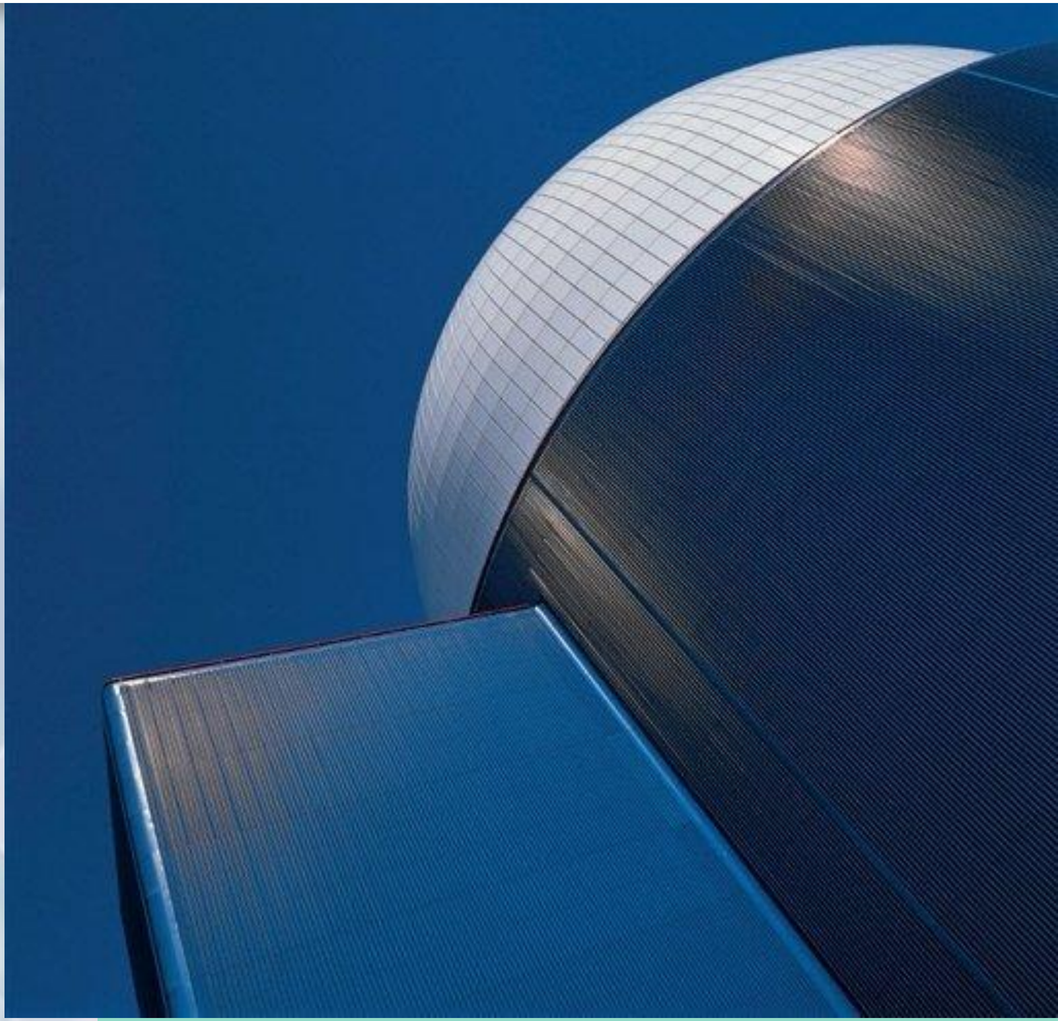
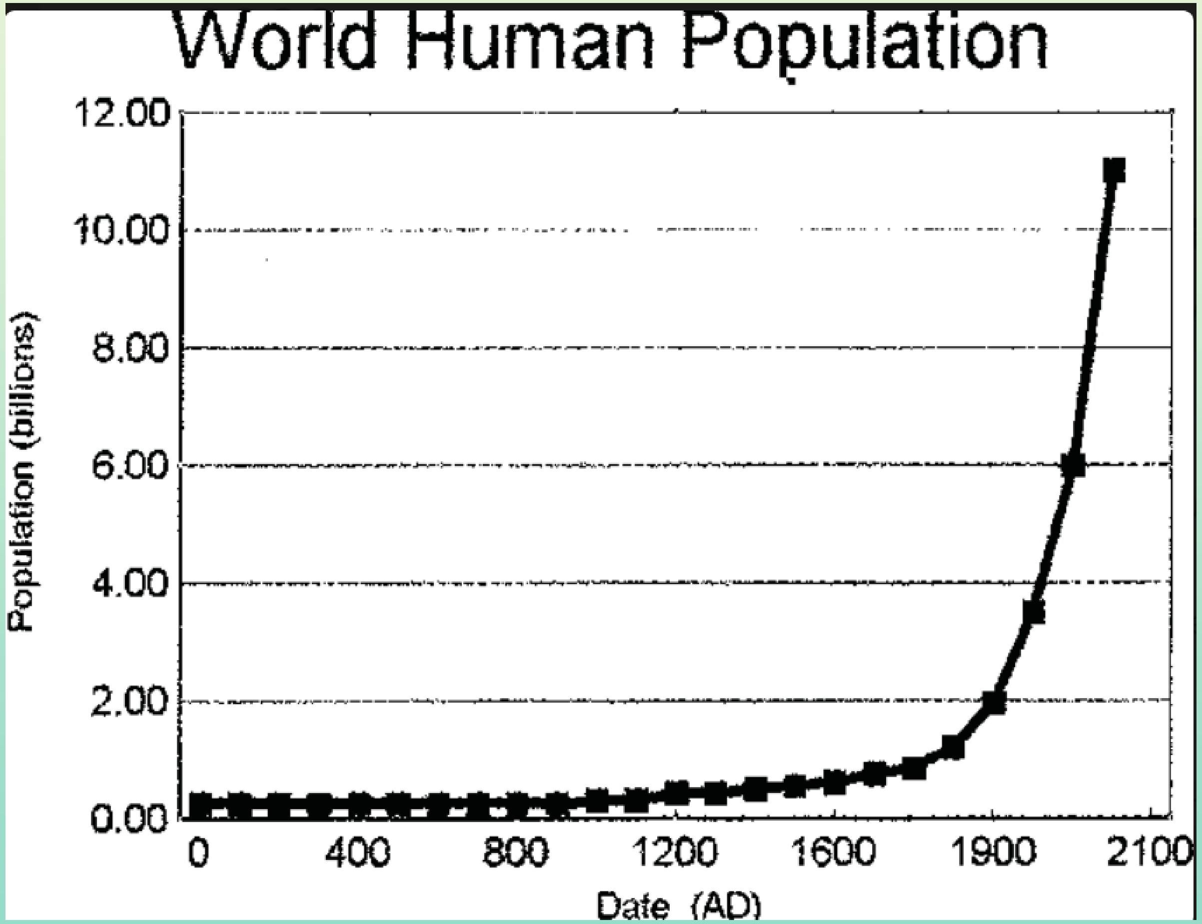
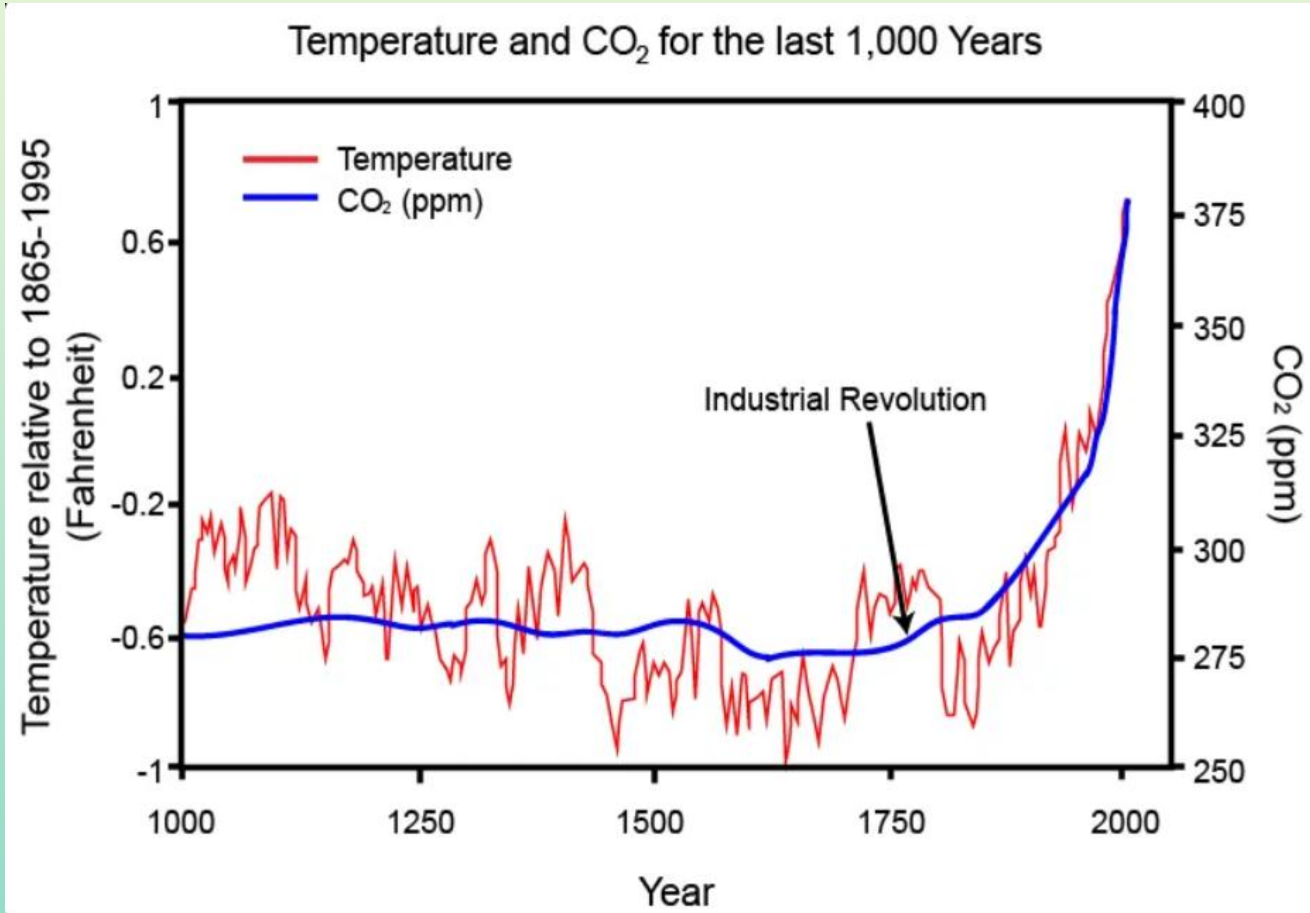
Kjernekraft – Bærekraftig energi i uoverskuelig tid



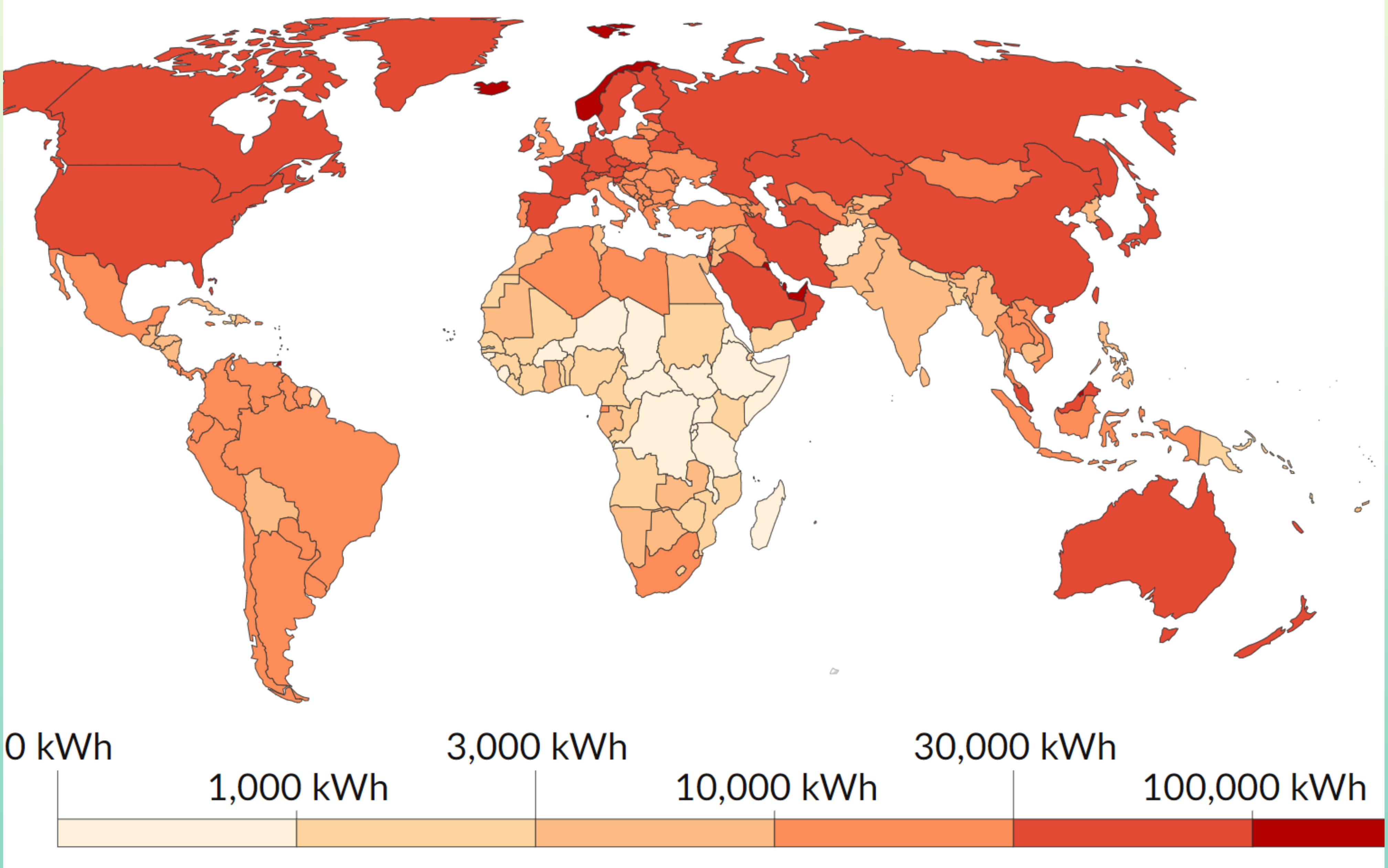
- **Litt vitenskapshistorie / tidspespektiv**
- **Dagens kjernekraftreaktorer.**
- **Hva kan være brensel i en atomreaktor?**
- **Nye typer reaktorer**
- **Verdens resurser i et tidsperspektiv**

Befolkning / Forurensning / Klima

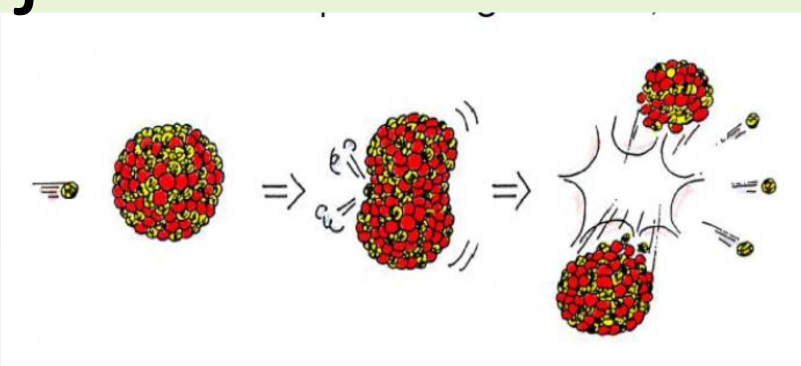




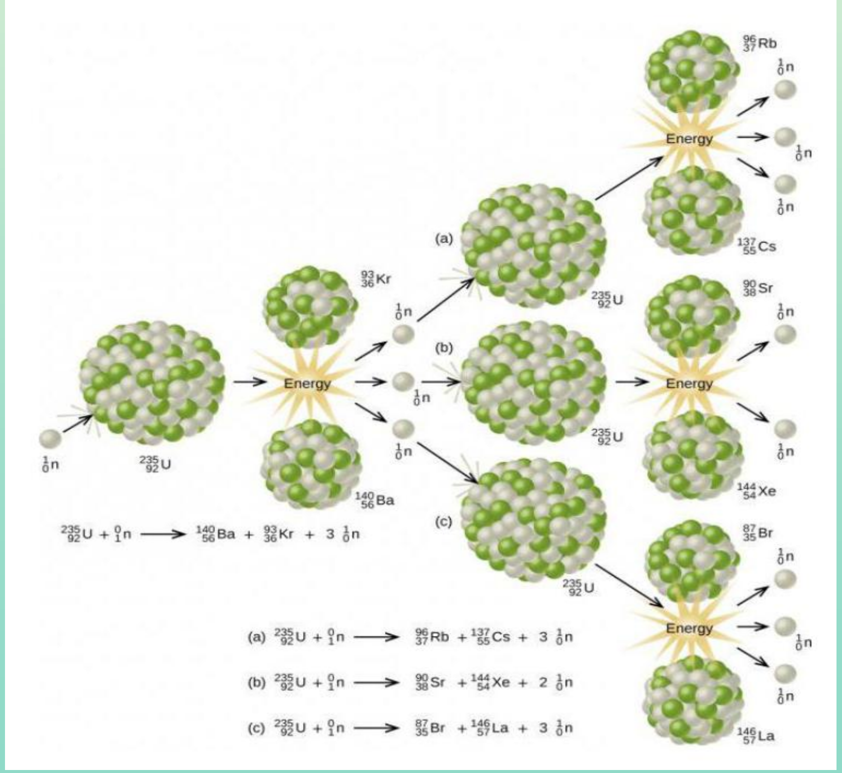
Energiforbruk per person



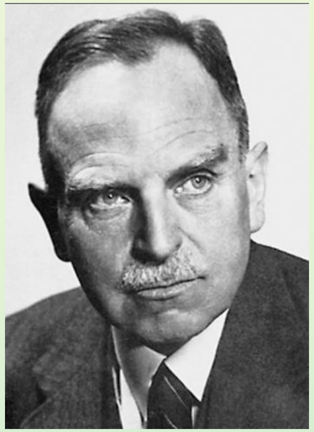
1938 : Fisjon



1933/1942 : Kjedereaksjon

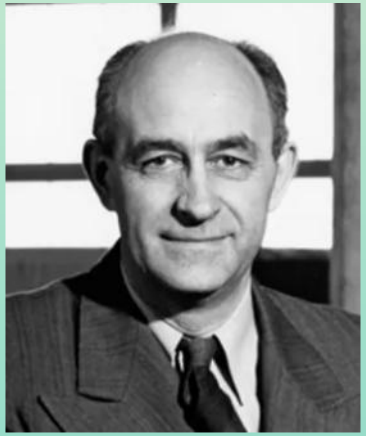


Lise Meitner
(1878 - 1968)



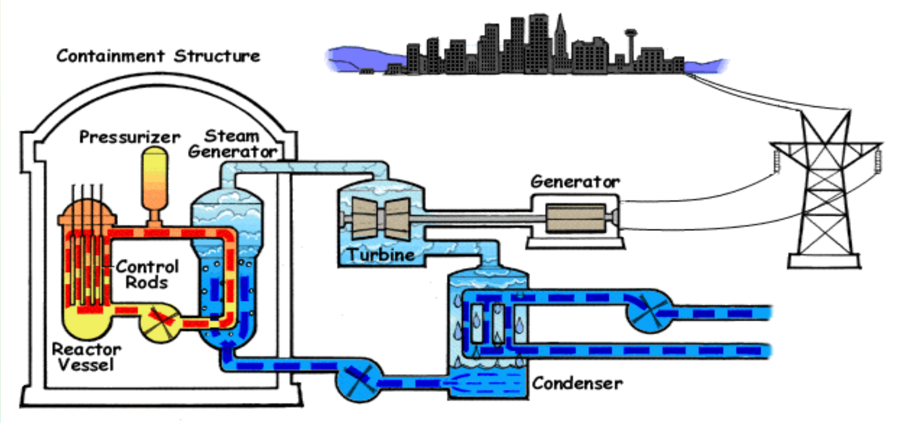
Otto Hahn
(1879 - 1968)

Leó Szilárd
(1898 – 1964)



Enrico Fermi
(1901 - 1954)

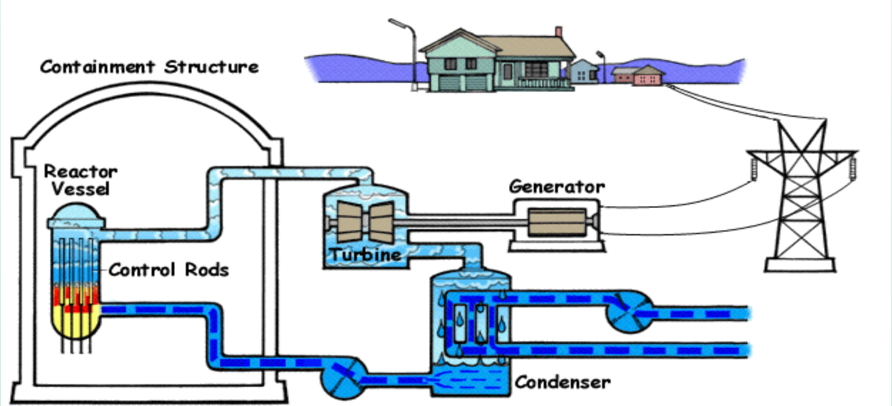
Mye brukte reaktortyper av dagen 440 kommersielle reaktorer.



- TRYKKVANNSREAKTOR

  Pressurized Water Reactor (PWR)

  300 stk

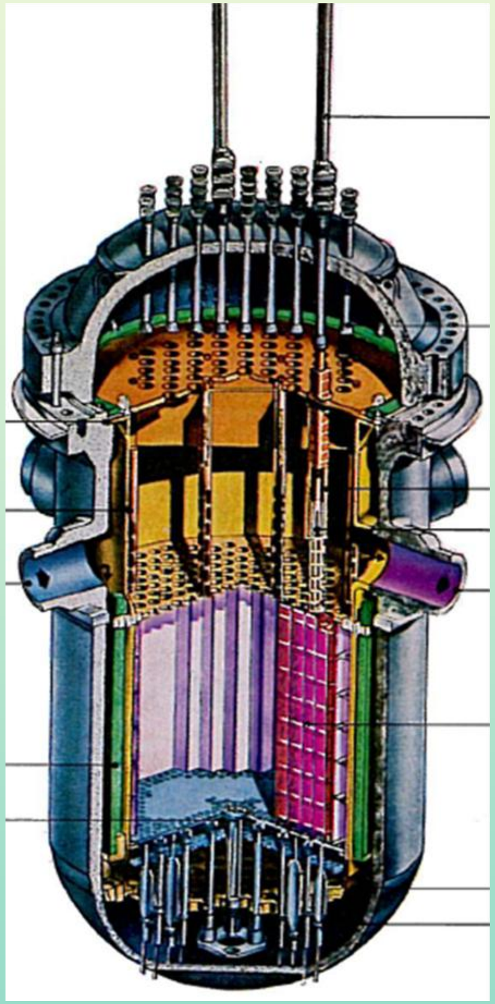


- KOKVANNSREAKTOR

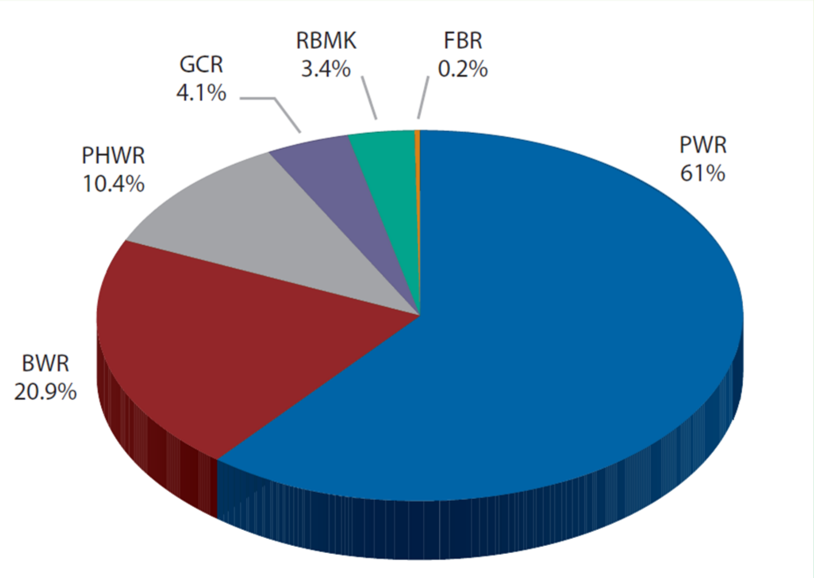
  Boiling Water Reactor (BWR)

  78 stk

PWR

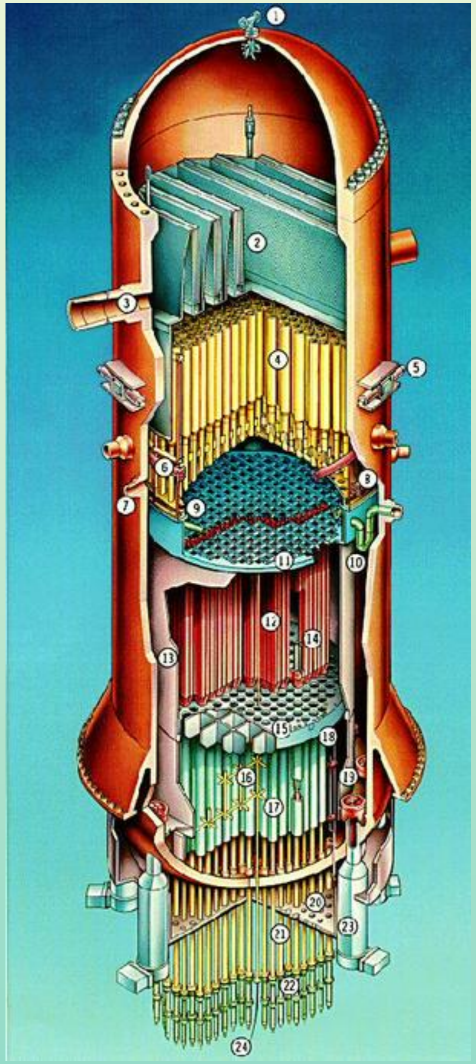


80-100
tonn brensel



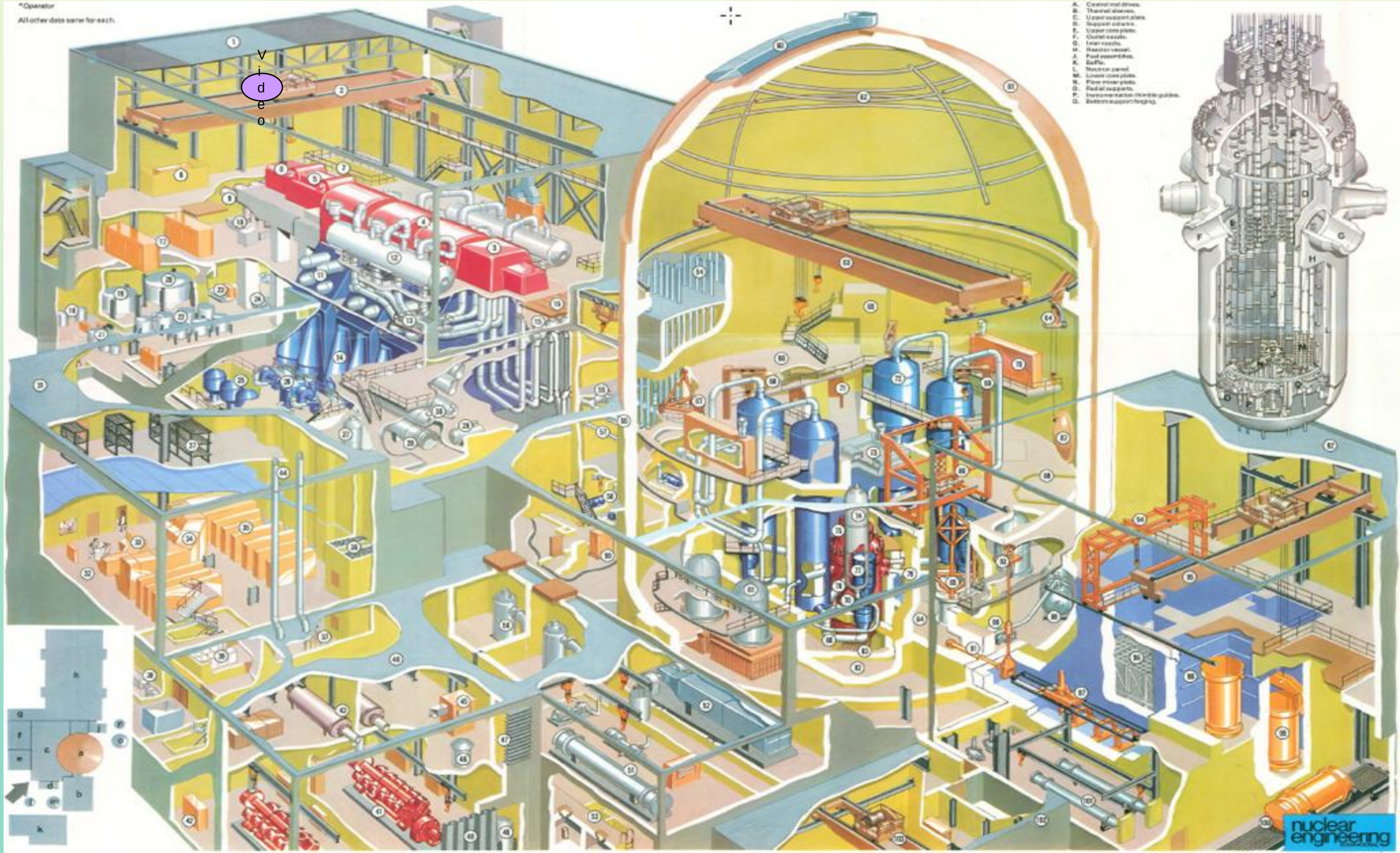
- 🟥 Boiling water reactors (BWR)
- ⬜ Pressurised heavy water reactors (PHWR)
- 🟪 Gas-cooled reactors (GCR)
- 🟩 *Reaktor Bolshoi Moshchnosti Kanalnye* (RBMK)
- 🟧 Fast breeder reactors (FBR)

BWR



120-140
tonn brensel

Wolf Creek Generating Station - 3000 MWt ~1000 MWe

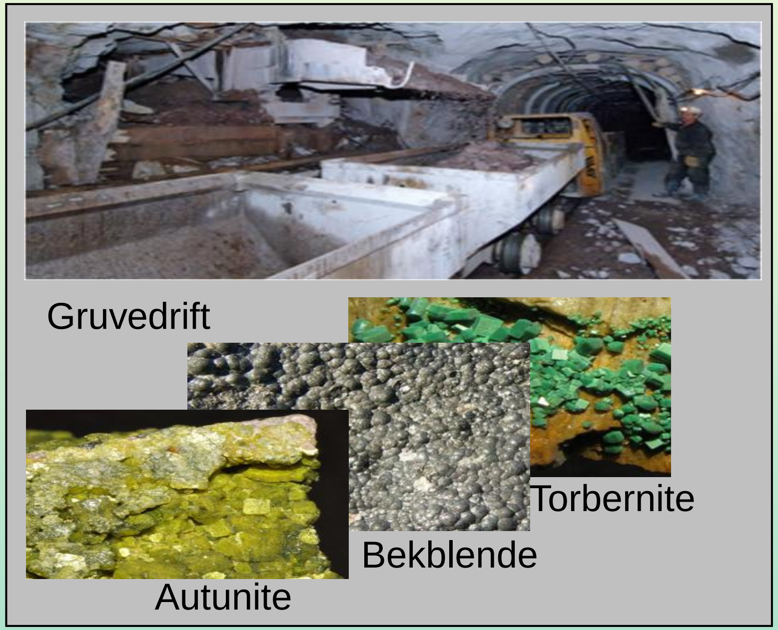


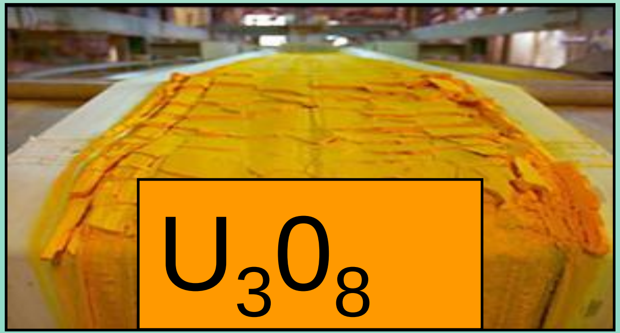
Video

Fremstilling av uranbrensel

Naturlig
uran

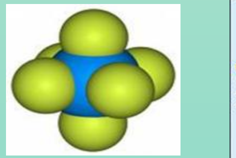
0,7% U-235
99,3% U-238

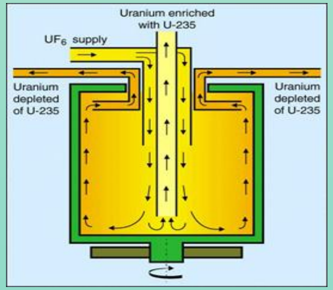


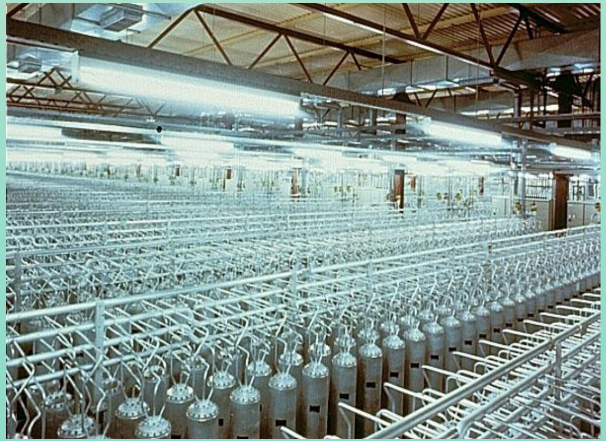


U_3O_8

Anrikning
med sentrifuger







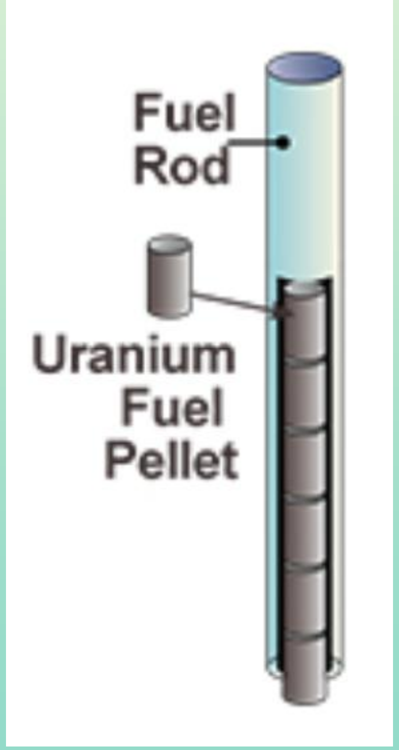
UF_6

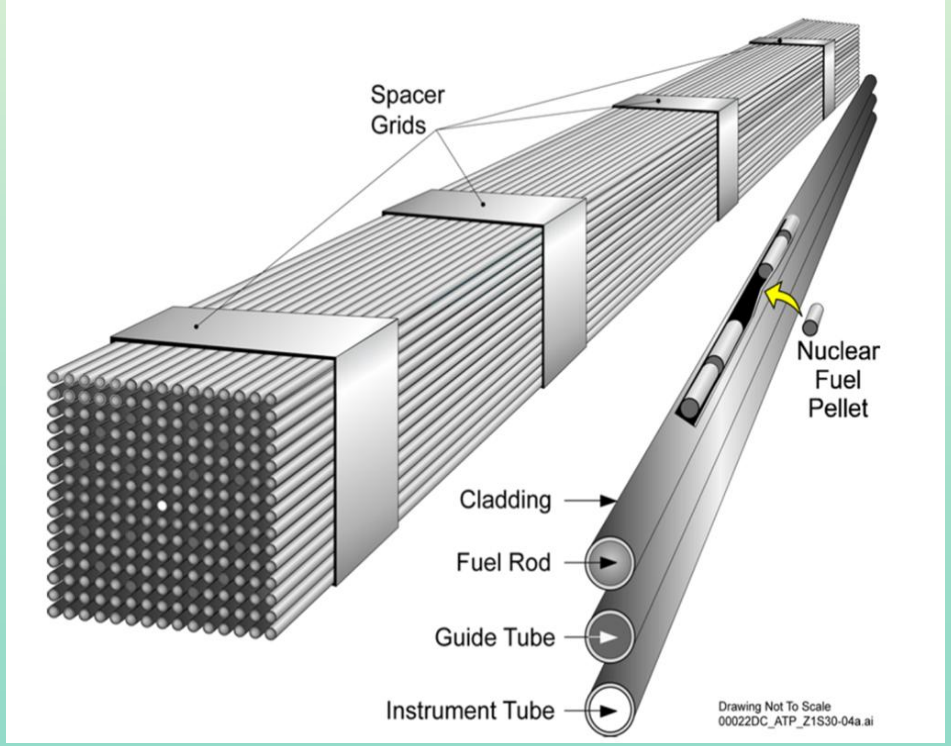
Uran i reaktorbrensel

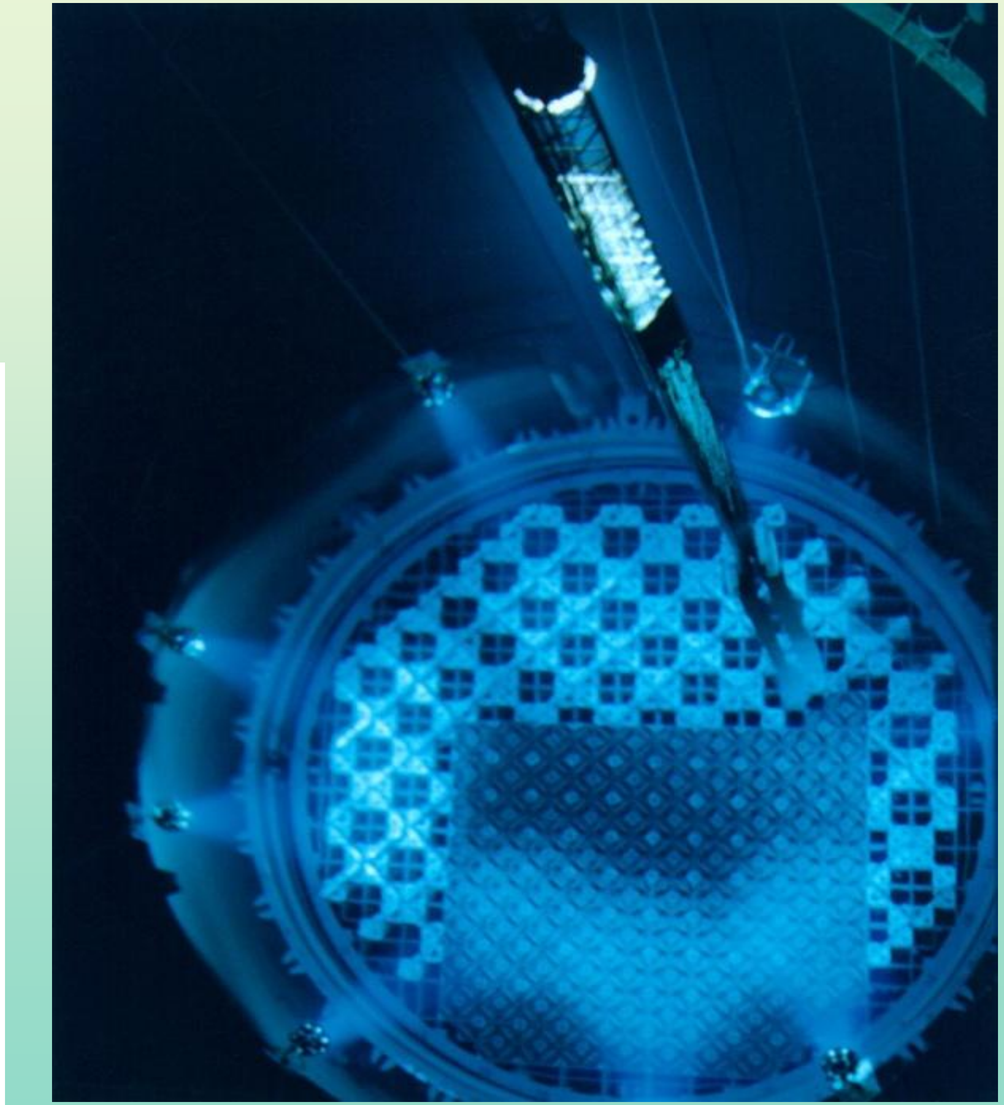
4,5% U-235
95.5% U-238

UO_2

Reaktorbrensel







Energitetthet

KULL

7,5 tonn

OLJE

34 fat á 200 liter
(5,5 tonn)

VED

16 favner
(13 tonn)

URAN

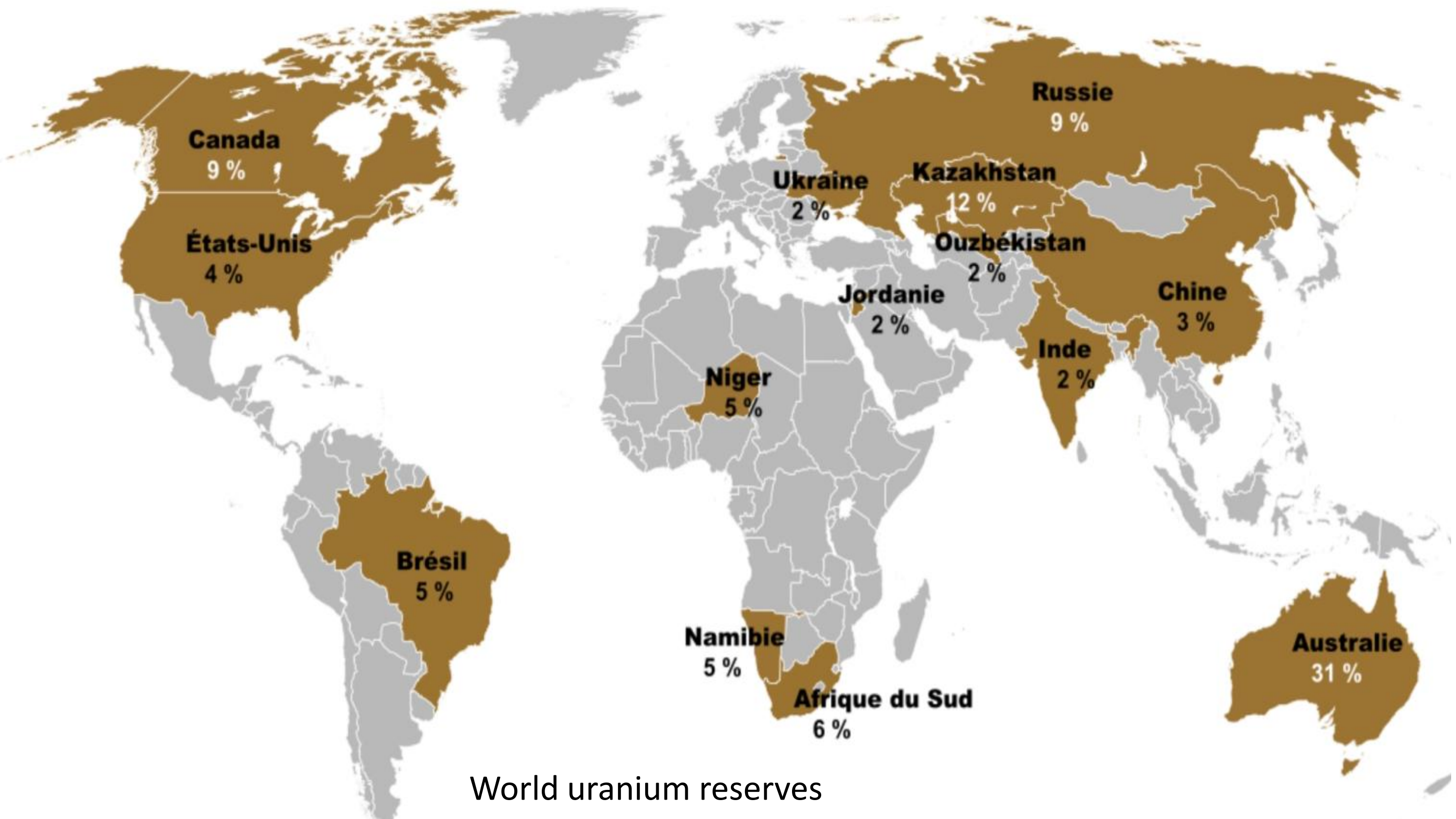
60 gram

FORBRUK AV ELEKTRISK ENERGI
TIL EN BOLIG I ET ÅR
24 000 kWh

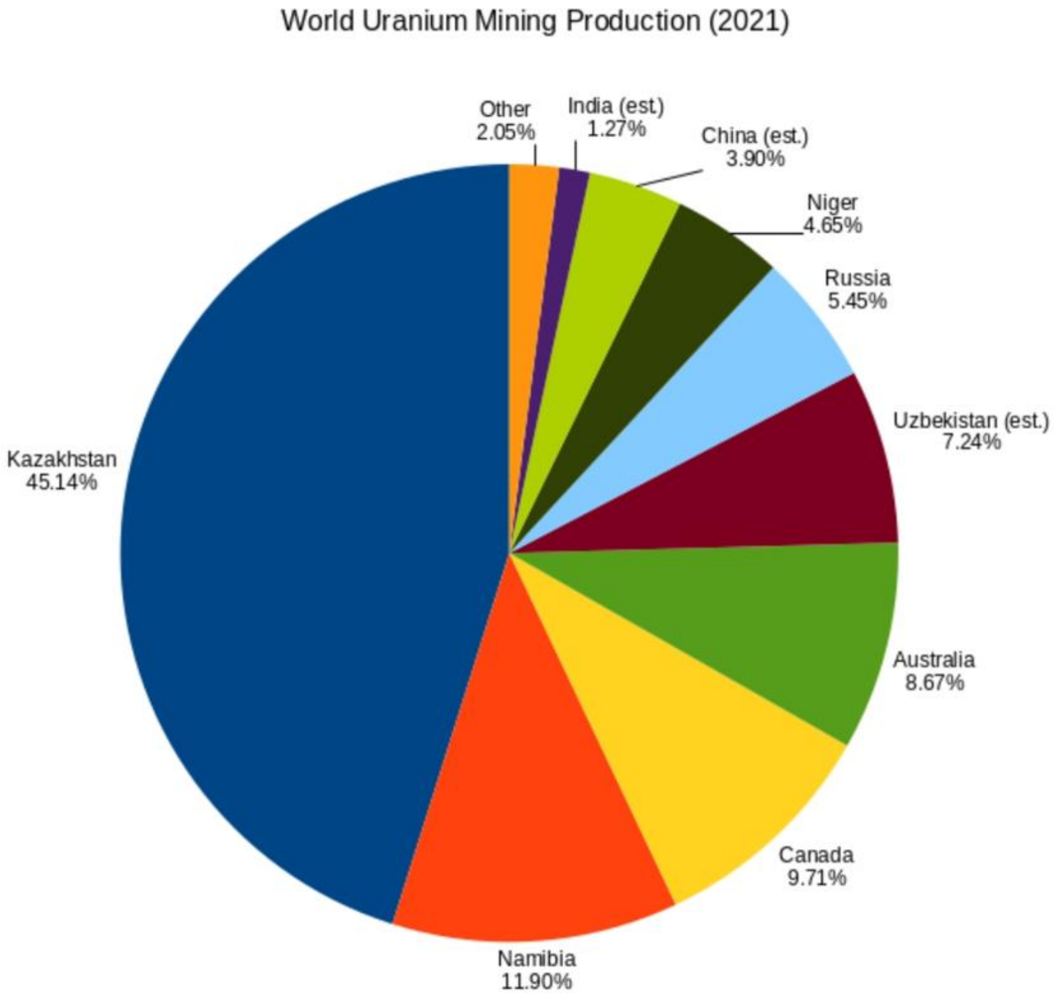
Verdens kjente landbaserte uranforekomster : ca 8 000 000 tonn

Årlig forbruk : ca 65 000 tonn (440 reaktorer)

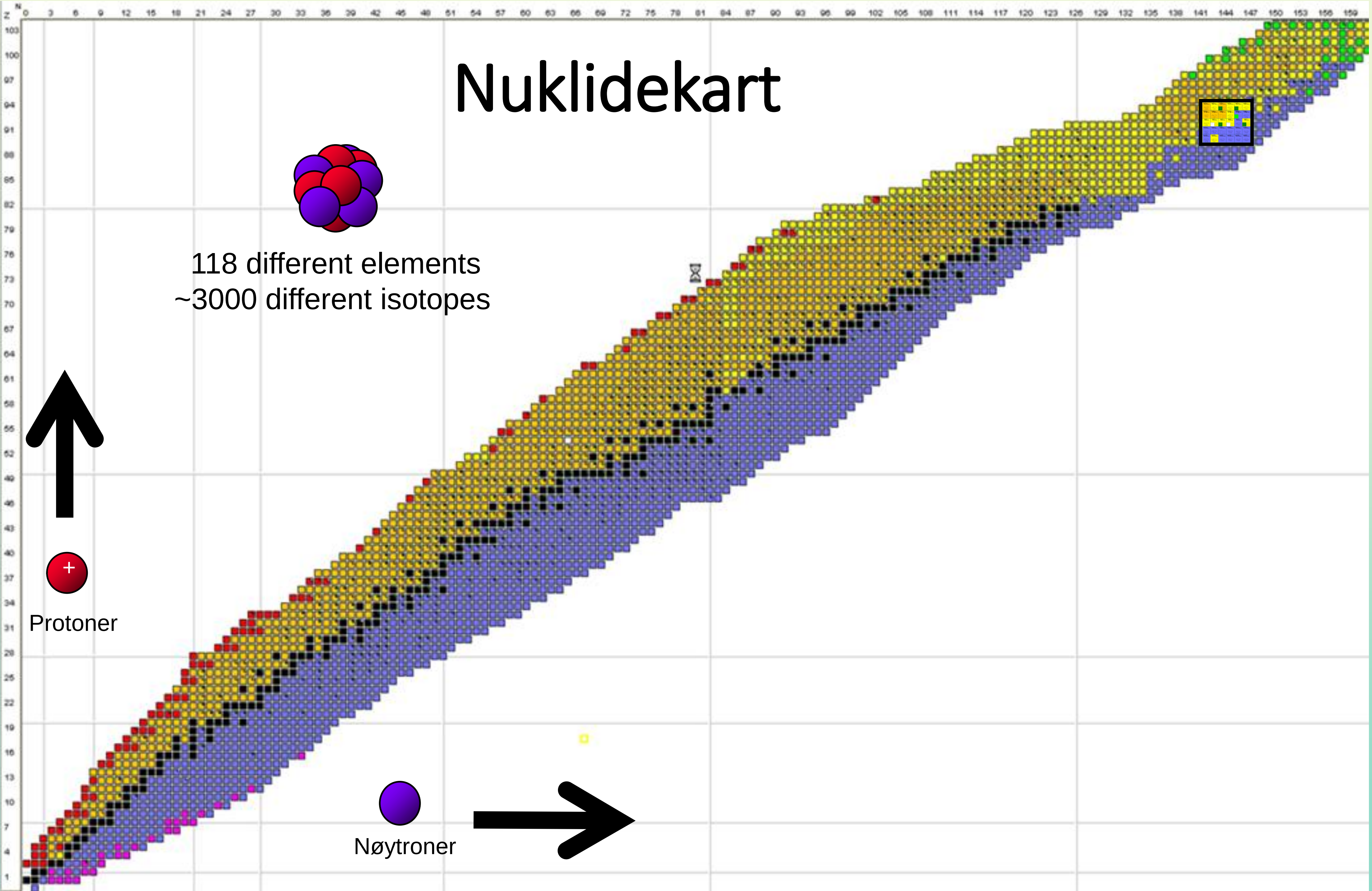
Med dagens forbruk varer dette i ca 120 år



World uranium reserves

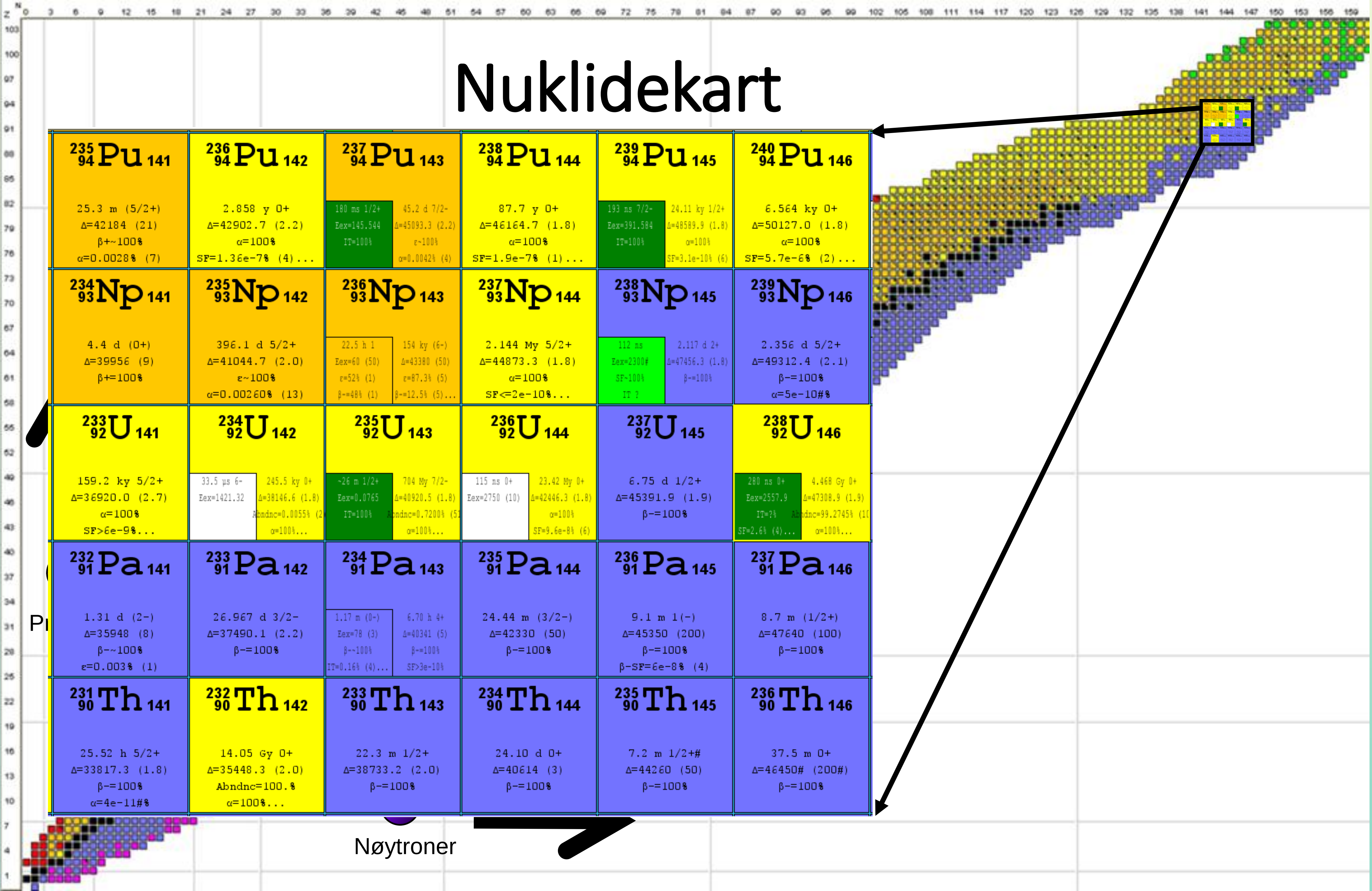


Nuklidekart



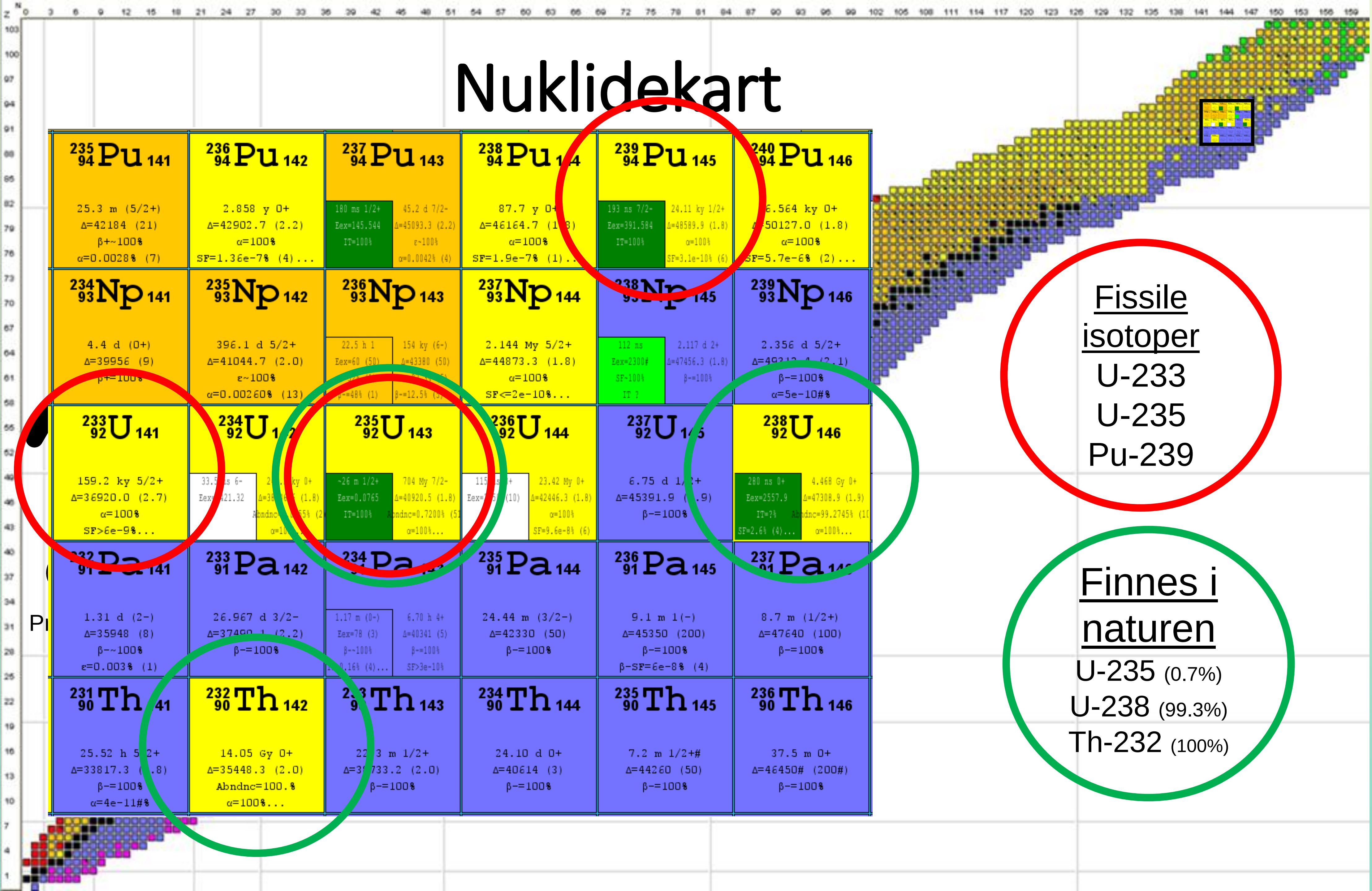
118 different elements
~3000 different isotopes

Nuklidekart



$^{235}_{94}\mathrm{Pu}_{141}$ 25.3 m (5/2+) Δ=42184 (21) β+~100% α=0.0028% (7)	$^{236}_{94}\mathrm{Pu}_{142}$ 2.858 y 0+ Δ=42902.7 (2.2) α=100% SF=1.36e-7% (4)...	$^{237}_{94}\mathrm{Pu}_{143}$ 180 ms 1/2+ Eex=145.544 IT=100% 45.2 d 7/2- Δ=45093.3 (2.2) ε~100% α=0.0042% (4)	$^{238}_{94}\mathrm{Pu}_{144}$ 87.7 y 0+ Δ=46164.7 (1.8) α=100% SF=1.9e-7% (1)...	$^{239}_{94}\mathrm{Pu}_{145}$ 193 ns 7/2- Eex=391.584 IT=100% 24.11 ky 1/2+ Δ=48589.9 (1.8) α=100% SF=3.1e-10% (6)	$^{240}_{94}\mathrm{Pu}_{146}$ 6.564 ky 0+ Δ=50127.0 (1.8) α=100% SF=5.7e-6% (2)...
$^{234}_{93}\mathrm{Np}_{141}$ 4.4 d (0+) Δ=39956 (9) β+=100%	$^{235}_{93}\mathrm{Np}_{142}$ 396.1 d 5/2+ Δ=41044.7 (2.0) ε~100% α=0.00260% (13)	$^{236}_{93}\mathrm{Np}_{143}$ 22.5 h 1 Eex=60 (50) ε=52% (1) β-=48% (1) 154 ky (6-) Δ=43380 (50) ε=87.3% (5) β-=12.5% (5)...	$^{237}_{93}\mathrm{Np}_{144}$ 2.144 My 5/2+ Δ=44873.3 (1.8) α=100% SF<=2e-10%...	$^{238}_{93}\mathrm{Np}_{145}$ 112 ns Eex=2300# SF~100% IT ? 2.117 d 2+ Δ=47456.3 (1.8) β-=100%	$^{239}_{93}\mathrm{Np}_{146}$ 2.356 d 5/2+ Δ=49312.4 (2.1) β-=100% α=5e-10#%
$^{233}_{92}\mathrm{U}_{141}$ 159.2 ky 5/2+ Δ=36920.0 (2.7) α=100% SF>6e-9%...	$^{234}_{92}\mathrm{U}_{142}$ 33.5 μs 6- Eex=1421.32 245.5 ky 0+ Δ=38146.6 (1.8) Abndnc=0.0055% (2 α=100%...	$^{235}_{92}\mathrm{U}_{143}$ ~26 m 1/2+ Eex=0.0765 IT=100% 704 My 7/2- Δ=40920.5 (1.8) Abndnc=0.7200% (51 α=100%...	$^{236}_{92}\mathrm{U}_{144}$ 115 ns 0+ Eex=2750 (10) 23.42 My 0+ Δ=42446.3 (1.8) α=100% SF=9.6e-8% (6)	$^{237}_{92}\mathrm{U}_{145}$ 6.75 d 1/2+ Δ=45391.9 (1.9) β-=100%	$^{238}_{92}\mathrm{U}_{146}$ 280 ns 0+ Eex=2557.9 IT=?% SF=2.6% (4)... 4.468 Gy 0+ Δ=47308.9 (1.9) Abndnc=99.2745% (1(α=100%...
$^{232}_{91}\mathrm{Pa}_{141}$ 1.31 d (2-) Δ=35948 (8) β-~100% ε=0.003% (1)	$^{233}_{91}\mathrm{Pa}_{142}$ 26.967 d 3/2- Δ=37490.1 (2.2) β-=100%	$^{234}_{91}\mathrm{Pa}_{143}$ 1.17 m (0-) Eex=78 (3) β-~100% IT=0.16% (4)... 6.70 h 4+ Δ=40341 (5) β-=100% SF>3e-10%	$^{235}_{91}\mathrm{Pa}_{144}$ 24.44 m (3/2-) Δ=42330 (50) β-=100%	$^{236}_{91}\mathrm{Pa}_{145}$ 9.1 m 1(-) Δ=45350 (200) β-=100% β-SF=6e-8% (4)	$^{237}_{91}\mathrm{Pa}_{146}$ 8.7 m (1/2+) Δ=47640 (100) β-=100%
$^{231}_{90}\mathrm{Th}_{141}$ 25.52 h 5/2+ Δ=33817.3 (1.8) β-=100% α=4e-11#%	$^{232}_{90}\mathrm{Th}_{142}$ 14.05 Gy 0+ Δ=35448.3 (2.0) Abndnc=100.% α=100%...	$^{233}_{90}\mathrm{Th}_{143}$ 22.3 m 1/2+ Δ=38733.2 (2.0) β-=100%	$^{234}_{90}\mathrm{Th}_{144}$ 24.10 d 0+ Δ=40614 (3) β-=100%	$^{235}_{90}\mathrm{Th}_{145}$ 7.2 m 1/2+# Δ=44260 (50) β-=100%	$^{236}_{90}\mathrm{Th}_{146}$ 37.5 m 0+ Δ=46450# (200#) β-=100%

Nuklidekart



$^{235}_{94}\mathrm{Pu}$ 141 25.3 m (5/2+) Δ=42184 (21) β+~100% α=0.0028% (7)	$^{236}_{94}\mathrm{Pu}$ 142 2.858 y 0+ Δ=42902.7 (2.2) α=100% SF=1.36e-7% (4)...	$^{237}_{94}\mathrm{Pu}$ 143 180 ms 1/2+ Eex=145.544 IT=100% 45.2 d 7/2- Δ=45093.3 (2.2) ε~100% α=0.0042% (4)	$^{238}_{94}\mathrm{Pu}$ 144 87.7 y 0+ Δ=46164.7 (1.8) α=100% SF=1.9e-7% (1)...	$^{239}_{94}\mathrm{Pu}$ 145 193 ns 7/2- Eex=391.584 IT=100% 24.11 ky 1/2+ Δ=48589.9 (1.8) α=100% SF=3.1e-10% (6)	$^{240}_{94}\mathrm{Pu}$ 146 6.564 ky 0+ Δ=50127.0 (1.8) α=100% SF=5.7e-6% (2)...
$^{234}_{93}\mathrm{Np}$ 141 4.4 d (0+) Δ=39956 (9) β+=100%	$^{235}_{93}\mathrm{Np}$ 142 396.1 d 5/2+ Δ=41044.7 (2.0) ε~100% α=0.00260% (13)	$^{236}_{93}\mathrm{Np}$ 143 22.5 h 1 Eex=60 (50) [illegible] β-=48% (1) 154 ky (6-) Δ=43380 (50) [illegible] β-=12.5% (5)	$^{237}_{93}\mathrm{Np}$ 144 2.144 My 5/2+ Δ=44873.3 (1.8) α=100% SF<=2e-10%...	$^{238}_{93}\mathrm{Np}$ 145 112 ns Eex=2300# SF~100% IT ? 2.117 d 2+ Δ=47456.3 (1.8) β-=100%	$^{239}_{93}\mathrm{Np}$ 146 2.356 d 5/2+ Δ=49312.4 (2.1) β-=100% α=5e-10#%
$^{233}_{92}\mathrm{U}$ 141 159.2 ky 5/2+ Δ=36920.0 (2.7) α=100% SF>6e-9%...	$^{234}_{92}\mathrm{U}$ 142 33.5 [illegible]s 6- Eex=1421.32 2[illegible] ky 0+ Δ=38[illegible] (1.8) Abndnc=[illegible]55% (2 α=10[illegible]	$^{235}_{92}\mathrm{U}$ 143 ~26 m 1/2+ Eex=0.0765 IT=100% 704 My 7/2- Δ=40920.5 (1.8) Abndnc=0.7200% (51 α=100%...	$^{236}_{92}\mathrm{U}$ 144 115 [illegible]s [illegible]+ Eex=[illegible] (10) 23.42 My 0+ Δ=42446.3 (1.8) α=100% SF=9.6e-8% (6)	$^{237}_{92}\mathrm{U}$ 145 6.75 d 1/2+ Δ=45391.9 ([illegible].9) β-=100%	$^{238}_{92}\mathrm{U}$ 146 280 ns 0+ Eex=2557.9 IT=?% SF=2.6% (4)... 4.468 Gy 0+ Δ=47308.9 (1.9) Abndnc=99.2745% (10 α=100%...
$^{232}_{91}\mathrm{Pa}$ 141 1.31 d (2-) Δ=35948 (8) β-~100% ε=0.003% (1)	$^{233}_{91}\mathrm{Pa}$ 142 26.967 d 3/2- Δ=37490.1 (2.2) β-=100%	$^{234}_{91}\mathrm{Pa}$ 143 1.17 m (0-) Eex=78 (3) β-~100% I[illegible]0.16% (4)... 6.70 h 4+ Δ=40341 (5) β-=100% SF>3e-10%	$^{235}_{91}\mathrm{Pa}$ 144 24.44 m (3/2-) Δ=42330 (50) β-=100%	$^{236}_{91}\mathrm{Pa}$ 145 9.1 m 1(-) Δ=45350 (200) β-=100% β-SF=6e-8% (4)	$^{237}_{91}\mathrm{Pa}$ 146 8.7 m (1/2+) Δ=47640 (100) β-=100%
$^{231}_{90}\mathrm{Th}$ 141 25.52 h 5/2+ Δ=33817.3 ([illegible].8) β-=100% α=4e-11#%	$^{232}_{90}\mathrm{Th}$ 142 14.05 Gy 0+ Δ=35448.3 (2.0) Abndnc=100.% α=100%...	$^{233}_{90}\mathrm{Th}$ 143 22.3 m 1/2+ Δ=38733.2 (2.0) β-=100%	$^{234}_{90}\mathrm{Th}$ 144 24.10 d 0+ Δ=40614 (3) β-=100%	$^{235}_{90}\mathrm{Th}$ 145 7.2 m 1/2+# Δ=44260 (50) β-=100%	$^{236}_{90}\mathrm{Th}$ 146 37.5 m 0+ Δ=46450# (200#) β-=100%

<u>Fissile isotoper</u>

U-233

U-235

Pu-239

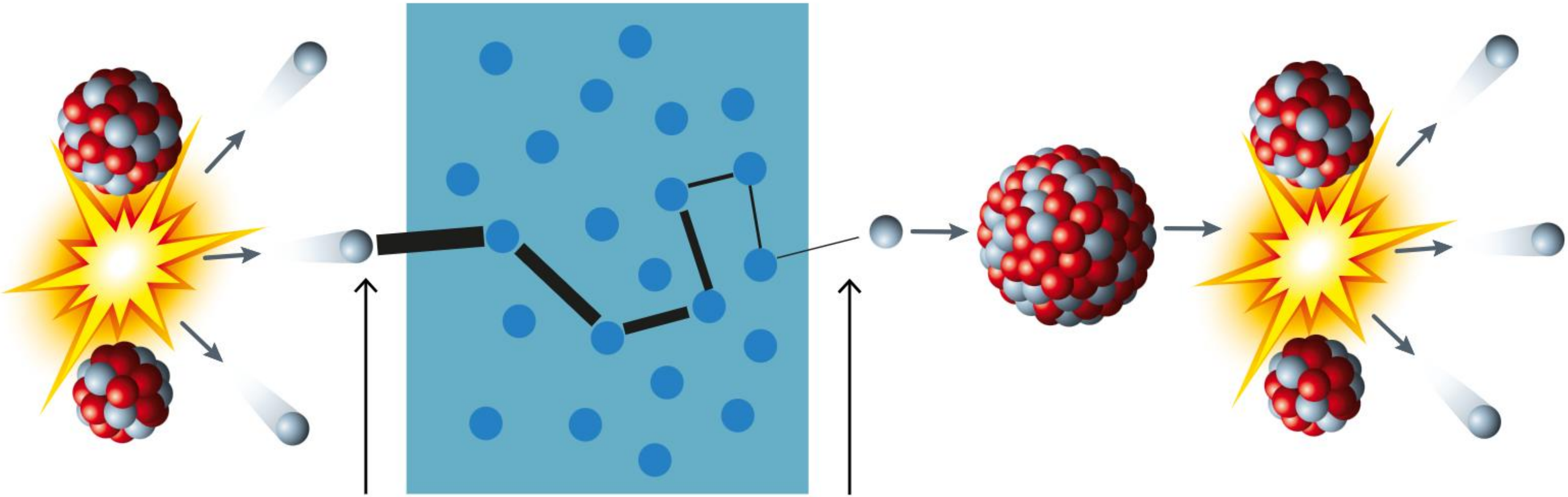
<u>Finnes i naturen</u>

U-235 (0.7%)

U-238 (99.3%)

Th-232 (100%)

Termisk reaktor

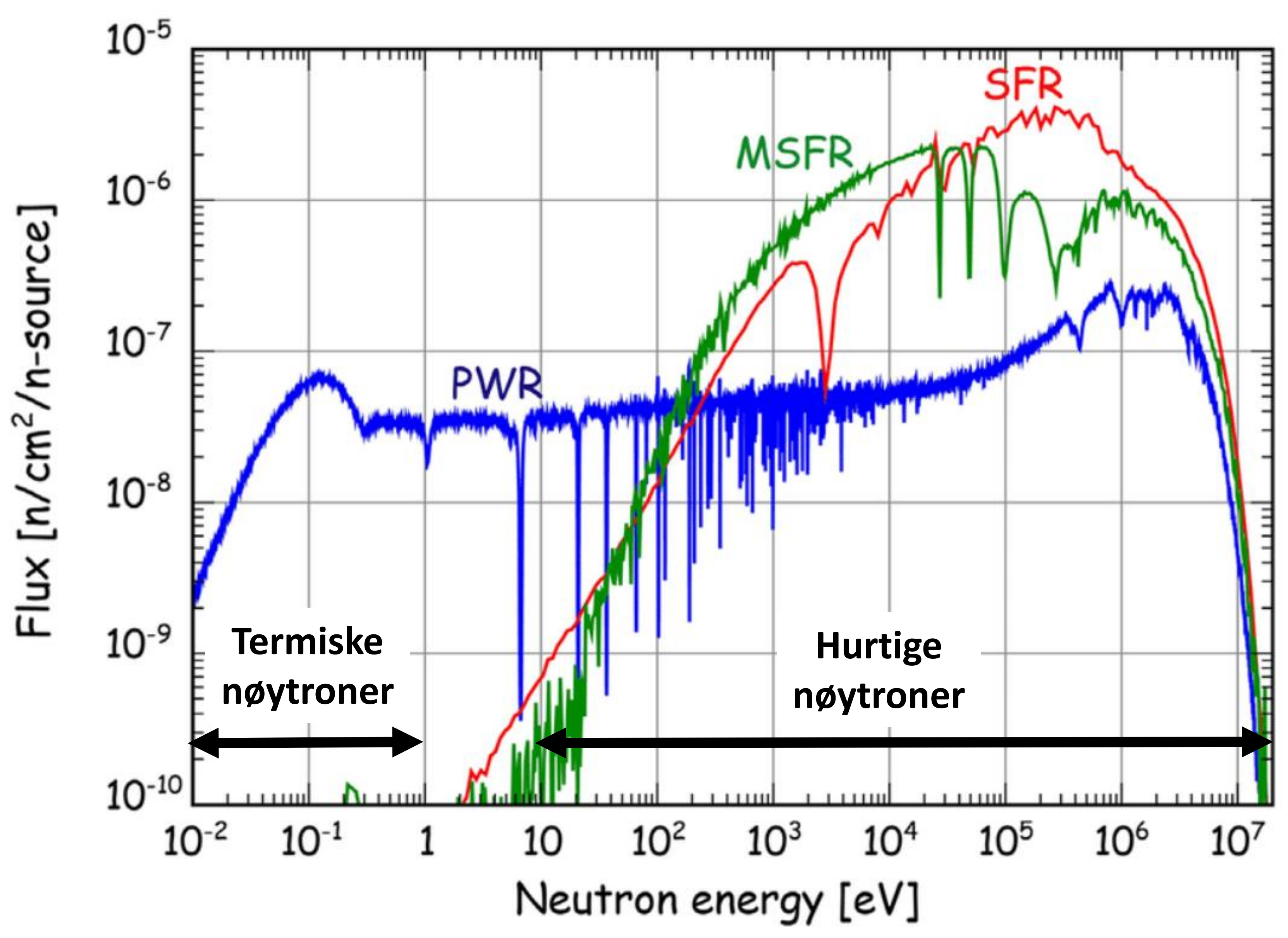


HURTIG NØYTRON
(E = 1 750 000 eV)

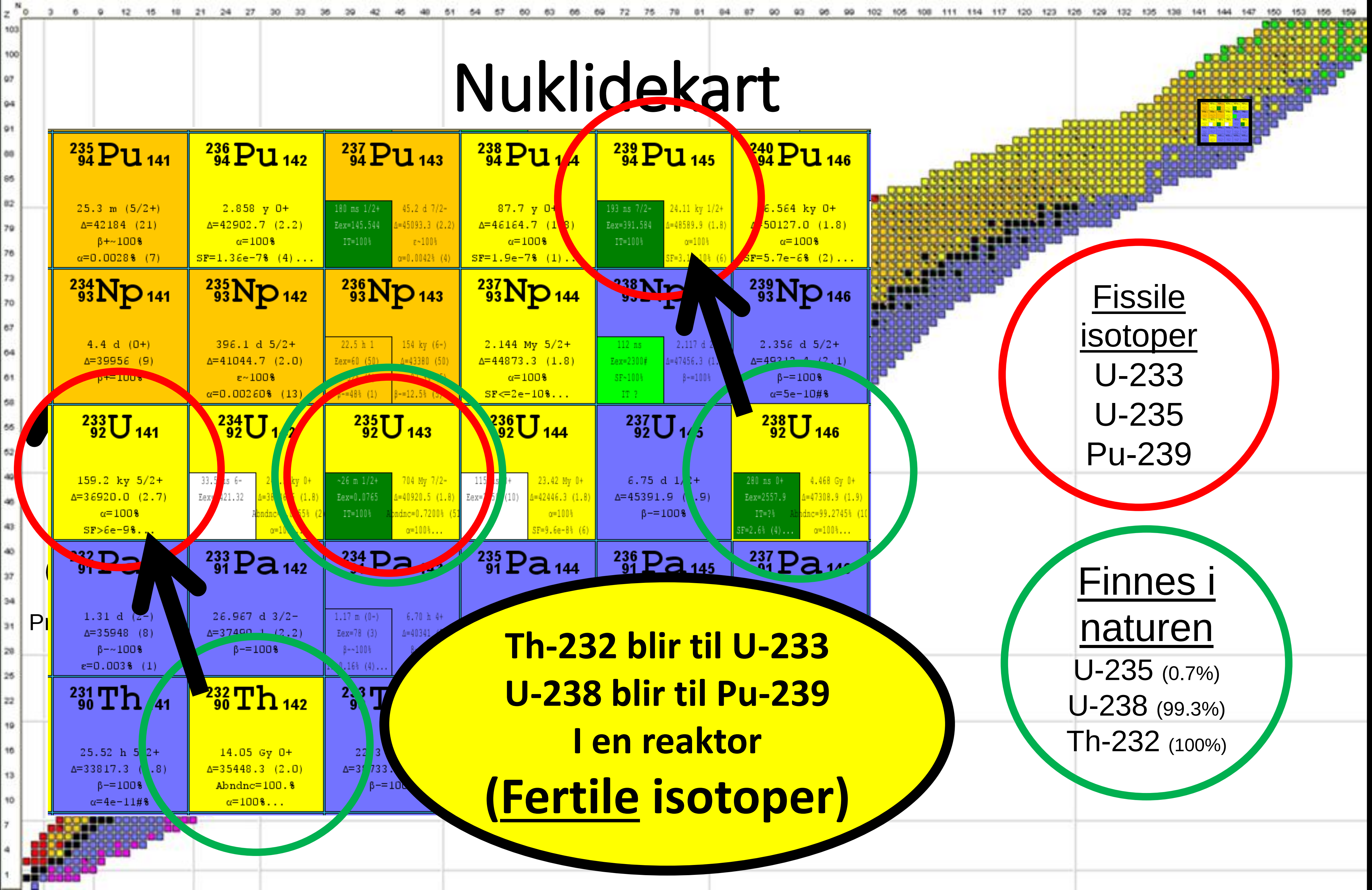
MODERATOR
(LETTE ATOMER)

TERMISK NØYTRON
(E = 0,025eV)

Termisk reaktor vs hurtig reaktor



Nuklidekart



Th-232 blir til U-233
U-238 blir til Pu-239
I en reaktor
(<u>Fertile</u> isotoper)

<u>Fissile isotoper</u>
U-233
U-235
Pu-239

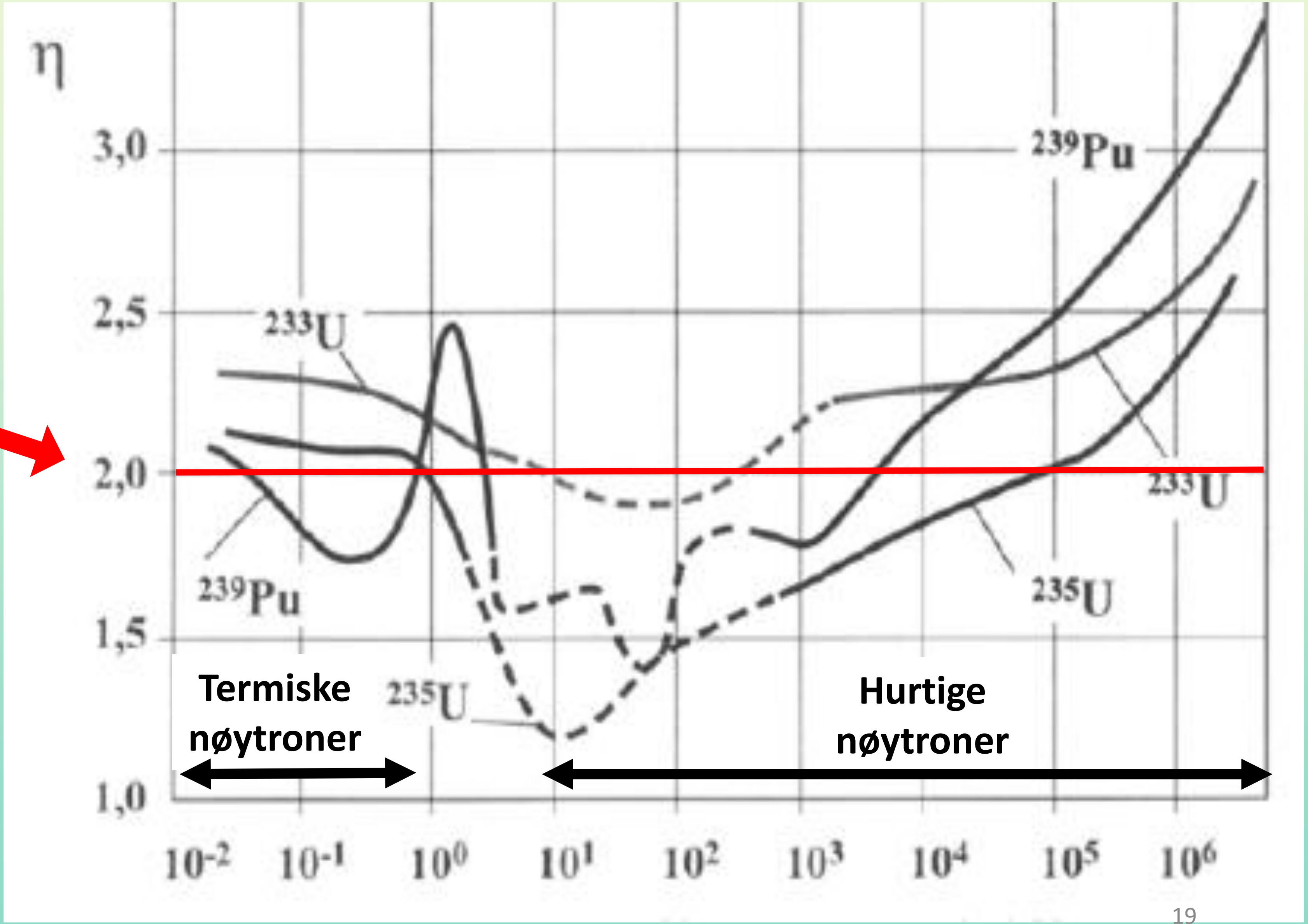
<u>Finnes i naturen</u>
U-235 (0.7%)
U-238 (99.3%)
Th-232 (100%)

Formeringsreaktor - Breeding

η : Antall nøytroner fra hver fisjon.

η > 2
for å få til
formeringsreaktor:

- ✓ Et nøytron for å vedlikeholde fisjonsreaksjonene
- ✓ Et nøytron for å lage et nytt fisjonerbart atom

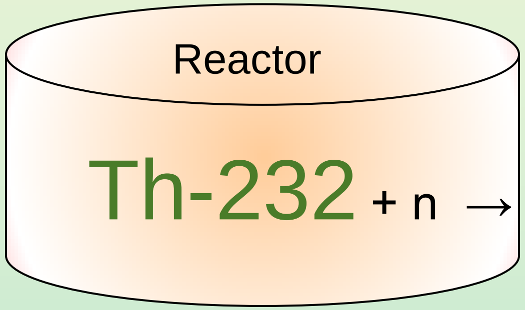


Thorium-232 og uran-238 er fertile – ikke fissile som U-235

Thorium konverteres til fissil isotop :

TERMISK- eller

HURTIG reaktor

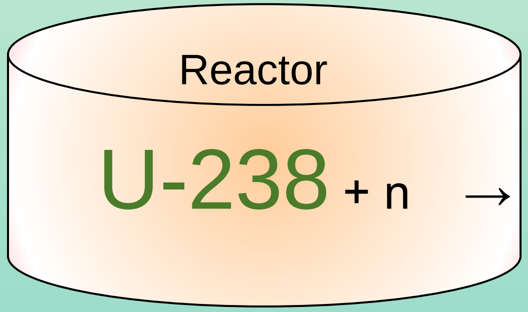


Th-232 + n → Th-233 $\xrightarrow[\text{22 min}]{}$ Pa-233 $\xrightarrow[\text{27 d}]{}$ U-233 (159 000 y)

Uran 238 konverteres til fissil isotop:

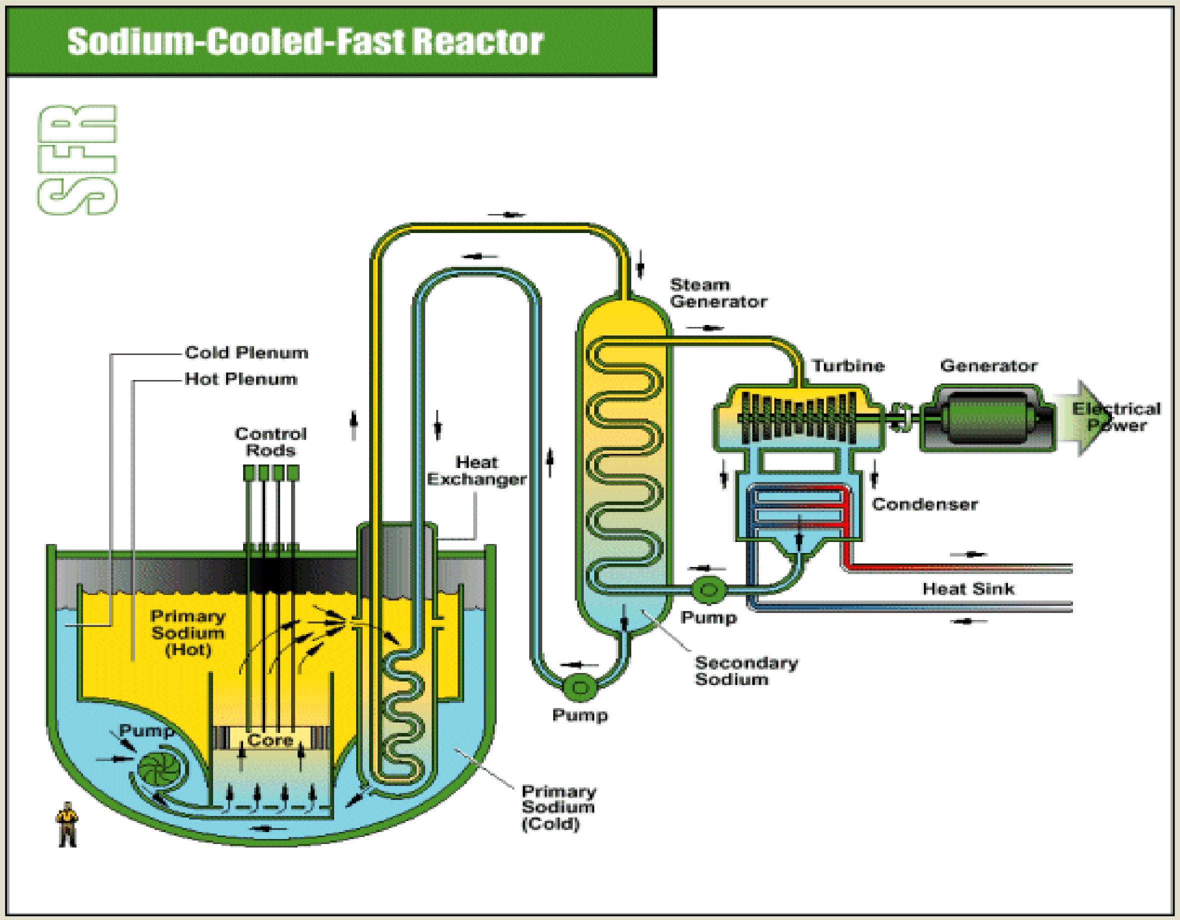
Må være

HURTIG reaktor

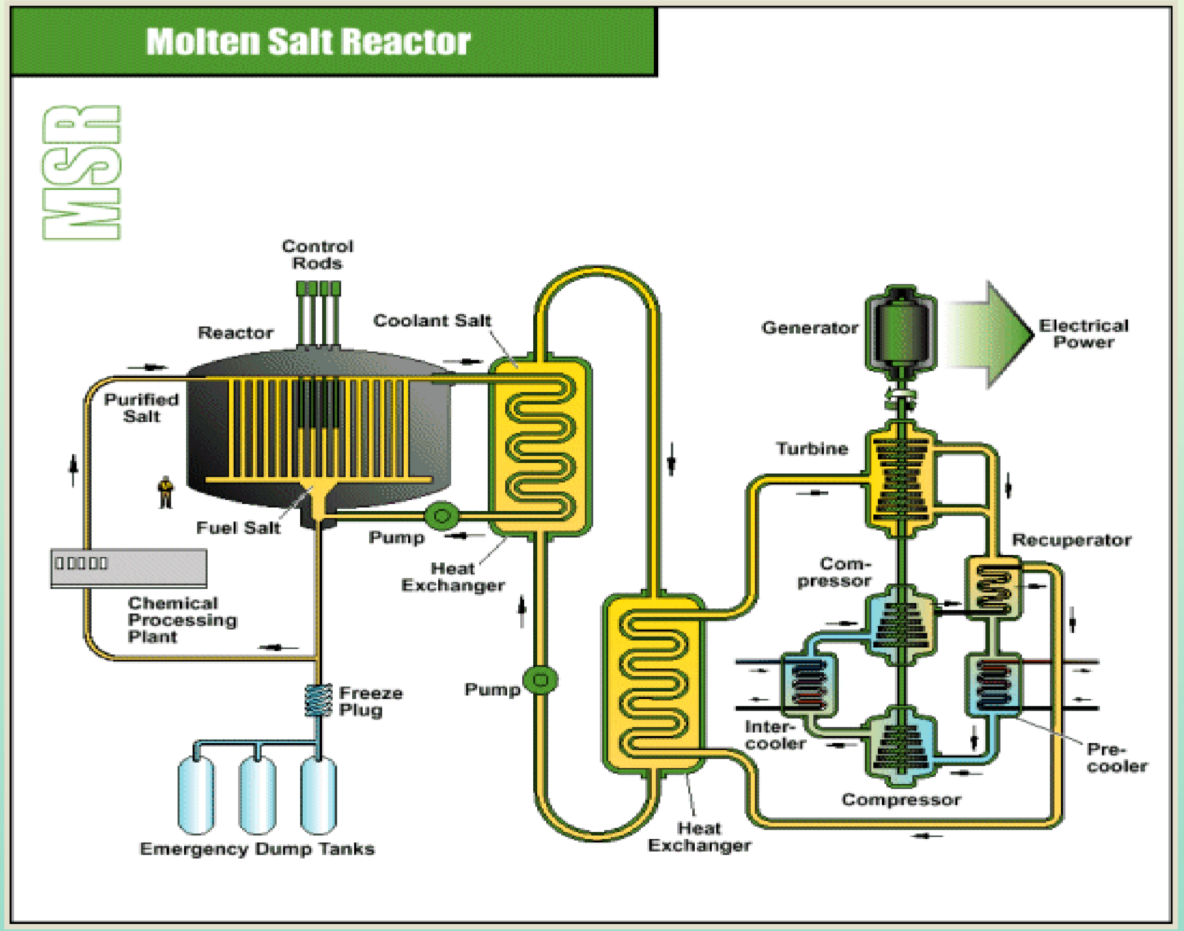


U-238 + n → U-239 $\xrightarrow[\text{24 min}]{}$ Np-239 $\xrightarrow[\text{2,4 d}]{}$ Pu-239 (24 000 y)

Generation IV reactors



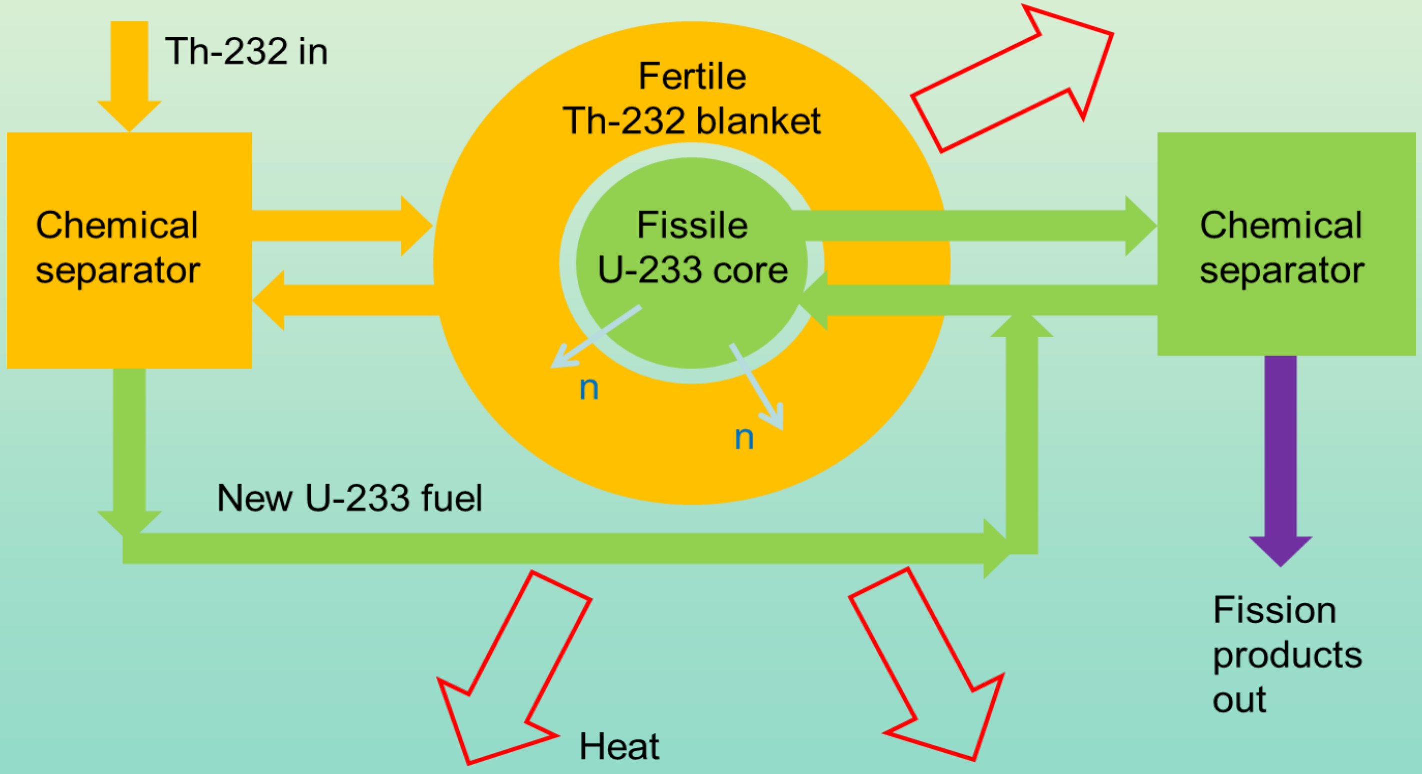
- Temp. 550 ^{o}C
- Low pressure
- Fast Breeder



- Temp. 700 - 800 ^{o}C
- Low pressure
- Waste burner
- Thermal / epithermal
- Fuel : ^{232}Th / ^{233}U

Hvordan utnytte thorium?

En mulighet er saltsmeltereaktor.



Th-232 in

Chemical separator

Fertile Th-232 blanket

Fissile U-233 core

n

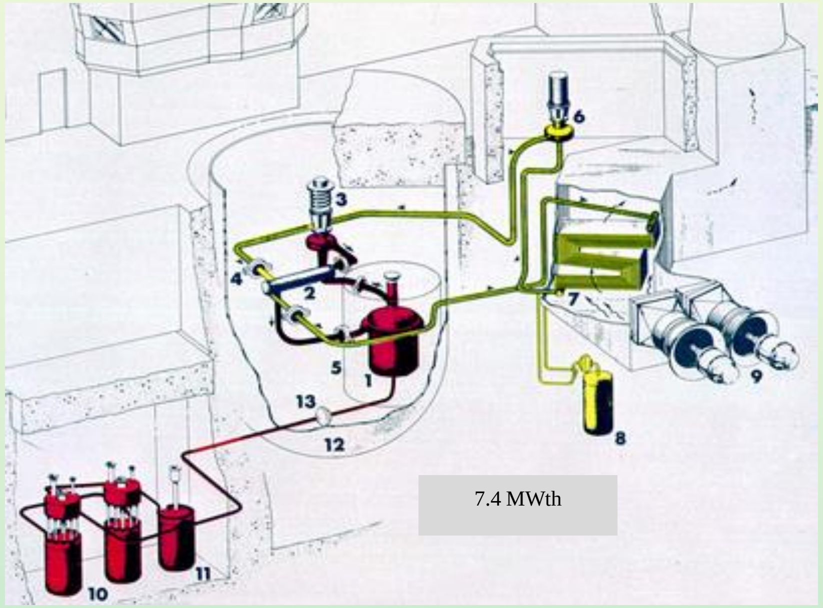
n

Chemical separator

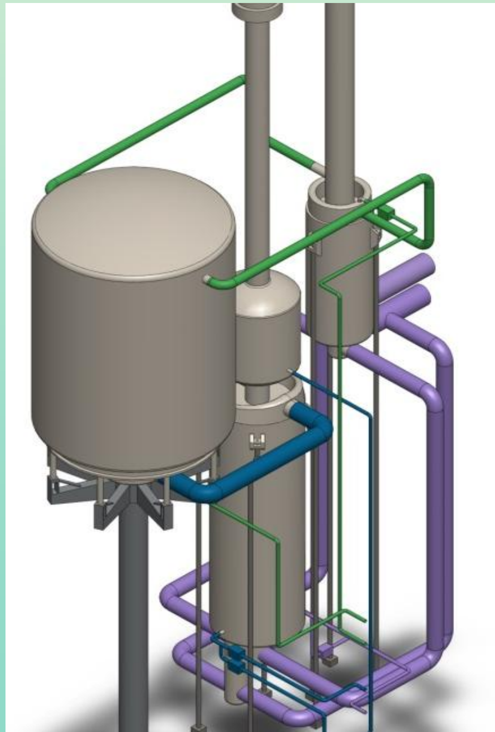
New U-233 fuel

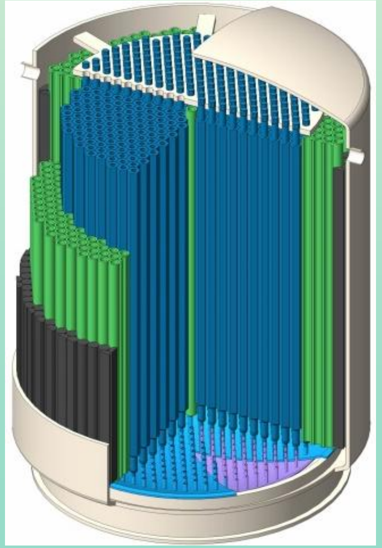
Heat

Fission products out



Molten-Salt Reactor Experiment (1965-1969)





BN-800

Hurtig formeringsreaktor med natriumkjøling. 800 MWe. Startet i 2016.

Belojarsk kjernekraftverk er et russisk kjernekraftverk i Sverdlovsk Oblast (fylke) øst for Uralfjellene

CFR-600 (China Institute of Atomic Energy, China)

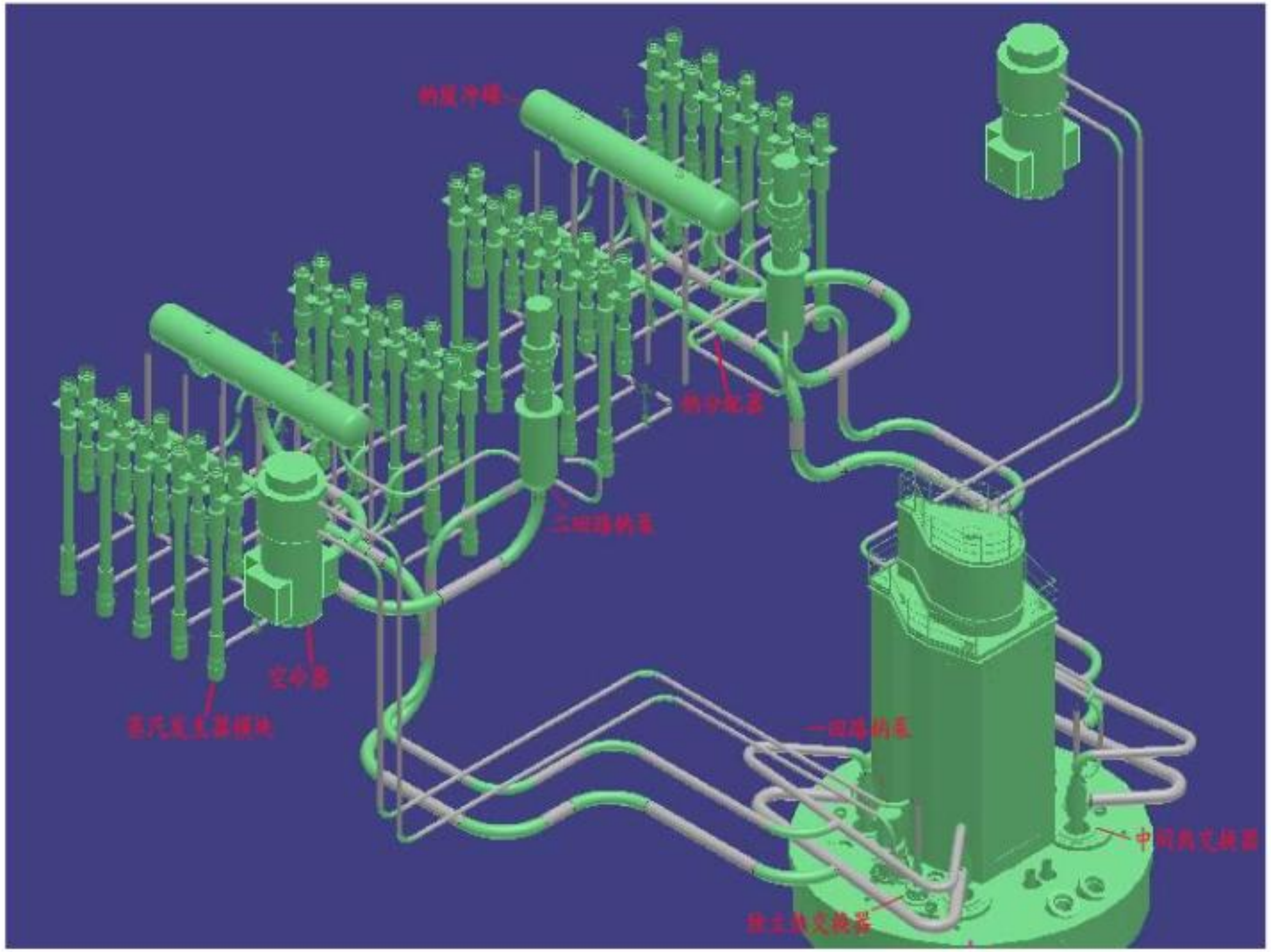
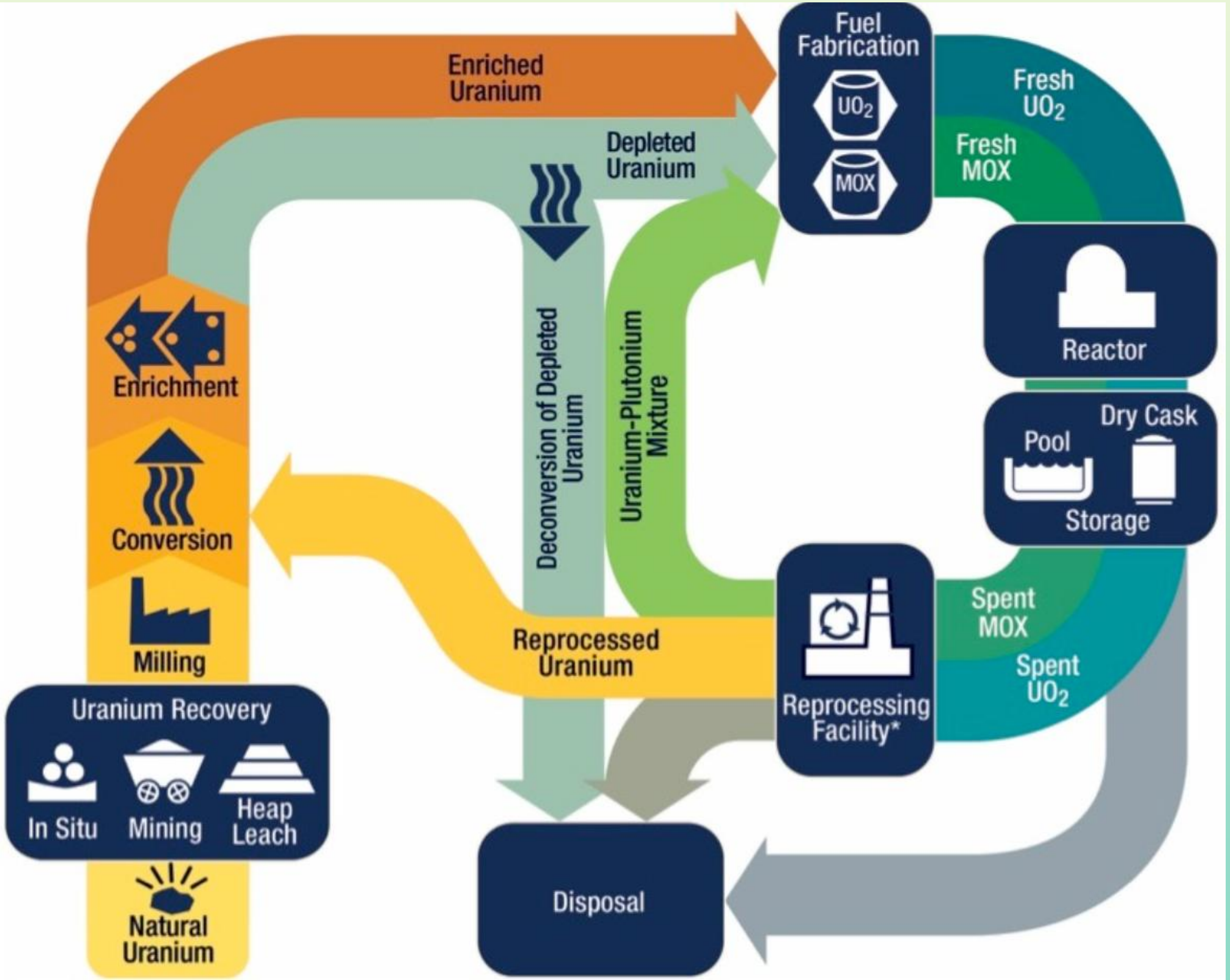


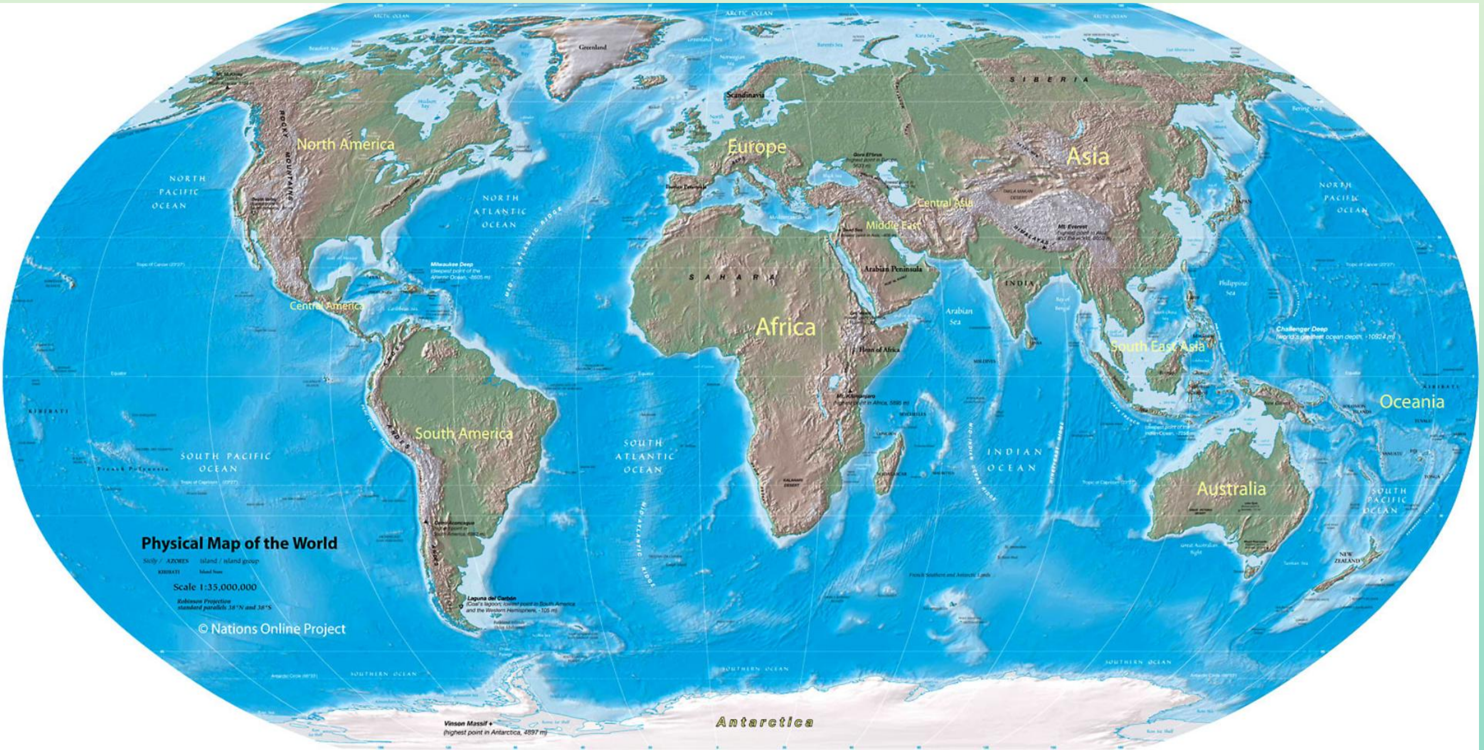
FIG. 5. Schematic representation of CRF-600.

Ferdigstilles i 2025 og gi 600 MWe

Reprosessering av brensel.

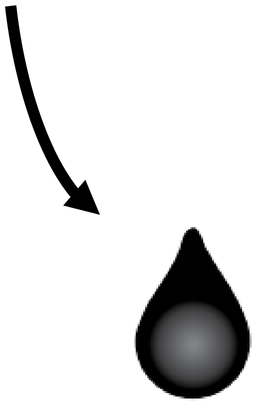


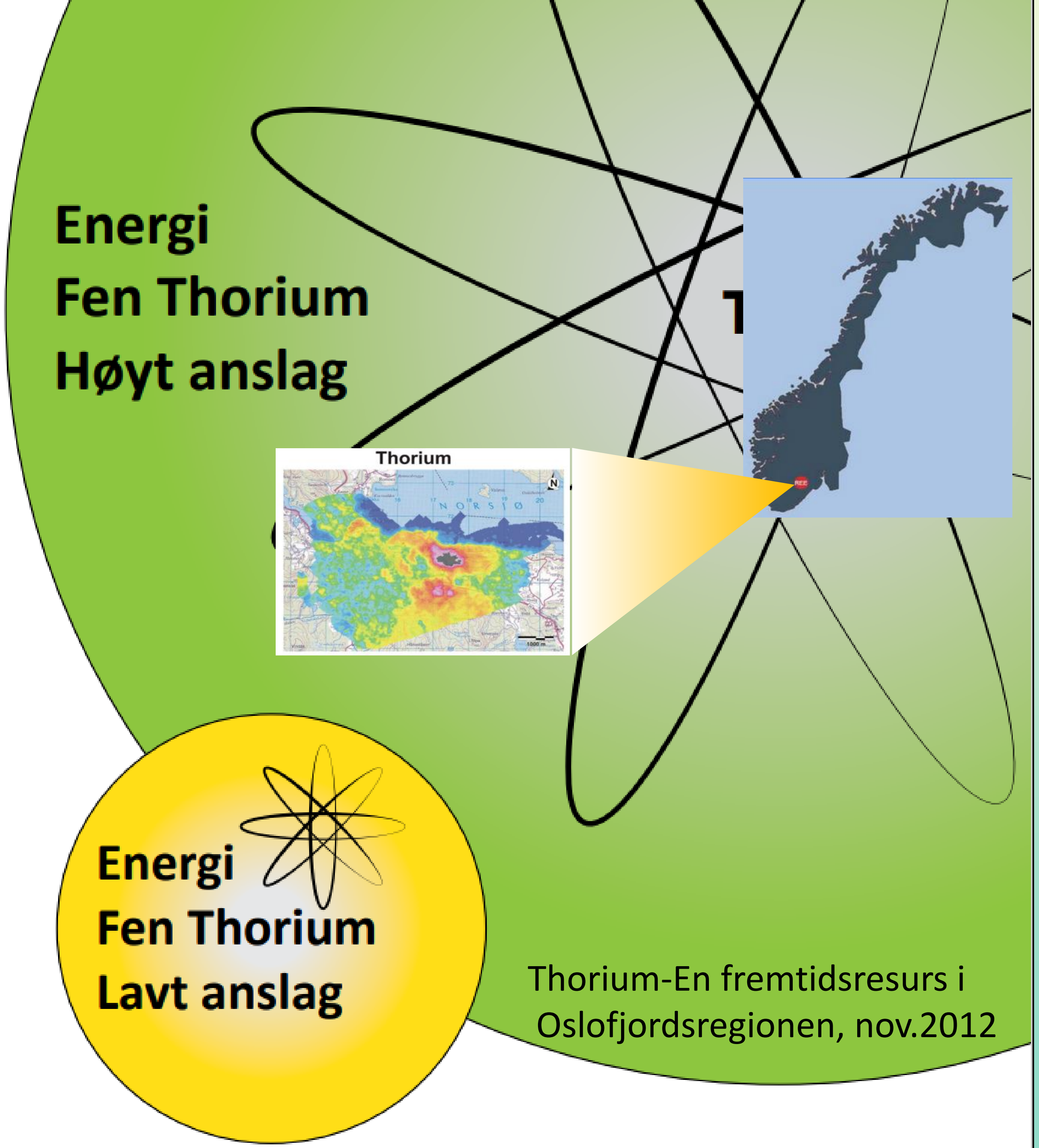
- Verdens kjente landbaserte uranforekomster : 8 000 000 tonn
- Verdens kjente thoriumforekomster : 6 355 000 tonn
- Uran i havet: 4 600 000 000 tonn



3,3 mikrogram pr liter (8.25 g i et OL-baseng) . Tilsvarer ca 575 ganger kjente landforekomster

Thorium i Fensfeltet kan gi minst 10 , muligens 100, ganger mer energi enn all samlet olje og gass fra norsk sokkel





Energi
Fen Thorium
Høyt anslag

Energi
Fen Thorium
Lavt anslag

Thorium-En fremtidsresurs i
Oslofjordsregionen, nov.2012

Vindkraft er resurskrevende mhp materialer, vedlikehold, transport, destruksjon mm.

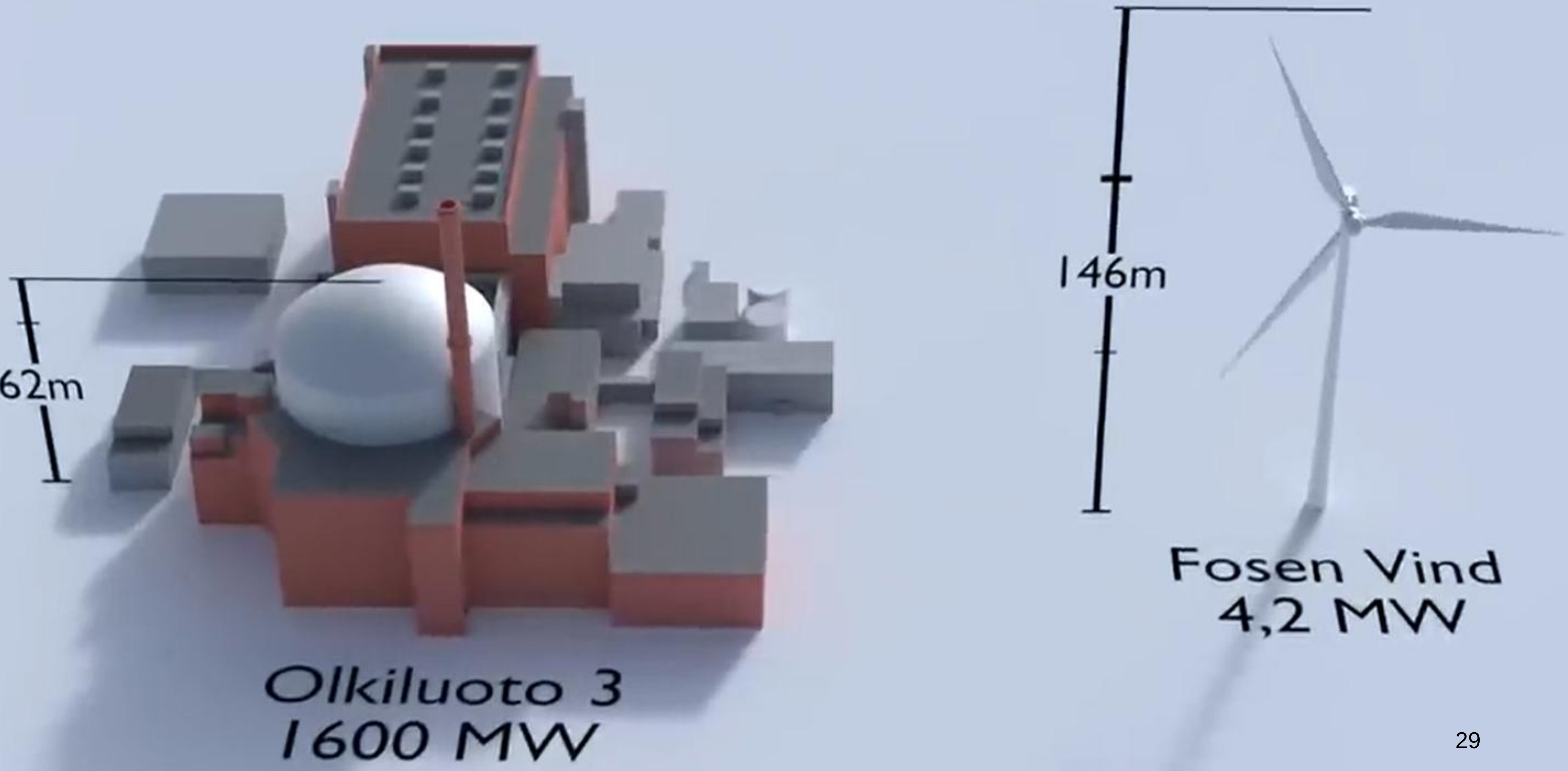
For å bygge en 3,6 MW vindturbin (ca 0.01 TWh/år) trengs:

- 475 tonn stål
- 400 m3 betong
- 36 tonn kobber
- 2,6 tonn bly
- 1,3 tonn aluminium
- 400 kg nikkel
- 400 kg neodymium
- 80 kg dysprosium

- ½ fotbalbane til oppstillingsplass
- 800 meter vei

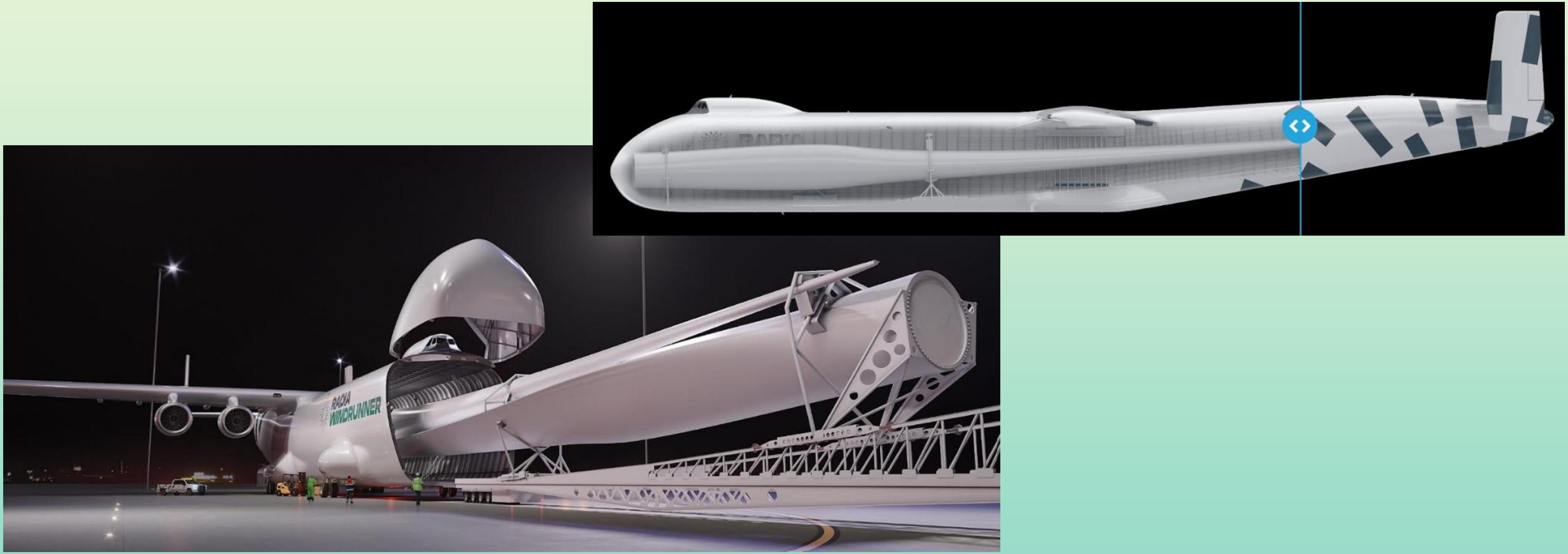
1300 turbiner i Norge (status 2023) har krevd 1000 km vei i urørt natur på bekosning av dyre-, fugle-, planteliv og rekreasjonsområder for befolkning.

NVE

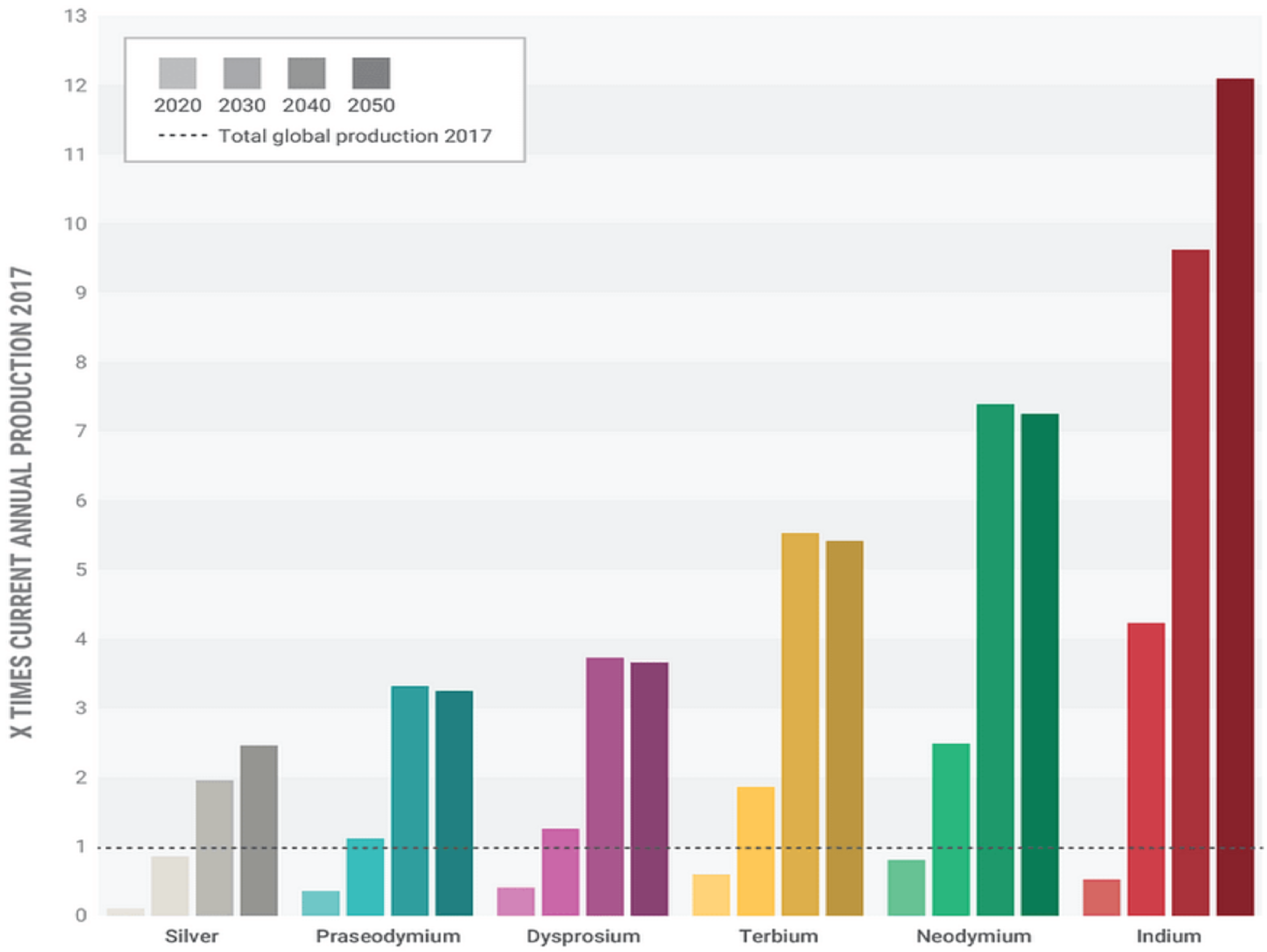

62m
Olkiluoto 3
1600 MW
146m
Fosen Vind
4,2 MW

Vindkraft er resurskrevende mhp materialer, vedlikehold, transport, destruksjon mm.

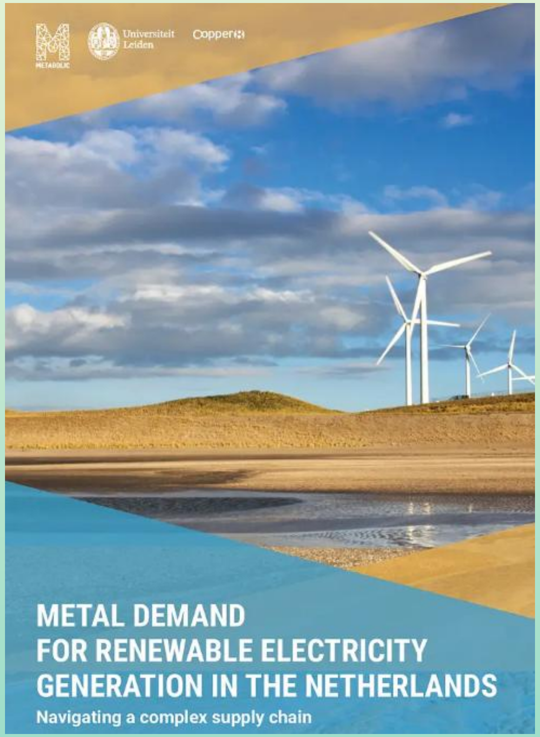
Vindkraft er resurskrevende mhp materialer, vedlikehold, transport, destruksjon mm.



Deponering av vindturbin-blader



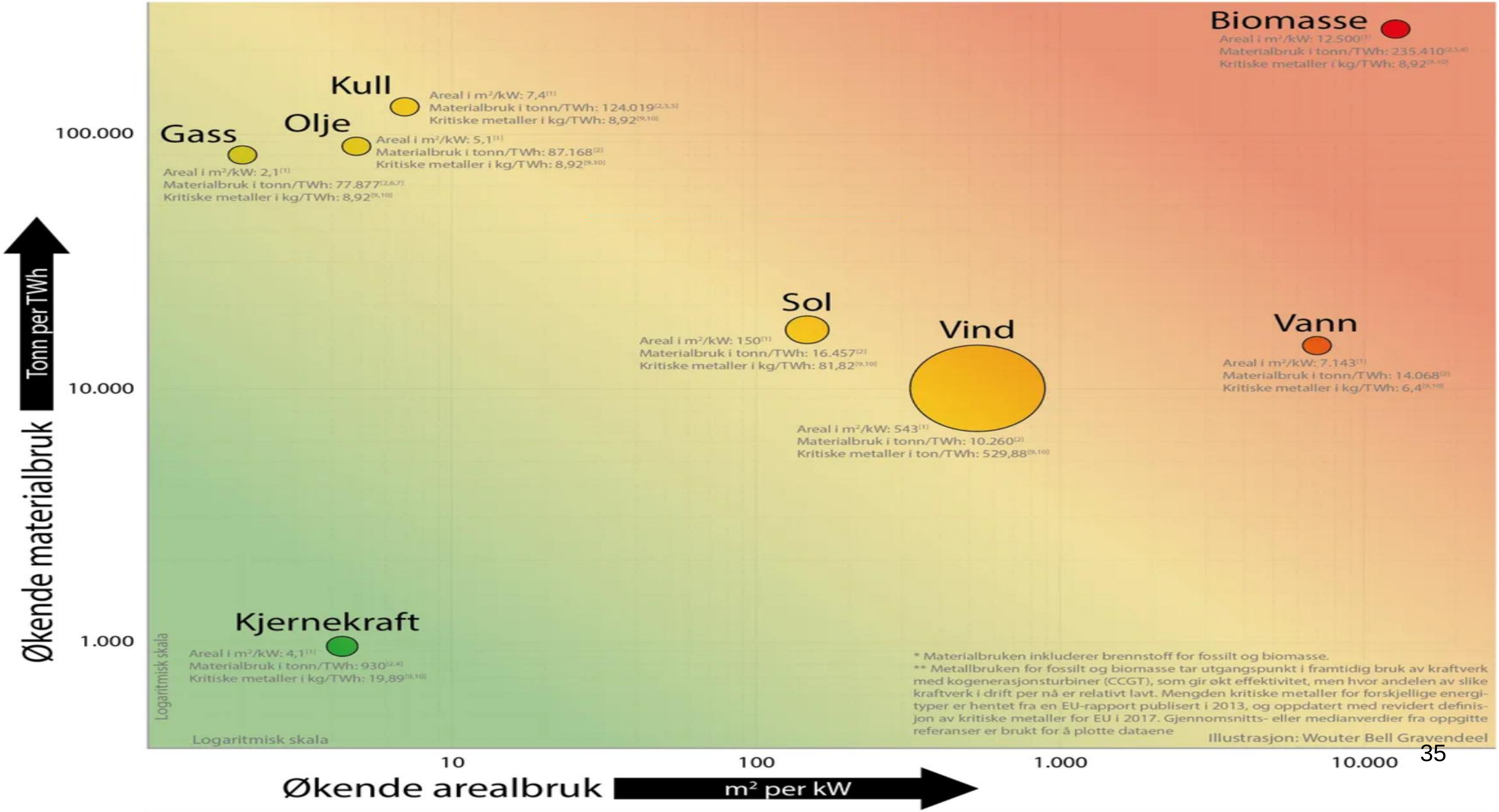
“At Metabolic, we strive to transition the global economy to a fundamentally sustainable state.”



info@metabolic.nl
+31 203 69 09 77
Gedempt Hamerkanaal 29
1021 KL Amsterdam
Netherlands

Areal- og materialbruk per energikilde*

Størrelsen på sirklene viser forbruk av kritiske metaller**



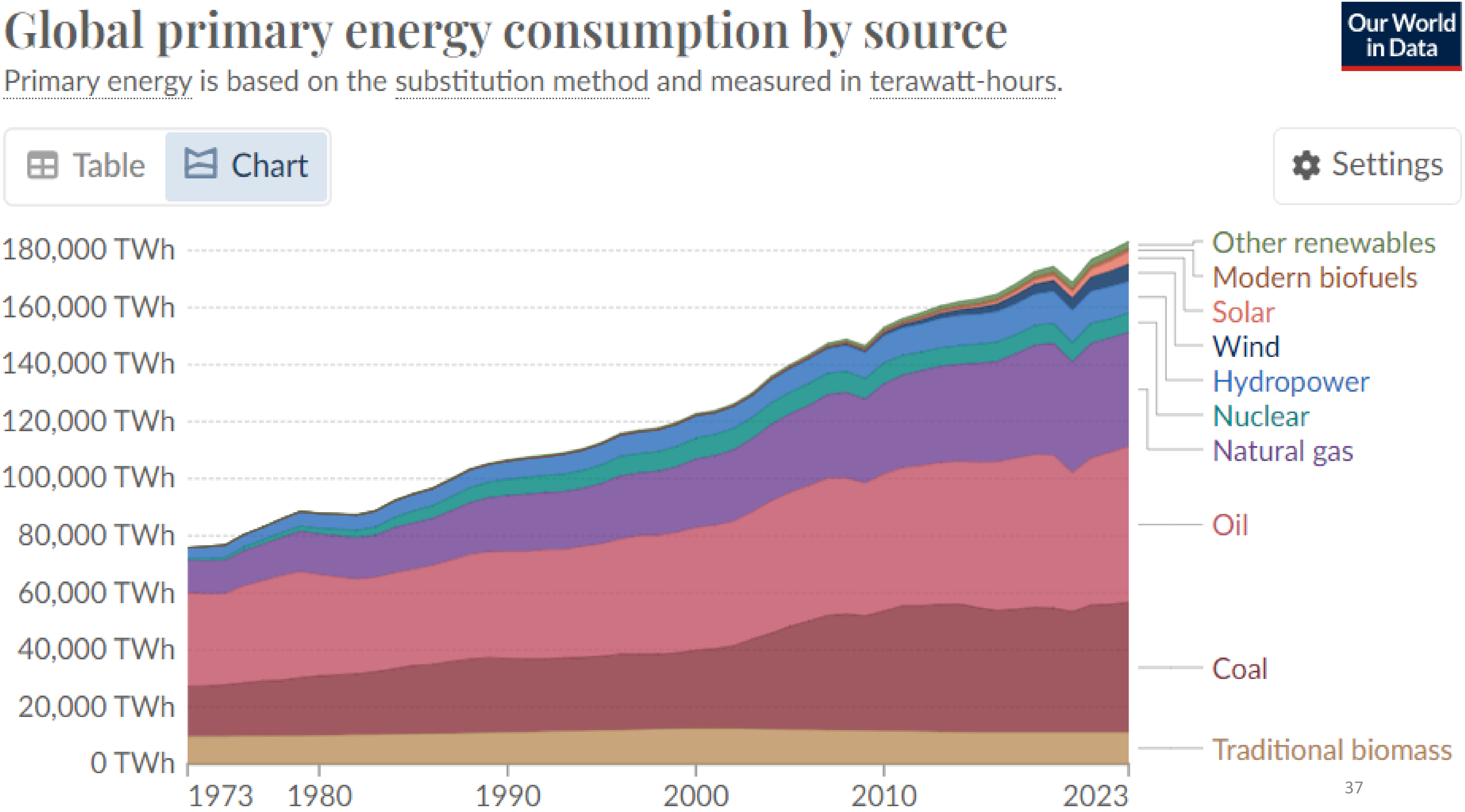
* Materialbruken inkluderer brennstoff for fossilt og biomasse.

** Metallbruken for fossilt og biomasse tar utgangspunkt i framtidig bruk av kraftverk med kogenerasjonsturbiner (CCGT), som gir økt effektivitet, men hvor andelen av slike kraftverk i drift per nå er relativt lavt. Mengden kritiske metaller for forskjellige energityper er hentet fra en EU-rapport publisert i 2013, og oppdatert med revidert definisjon av kritiske metaller for EU i 2017. Gjennomsnitts- eller medianverdier fra oppgitte referanser er brukt for å plotte dataene

Illustrasjon: Wouter Bell Gravendeel

Utvinning av litium truer tilgang på rent vann

I «litiumtrekanten» – en region som spenner over Argentina, Chile og Bolivia – sitter urfolksgrupper på metall verdt anslagsvis tusenvis av milliarder dollar.

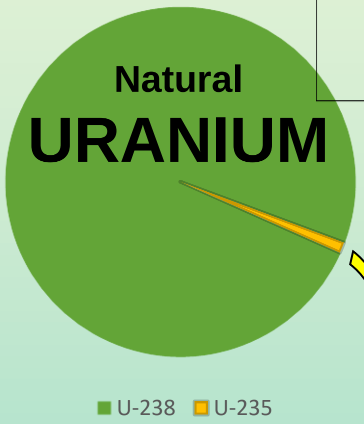


Global primary energy consumption by source

Primary energy is based on the substitution method and measured in terawatt-hours.

Formeringsreaktor (Breeder)

Uran



$$\text{U-238}+n \rightarrow \text{U-239} \xrightarrow{23.4\ \text{m}} \text{Np-239} + \beta \xrightarrow{2.4\ \text{d}} \text{Pu-239} + \beta$$

Gen IV reaktorer and reprocessing of fuel

Natural

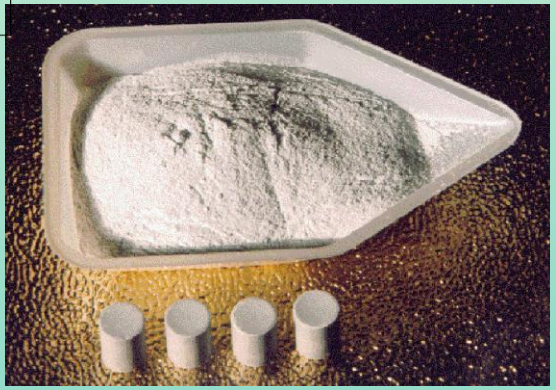
THORIUM

U-233

$$\text{Th-232}+n \rightarrow \text{Th-233} \xrightarrow{22.4\ \text{m}} \text{Pa-233} + \beta \xrightarrow{27\ \text{d}} \text{U-233} + \beta$$

Existing reactors

Existing reactors



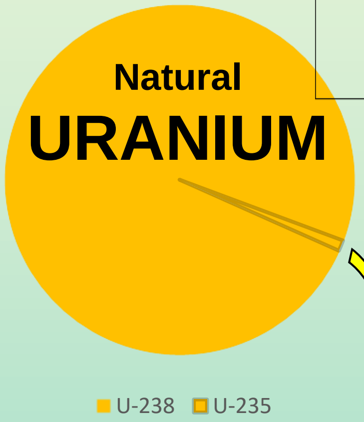
Formeringsreaktor (Breeder)

Vi kan ta ut minst

60 ganger

så mye energi

Uran



$$\text{U-238} + n \rightarrow \text{U-239} \xrightarrow{23.4\ \text{m}} \text{Np-239} + \beta \xrightarrow{2.4\ \text{d}} \text{Pu-239} + \beta$$

Gen IV reaktorer and reprocessing of fuel

Natural

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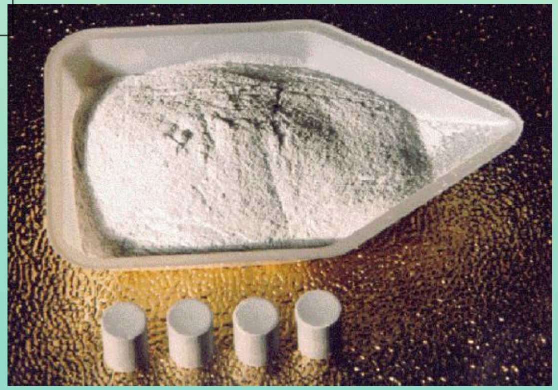
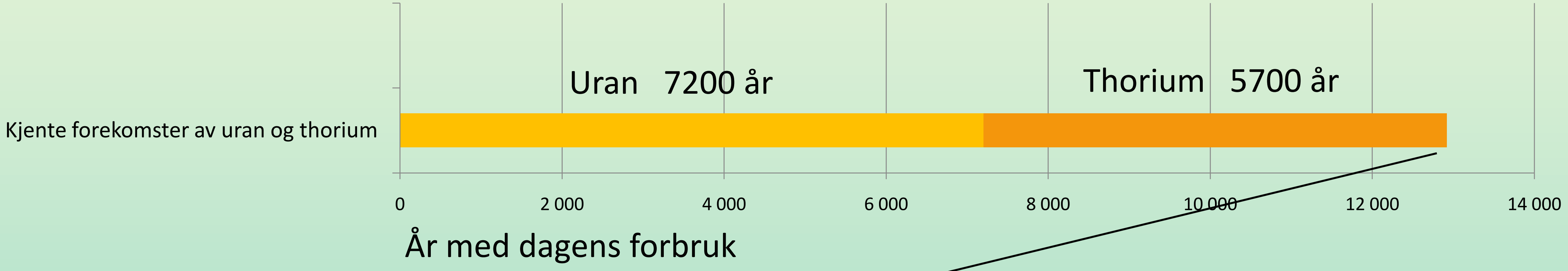
Existing reactors

Existing reactors



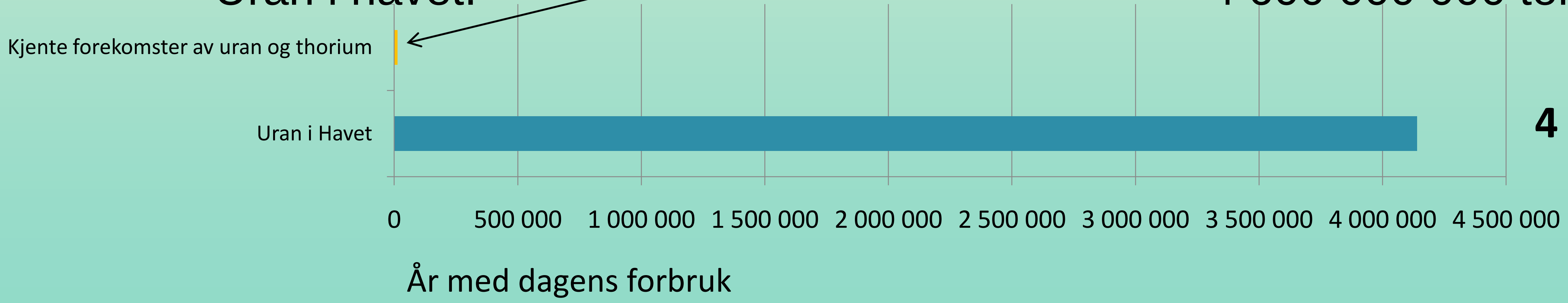
Hvor lenge kan vi kjøre formeringsreaktorer ?

Verdens kjente landbaserte uranforekomster :	8 000 000 tonn
Verdens kjente thoriumforekomster :	6 355 000 tonn



12900 år

Uran i havet: 4 600 000 000 tonn



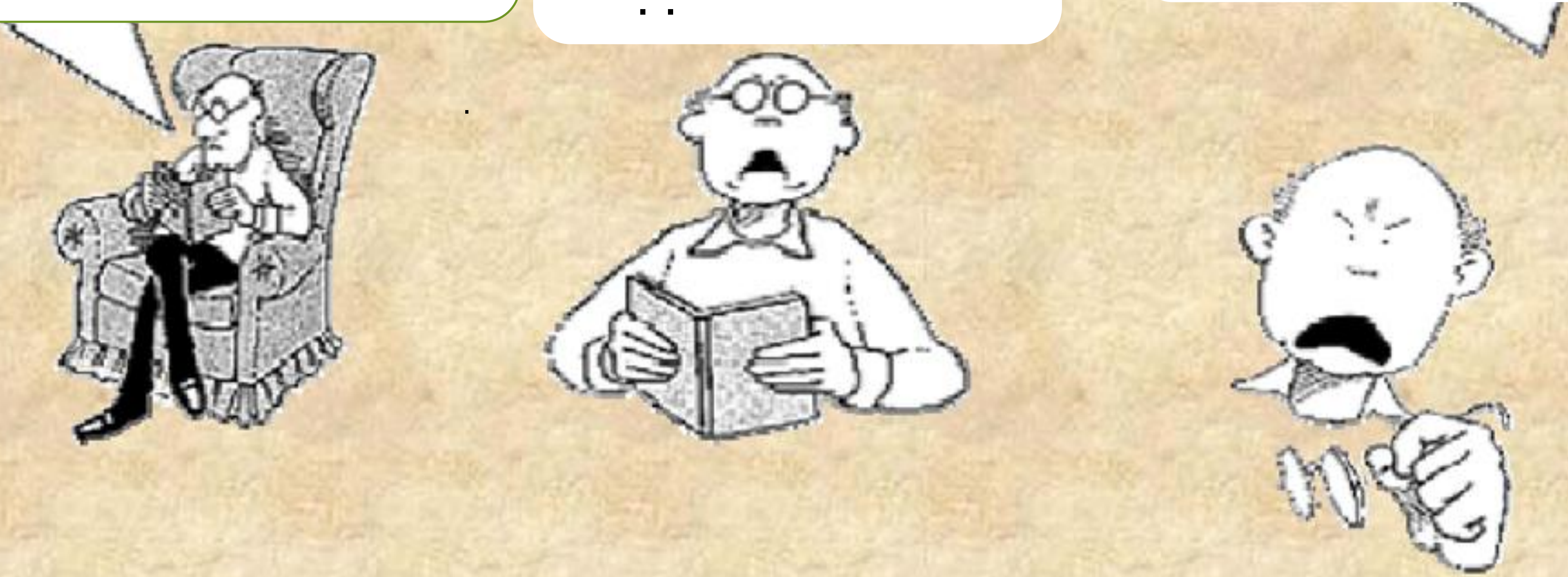
4 100 000 år

Kjernekraft

Dette kan godt være en god bok, men jeg har to problemer med kjernekraft . . . .

. . . jeg kan absolutt ingenting om det . . .

. . .og jeg stoler ikke på de som vet



Takk for oppmerksomheten