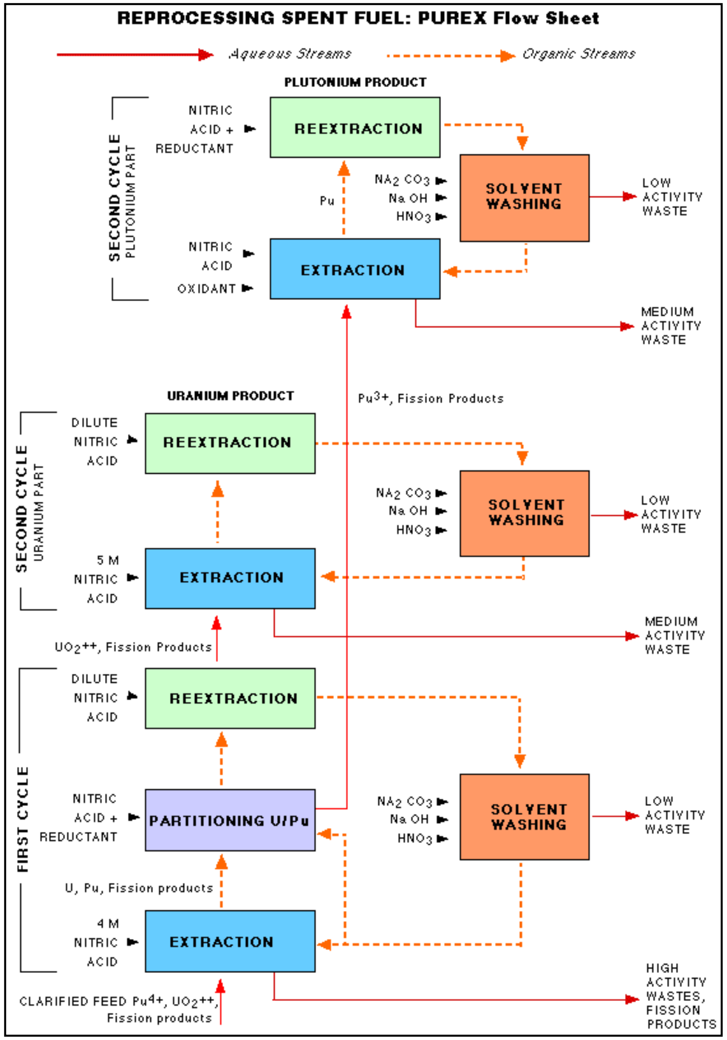


Uranium - REPROCESSING (PUREX)

- Reprocessing separates U and Pu from waste products (and from the fuel assembly cladding) by chopping up the fuel rods and dissolving them in acid to separate the various materials.
- Recovered uranium can be returned to the conversion plant for re-conversion to UF6 and subsequent re-enrichment.
- Reprocessing facilitates recycling and produces an important reduced volume of waste



The Thermal Oxide Reprocessing Plant (THORP) in UK. This commercial facility treats spent fuel from UK and overseas reactors, separating the high-level waste from uranium & plutonium. The smaller black building on the right is the vitrification plant for this waste.



Uranium - RECYCLING

The reactor-grade plutonium can be blended with enriched uranium to produce a mixed oxide (MOX) fuel, in a fuel fabrication plant.

The uranium from reprocessing, which typically contains a slightly higher concentration of U-235 than occurs in nature, can be reused as fuel after conversion and enrichment, if necessary.

The plutonium can be made into mixed oxide (MOX) fuel, in which uranium and plutonium oxides are combined.

MOX fuel fabrication occurs at five facilities in Belgium, France, Germany and UK. There have been many years of experience in this, and the first large-scale plant, MELOX, started operation in France in 1995.

In Europe, many reactors are licensed to load 20-50% of their cores with MOX fuel.

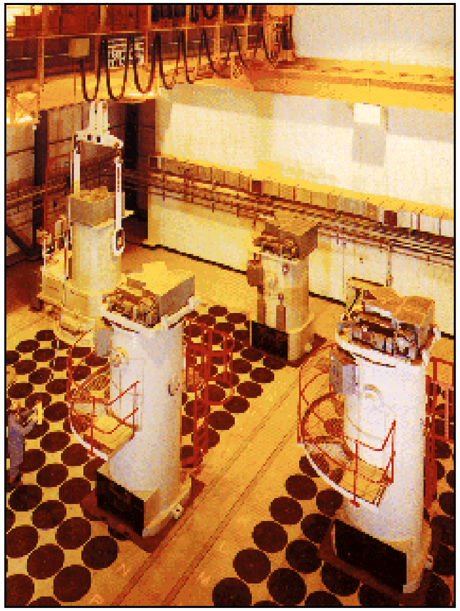
Uranium - REPROCESSED FUEL STORAGE

The remaining 3% of high-level radioactive wastes (some 750 kg per year from a 1000 MWe reactor) can be stored in liquid form and subsequently solidified. Reprocessing of spent fuel occurs at several facilities in UK and France

After reprocessing the liquid high-level waste can be calcined (heated strongly) to produce a dry powder which is incorporated into borosilicate (Pyrex) glass to immobilize the waste. The glass is then poured into stainless steel canisters, each holding 400 kg of glass.

A year's waste from a 1000 MWe reactor is contained in 5 tonnes of such glass, or about 12 canisters 1.3 meters high and 0.4 meters in diameter. These can be readily transported and stored, with appropriate shielding.

Loading silos with canisters containing vitrified high-level waste in UK

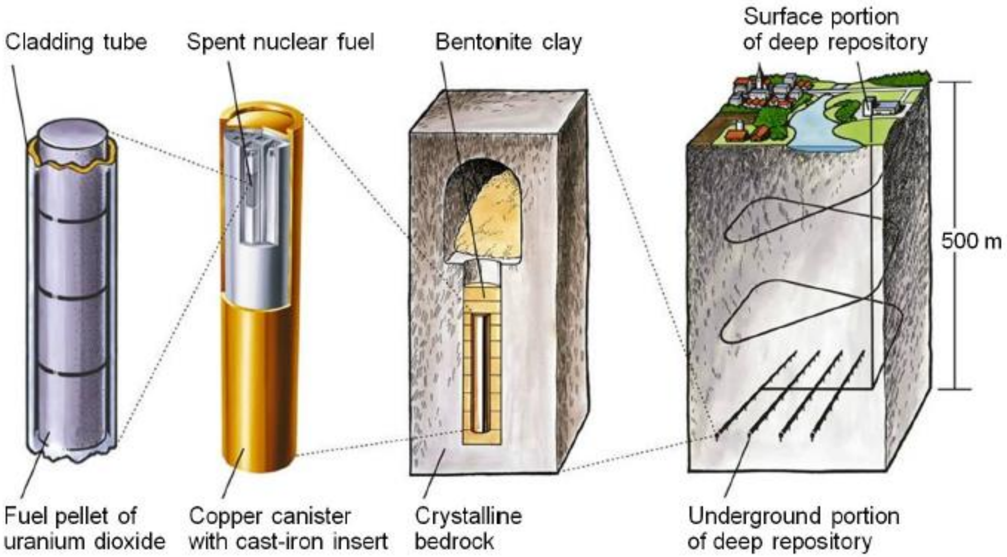


Uranium - FINAL DISPOSAL

The final **disposal of high-level radioactive wastes:** deep geological repositories

The **most widely accepted plans** are to bury vitrified high-level wastes sealed into stainless steel canisters, or to encapsulate spent fuel rods in corrosion resistant metals such as copper or stainless steel, and for these to be buried in stable rock structures deep underground.

Dry, stable geological formations such as granite, volcanic tuff, salt or shale appear suitable.



See case of Finland at : https://www.revistanuclear.es/wp-content/uploads/2023/10/Art-spent-fuel.pdf

2. ND Needs in the Nuclear Fuel Cycle

Fission Reactor

Reactor Core Design

- Criticality, Burnup, Shielding
- Source term prediction (FPs, TRUs)
- Start-up sources

Reactor Core Analysis

- Effective multiplication factor
- Neutron spectrum
- Reactor power distribution
- Reactivity coefficients
- Controls rod worth
- Breading ratio
- Burnup – reactivity swing
- Spent fuel – source term
- Dopped fuel pins

Reactor Shielding

- Neutron and gamma leakage
- Heating
- Damage

Reactor Dynamics

- Reactivity changes

Reactor Safety Analysis

- Heating by decay heat
- Dose rate

Front-end: Nuclear Fuel Cycle

Enrichment, conversion plant, manufacturing

- Criticality
- Dose /radiotoxicity

Back-end: Nuclear Fuel Cycle

Fuel processing

- Criticality safety management (Neutron emission, Decay Heat)
- Dose rate/radiotoxicity

Nuclear Material transport

- Dose rate
- Criticality

Reprocessing

- Criticality: FPs, TRUs

Waste Disposal

- Environmental safety
- Criticality

Decommissioning

Handling remote/no-remote

Activation estimation

- Building
- Reactor structure

Waste disposal options

- Environmental safety

2. ND Needs in the Nuclear Fuel Cycle

Fission Reactor

Reactor Core Design

- Criticality, Burnup, Shielding
- Source term prediction (FPs, TRUs)
- Start-up sources … **(α,n), (γ,n) XSs**

Reactor Core Analysis

- Effective multiplication factor
- Neutron spectrum … **FPNS, elastic, inelastic**
- Reactor power distribution … **238U(n,n’)**
- Reactivity coefficients
- Controls rod worth
- Breading ratio … **238U(n, γ)**
- Burnup – reactivity swing … **FPs(n,γ),…^{151}Sm**
- Spent fuel – source term…
- Dopped fuel pins …**$^{166,\ 167}$Er, ^{155,157}Gd,…**

Reactor Shielding

- Neutron and gamma leakage… **63Cu and 65Cu**
- Heating
- Damage …. **PKA + Damage XSs**

Reactor Dynamics

- **Delay neutron energy, production…6/8 families**

Reactor Safety Analysis

- Heating by decay heat
- Dose rate …**FYs/DD**

- **^{90,92}Zr**
- **^{54,56,57}Fe**
- **^{235,238}U**
- **^{239}Pu(nubar)**
- **^{239}Pu(n,fission and gamma)**
- **^{240}Pu (n,gamma)**
- **^{241}Pu (n,fission)**
- **…**
- **TSL H in H2O**
- **…**
- **^{237}Np**
- **^{241,242m,243}Am**
- **$^{242,244,…}$Cm**
- **…**

+ uncertainties

Questions ?

References

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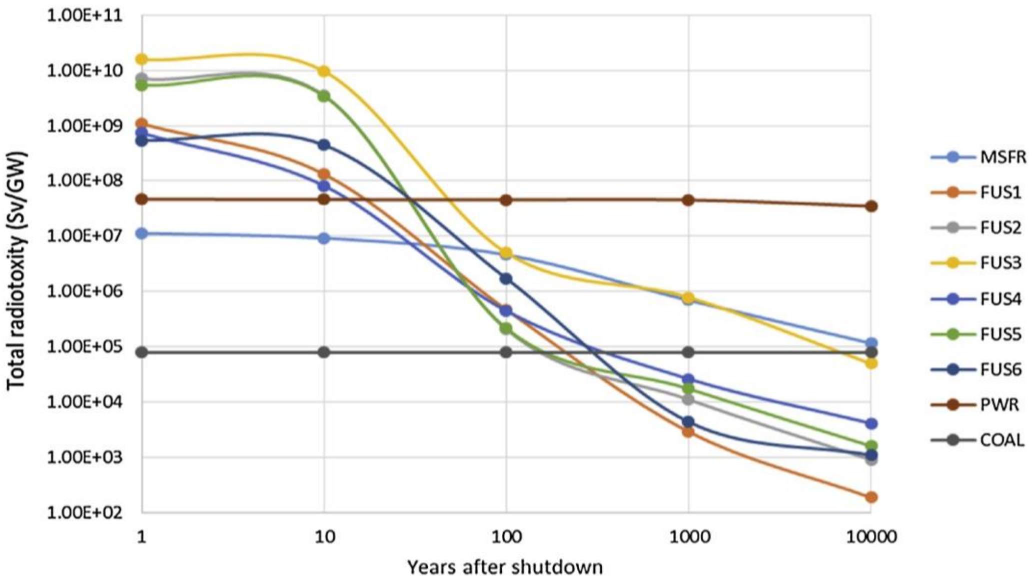
Back-up slides ?

Waste Management

An exercise of comparison of radioactivity, radiotoxicity, radioactive waste in fusion power plants, advanced and conventional fission power plants

Figure. A comparison of total radiotoxicity of PWR, Fusion, and GEN IV reactors. Radioactivity from coal-fired plant ashes are included too.

Note: All results are normalized to a 1000 MWe power electricity production.



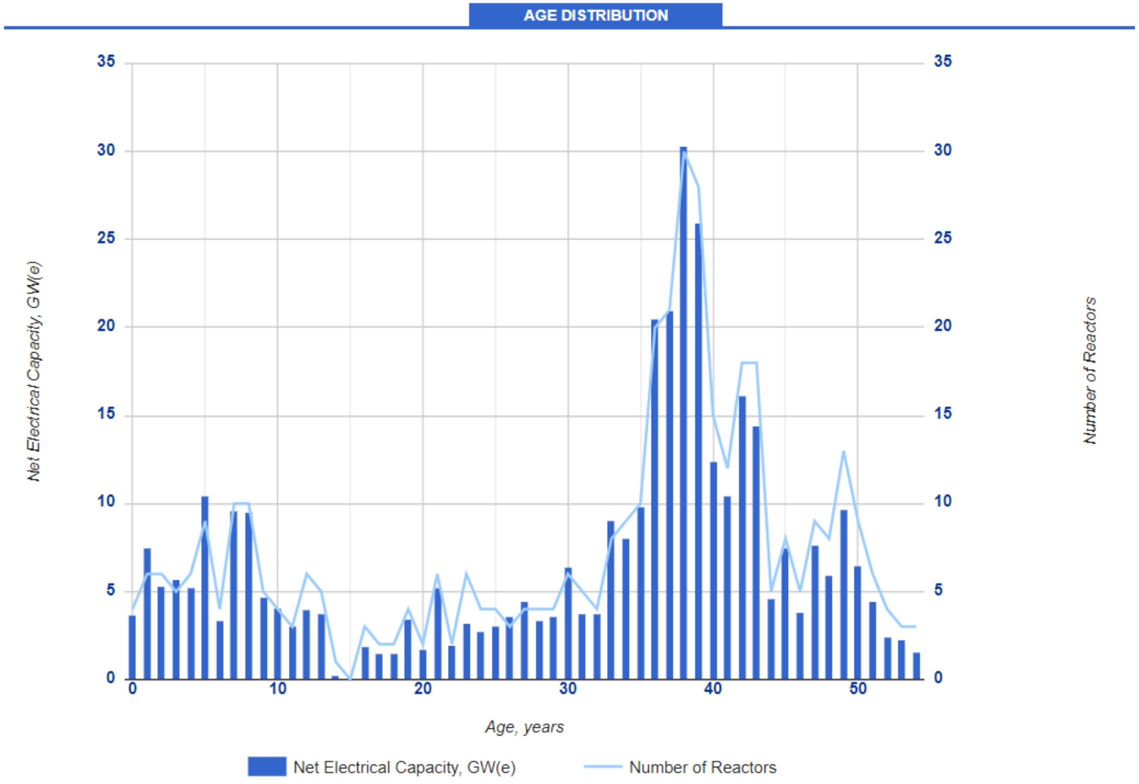
FUS1 = V alloy, Li_2O
FUS2 = RAFM Steel, PbLi
FUS3 = RAFM Steel, Li_4SiO_4
FUS4 = SiC composite, PbLi
FUS5 = RAFM Steel, PbLi
FUS6 = SiC composite, Li_4SiO_4

- Low-activation materials must be used to avoid long-lived waste and a too high decay heat (e.g. RAFM (reduced activation ferritic martensitic) steels)
- Many common alloying elements (Ni, Mo, Nb, etc.) need to be avoided

Source: M. Zucchetti, Fusion Engineering and Design 136 (2018) 1529-1533.

Current Status of the Existing NPP: Average age

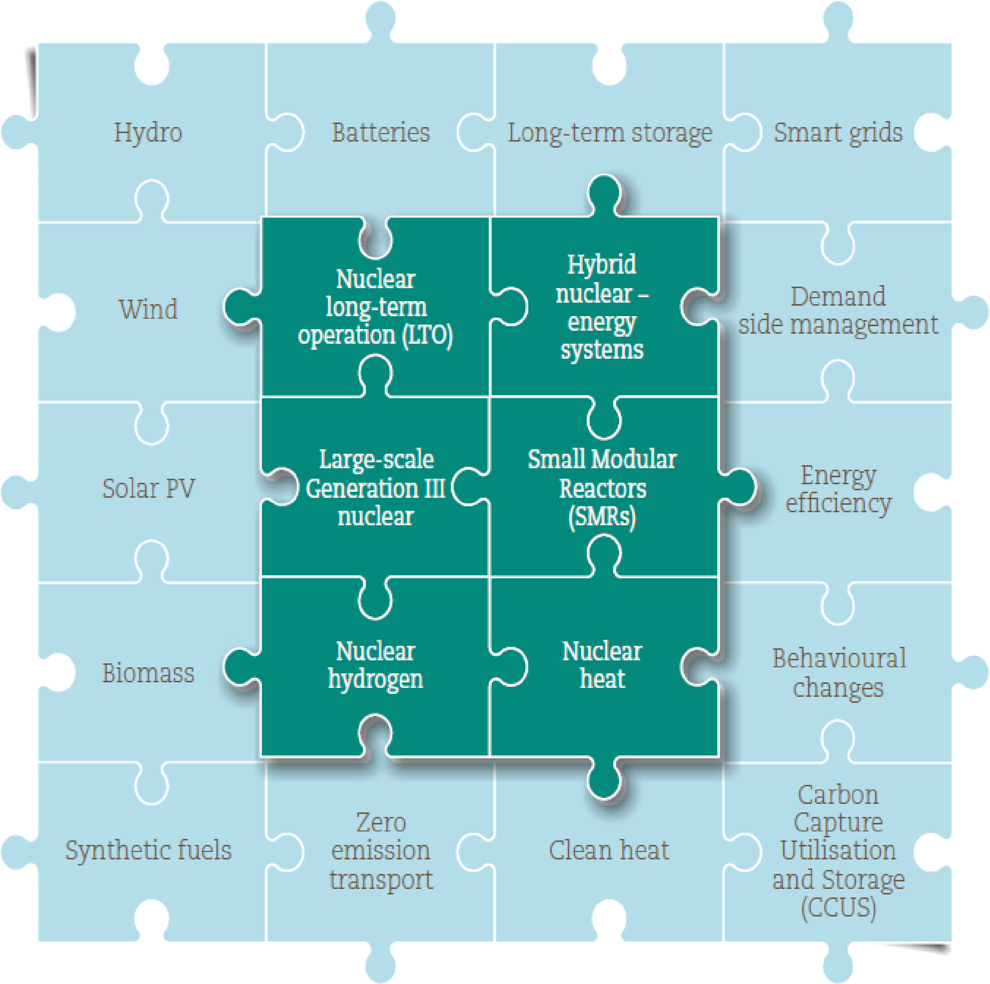
- Average age of the global nuclear fleet: **32 years**
- More than 100 plants have already operated more than **40 years**
- 30% of global nuclear capacity is already **in long term operation (LTO)**, mostly in the U.S. and Europe
- Globally, **most reactors will operate 60 years,** according to current long term operation plans



Source: IAEA PRIS database https://pris.iaea.org/pris/home.aspx
(Last update on 2023-10-10)

A decarbonisation pathway…

- A **decarbonisation pathway** requires the evaluation of several dimensions simultaneously:
  - ○ Technology
  - ○ Economics
  - ○ Environment
  - ○ Society
- Each scenario has associated **uncertainties and technology risks** that could increase the total costs
- **Nuclear fission technologies and applications** play a role in future low-carbon energy systems



Source: [Meeting Climate Change Targets: The Role of Nuclear Energy](), OECD/NEA #7628, 2022