De toekomst van kernenergie

Prof Jan Leen Kloosterman
Delft University of Technology

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REACTOR INSTITUTE DELFT

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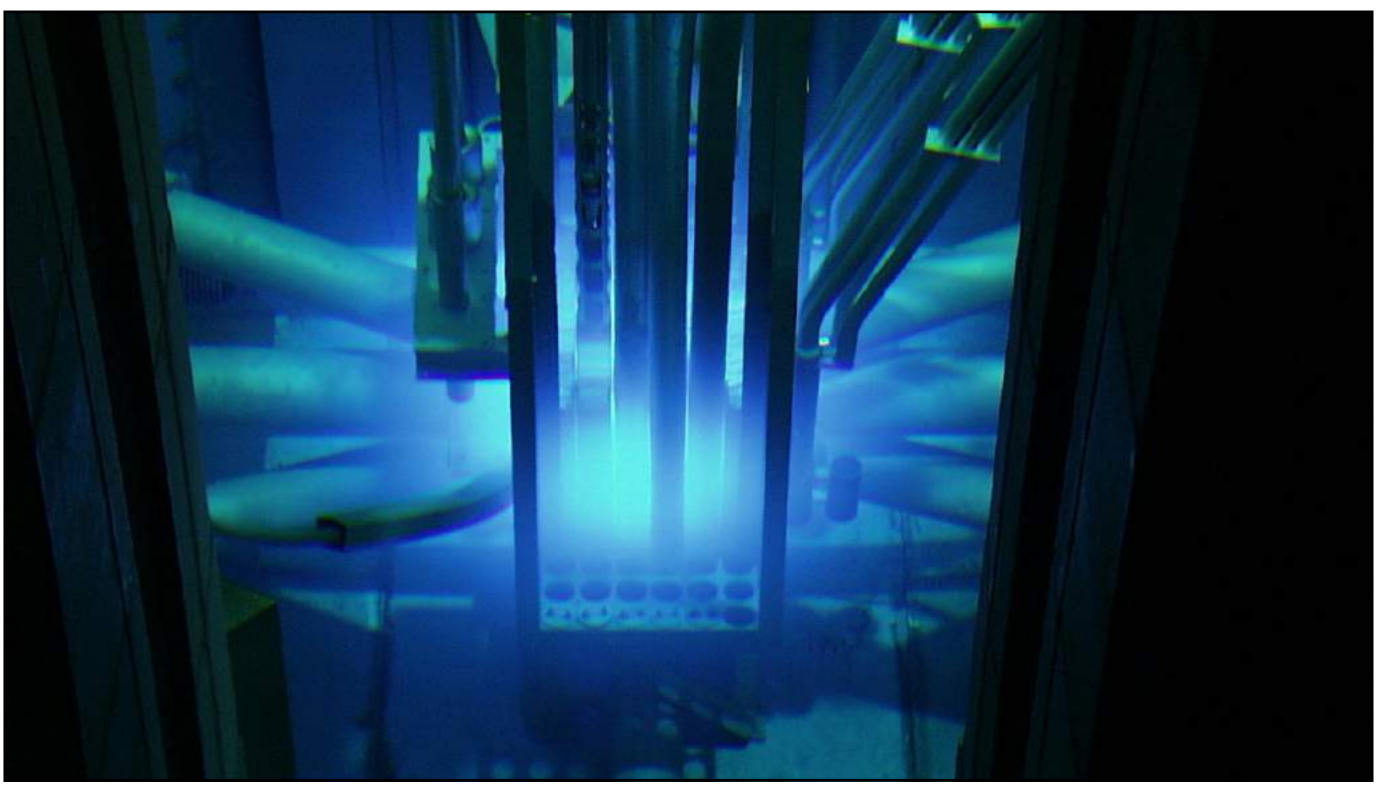

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CO2 budget

Global warming between 1850–1900 and 2010–2019 (°C)	Historical cumulative CO_2 emissions from 1850 to 2019 *(GtCO₂)*
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 *(GtCO₂)* — *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

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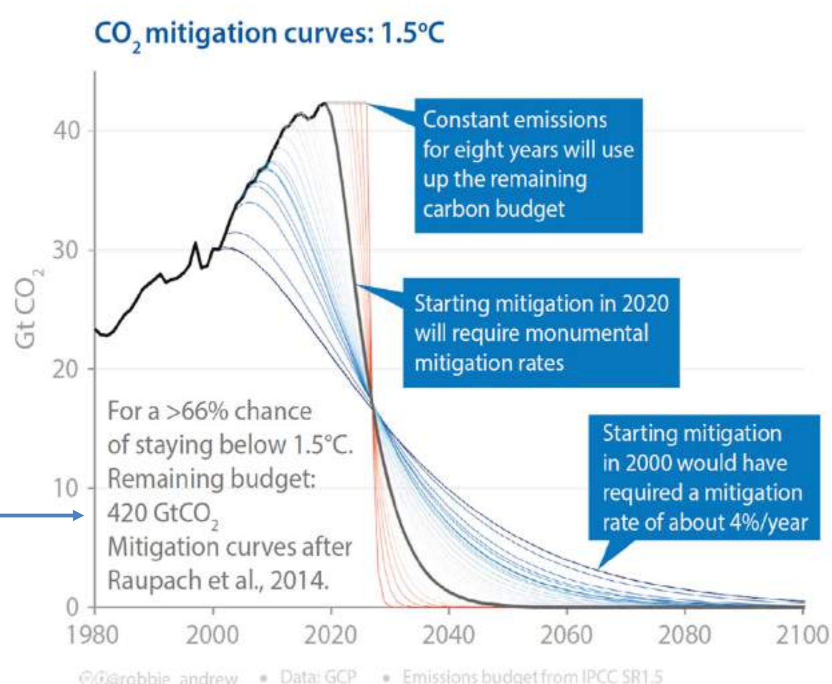
IPCC, Climate Change 2021; The Physical Science Basis, 2021

230-670 GtCO2

https://doi.org/10.1038/s43247-020-00064-9 (2021)



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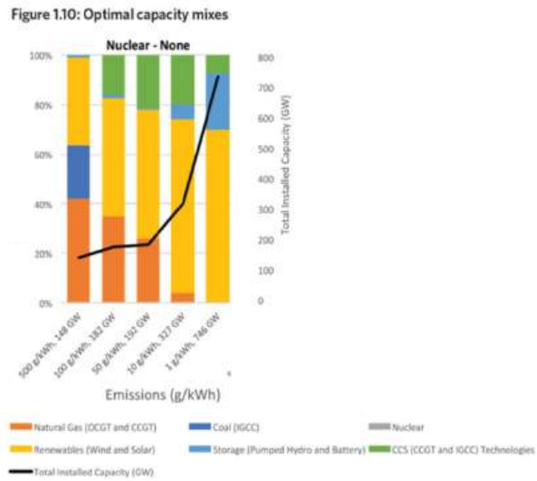
NEA, Meeting climate change targets: the role of nuclear energy, 2022

System mix electricity generation



MIT, The Future of Nuclear Energy in a Carbon-Constrained World, 2018

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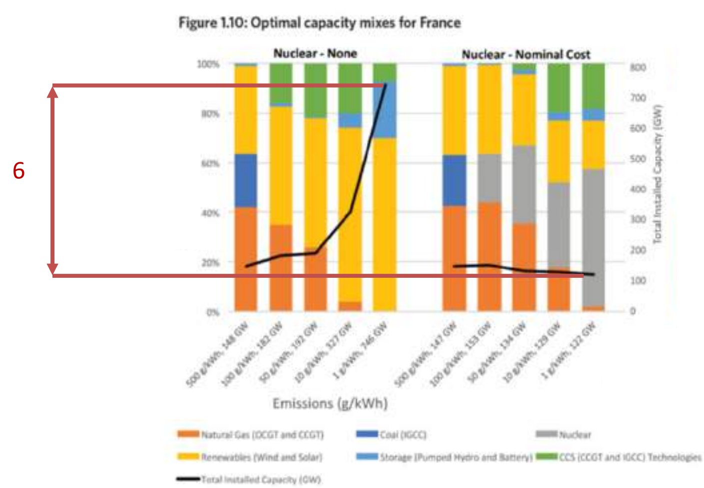
System mix electricity generation



MIT, The Future of Nuclear Energy in a Carbon-Constrained World, 2018

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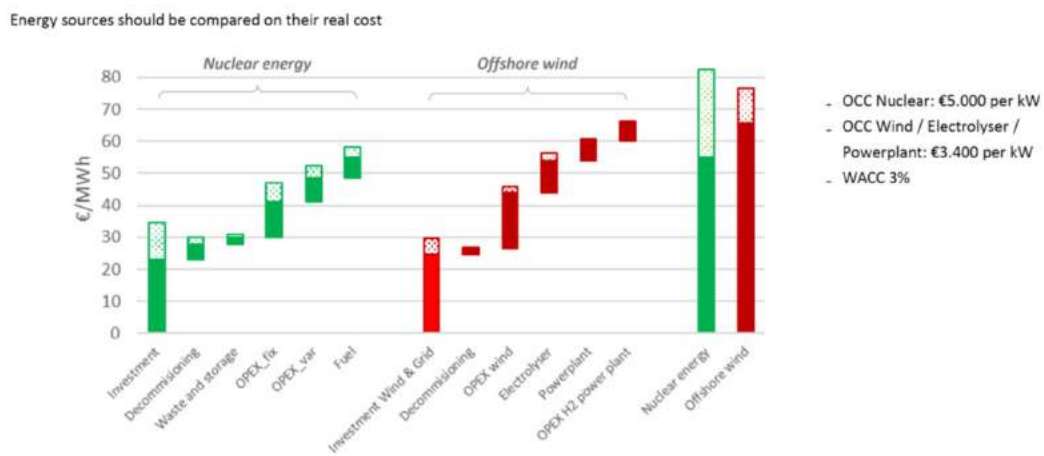
Real costs including backup



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Schalij en Van der Kloot Meyburg, De rol van Kernenergie in het Nederlandse energiesysteem, E-risk, (2020)

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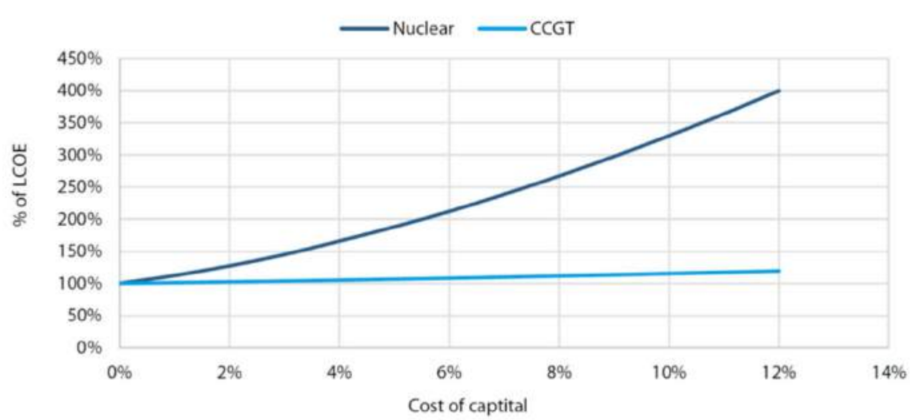
NPP cost vs cost of capital

Figure 10: **Generation costs as a function of the cost of capital, nuclear power vs. CCGT**



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OECD-NEA, Unlocking reductions in the construction costs of nuclear, 2020

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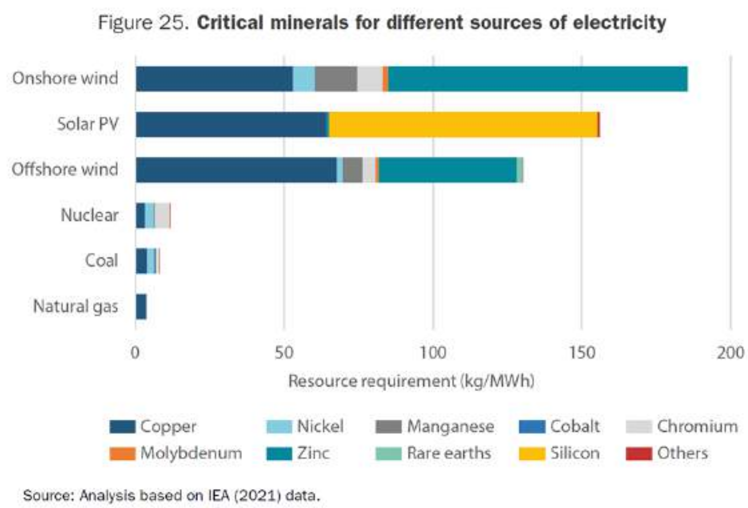
Critical mineral needs



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

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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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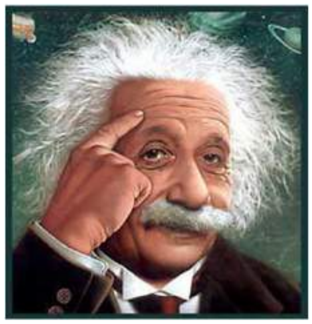
Werking van kerncentrales



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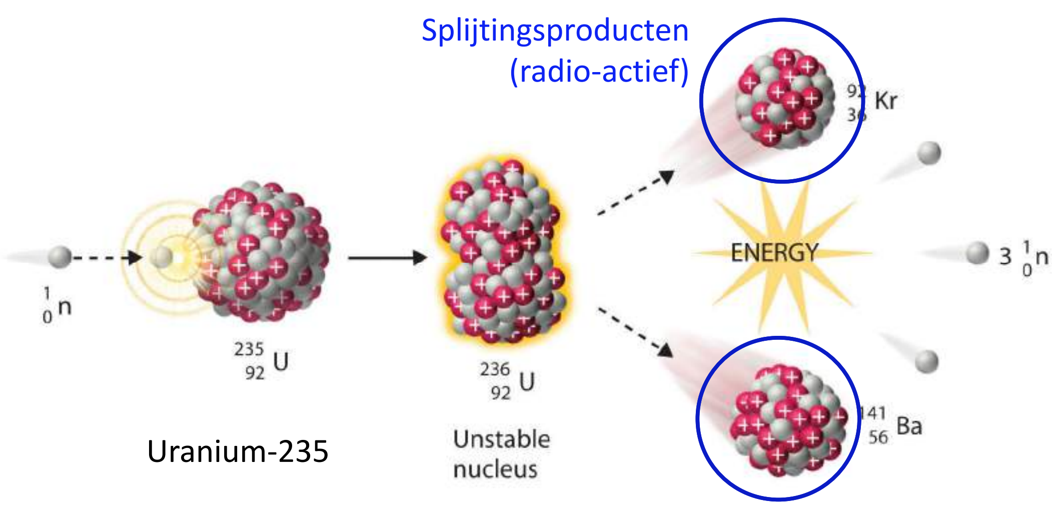
Kernsplijting



Chemwiki, CCPL

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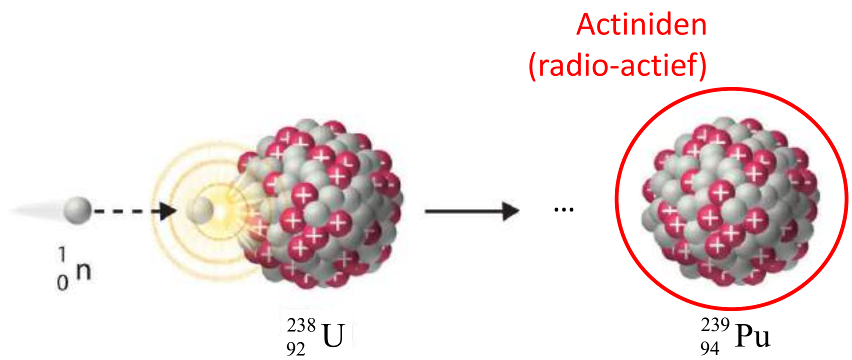
Productie van plutonium



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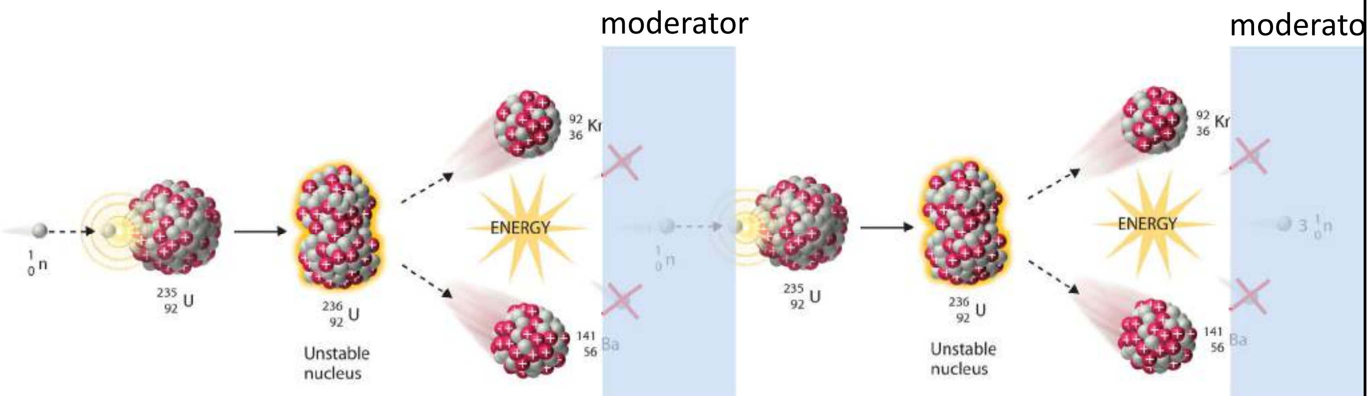
Splijtings kettingreactie



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Chemwiki, CCPL

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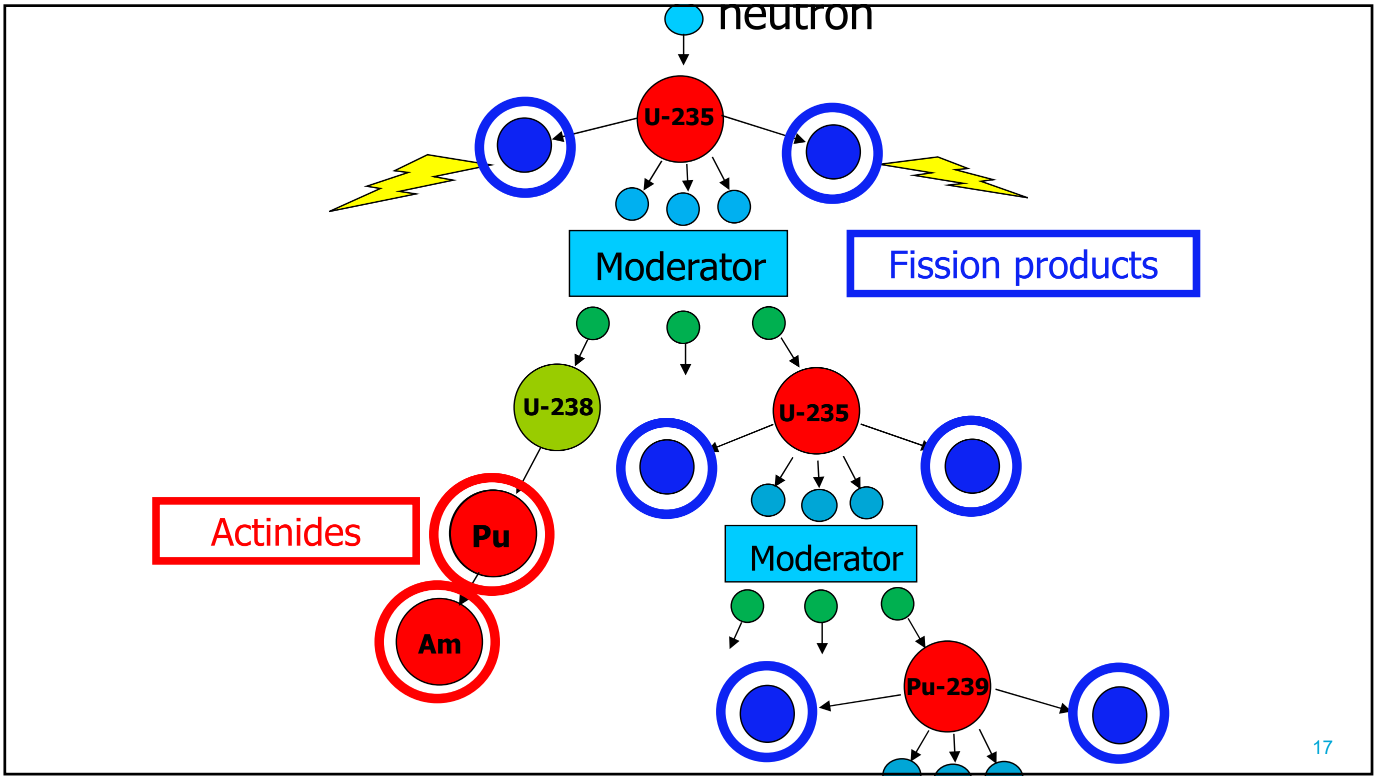

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Energy from 1 gram U-235

Gasoline

2500 liter

Coal

3000 kg

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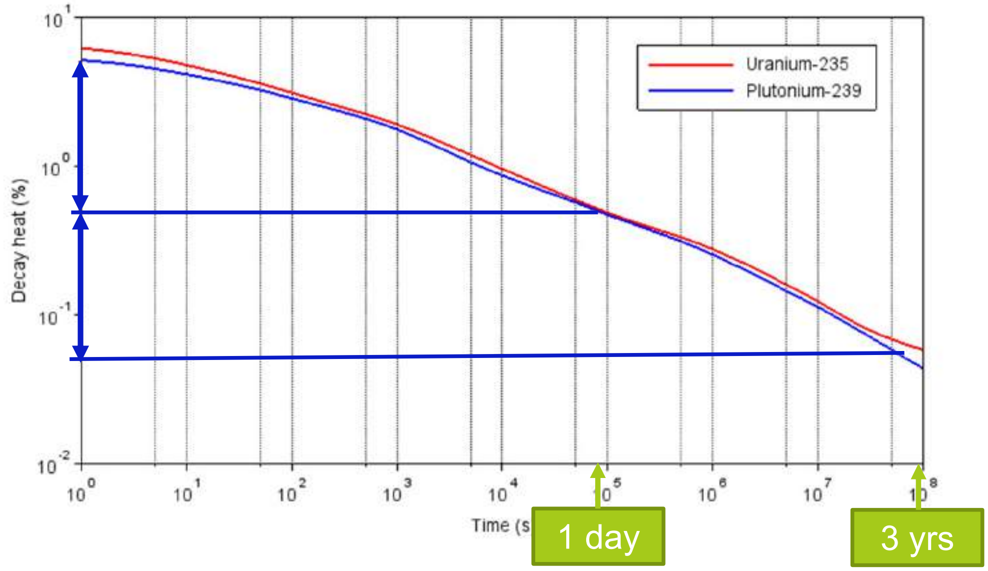
Decay heat production



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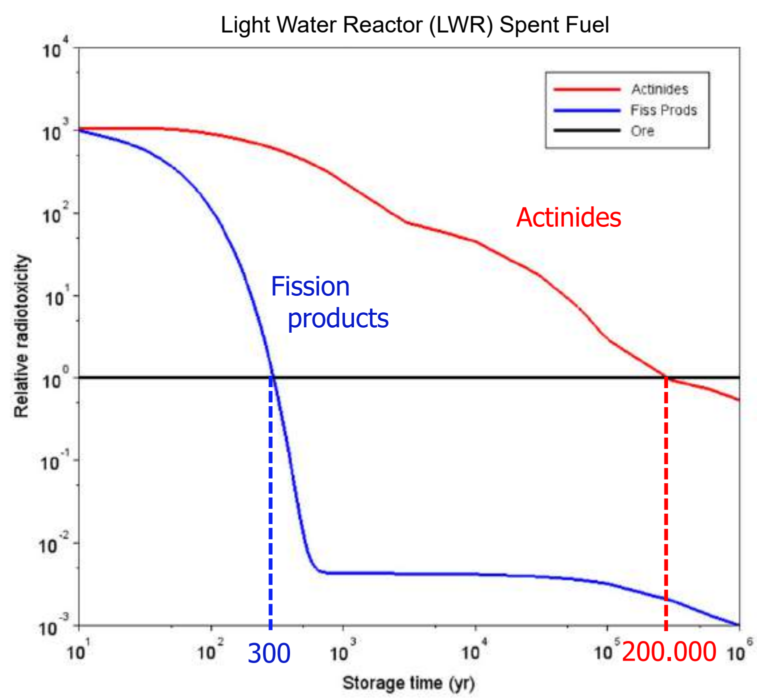

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Opslag van kernafval COVRA

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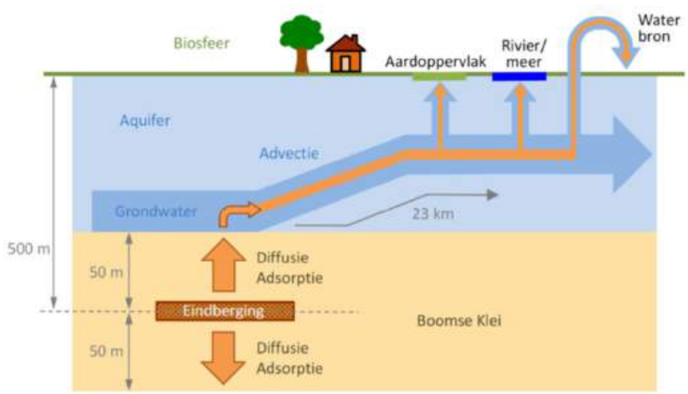
Geological disposal



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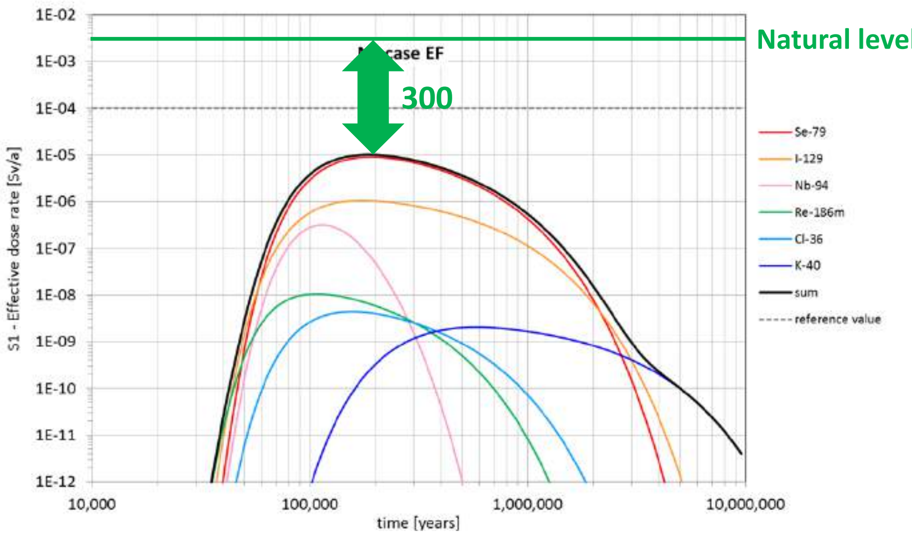
Dose values in Boom clay
Early failure scenario (1000 year)

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 23

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Ontwikkelingen in Kernenergie

LWR

SMR

MSR

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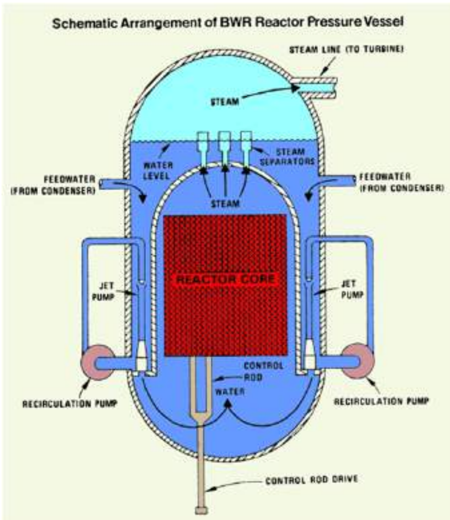
Generaties BWR

gen II



gen III

gen III+

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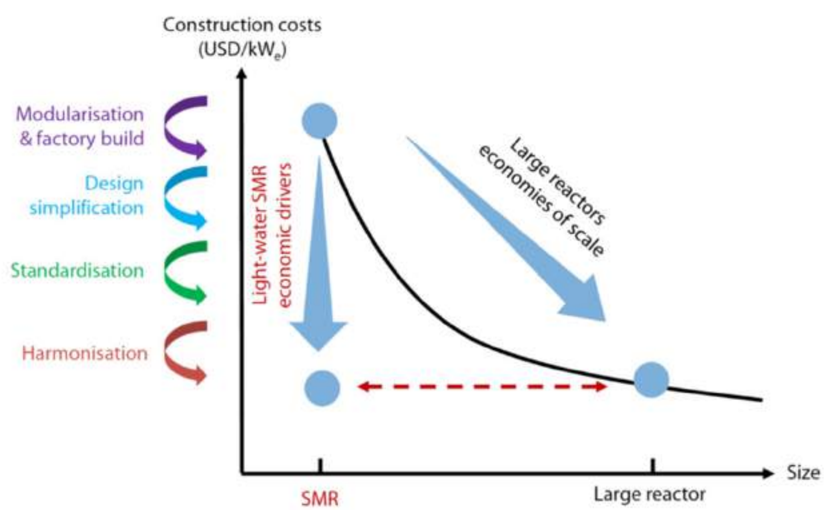
Cost reduction SMR



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

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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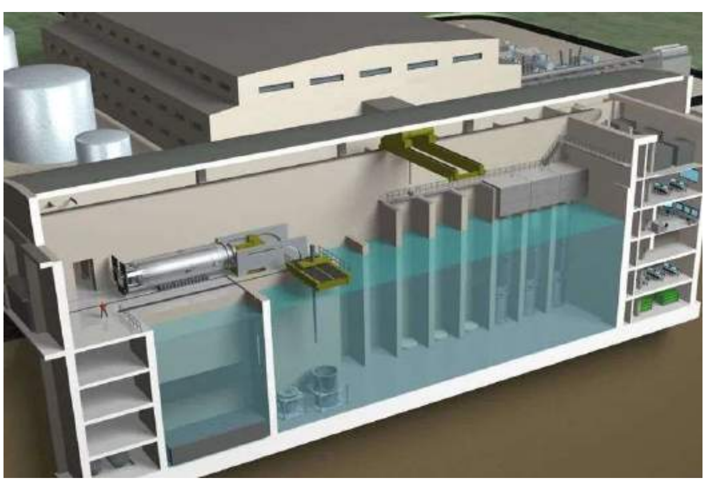
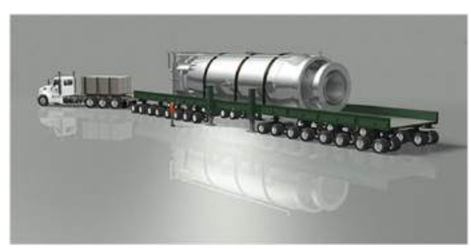
NuScale SMR VOYGR



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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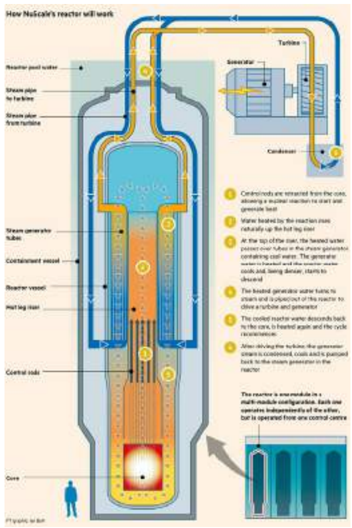
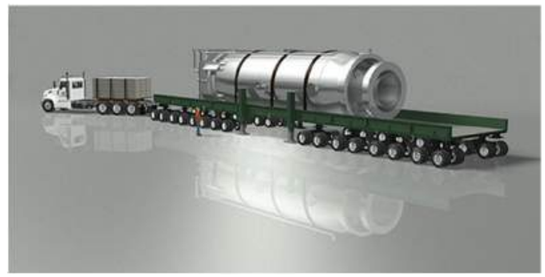
NuScale SMR VOYGR





Geschatte kostenreductie bijna 50%

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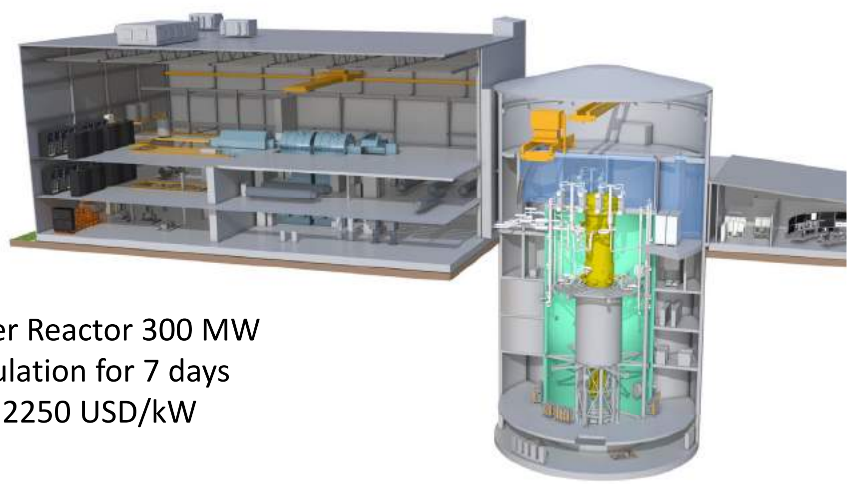
General Electric BWRX-300 SMR



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

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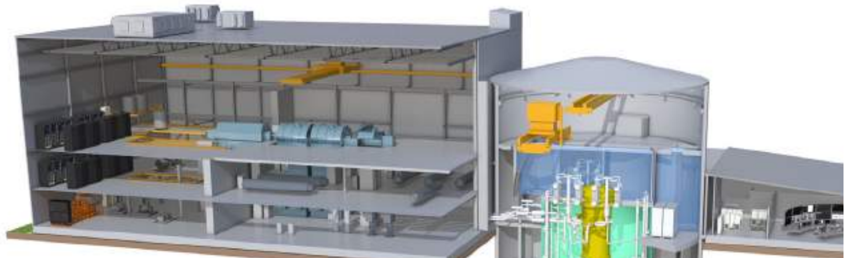
General Electric BWRX-300 SMR



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

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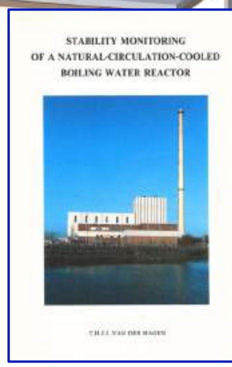

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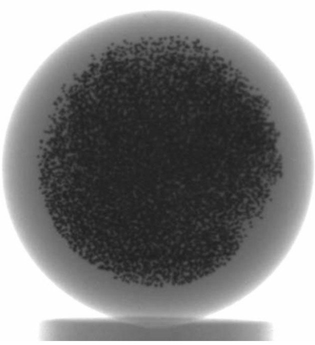
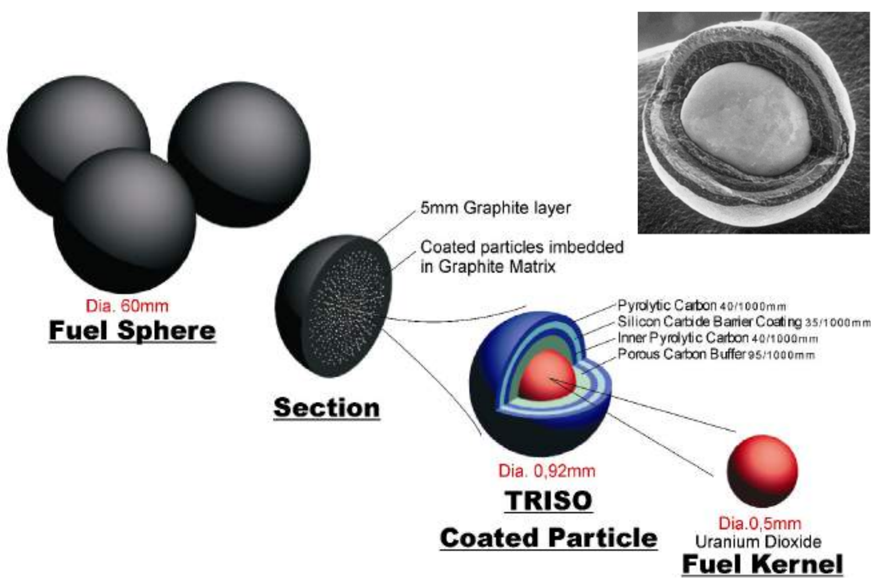


HTGR splijtstof



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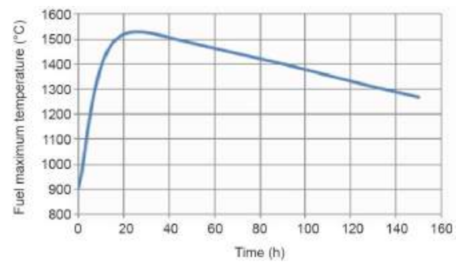
HTR-10, Beijing, China (2000)



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

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

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

The Urenco-led U-Battery consortium has completed the first stage of Canadian Nuclear Laboratories' (CNL) invitation to site a first-of-a-kind small modular reactor (SMR) at the Chalk River site. It is the fourth reactor design to do so.

Key to Layout

1. Turbine Generator
2. Heat Exchanger
3. Reactor
4. Maintenance Floor
5. Used Fuel Cartridge Store
6. Fuel Store Ventilation
7. Fuel Handling Facility
8. Control Room

A vision of a U-Battery plant (Image: Urenco)

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

At a Glance

- Single unit - U-Battery produces 10MWt which can be delivered in a CoGen configuration with up to 4MWe electricity or 750°C process heat.
- Gas cooled - Helium in primary circuit, nitrogen in secondary circuit.
- High integrity TRISO fuel - Enables simplicity of design.
- Construction - Adaptable configuration to meet local needs. It can be installed above or below ground level.
- Flexible - Installation can be single or in multiple units.

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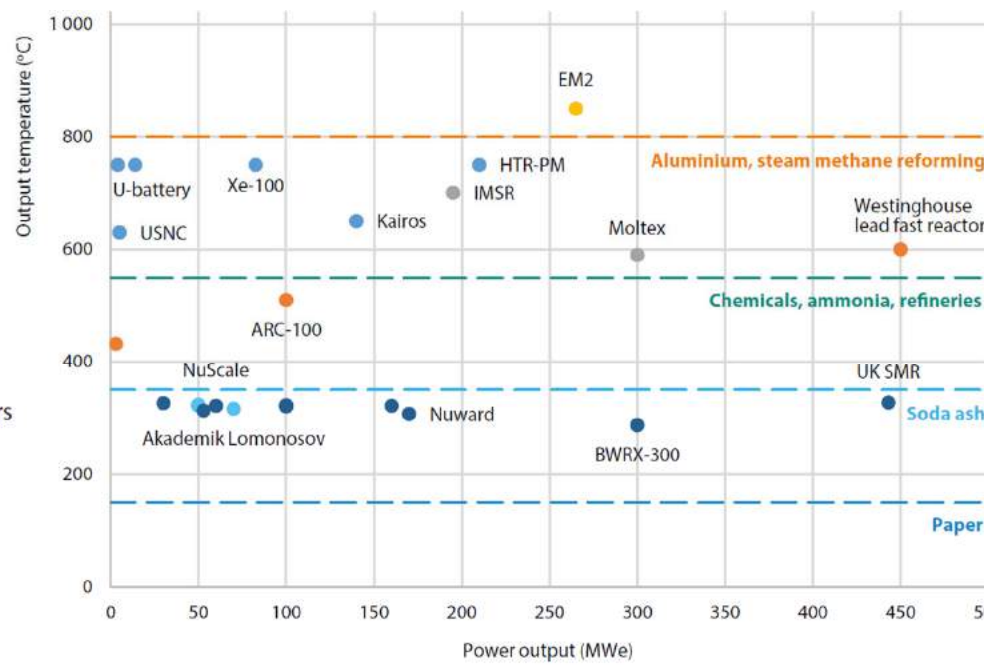
SMRs

- High temperature reactors
- Gas fast reactors
- Liquid metal fast reactors
- Floating light water reactors
- Molten salt reactors
- Light water reactors-SMRs



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

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Imagine a reactor with…

- No surplus of fuel in the core
- No decay heat removal issue
- No high pressure coolant
- No volatile fission products
- No long-lived nuclear waste
- Virtually unlimited resources

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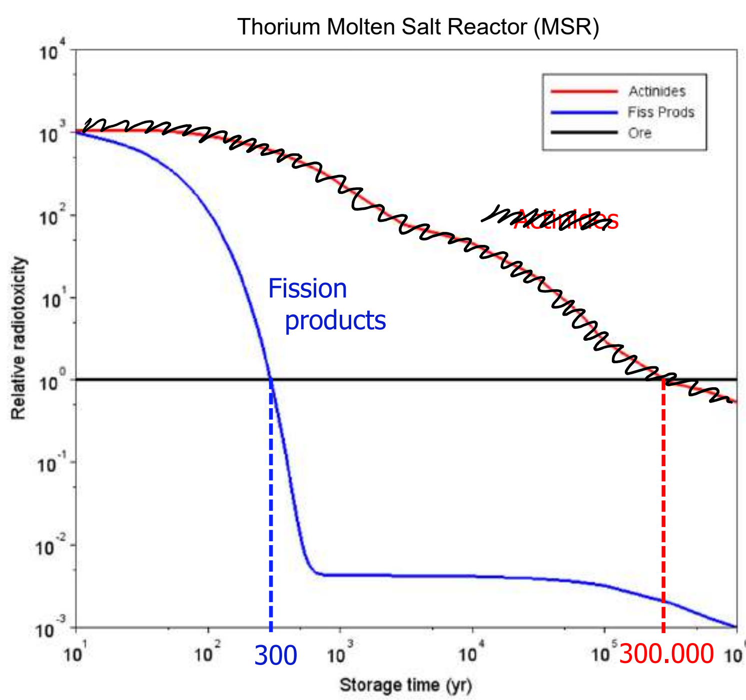

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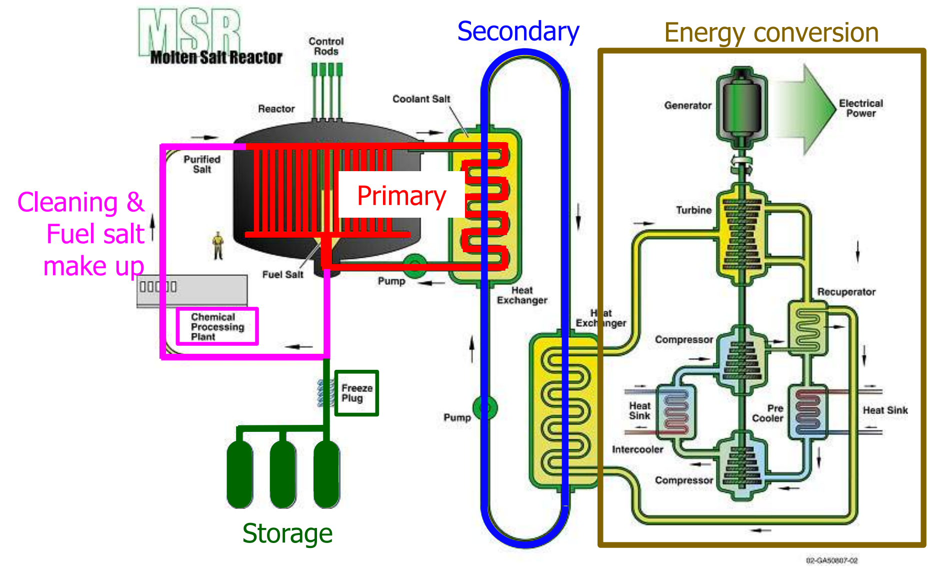
Molten Salt Reactor (MSR)



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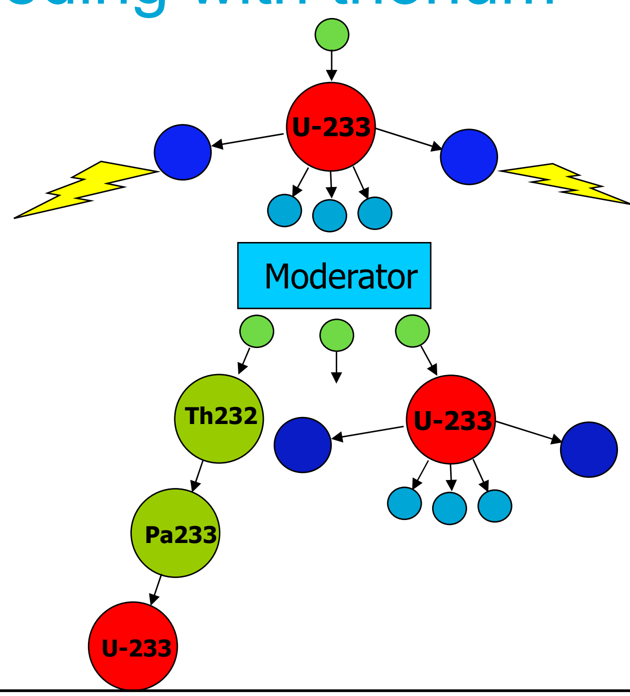
Breeding with thorium



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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

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wikimedia commons, GNU 41

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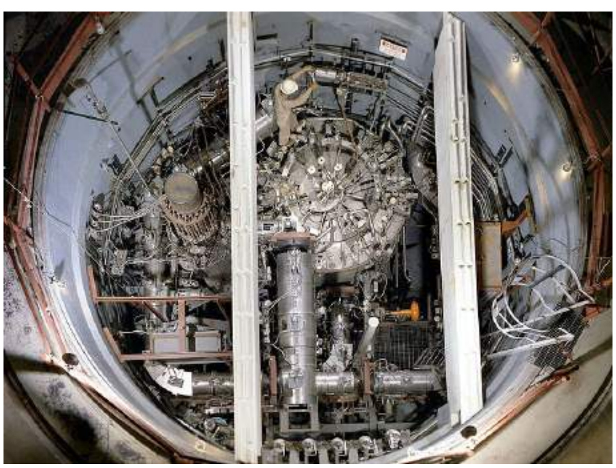
Molten Salt Reactor Experiment
1965-1969



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

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

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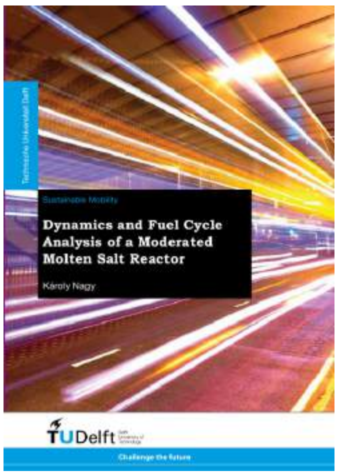
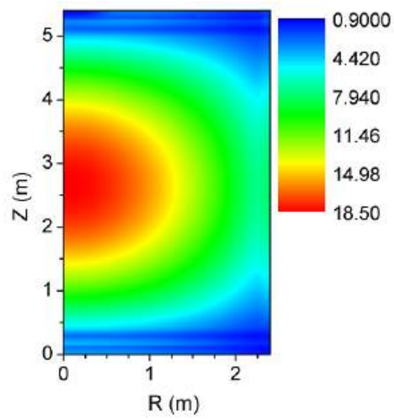
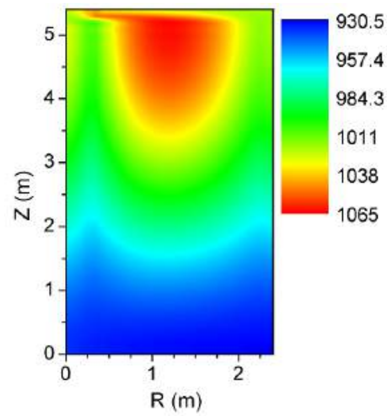
TUD Molten Salt Breeder Reactor





Power density [MW/m^3]



Salt temperature [K]

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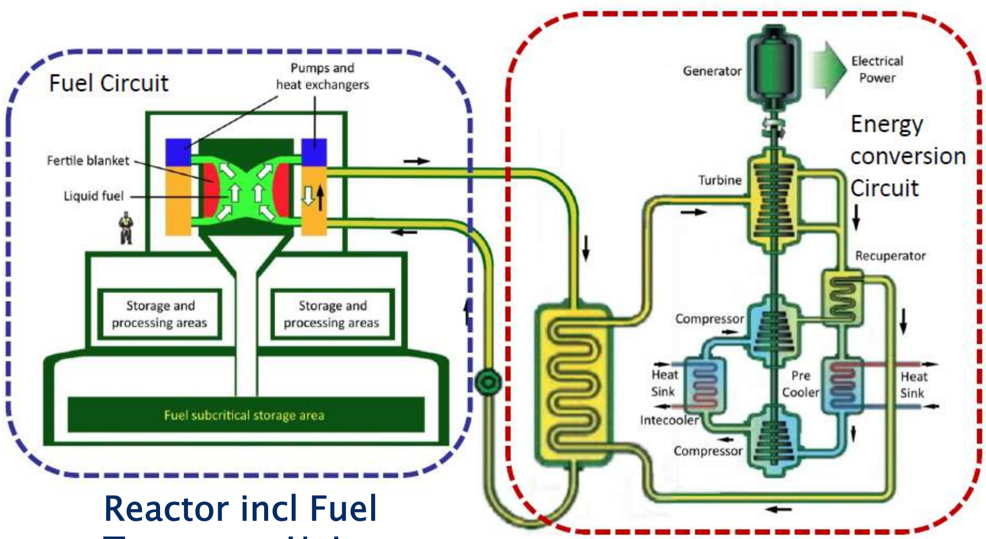
Molten Salt Fast Reactor



Reactor incl Fuel Treatment Unit

Energy Conversion System

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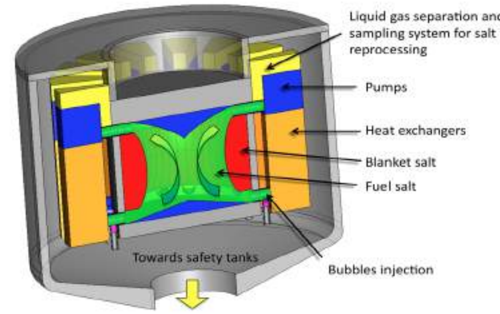
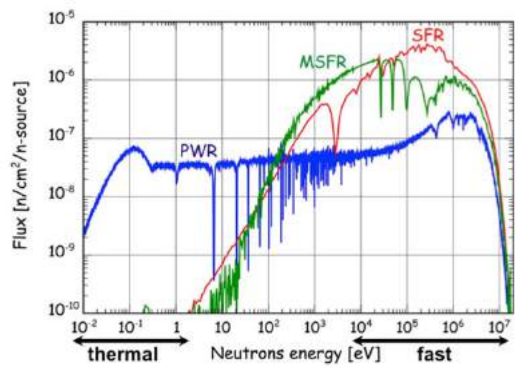
Thermal power	3000 MWth
Mean fuel salt temperature	725 °C
Fuel salt temperature rise in the core	100 °C
Fuel molten salt - Initial composition	LiF-ThF_4-UF_4-$(TRU)F_3$ with (77.7-6.7-12.3-3.3 mol%) and U enriched at 13%
Fuel salt melting point	585 °C
Fuel salt density	4.1 g/cm³
Fuel salt dilation coefficient	8.82 10^{-4} / °C
Fertile blanket salt - Initial composition	LiF-ThF_4 (77.5%-22.5%)
Breeding ratio (steady-state)	1.1
Total feedback coefficient	-5 to -8 pcm/K
Core dimensions	Diameter: 2.26 m Height: 2.26 m
Fuel salt volume	18 m³ (½ in the core + ½ in the external circuits)
Blanket salt volume	7.3 m³
Total fuel salt cycle	3.9 s





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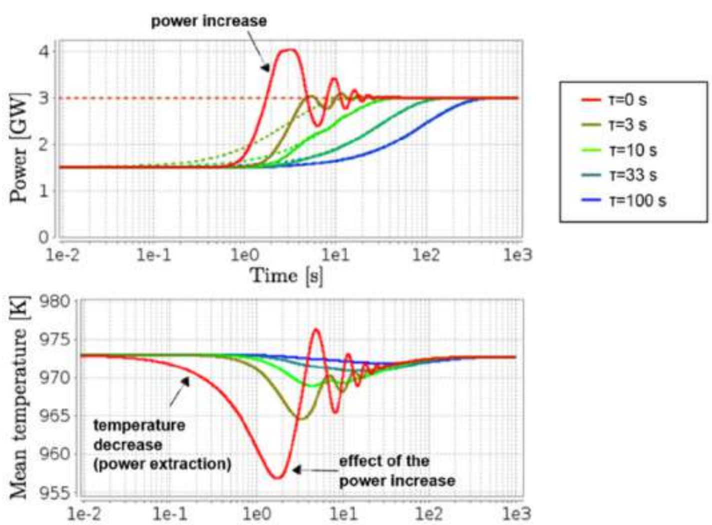
MSFR Load follow operation



50% power change in just a few minutes!

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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!

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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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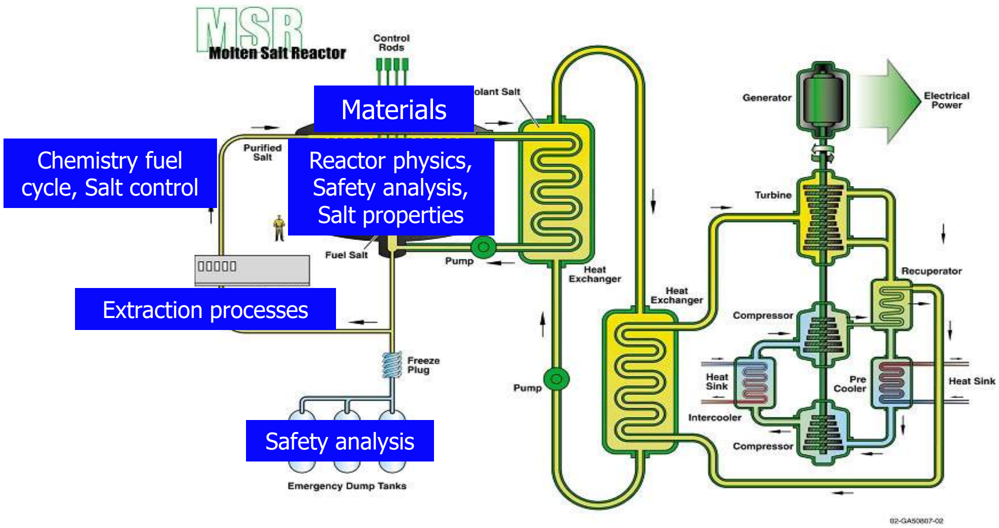
MSR research themes



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European SAMOFAR project

Safety analysis of the Molten Salt Fast Reactor

cnrs · TU Delft · CIRTEN · EDF · SAMOFAR · Cinvestav Unidad Saltillo · cea · IRSN Institut de Radioprotection et de Sûreté Nucléaire · KIT Karlsruher Institut für Technologie · Paul Scherrer Institut PSI · European Commission · AREVA

European SAMOSAFER project

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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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