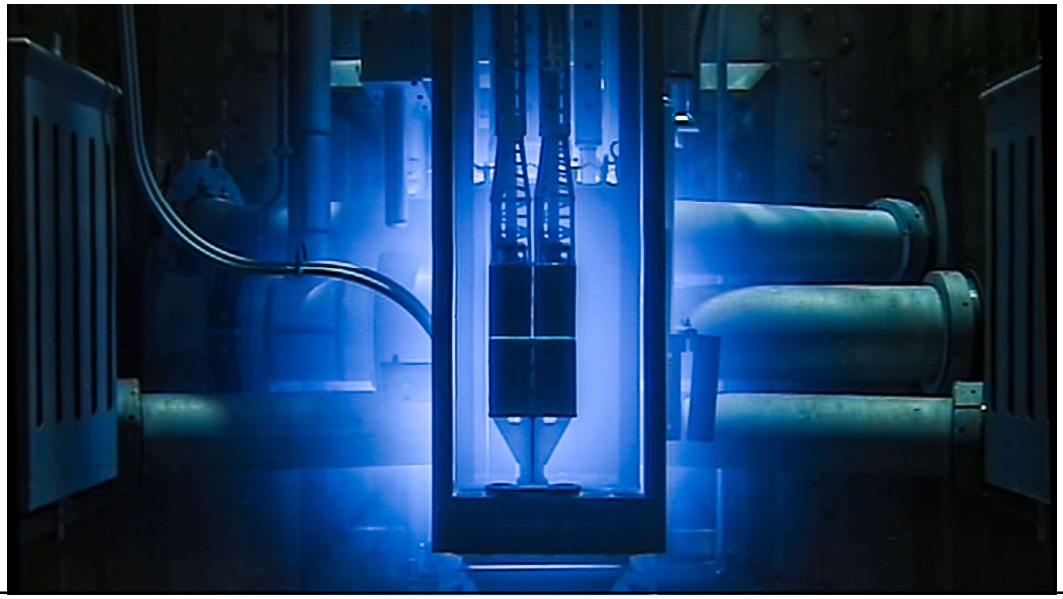
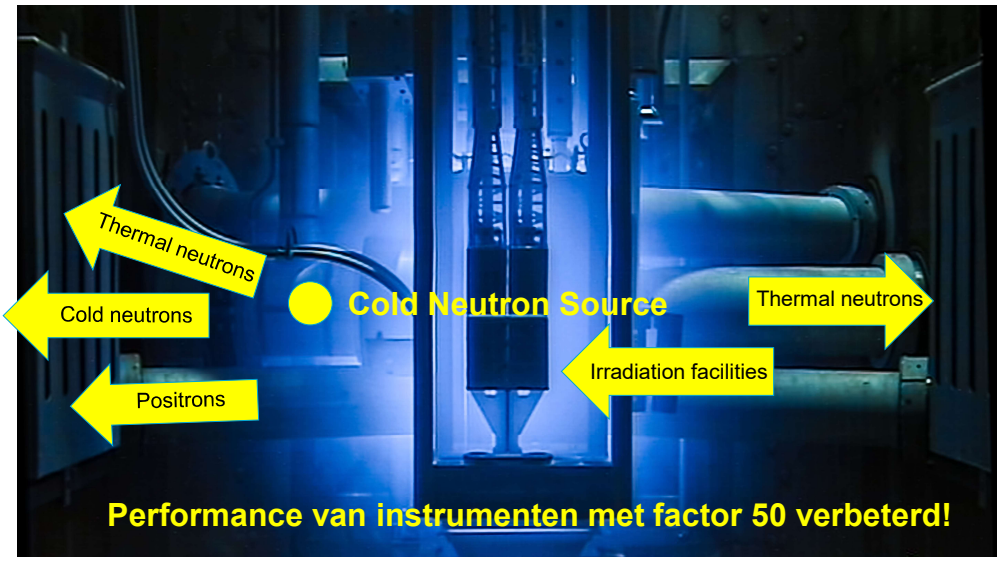
1

Wat is de kleur van Kernenergie?



2

OYSTER upgrade project succesvol afgerond



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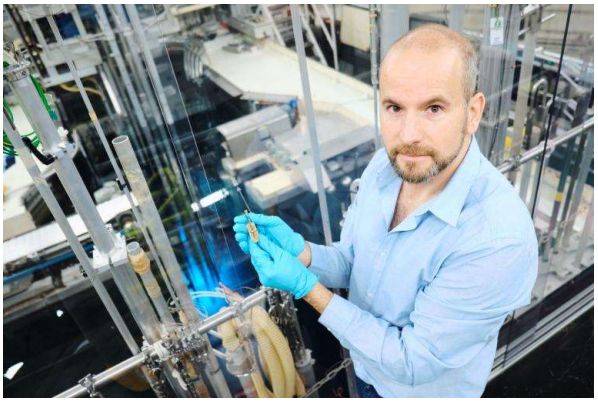
Neutrons



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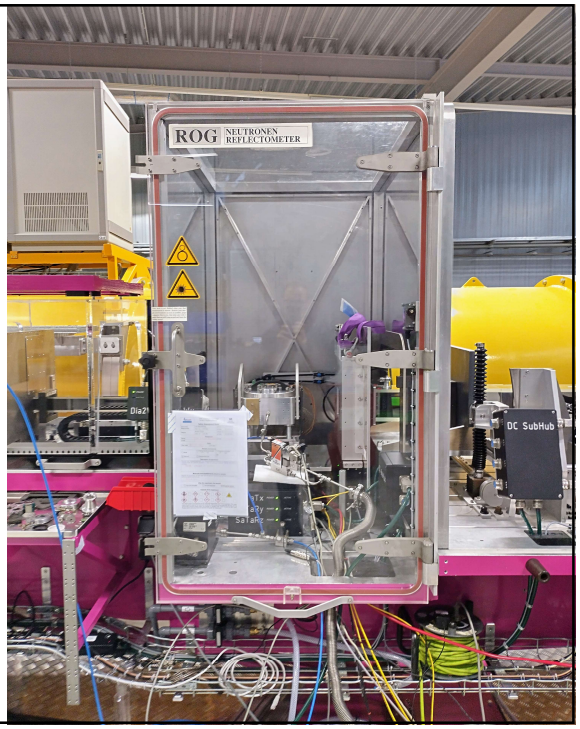

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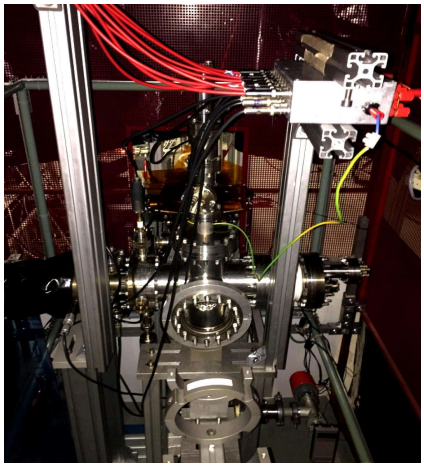
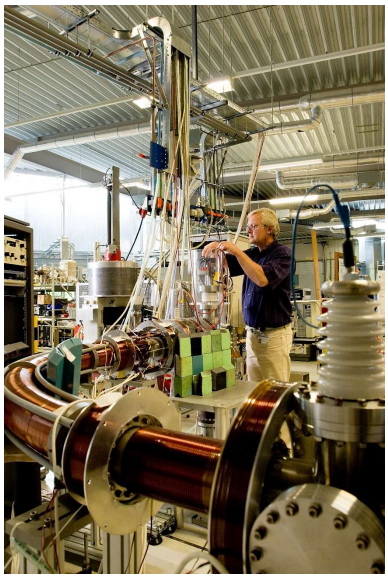
Positrons





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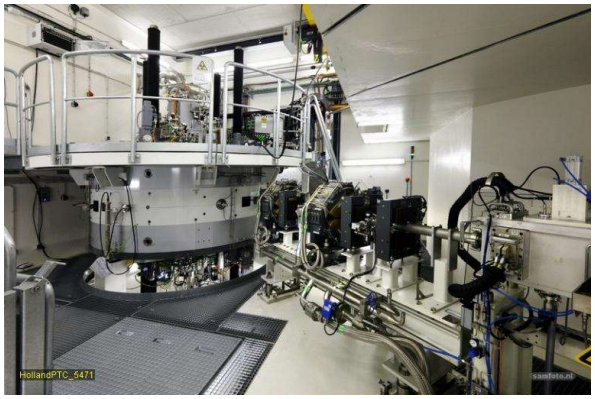
Protons



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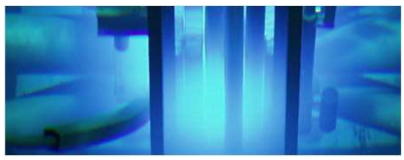
Radionuclides



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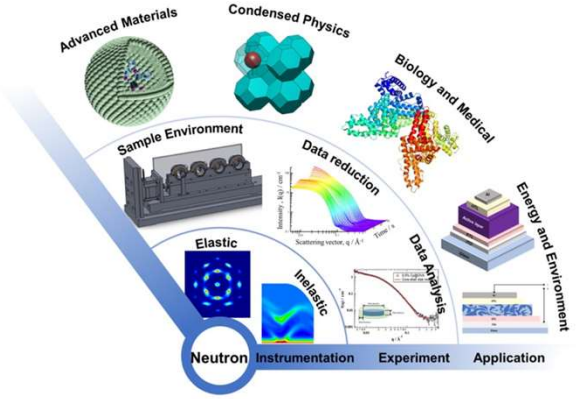
Toepassingen neutronen en positronen

- Battery materials
- Magnetism
- Colloid science
- Food science
- Polymers science
- Drug delivery systems
- Cultural heritage
- Fundamental physics
- Hydrogen economy
- CO2 storage
- Solar-PV
- Semi-conductors
- Etc.



TU Delft De Energietransitie is een Materialentransitie !

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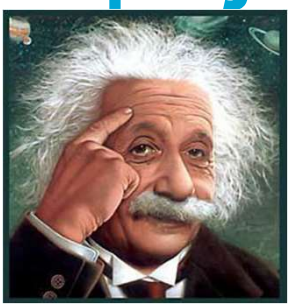
Noodzaak van kernsplijting



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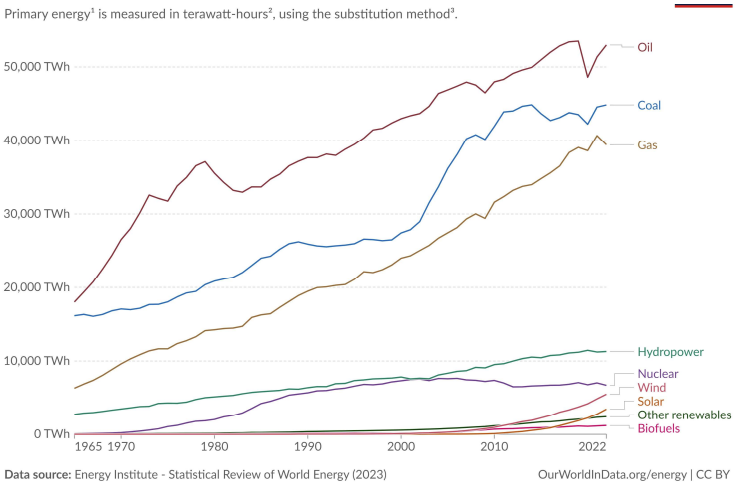
Primary energy consumption



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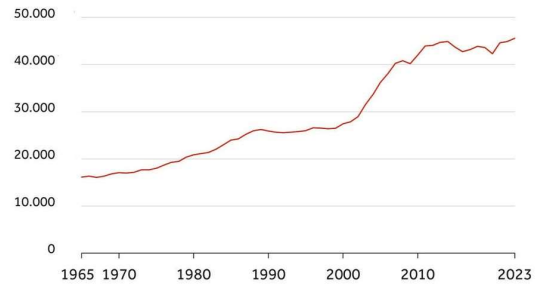
More information: https://www.iea.org/reports/key-world-energy-statistics-2021/final-consumption

10

Steenkoolverbruik wereldwijd

In terawattuur (TWh)



bron: bewerking van Our World in Data

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17 nov 2024

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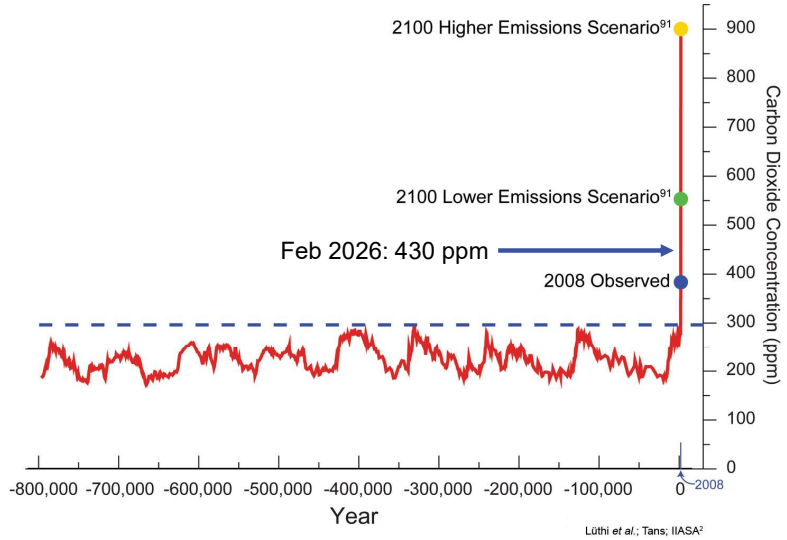

Lüthi *et al.*; Tans; IIASA[2]

Analysis of air bubbles trapped in an Antarctic ice core extending back 800,000 years documents the Earth's changing carbon dioxide concentration. Over this long period, natural factors have caused the atmospheric carbon dioxide concentration to vary within a range of about 170 to 300 parts per million (ppm). Temperature-related data make clear that these variations have played a central role in determining the global climate. As a result of human activities, the present carbon dioxide concentration of about 385 ppm is about 30 percent above its highest level over at least the last 800,000 years. In the absence of strong control measures, emissions projected for this century would result in the carbon dioxide concentration increasing to a level that is roughly 2 to 3 times the highest level occurring over the glacial-interglacial era that spans the last 800,000 or more years.

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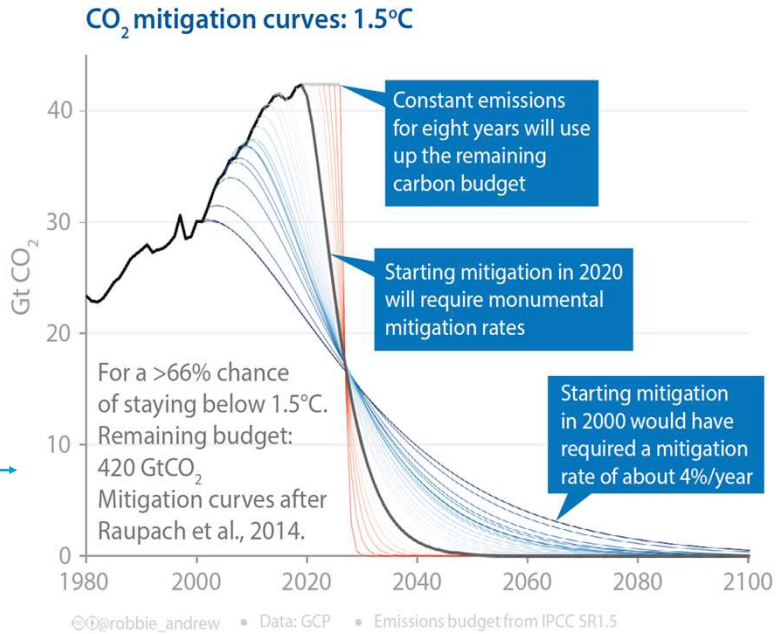
CO2 emissie

230-670 GtCO2

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



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

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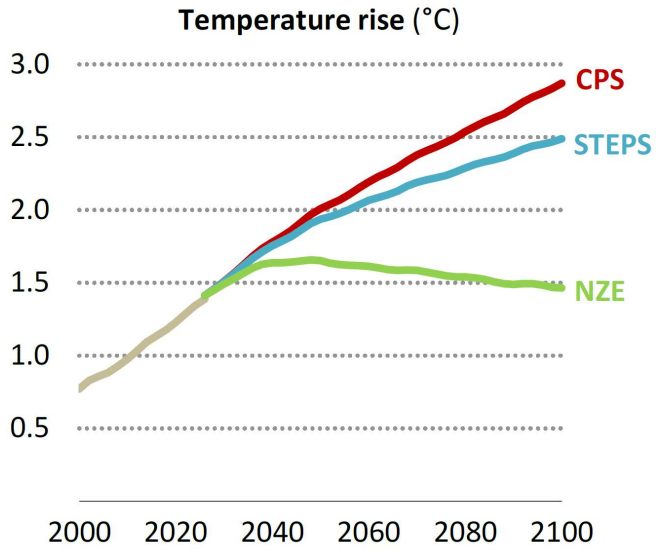

Notes: Gt = gigatonnes. CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario; NZE 20xx = NZE Scenario in the *World Energy Outlook* of the specified year. The figure shows median long-term average global temperature anomaly relative to 1850-1900 and matches the Intergovernmental Panel on Climate Change Sixth Assessment Report definition of warming of 0.85 °C between 1995-2014.

Sources: IEA analysis based on MAGICC 7.5.3 and IPCC (2022).

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Kernenergie karakteristieken

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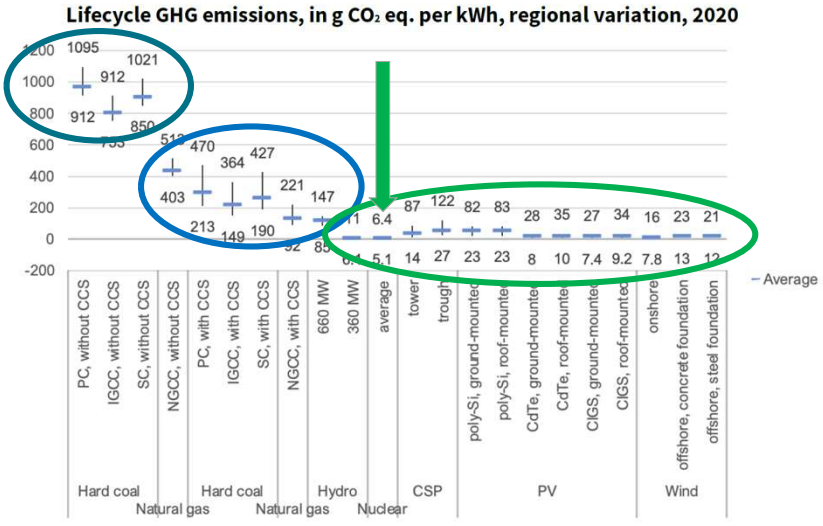
CO2 emission



Life cycle assesment of electricity generation options, United nations economic commission for Europe, 2021

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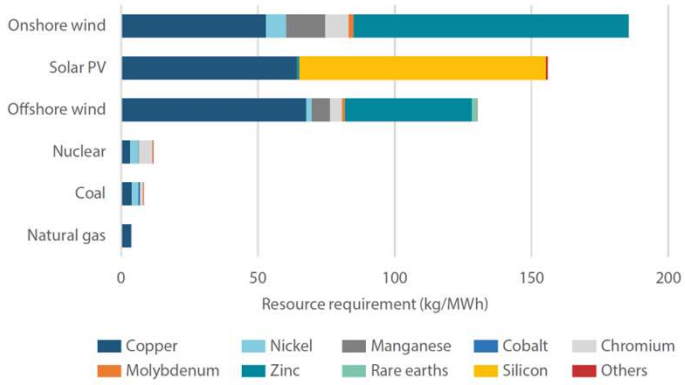
Critical mineral needs

Figure 25. **Critical minerals for different sources of electricity**



Source: Analysis based on IEA (2021) data.

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

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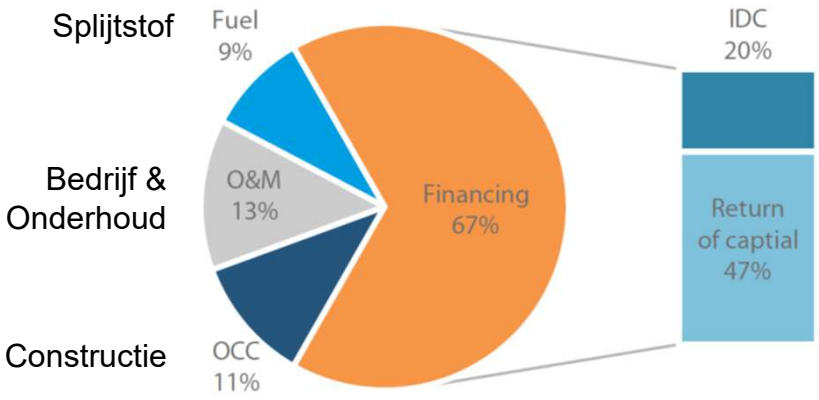
Kosten kernenergie



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

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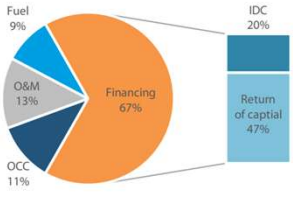
Uitleg kosten kernenergie

Table 2: **Cost breakdown for nuclear power levelised cost of electricity**

Levelised cost of electricity (LCOE) of nuclear power	**Levelised capital costs**	**Capitalised investment costs**	**Overnight construction costs (OCC):** includes the materials, components, manpower and cost of capital required to design, construct and commission the plant.
			Capitalised financial costs (CFC): includes interest during construction (IDC) and related fees.
		Return of capital: the cost of capital, which is a combination of the cost of debt (i.e. loan) and required return on equity (from the shareholders). IDC can also be added to this cost category to isolate the overall **financing costs.**	
	Operation and maintenance costs		**Operations and maintenance (O&M) costs:** all costs related to staffing, consumables and recurring maintenance activities necessary for safe operations once the plant has been built and commissioned.
			Fuel cycle cost: cost of the fuel used to produce electricity. In the case of nuclear power, includes costs related to mining, enrichment and the manufacture of fuel assemblies to be loaded in the core (i.e. front-end activities), as well as to managing the used nuclear fuel and waste (i.e. back-end activities).
	Decommissioning costs: Costs associated with dismantling the plant once it has reached the end of its lifetime and returning the site to greenfield state.		



Note: Calculations based on OCC of USD 4 500 per kilowatt of electrical capacity (/kW$_e$), a load factor of 85%, 60-year lifetime and 7-year construction time at a real discount rate of 9%.

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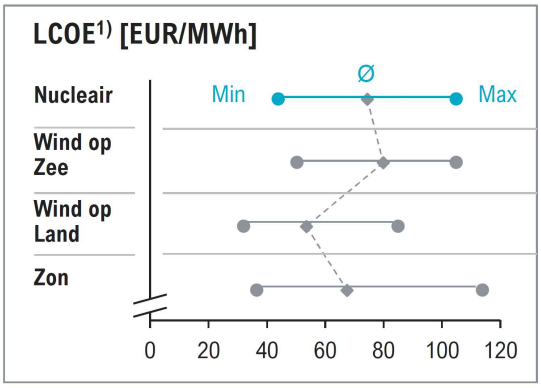
Kosten kernenergie in de electriciteitsmix



1) Ramingen op basis van verschillende bronnen: Kalavasta: Systeem effecten van nucleaire centrales, in klimaat-neutrale Energiescenario's 2050 (8 April 2020); MIT: The future of Nuclear Energy in a Carbon-Constrained World (3 Sept 2018); Turkenburg: Factsheet Visie op de Toekomst van Kernenergie in de energie transitie (23 oktober 2019); ENCO: Possible Role of Nuclear in the Dutch Energy Mix in the Future (1 Sept 2020); EIA: Levelized Costs of New Generation Resources in the Annual Energy Outlook 2021; IRENA: Renewable power generation costs in 2021 (July 2022); 2) Minder brandstofwissels, concentratie gradueel oplopend van 5% nu naar max. 19,5% bij generatie 4 reactoren
Bron: KPMG market consultation, Kalavasta, MIT, ENCO, IEA, IRENA

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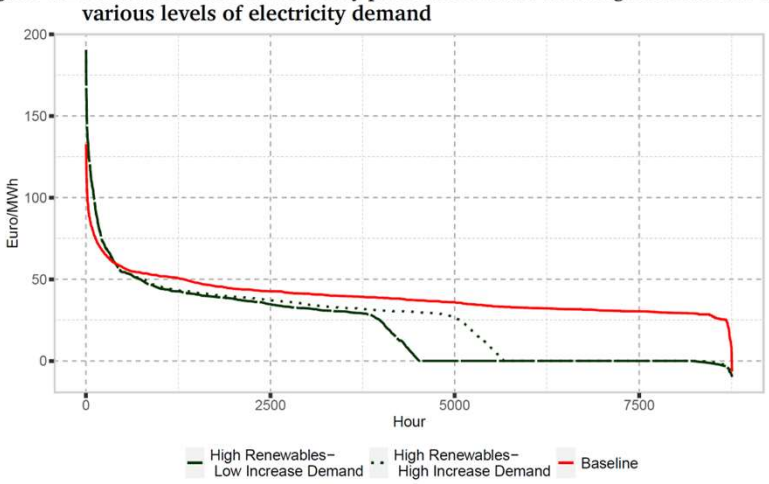
Electricity price with renewables

Figure 4.2 Duration curves of electricity price in scenarios with *High Renewables* and various levels of electricity demand



Veenstra et al, Economic Value of Nuclear Power in Future Energy Systems, CEER, RUG, 2022

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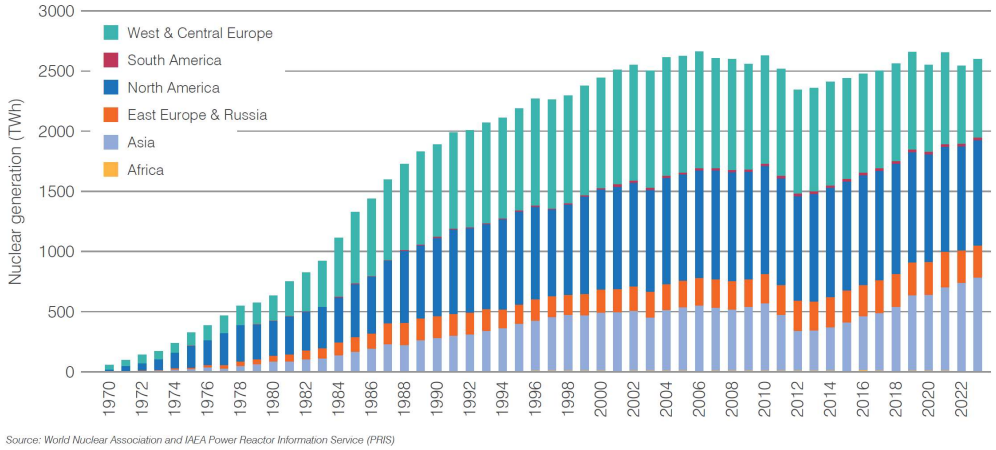
De wereld en kernenergie



Source: World Nuclear Association and IAEA Power Reactor Information Service (PRIS)

70 reactoren in aanbouw, waarvan de helft in China (2025)

https://world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide

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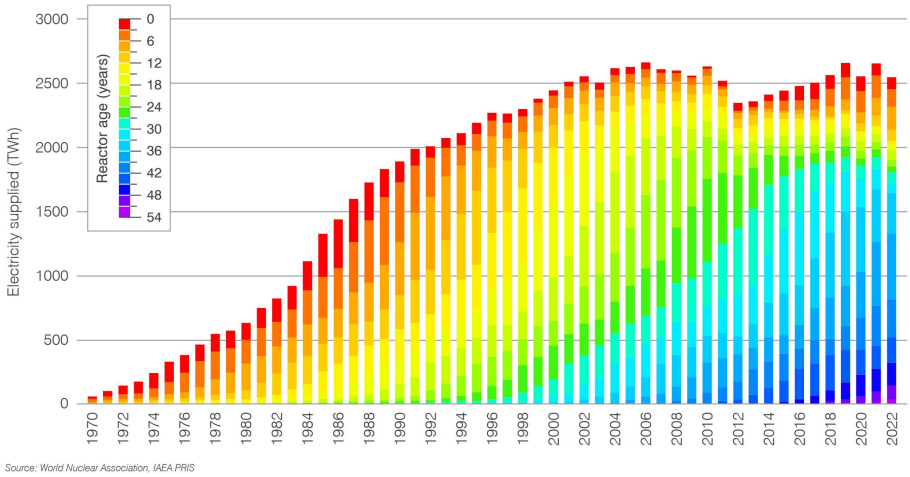
Leeftijd reactoren



Source: World Nuclear Association, IAEA PRIS

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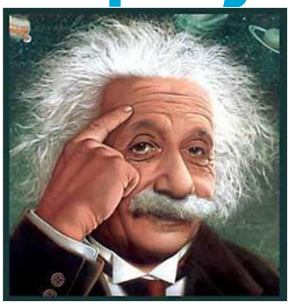
Werking van kernsplijting



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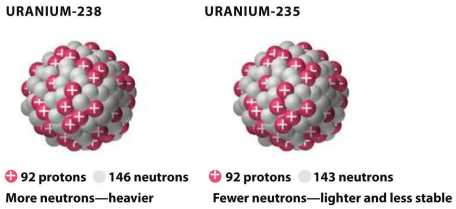
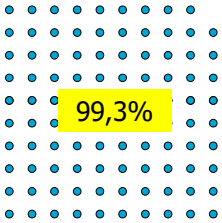
Uranium isotopen

Niet splijtbaar



Goede splijtstof



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Infographic 23.1 part 2
Environmental Science for a Changing World
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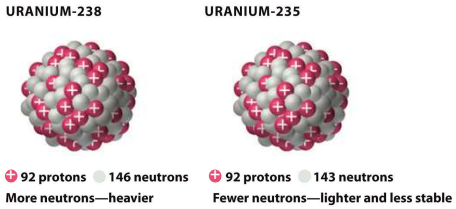
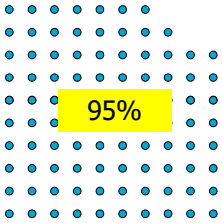
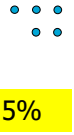
Uranium verrijking

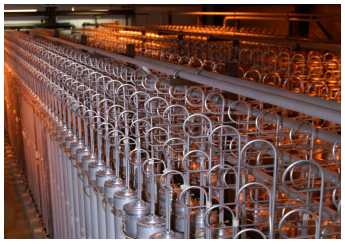
Niet splijtbaar



Goede splijtstof







Uranium enrichment centrifuges

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Infographic 23.1 part 2
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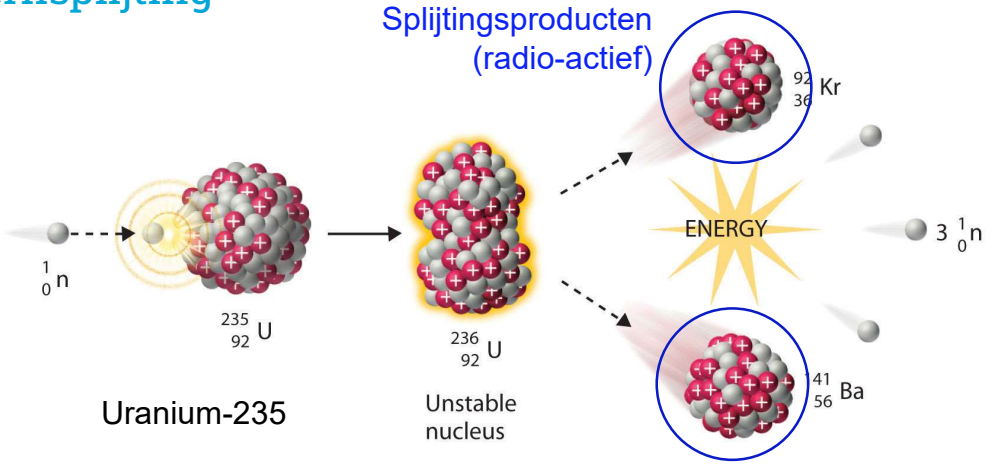
Kernsplijting



Uranium-235

Chemwiki, CCPL

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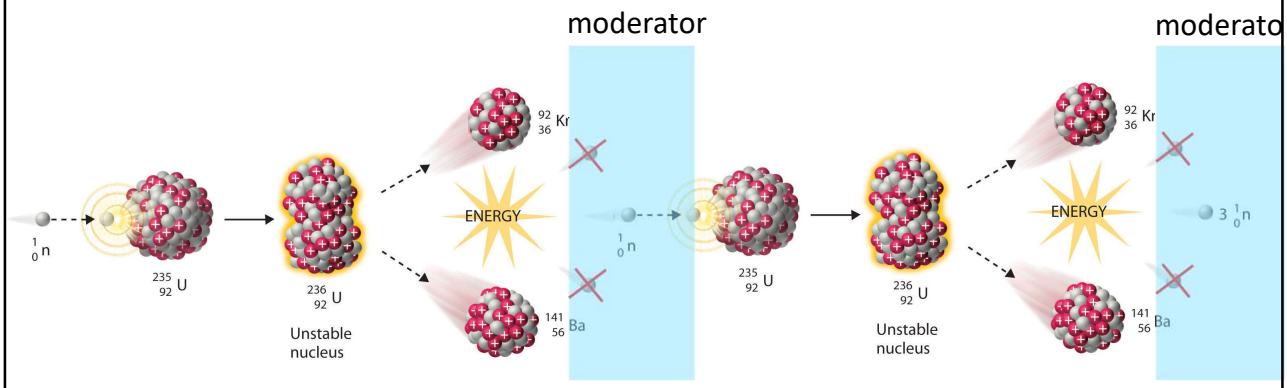
Splijtings kettingreactie



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Chemwiki, CCPL

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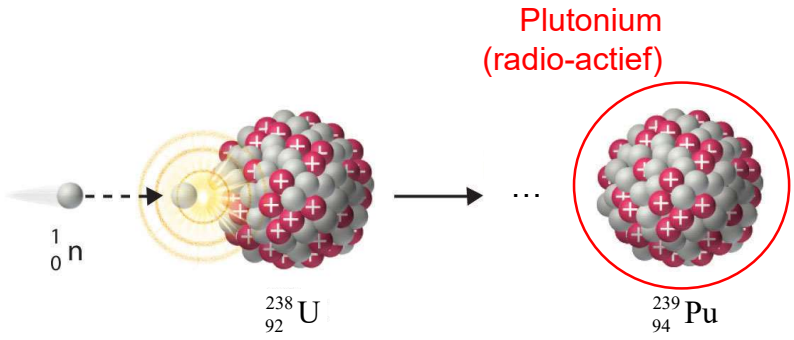
Productie van plutonium



Uranium-238 Plutonium

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Lots of energy from 1 gram U-235

Petrol

2500 liter

Coal

3000 kg

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1 gram nuclear waste vs 11 tonnes CO2

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Werking van kerncentrales

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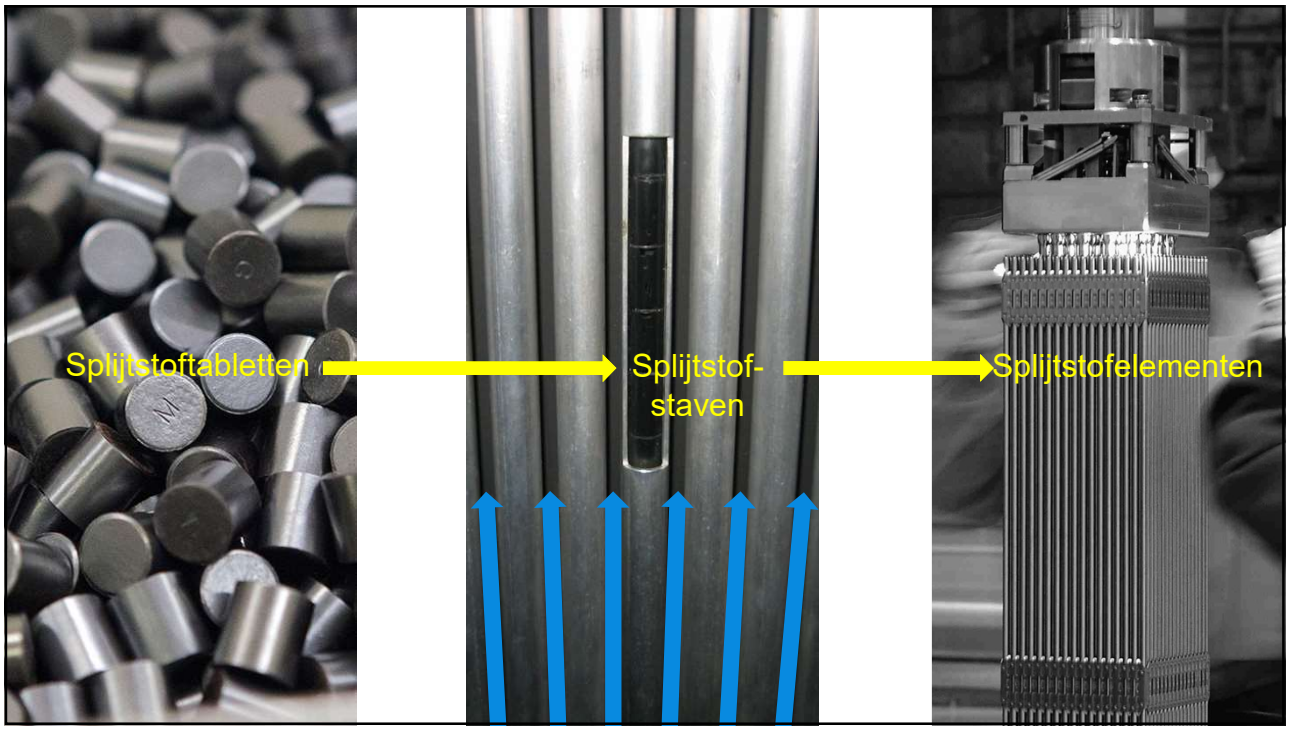

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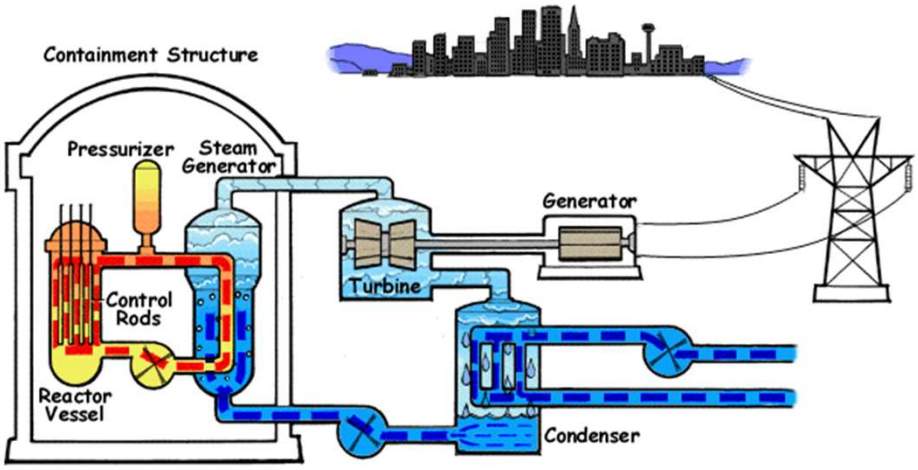
Pressurized Water Reactor (PWR) (Borssele)
Drukwaterreactoren



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Kerncentrale Borssele

121 fuel assemblies, 38 tonnes of fuel

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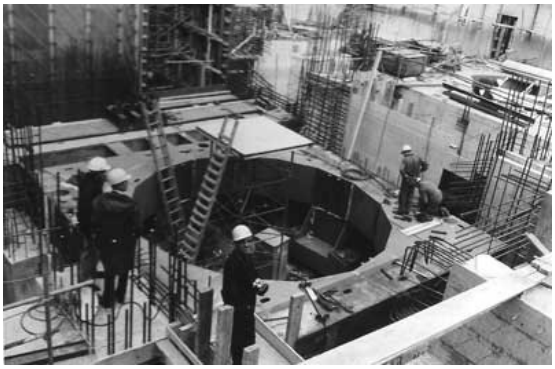
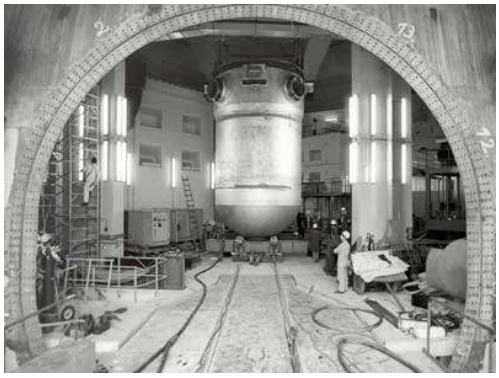
Kerncentrale Borssele





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

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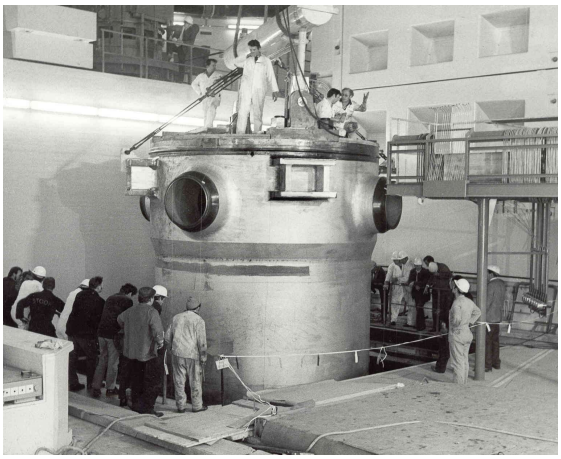
Reactor pressure vessel KCB (1972)



Jan Wieman, EPZ

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EPR Hinkley Point C

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EPR Hinkley Point C

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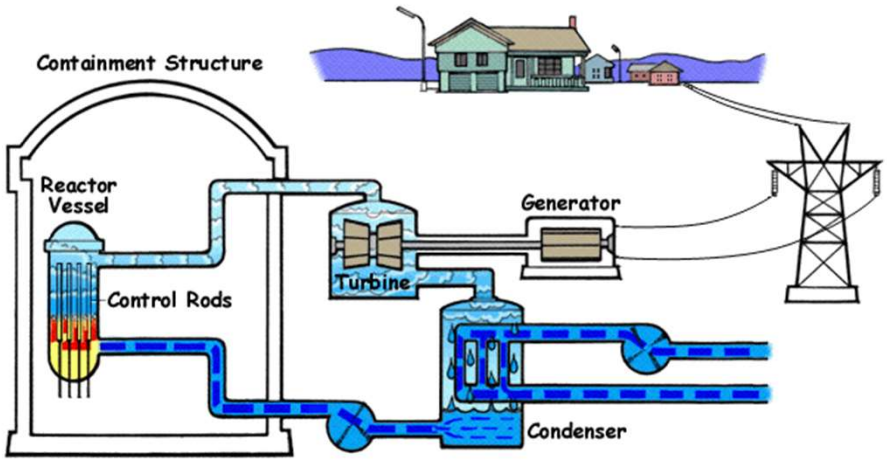
Boiling Water Reactoren (BWR)
Kokendwaterreactoren



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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 rendement van een LWR is ongeveer 35%.
- Het vermogen wordt gestuurd met regelstaven
- Het teveel aan neutronen wordt weggevangen in absorbers, zoals boorzuur of regelstaven
- Een optimale CO2-vrije energiemix is een diverse energiemix

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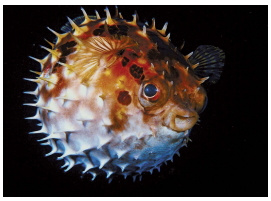
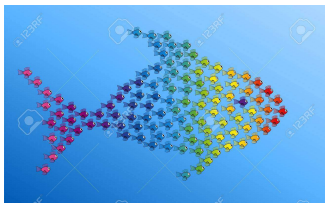
Trends in Kernenergie

LWR SMR MSR





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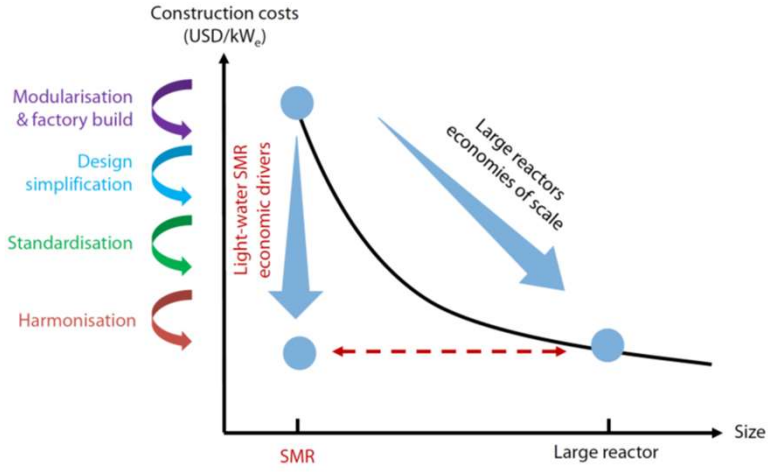
Kostenreductie kleine modulaire ontwerpen (SMR)



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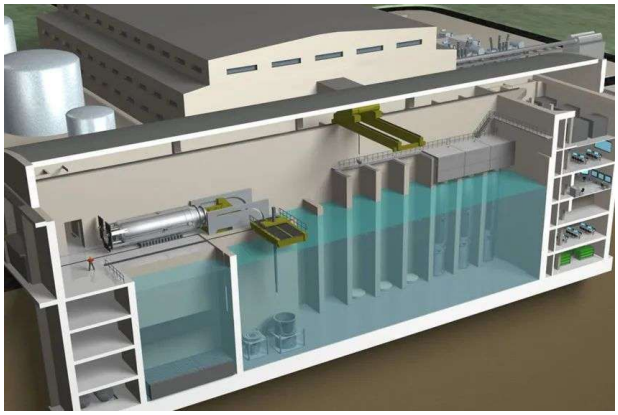
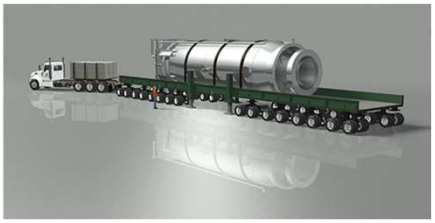
NuScale SMR Integral PWR



77 MWe per module
1 module per 200.000 huishoudens
4, 6 of 12 modules geschakeld
Operationeel 2030



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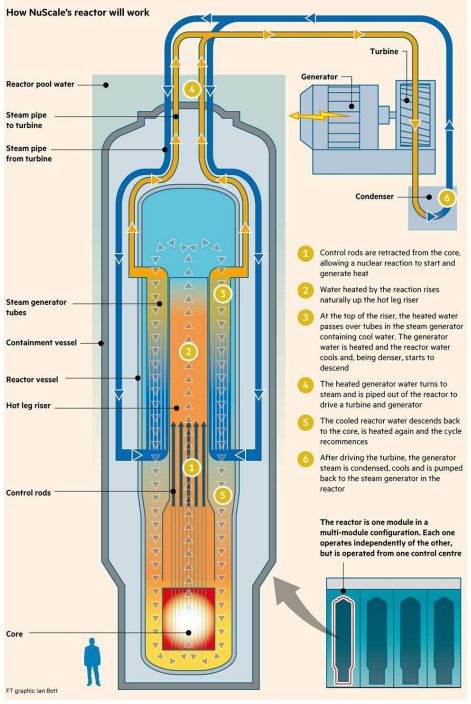
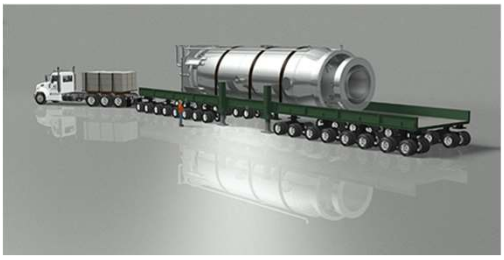


NuScale SMR Integral PWR



Geschatte kostenreductie bijna 50%

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Rolls Royce SMR

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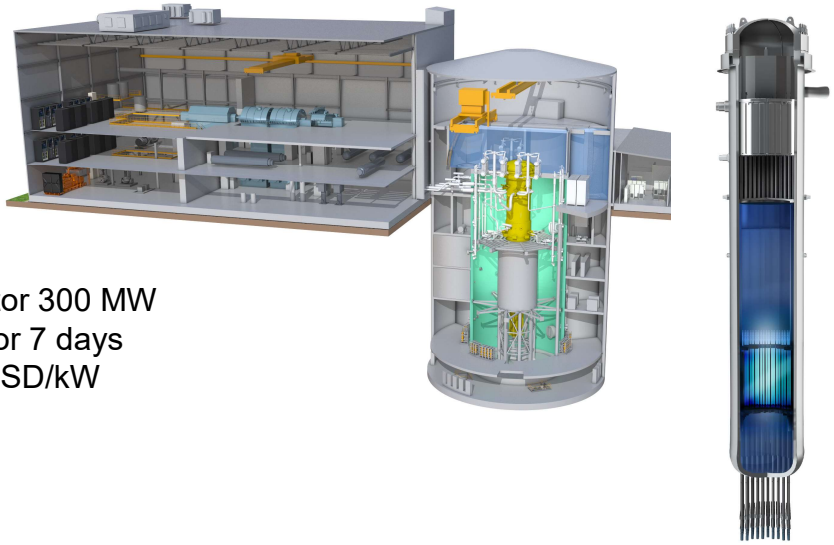
General Electric BWRX-300 SMR



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

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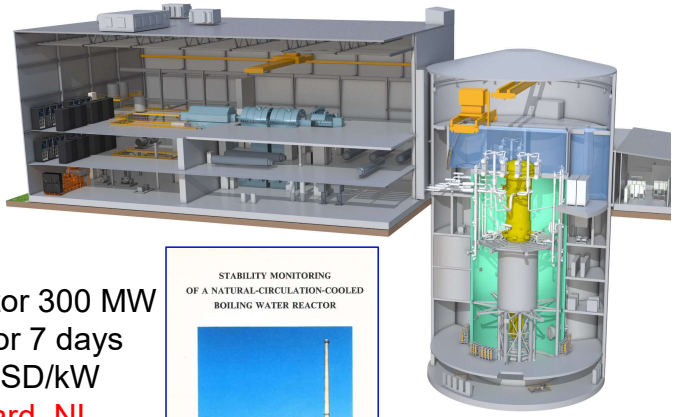
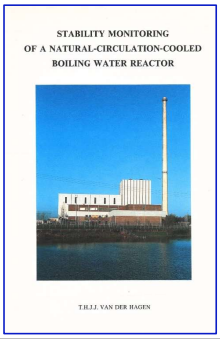
General Electric BWRX-300 SMR





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

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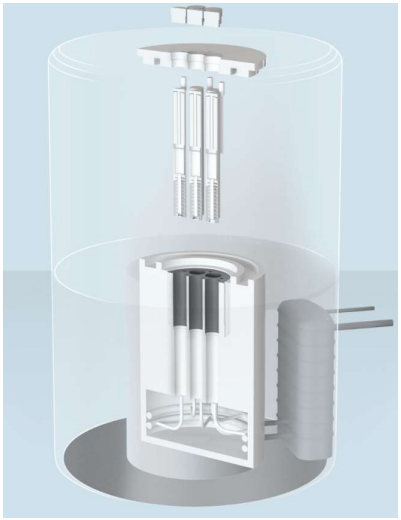
THORIZON Molten Salt Reactor (MSR)



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Micro reactoren
U-Battery (TU Delft, Manchester Uni, Urenco, …)

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.

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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MSR en HTR kerncentrales

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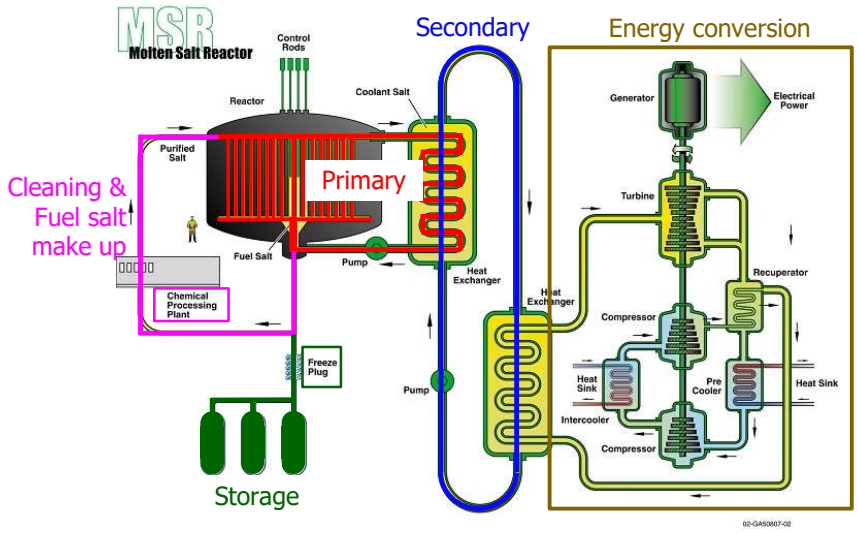
Molten Salt Reactor (MSR)



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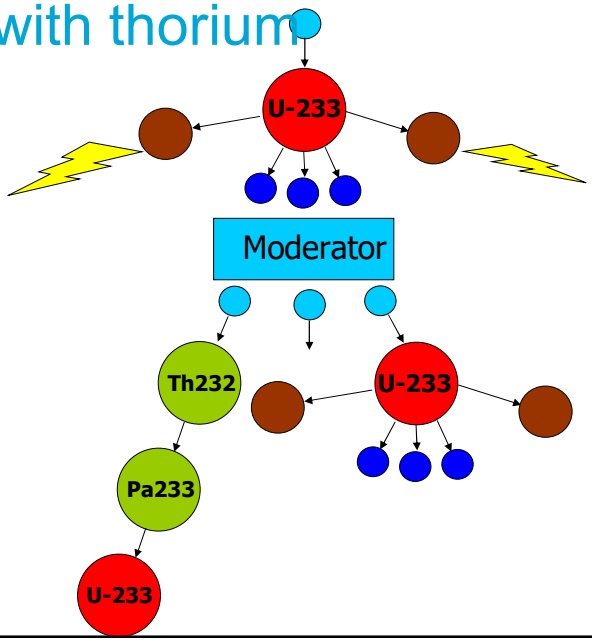
Breeding with thorium



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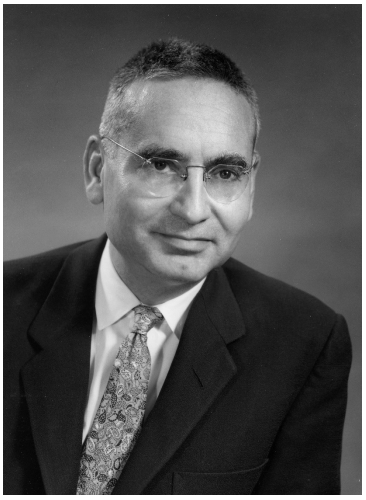
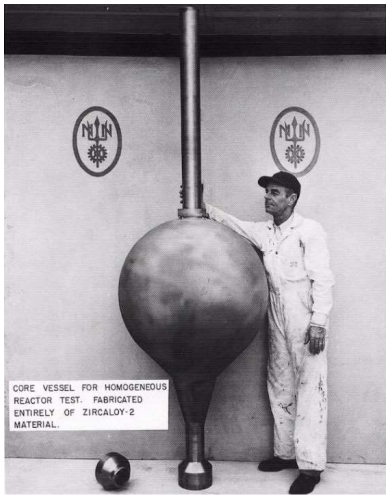
Alvin Weinberg
1915-2006



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

Alvin's 3P reactor
1952



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

wikimedia commons, GNU

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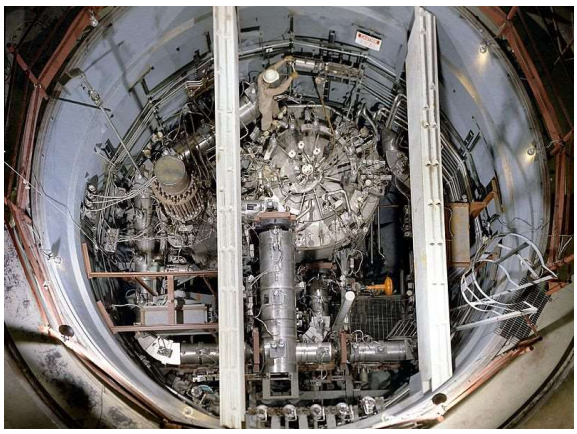
Molten Salt Reactor Experiment
1965-1969



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

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

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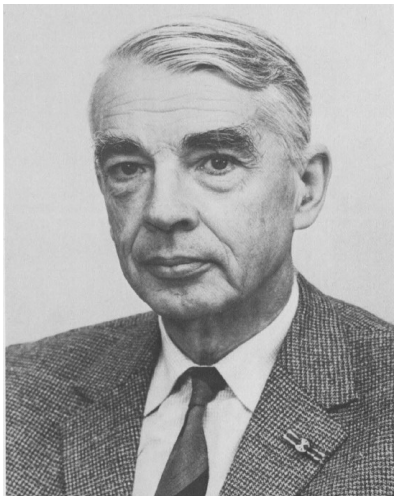
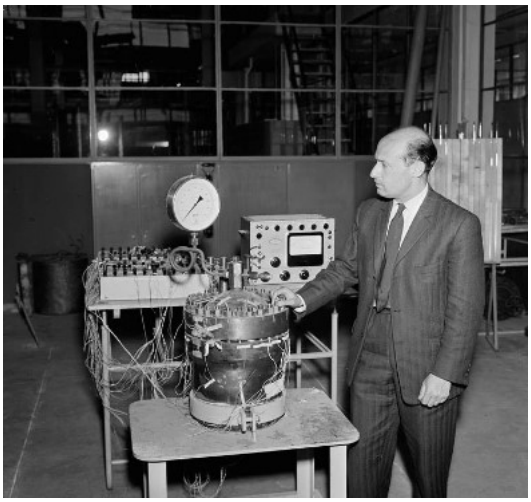
Historical research at TU Delft



Prof J.J. Went
(1907-1986)



Prof D.G.H. Latzko
(1924-2017)

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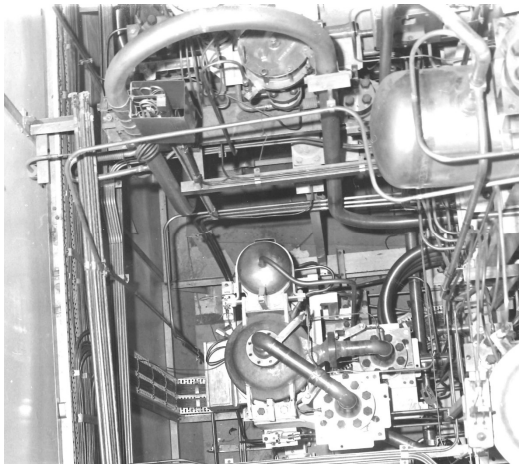
KEMA Suspension Test Reactor 1974-1977



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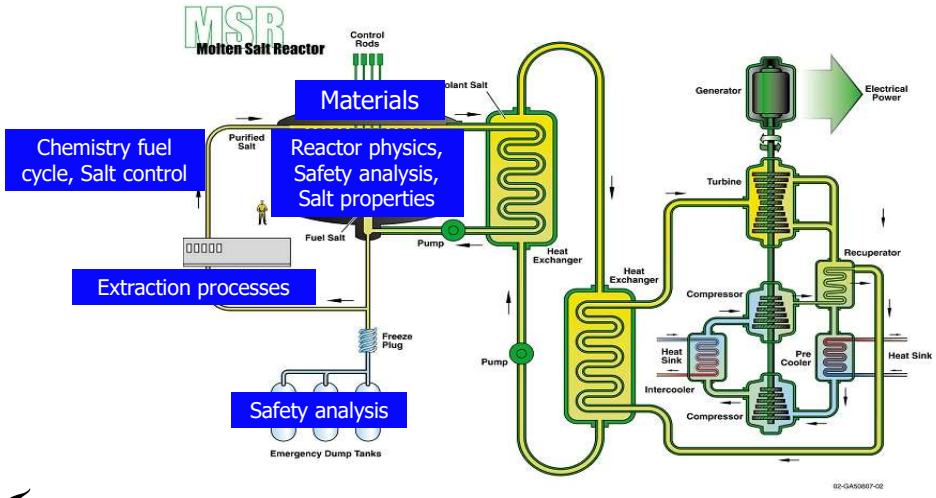
MSR research themes



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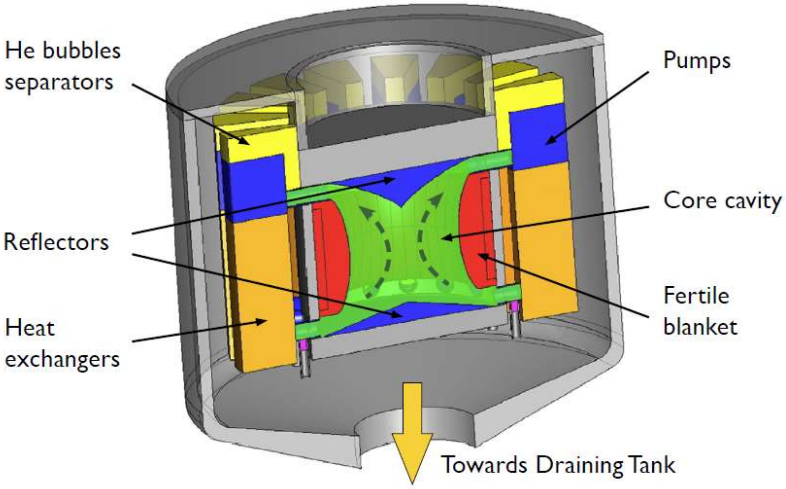
Fast MSFR design



- 'Empty' core cavity.
- Fertile blanket for breeding.
- Drainage, freeze plug, online chemical processing like in MSR.
- Suitable for Pu, MA burning, Th cycle.
- More challenging than thermal design: larger uncertainties, chemistry, weaker feedback.

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Thorium MSR (TMSR) China

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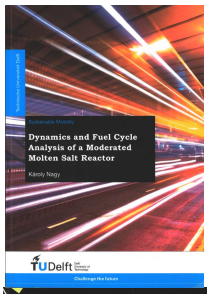
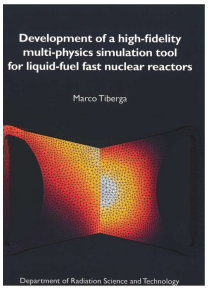
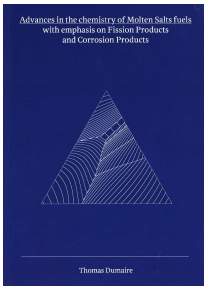
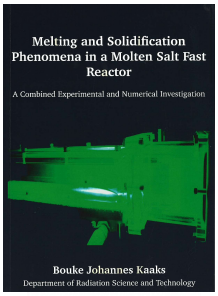
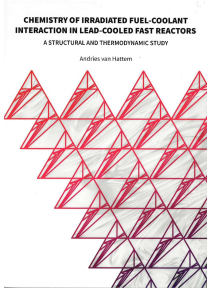
MSR research at TU Delft

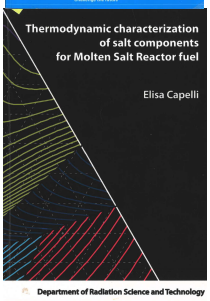


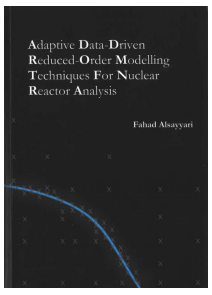


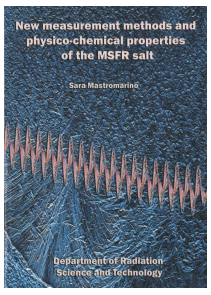


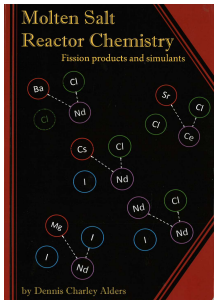












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MSR Start ups

Flibe ENERGY
TerraPower
TERRESTRIAL ENERGY
THORCON POWERING UP OUR WORLD
SEABORG
COPENHAGEN ATOMICS
THORIZON
moltex energy safer, cheaper, nuclear
TU Delft
naarea
STELLARIA

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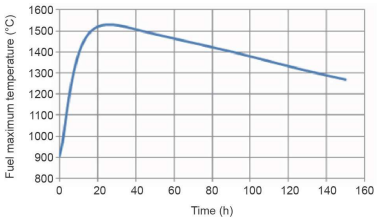
Hoge Temperatuur Gasgekoelde Reactor

HTR-10 Beijing
First criticality dec 2000

TU Delft

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



Temperatuur bij verlies aan koeling in HTR-PM

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

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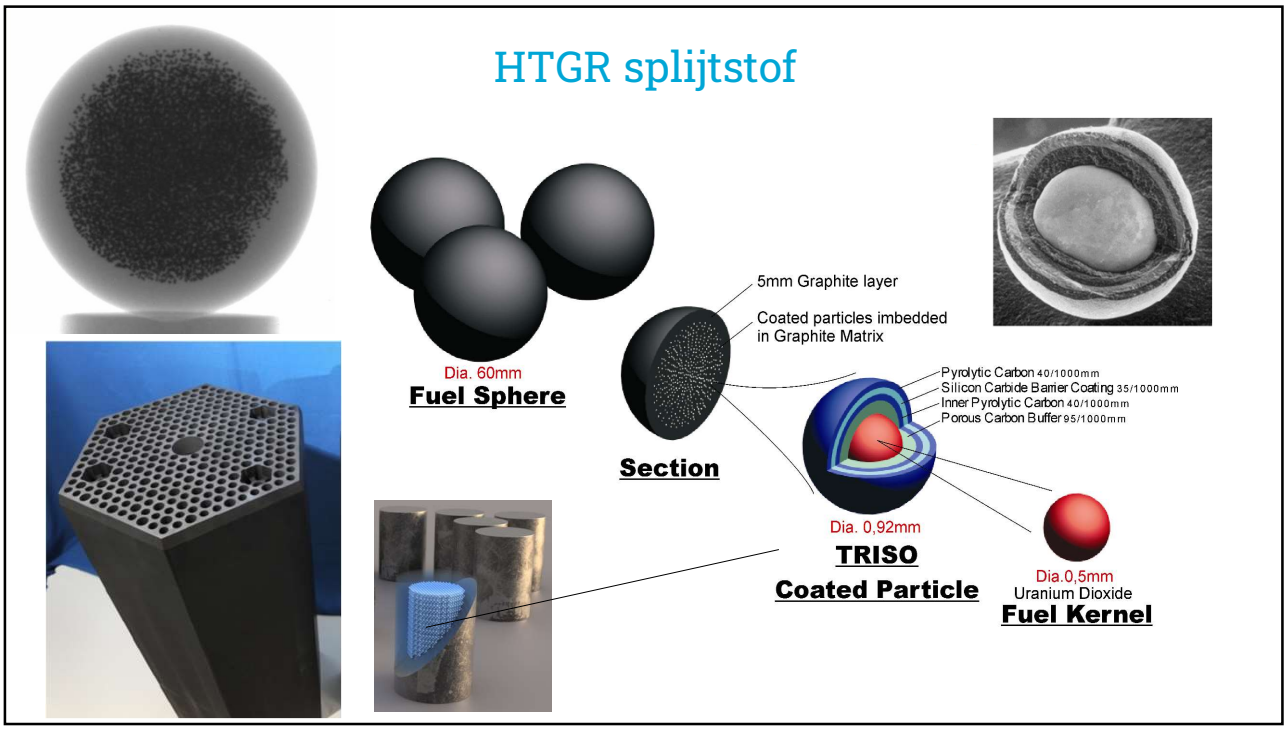
HTGR splijtstof
Dia. 60mm
Fuel Sphere
5mm Graphite layer
Coated particles imbedded
in Graphite Matrix
Section
Pyrolytic Carbon 40/1000mm
Silicon Carbide Barrier Coating 35/1000mm
Inner Pyrolytic Carbon 40/1000mm
Porous Carbon Buffer 95/1000mm
Dia. 0,92mm
TRISO
Coated Particle
Dia.0,5mm
Uranium Dioxide
Fuel Kernel

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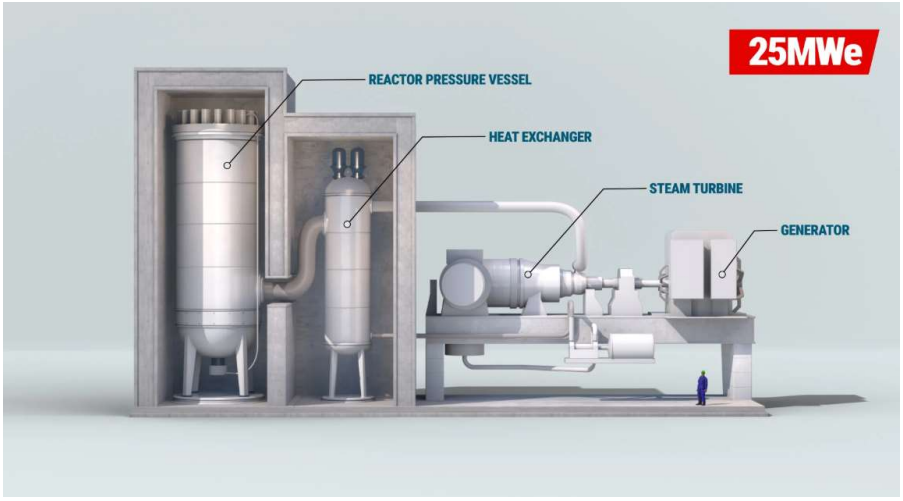
Allseas nuclear propulsion



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Future application of micro-reactors (e.g. microHTR)

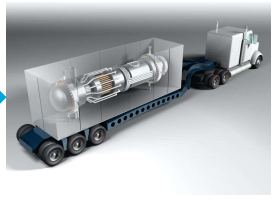
Data centers

Data transfer

Data transfer

Data transfer

Data transfer

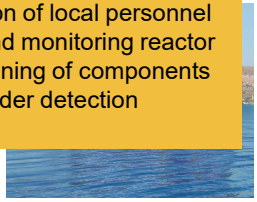


Mobile power supply
(isolated areas, military, …)

Digital twin used for:
- Supervision of local personnel
- Control and monitoring reactor
- Malfunctioning of components
- Early intruder detection
- …

Industrial heat or power

Deep sea mining



Power barges

Autonomous ships

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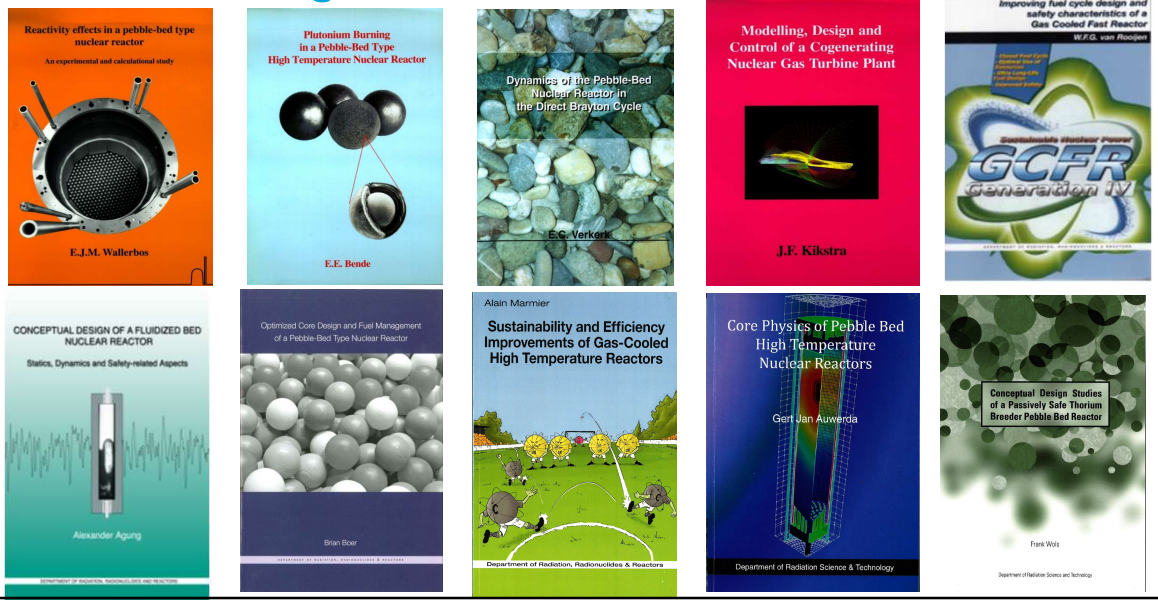
PhD students @ TU Delft



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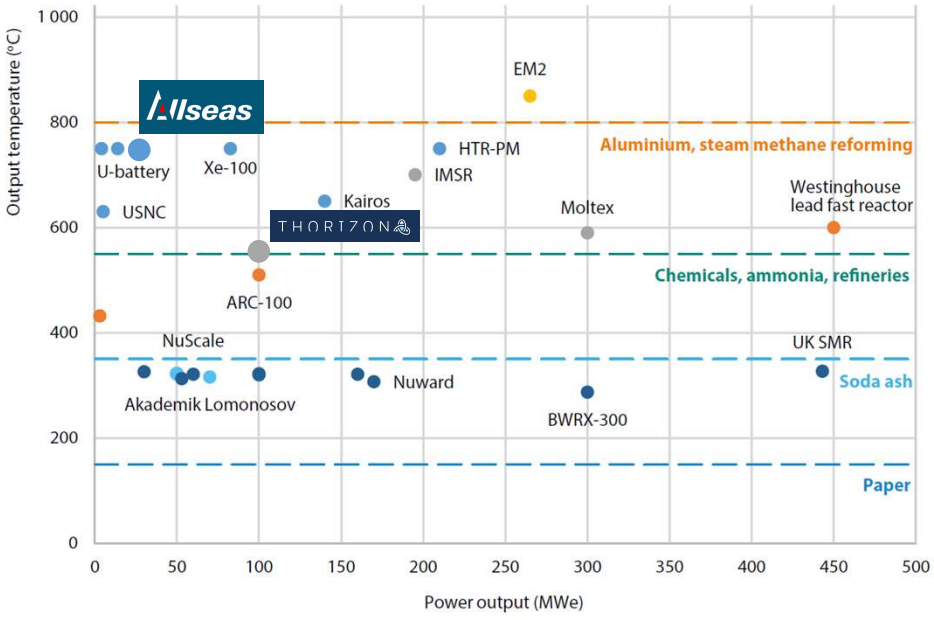
SMRs

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



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

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Onderwijs en onderzoek

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NUCLEAR ACADEMY

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Leerstoelen bij TU Delft

- Nuclear Reactor Physics (Prof. Jan Leen Kloosterman)
- Nuclear Computational Reactor Physics (Dr. Danny Lathouwers)
- Nuclear Reactor Physics and Data Sciences (Dr. Mauricio Tanos)
- Nuclear Reactor Thermal-Hydraulics and Transport Phenomena (Dr. Martin Rohde)
- Nuclear Fuel Materials Chemistry (Dr. Anna Smith, Prof. Rudy Konings)
- Nuclear Metals Science (Dr. Erik Offerman, Dr Niels van Dijk, and colleagues)
- Nuclear Structural Materials Science (new position)
- Nuclear Security (Marcel Schouwenburg)
- Nuclear Energy Technology (Dr. Jurriaan Peeters)
- Energy Conversion Systems (Prof. Rene Pecnik, and colleagues)
- Energy Ethics (Prof. Behnam Taebi, and colleagues)
- Energy Systems (Prof. Machteld van den Broek, Dr. Emile Chappin, and colleagues)
- Geo-Mechanics (Prof. Phil Vardon, Dr. Anne-Catherine Dieudonné, and colleagues)
- Radiochemistry (Dr. ir. Antonia Denkova, Dr. ir. Robin de Kruijff)
- Medical Imaging and Radiation Detectors (Dr. Marlies Goorden)
- Radiation Detection (Dr. Dennis Schaart)
- Radiation Dosimetry and Biophysics (Dr. Konstantinos Chatzipapas)
- Radiation Health Physics (Dr. Klazien Huitema, Dr. Marcel Schouwenburg, and colleagues)

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https://www.tudelft.nl/en/faculty-of-applied-sciences/business/facilities/tu-delft-reactor-institute/nuclear-education-at-tu-delft-1

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Doel:

- Ontwikkelen en ondersteunen van nucleair onderwijs bij MBO en HBO
- Ontwikkelen van cursussen voor bijscholing overheid en zij-instromers
- Vormen van een nuclear community in Nederland die elkaar inspireert en ondersteunt.

TU Delft

TU Delft · EPZ · NRG PALLAS Nuclear. For Life. · COVRA · urenco

Partners onderwijs

Wij werken momenteel samen met:

University of Applied Sciences · roc van twente · BÈTAPARTNERS · Universiteit Utrecht · Scalda · NK · Talland College

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Nederland heeft goede uitgangs-positie voor kernenergie:

- Uitgebreide nucleaire infrastructuur (onderzoek, onderwijs, uraniumverrijking, energieproductie, afvalbehandeling, medische toepassingen, materiaalonderzoek)
- Ligging aan zee met veel koelwater
- Havens, energie-intensieve industrie, maritieme industrie etc
- Opkomende Nederlandse nucleaire industrie gebaseerd op innovatie

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