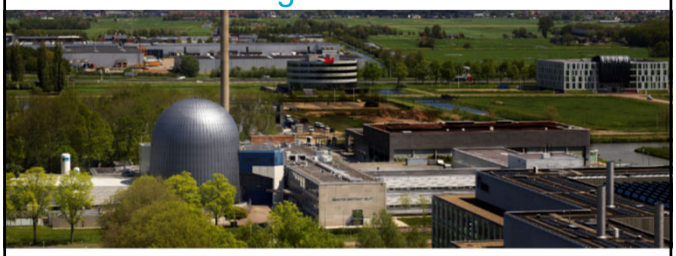
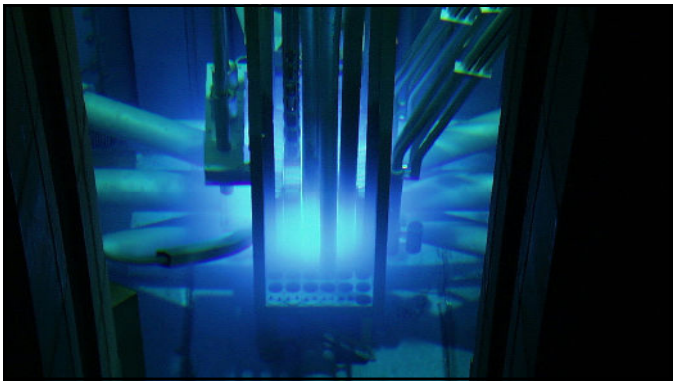
Kernenergie: trends en thorium



Prof Jan Leen Kloosterman
Delft University of Technology

1



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Waarom kernenergie?

5

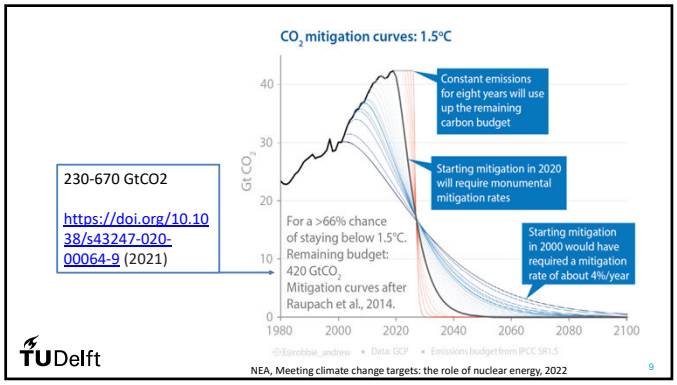
CO2 budget

Global warming between 1850–1900 and 2010–2019 (°C)	Historical cumulative CO_2 emissions from 1850 to 2019 ($GtCO_2$)
1.07 (0.8–1.3; *likely* range)	2390 (± 240; *likely* range)

Approximate global warming relative to 1850–1900 until temperature limit (°C)*(1)	Additional global warming relative to 2010–2019 until temperature limit (°C)	Estimated remaining carbon budgets from the beginning of 2020 ($GtCO_2$) *Likelihood of limiting global warming to temperature limit*(2)* 17%	33%	50%	67%	Years
1.5	0.43	900	650	500	400	10
2.0	0.93	2300	1700	1350	1150	27

IPCC, Climate Change 2021; The Physical Science Basis, 2021

8



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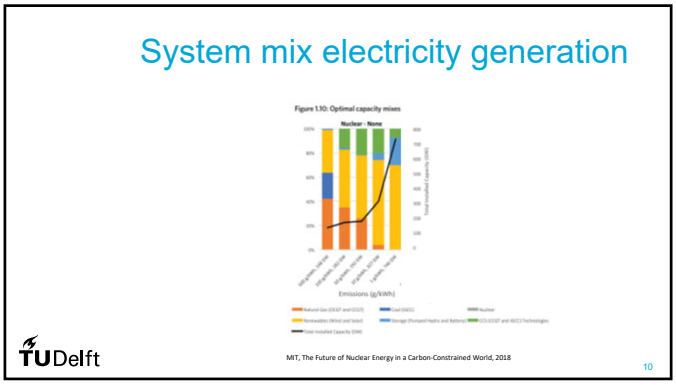

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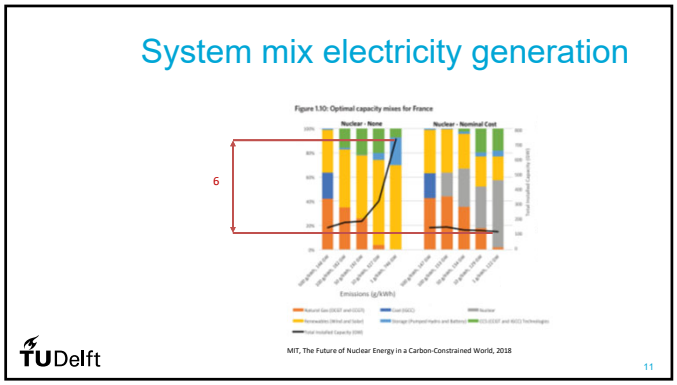

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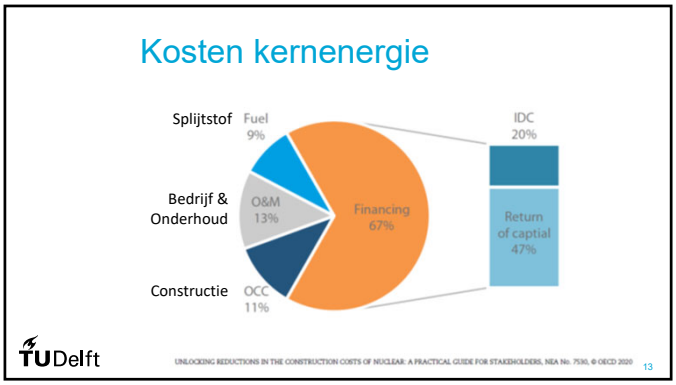

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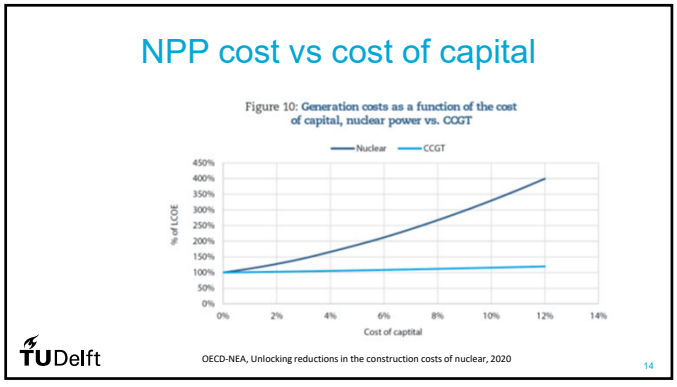

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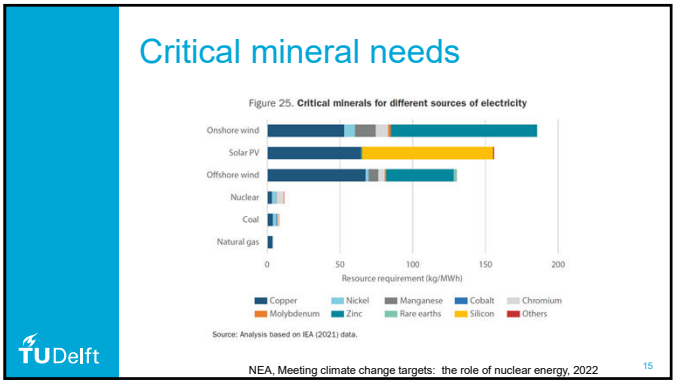

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Energy scenario studies

- Output determined by assumptions on cost, technology, economy, society, …
- Scenario is no prediction, and never reality
- Most scenarios target at minimizing cost, not at minimizing risk of climate change
- Diversity in technology and sources leads to:
  - Higher security of supply
  - More robust energy system
  - Lower risk of climate change

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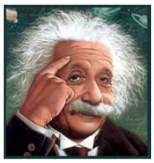
Werking van kerncentrales



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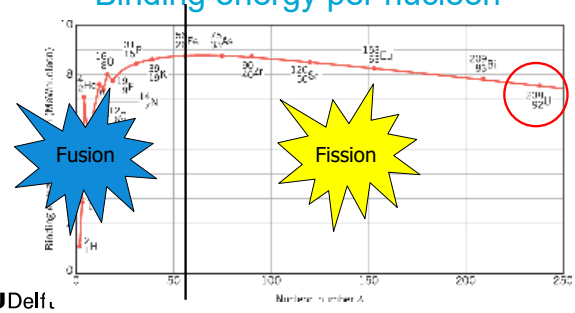
Binding energy per nucleon



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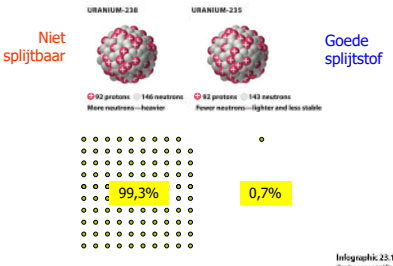
Uranium isotopen



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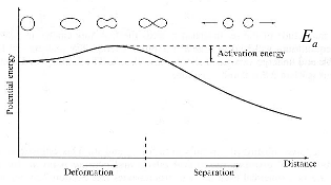
Coulomb barrier for fission



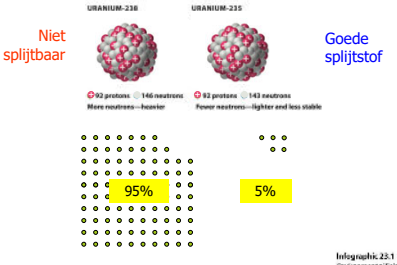
^{235}U: E_b=6.6 MeV ^{236}U: E_a=5.3 MeV

^{238}U: E_b=5.1 MeV ^{239}U: E_a=5.5 MeV

20

20

Uranium verrijking



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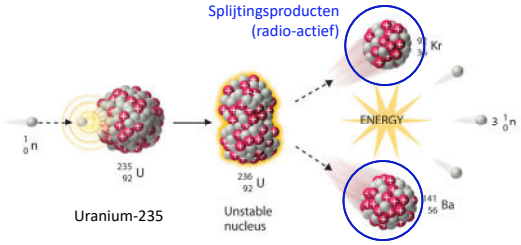
Kernsplijting



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Chemwiki, CCPL 22

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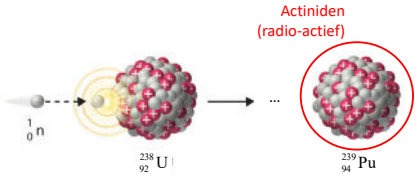
Productie van plutonium



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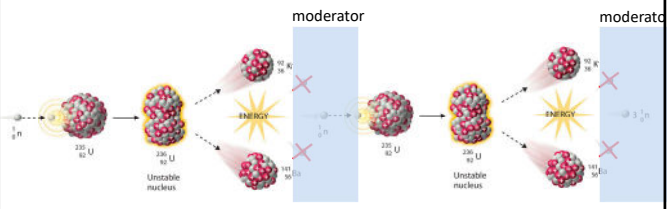
Splijtings kettingreactie



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Chemwiki, CCPL 24

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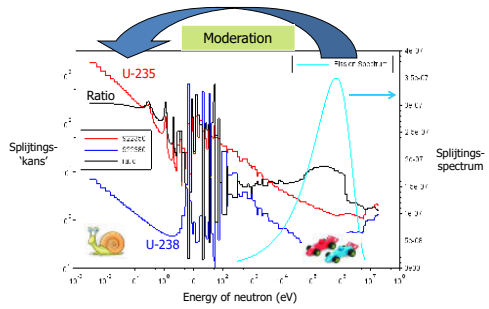
Kans op splijting



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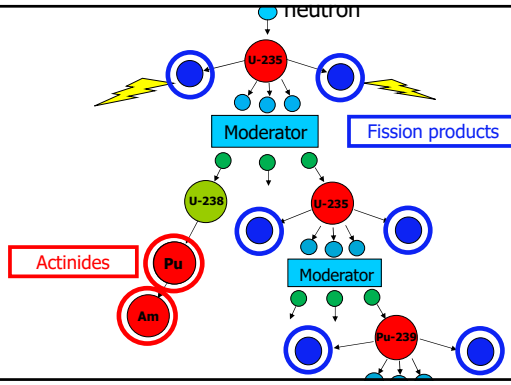

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Energy from 1 gram U-235

Gasoline

2500 liter

Coal

3000 kg

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27

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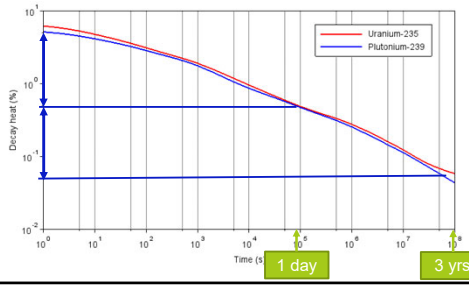
Decay heat production



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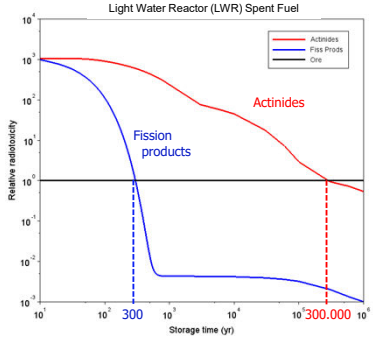
Light Water Reactor (LWR) Spent Fuel



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Opslag van kernafval COVRA

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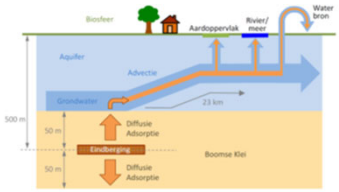
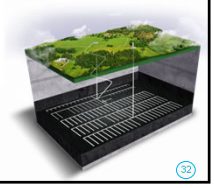
Geological disposal



We know how to handle nuclear waste and how to store it safely underground such that no harm is done to people. See Covra.nl



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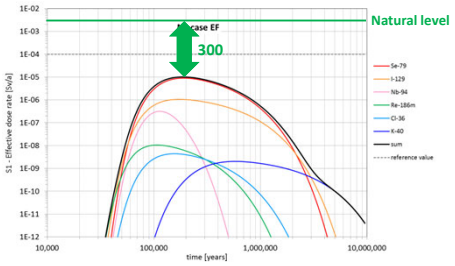
Dose values in Boom clay
Early failure scenario (1000 year)

The effective dose rate S1 represents the annual individual effective dose to an average member of the group of the most exposed individuals. It takes into account dilution and accumulation in the biosphere, various exposure pathways as well as living and nutrition habits.



Safety assessment calculations: Central Assessment Case of the Normal Evolution Scenario, OPERA-PU-NRG7331

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Kerncentrales in de praktijk

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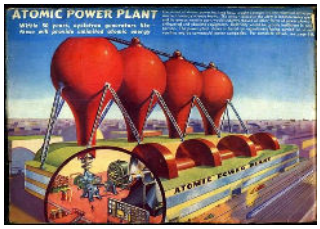

October 1939 issue of Amazing Stories
https://www.pinterest.com/pin/540502392754920870/

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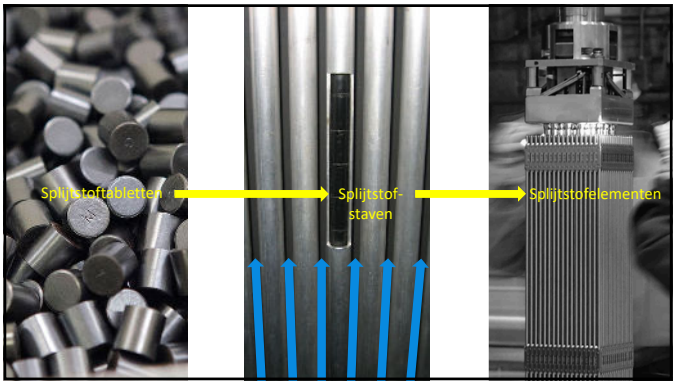

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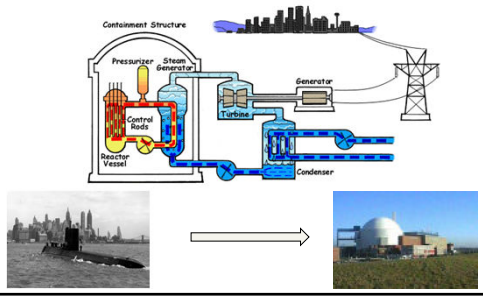
Pressurized Water Reactor (PWR)
Drukwaterreactoren



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Kerncentrale Borssele

121 fuel assemblies, 38 tonnes of fuel

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Kerncentrale Borssele

http://www.euronuclear.org/e-news/e-news-22/Borssele%20.htm

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Reactor pressure vessel KCB (1972)

Jan Wieman, EPZ

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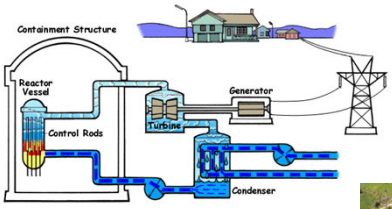
Boiling Water Reactor (BWR)
Kokendwaterreactoren



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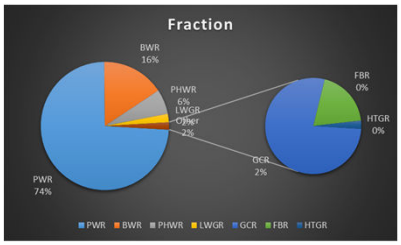
Fraction of reactor types



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Based on: https://pris.iaea.org/PRIS/WorldStatistics/OperationalReactorsByType.aspx

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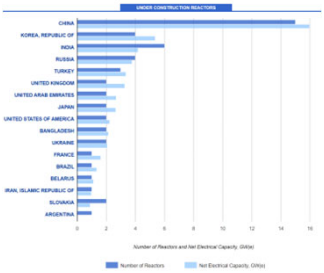
Reactors under construction (2022)



Origin	number
Russia	18
China	16
Korea	6
EU/France	3
US/Japan	2
Total	51

WANO (15-3-2022)

TUDelft

https://pris.iaea.org/PRIS/WorldStatistics/UnderConstructionReactorsByCountry.aspx consulted 15-3-2022

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Samenvatting werking kerncentrales

- De reactorkern levert warmte die wordt omgezet in stoom.
- Deze stoom drijft een turbine aan die is gekoppeld aan een generator.
- Het nucleaire deel is slechts een klein deel van een centrale, het grootste deel is conventioneel.
- Het rendement van een LWR is ongeveer 35%.
- Het reactorvermogen wordt gestuurd met regelstaven.
- Het teveel aan neutronen wordt weggevangen in absorbers, zoals boorzuur.

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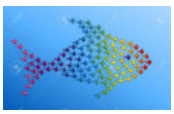
Ontwikkelingen in Kernenergie

LWR SMR MSR



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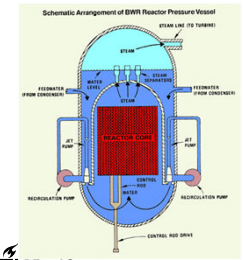
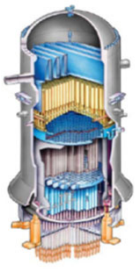
Generaties BWR

gen II



gen III



gen III+

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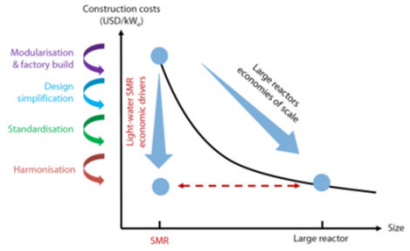
Cost reduction SMR



UNLOCKING REDUCTIONS IN THE CONSTRUCTION COSTS OF NUCLEAR: A PRACTICAL GUIDE FOR STAKEHOLDERS, NEA No. 7530, © OECD 2020

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Small Modular Reactors
Kleine modulaire reactoren

- Licht Water Reactoren (LWR)
- Hoge Temperatuur Gasgekoelde Reactoren (HTGR)
- Vloeibaar Metaal-gekoelde Reactoren (LMR)
- Gesmolten Zout Reactoren (MSR)

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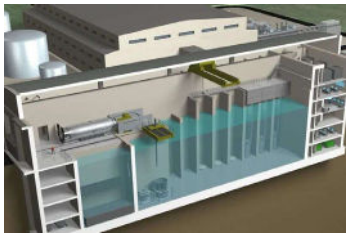
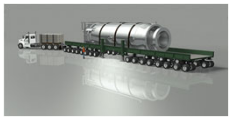
NuScale SMR VOYGR



77 MWe per module
1 module per 200.000 huishoudens
4, 6 of 12 modules geschakeld
Kostenreductie 50% (claim)
Operationeel 2030



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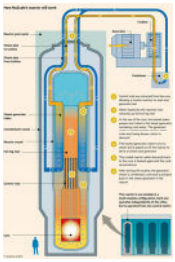
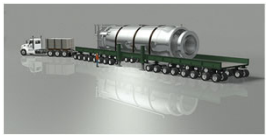
NuScale SMR VOYGR



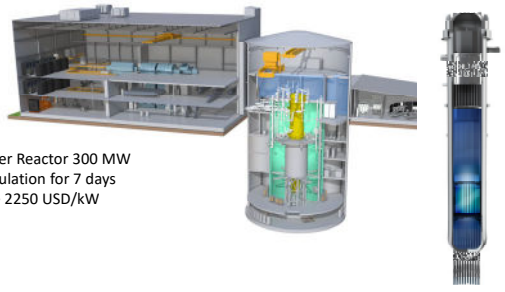


Geschatte kostenreductie bijna 50%

50

50

General Electric BWRX-300 SMR



Boiling Water Reactor 300 MW
Natural circulation for 7 days
Target price 2250 USD/kW
Proven at:
By:

51

51

General Electric BWRX-300 SMR

Boiling Water Reactor 300 MW
Natural circulation for 7 days
Target price 2250 USD/kW
Proven at: Dodewaard, NL
By:

52

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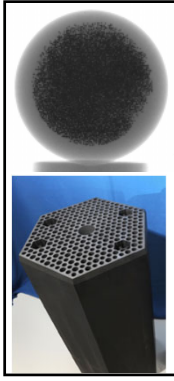
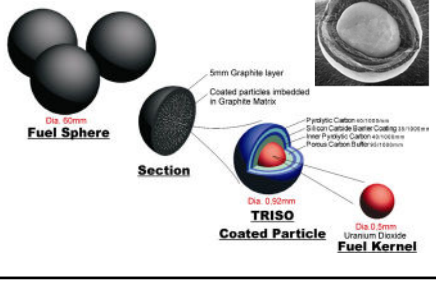
HTGR splijtstof





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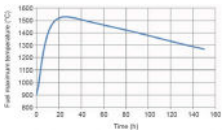
HTR-10, Beijing, China (2000)



Temperatuur bij verlies aan koelmiddel in HTR-PM

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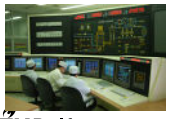
Hoge Temperatuur Gasgekoelde Reactor

HTR-10 Beijing
First criticality dec 2000



HTR-PM 2x250 MWt
Power 210 MWe
First criticality
12-09-2021

https://world-nuclear-news.org/Articles/Chinas-HTR-PM-reactor-achieves-first-criticality

55

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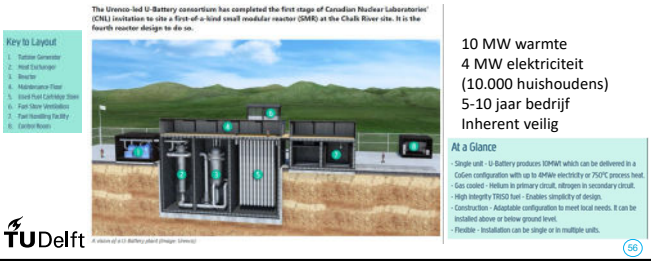
U-Battery

Onderzoek bij TU Delft en Manchester Uni
Commerciële ontwikkeling door Urenco c.s.



10 MW warmte
4 MW elektriciteit
(10.000 huishoudens)
5-10 jaar bedrijf
Inherent veilig

56

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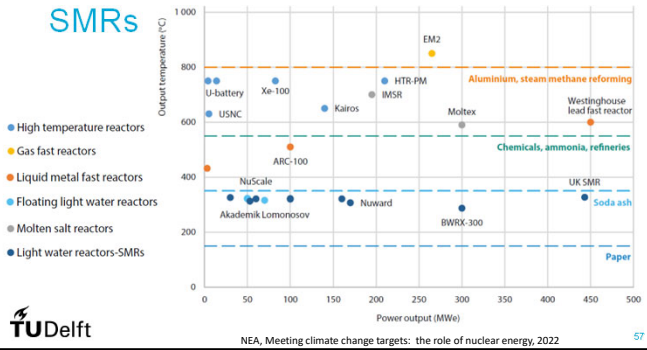
SMRs



NEA, Meeting climate change targets: the role of nuclear energy, 2022

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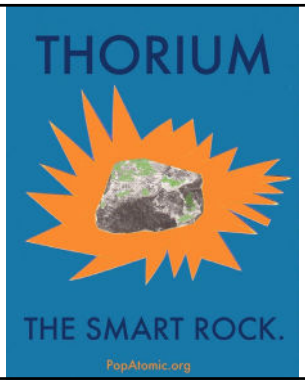

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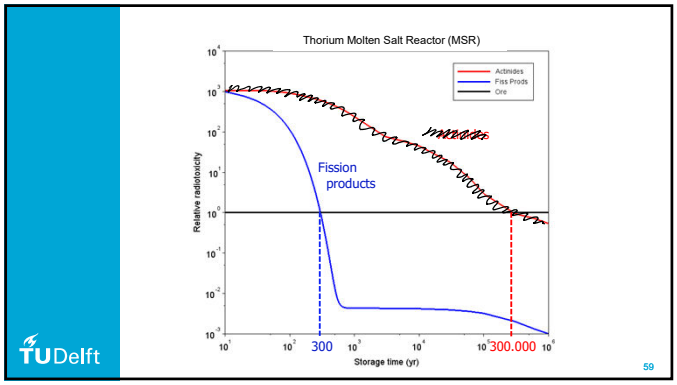

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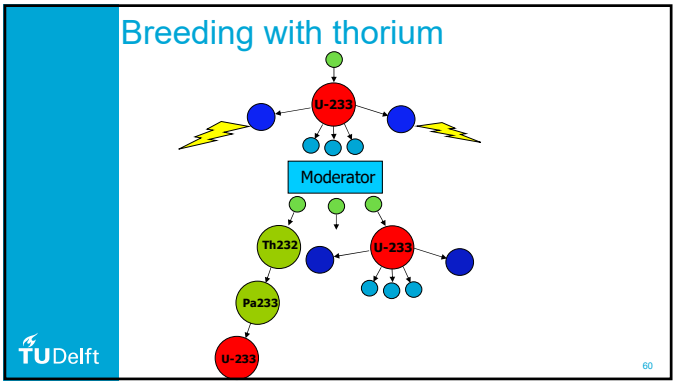

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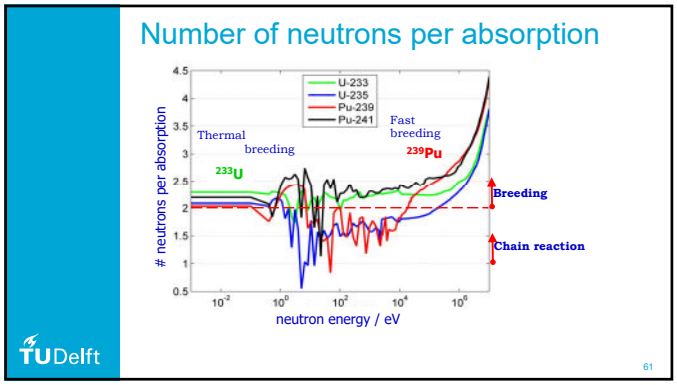

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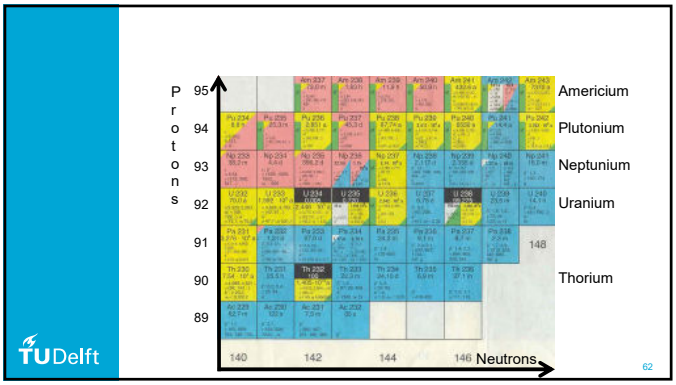

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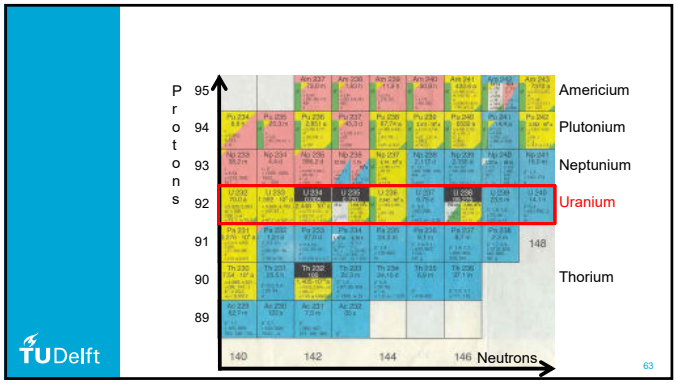

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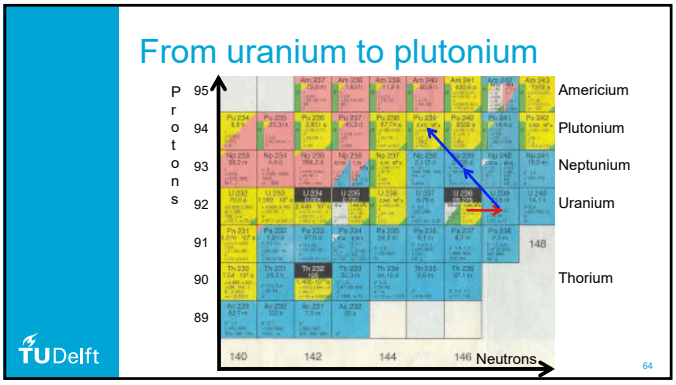

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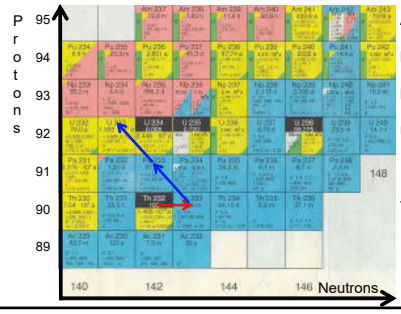
From thorium to uranium-233



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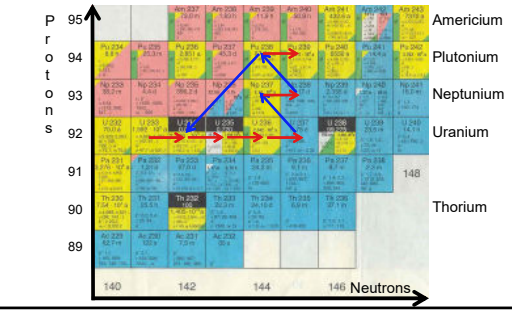
From uranium-233 to plutonium



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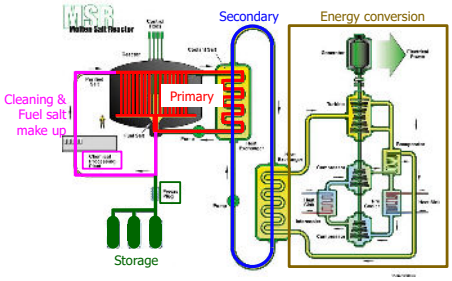
Molten Salt Reactor (MSR)



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Heat Transfer Reactor Experiments (1956)

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Heat Transfer Reactor Experiment 3 (1958-1960)

HTRE-3
(30
MWth)

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Aircraft Nuclear Propulsion program

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Alvin Weinberg
1915-2006

https://www.ornl.gov/content/alvin-m-weinberg-fellowship

Alvin's 3P reactor
1952

https://en.wikipedia.org/wiki/Aqueous_homogeneous_reactor

wikimedia commons, GNU

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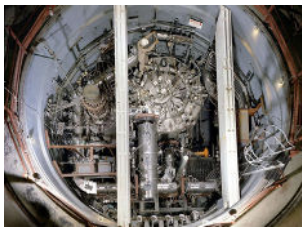
Molten Salt Reactor Experiment
1965-1969



https://en.wikipedia.org/wiki/Molten-Salt_Reactor_Experiment

See movie: http://energyfromthorium.com/2016/10/16/ornl-msre-film/

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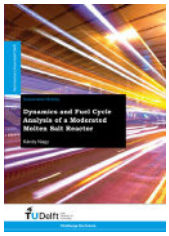
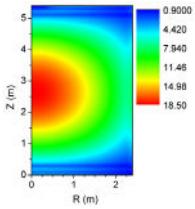
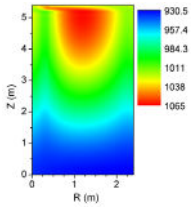
TUD Molten Salt Breeder Reactor





Power density [MW/m³]



Salt temperature [K]

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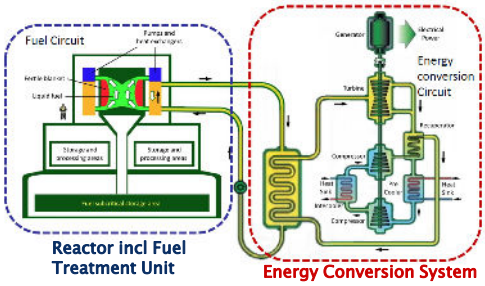
Molten Salt Fast Reactor



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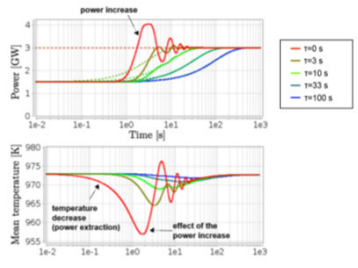
MSFR Load follow operation



50% power change in just a few minutes!

Elsa Merle-Lucotte *et al*, CNRS, France

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Thorium by-product mining

Summary of Cumulative By-Product Thorium Availability from Multiple Sources

Primary Commodity	Potential Associated Thorium Yield (tonnes/yr Th)
Titanium	79 800
Uranium	9000
REEs ("Direct")	780
Tin	760
Iron	330
Total	90 700

40 years of global electricity production!

Ault *et al*, Nuclear Technology, **189**:152-162, 2015

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Abundancy of thorium

On some beaches the energy contents of one kilogram of sand corresponds to thousands of litres of gasoline

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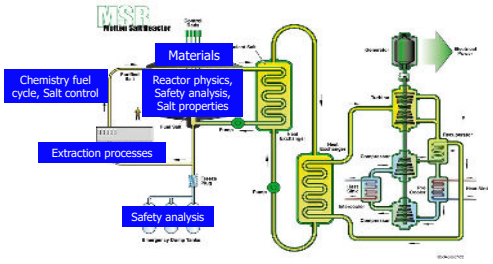
MSR research themes



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European SAMOFAR project

Safety analysis of the Molten Salt Fast Reactor

SAMOFAR

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European SAMOSAFER project

SAMOSAFER

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European MIMOSA project

MIMOSA

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MSR Start ups

And more ....

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Conclusies

- ‘Economy of scale’ voor grootschalige elektriciteitsproductie
- Nieuwe generatie LWRs zijn zeer veilig èn voordelig in de energiemix
- ‘Economy of number’ (SMR) in opkomst
- Gesmolten zout reactoren (MSR)
  - Thorium-uranium, geen productie plutonium
  - Thorium-plutonium, versplijten plutonium
  - Uranium-plutonium, optioneel

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Conclusions

- Thorium-MSR power plant:
  - Is safe and sustainable
  - Produces much less long-lived nuclear waste
  - Consumes thorium, uranium or plutonium+
- Research areas:
  - Fuel salt (properties, chemistry, extraction, (re)processing)
  - Structural materials (radiation, temperature, corrosion)
  - Numerical simulation (design, safety analysis, licensing)
  - Experimental validation (freeze plugs, salt flow, freezing, components testing, …)

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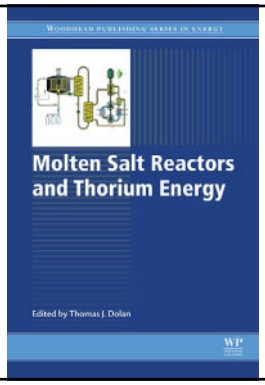

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