IS DUAL FLUID REACTOR GENERATION IV OR V?

Mariusz Dąbrowski
National Centre for Nuclear Research,
Warszawa-Świerk, Poland

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Plan:

1. Polish Nuclear Energy Program - generation III and IV

2. High Temperature Gas-cooled Reactors

3. Dual Fluid Reactor (DFR) - main characteristics

4. Is DFR generation IV or V and why?

5. Summary

1. Polish Nuclear Energy Program - generation III and IV

<u>“Polish Nuclear Energy Program” PPEJ (2009 - now)</u>

An appeal to EU „Climate package” about 50 bln euro

to reduce CO2 emission

13.01.2009 Republic of Poland Council of Ministry Legal Act

...” at least two NPPs will be build. The works will be parallel and at least one NPP should start working at 2020…”

PPEJ actions:

- 12.05.2009 - Government Plenipotentiary for Nuclear Energy
- 2010 – Ministry of Economy (ME) prepares a PPEJ project as well as Environmental Impact document
- 30.12.2010 – 31.03.2011 - public consultations positive
- 11.03.2011 - Fukushima accident (impact on German policy)
- 14.03.2011 - ME prepares nuclear sites ranking
- 18.07.2011 – 31.05.2013 trans-borders consultations: Lithuania, Sweden, Denmark, Germany (hardest!), Austria, Czech, Slovakia and Finland.
- 28.01.2014 - Council of Ministries accepts PPEJ by a Legal Act
- Nov. 2015 - a new government takes power - PPEJ is continued though priority is given again for coal and mining
- 14.02.2017 - Governmental "Strategy for Responsible Development" (SOR) for Poland - inclusion of Generation IV reactors
- 13.07.2016 - 11.01.2018 A new Ministry of Energy "Committee for deployment of high temperature reactors" was working and prepared the final report.

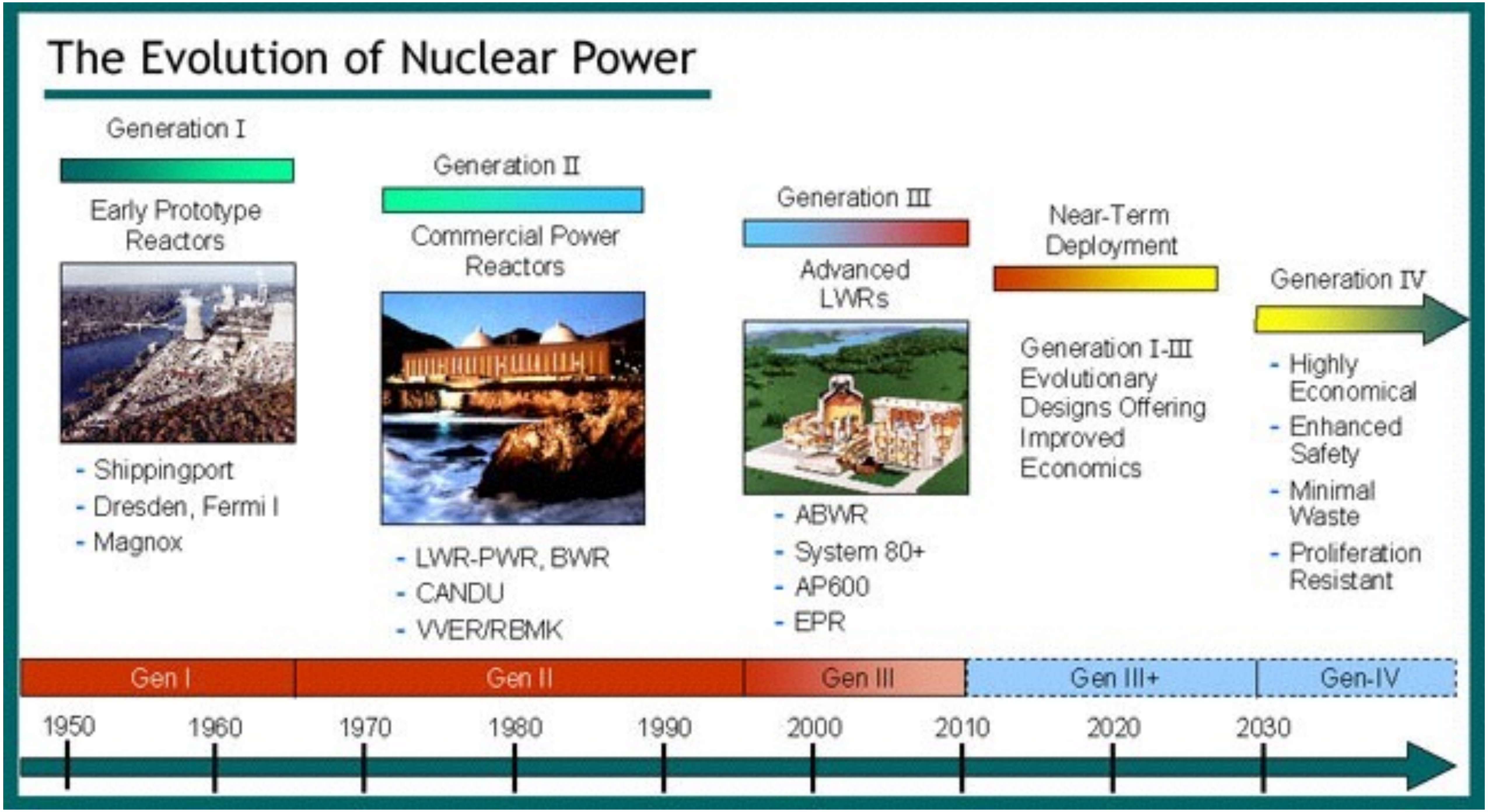
„Strategy for responsible development”.
- the governmental plan for Polish economy grow

List of energy actions contains:
Preparation of HTR deployment for industrial heat production in cogeneration, using industrial & scientific potential of Poland.
Support for Polish R&D on materials for gen.IV reactors.

Ministry of Energy on 13 July 2016 appointed
„Committee for deployment of high temperature reactors”.

Terms of reference:
- Analysis of Polish economy needs & export potential
- Inventory of relevant design & manufacturing capabilities of Polish science & industry
- Cost estimate, business model, funding possibilities
- Analysis of legal framework
- Establishing international cooperation

Which generation of nuclear technology?



Polish heat market

Cogeneration:

- 13 largest chemical plants need 6500 MW of heat at T=400-550°C
- They use 200 TJ / year, equivalent to burning of >5 mln t of natural gas or oil

Electricity:

- ~50 units of 200 MW_e to be replaced >2035

Plant	boilers	MW
ZE PKN Orlen S.A.Płock	8	2140
Arcelor Mittal Poland S.A.	8	1273
Zakłady Azotowe "Puławy" S.A.	5	850
Zakłady Azotowe ANWIL SA	3	580
Zakłady Chemiczne "Police" S.A.	8	566
Energetyka Dwory	5	538
International Paper - Kwidzyn	5	538
Grupa LOTOS S.A. Gdańsk	4	518
ZAK S.A. Kędzierzyn	6	474
Zakl. Azotowe w Tarnowie Moscicach S.A.	4	430
MICHELIN POLSKA S.A.	9	384
PCC Rokita SA	7	368
MONDI ŚWIECIE S.A.	3	313

Best-fit unit parameters:

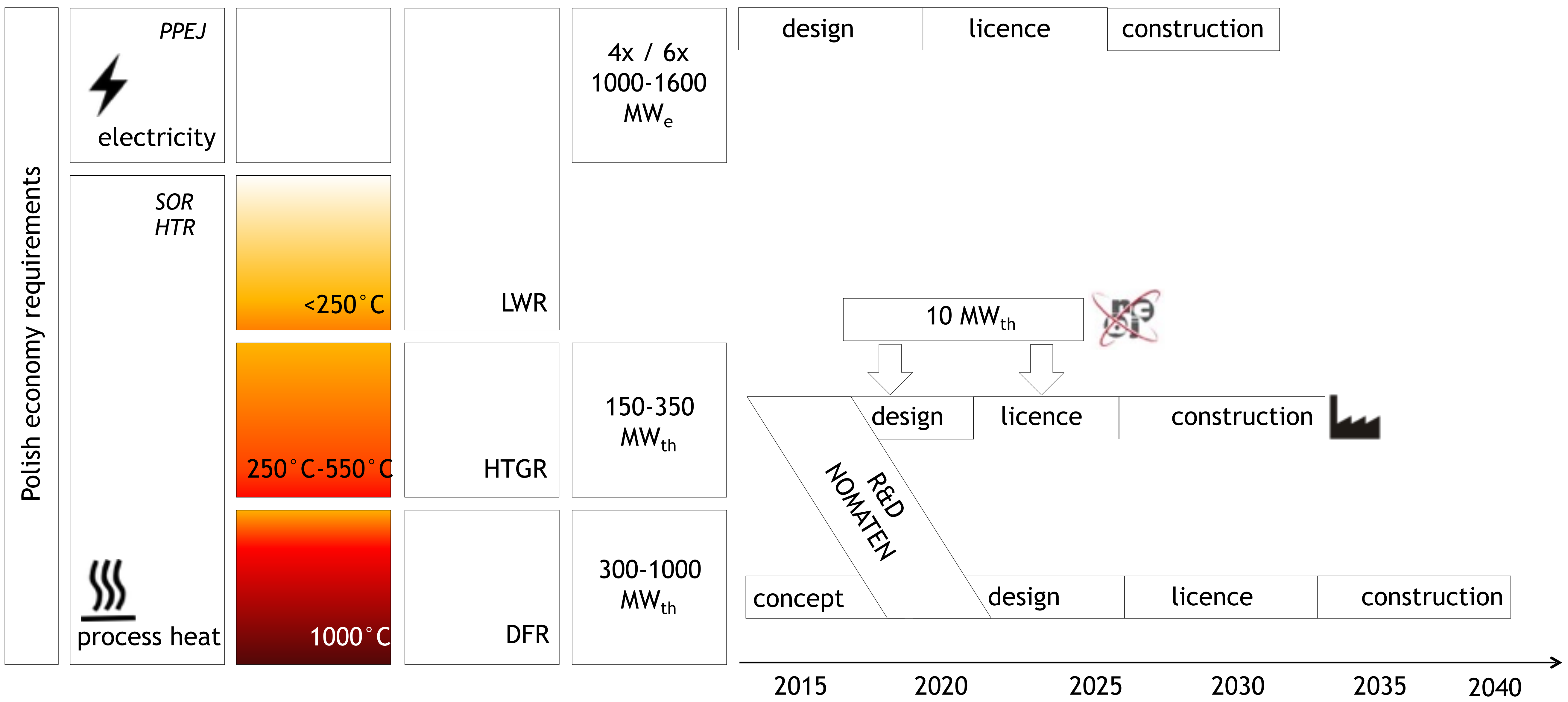
T = 540°C,

p = 13.4 MPa,

power: 165 MW_{th}

steam prod. 230 t/h

Polish Nuclear Roadmap - 2018



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Consider 2 technologies of Generation IV or higher

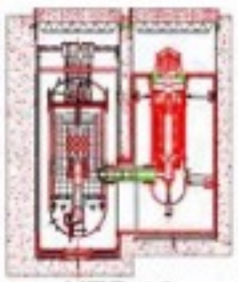
1. High-Temperature and Very High-Temperature reactors (HTR and VHTR) - *High-Temperature Gas-Cooled Reactors* (HTGR) - implementation
2. Super Critical Water Reactors (SCWR)
3. Molten-Salt Reactors (MSR) (thermal, epithermal, fast)
4. Lead-cooled Fast Reactors (LFR)
5. Sodium-cooled Fast Reactors (SFR)
6. Gas-cooled Fast Reactor (GFR)

7. *Dual-Fluid Reactor* (DFR) - new technology of polish-german group lead by K. Czerski - research

2. High temperature reactors for polish industry

HTGR: 150 - 300 MW

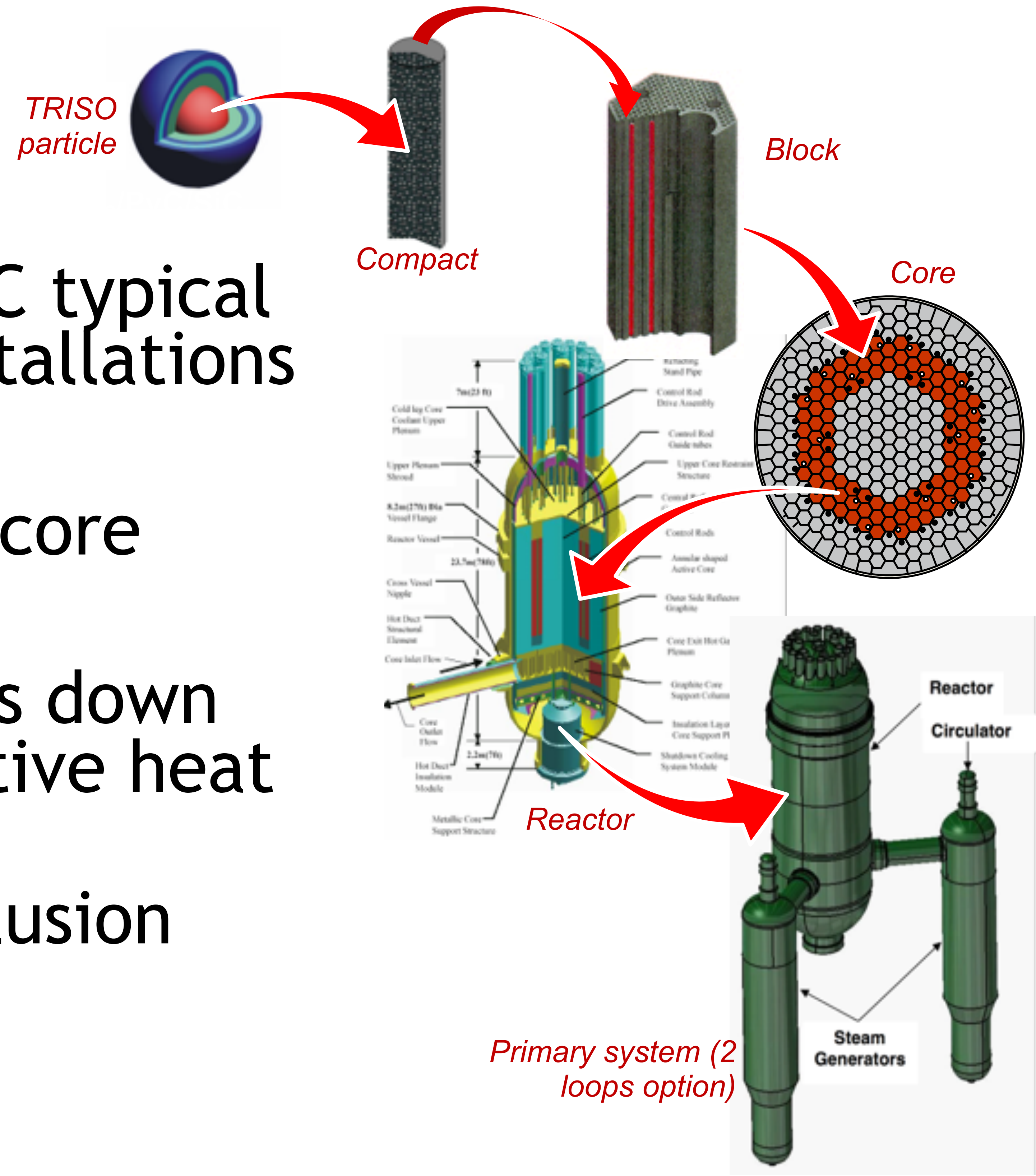
Helium Cooled TRISO HTGRs Built World-Wide

	Power Reactors			Research Reactors			
	Peach Bottom 1 1966-1974	Fort St Vrain 1976-1989	THTR 1986-1989	Dragon 1966-1975	AVR 1967-1988	HTTR 2000-	HTR-10 2003-
Power Level:							
MW(t)	115	842	750	20	46	30	10
MW(e)	40	330	300	-	15		--
Coolant:							
Pressure, Mpa	2.5	4.8	4	2	1.1	4	3
Inlet Temp, °C	344°C	406°C	250°C	350°C	270°C	395°C	250°C/300°C
Outlet Temp, °C	750°C	785°C	750°C	750°C	950°C	850°C/950°C	700°C/900°C
Fuel type	$(U\text{-}Th)C_2$	$(U\text{-}Th)C_2$	$(U\text{-}Th)O_2$	$(U\text{-}Th)C_2$	$(U\text{-}Th)O_2$	$(U\text{-}Th)O_2$	$(U\text{-}Th)O_2$
Peak fuel temp, °C	~1000°C	1260°C	1350°C	~1000°C	1350°C	~1250°C	
Fuel form	Graphite compacts in hollow rods	Graphite Compacts in Hex blocks	Graphite Pebbles	Graphite Hex blocks	Graphite Pebbles	Graphite compacts in Hex blocks	Graphite Pebbles

High T Gas-cooled Reactor (HTGR)

- Coolant: Helium 700°C
- 2nd cuircut: steam 550°C typical for existing chemical installations
- TRISO fuel
- Pebble-bed or prismatic core
- Intrinsic safety
- In case of accident, cools down by conduction and radiative heat transfer
- No core damage, no exclusion zone



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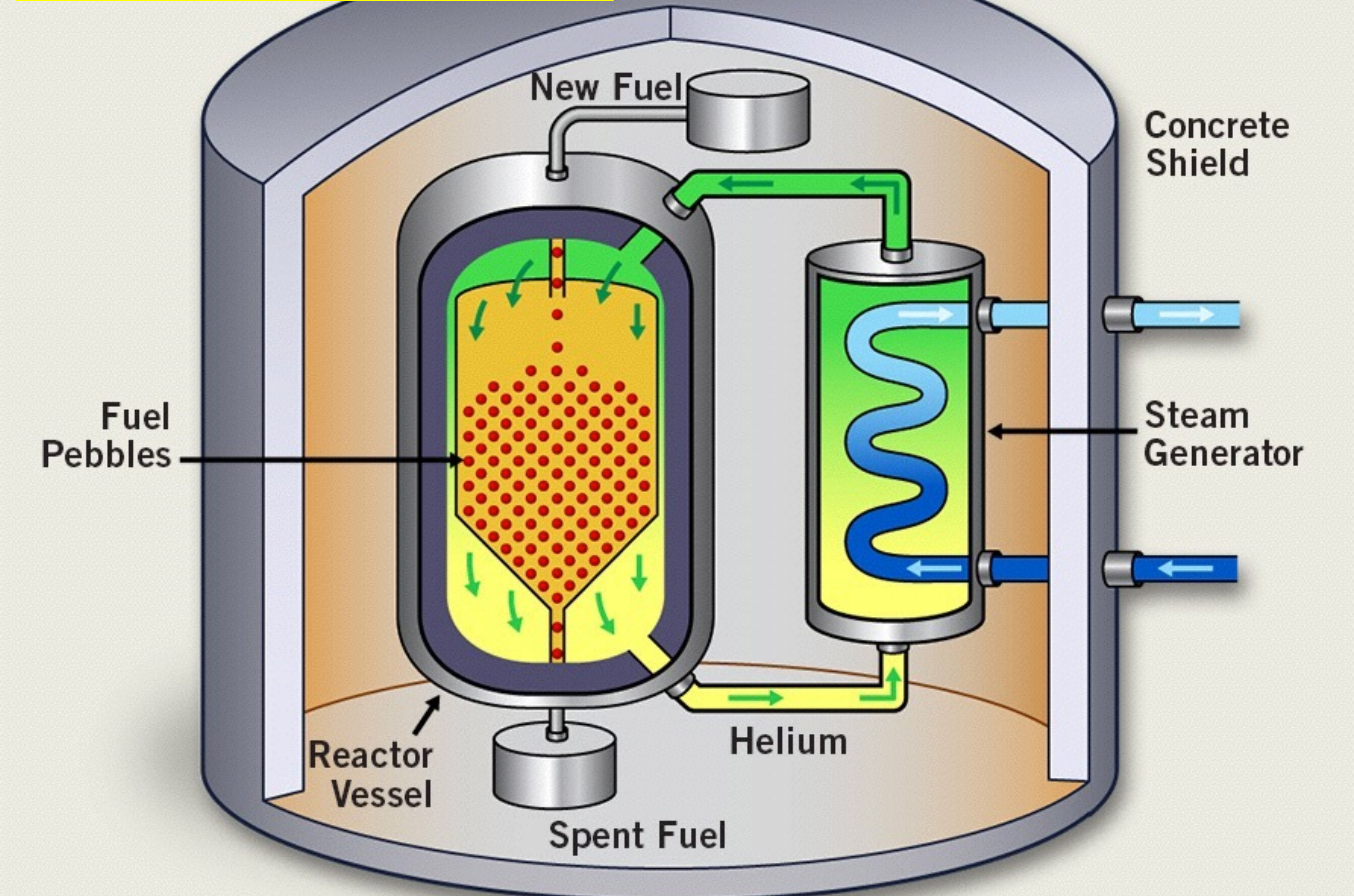
Courtesy: G. Wrochna

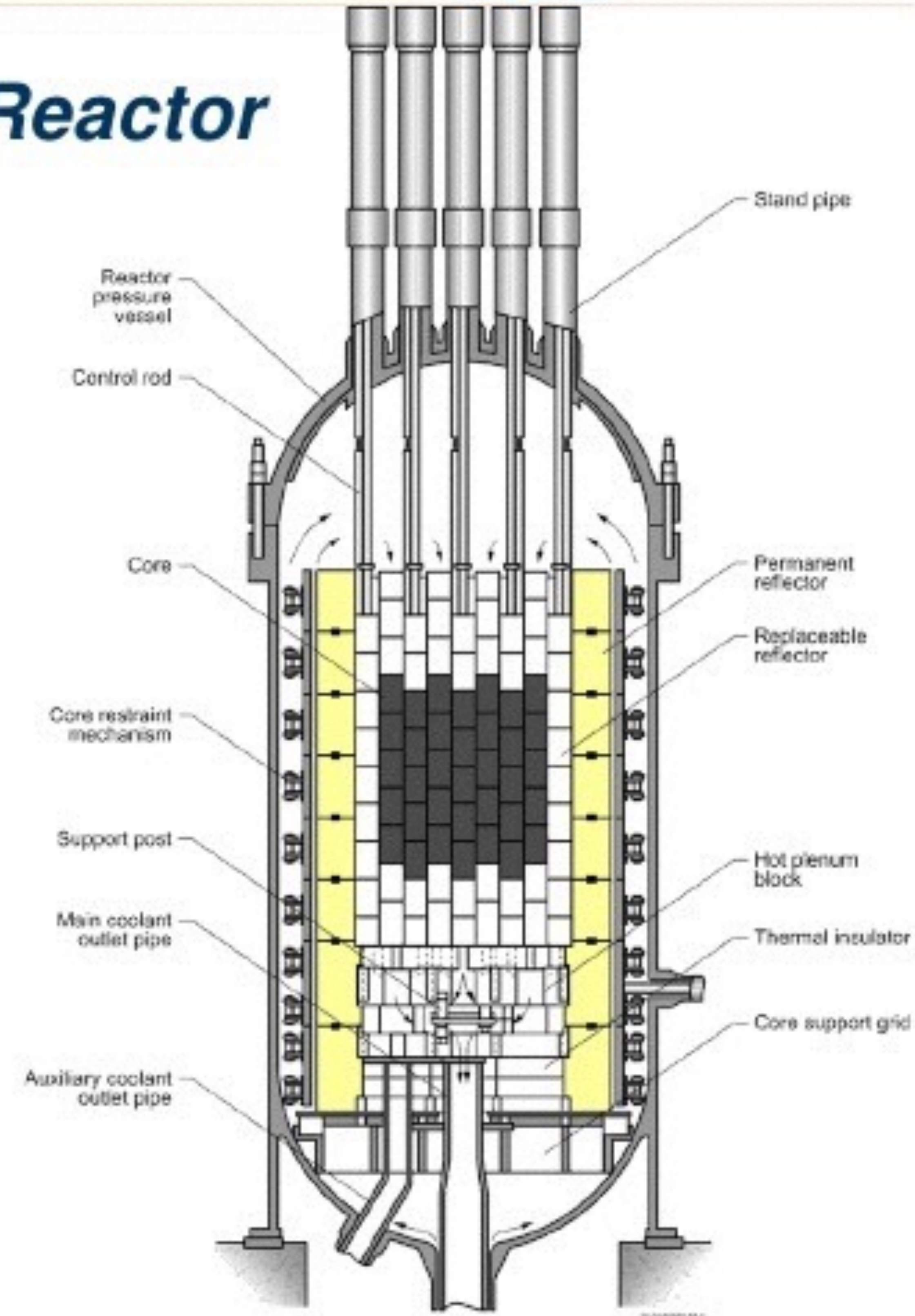
Pebble bed technology



Preliminary agreement on collaboration with JAEA - HTTR

High Temperature Test Reactor (HTTR)

- 30 MWt
- Graphite Moderated/Reflected
- Core Diameter = 2.3 m
- Core Height = 2.9 m
- Helium Coolant
- 150 Fuel Assemblies
- 30 Fuel Columns



Idaho National Laboratory

NGNP Next Generation Nuclear Plant

HTGR demo.: GEMINI+ Project

➢ Objective: to be ready for launching demo.

INPUT

The European legacy

- The historical German HTGR programme
- **18 years of HTGR related projects (FP4-7)**
  - **HTGR technology**
  - **Understanding industry process heat needs**

NC2I

Nuclear Cogeneration Industrial Initiative

European partners

- TSOs
- Nuclear industry
- Industrial end-users
- Research organisations

+ Innovation

GEMINI+ Project

International partners

- NGNP Industry Alliance
- JAEA
- KAERI

OUTPUT

- A licensing framework
- A large industrial site selected
- A team trained for demo.
- A design base
- Feasibility of demo. on the selected site
- A business plan for the demo.
- International partnership to support demo.

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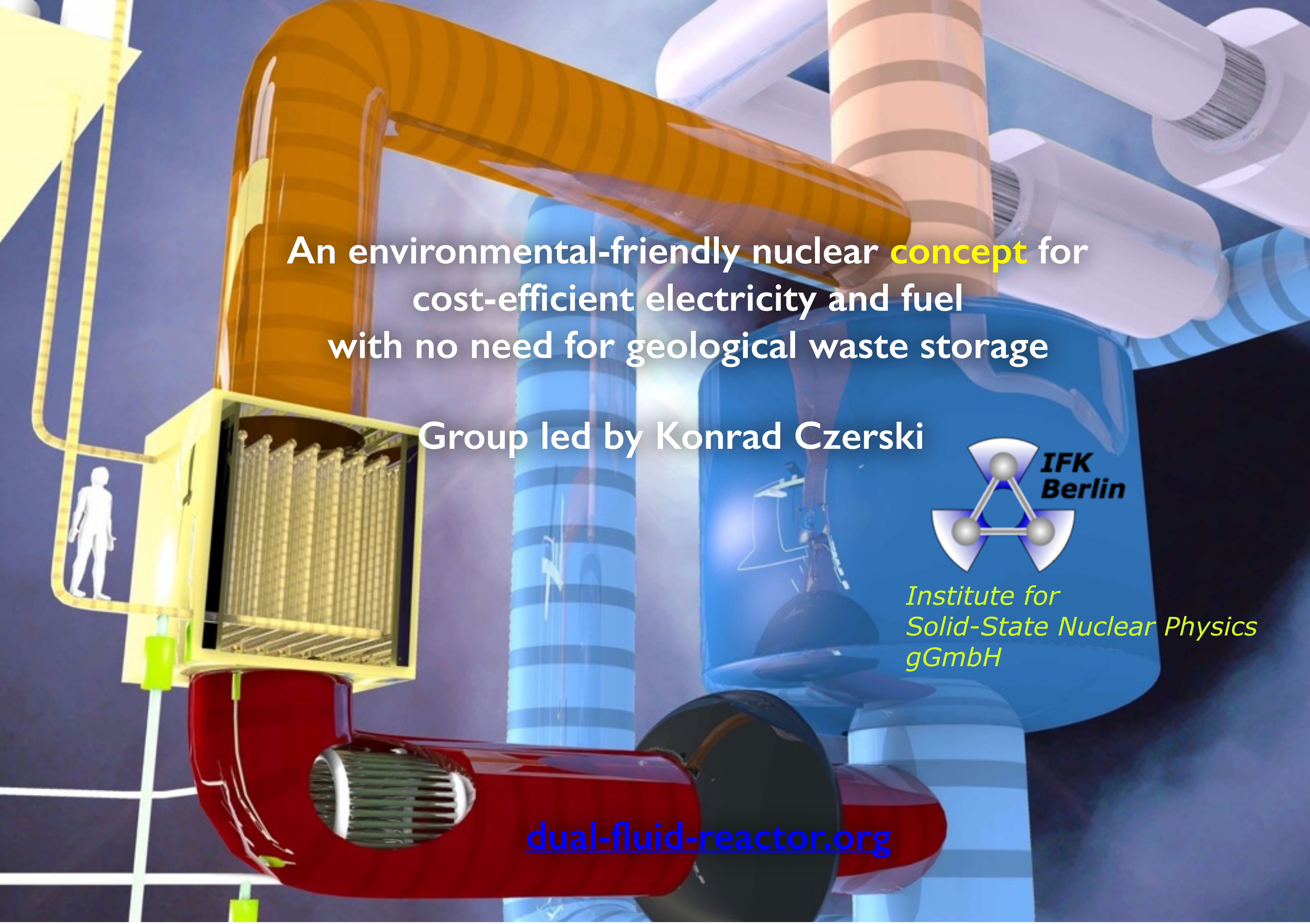
Courtesy: G. Wrochna

3. Dual Fluid Reactor (DFR) - main characteristics

An environmental-friendly nuclear concept for cost-efficient electricity and fuel with no need for geological waste storage

Group led by Konrad Czerski



IFK Berlin

Institute for Solid-State Nuclear Physics gGmbH

dual-fluid-reactor.org

NCBJ, Univ. Szczecin and IFK Berlin

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journal homepage: www.elsevier.com/locate/anucene

The Dual Fluid Reactor – A novel concept for a fast nuclear reactor of high efficiency

Armin Huke [a,*], Götz Ruprecht [a], Daniel Weißbach [a,b], Stephan Gottlieb [a], Ahmed Hussein [a,c], Konrad Czerski [a,b]

[a] Institut für Festkörper-Kernphysik gGmbH, Leistikowstr. 2, 14050 Berlin, Germany
[b] Instytut Fizyki, Wydział Matematyczno-Fizyczny, Uniwersytet Szczeciński, ul. Wielkopolska 15, 70-451 Szczecin, Poland
[c] Department of Physics, University of Northern British Columbia, 3333 University Way, Prince George, BC V6P 3S6, Canada

Patent pending in 8 countries: European Union, USA, Canada, India, Japan, South Korea, Russia

Patents: DFR/s; DFR/m; 3D plotter SiC, ZrC, TiC (2016); Pyrochemical Processing Unit

More literature on DFR 3000 MWth:

X. Wang, *Analysis and Evaluation of the Dual Fluid Reactor Concept*, Ph.D. thesis, Technische Univ. Munich 2017 (supervisor: R. Macian-Juan)

Review of DFR:

A. Huke et al. *Dual-fluid reactor*, in: Molten Salt Reactors and Thorium Energy, Thomas J. Dolan (ed.) (Elsevier 2017) pp. 619-633.

https://doi.org/10.1016/B978-0-08-101126-3.00025-7

(J. Dolan is an emeritus prof. of Univ. Illinois, Urbana/Champaign)

What is DFR?

Dual Fluid Reactor (DFR) is a novel concept of a very high temperature nuclear reactor on fast neutrons. Its name comes from the fact that there are two fluid flows: fuel and coolant and that they are separated.

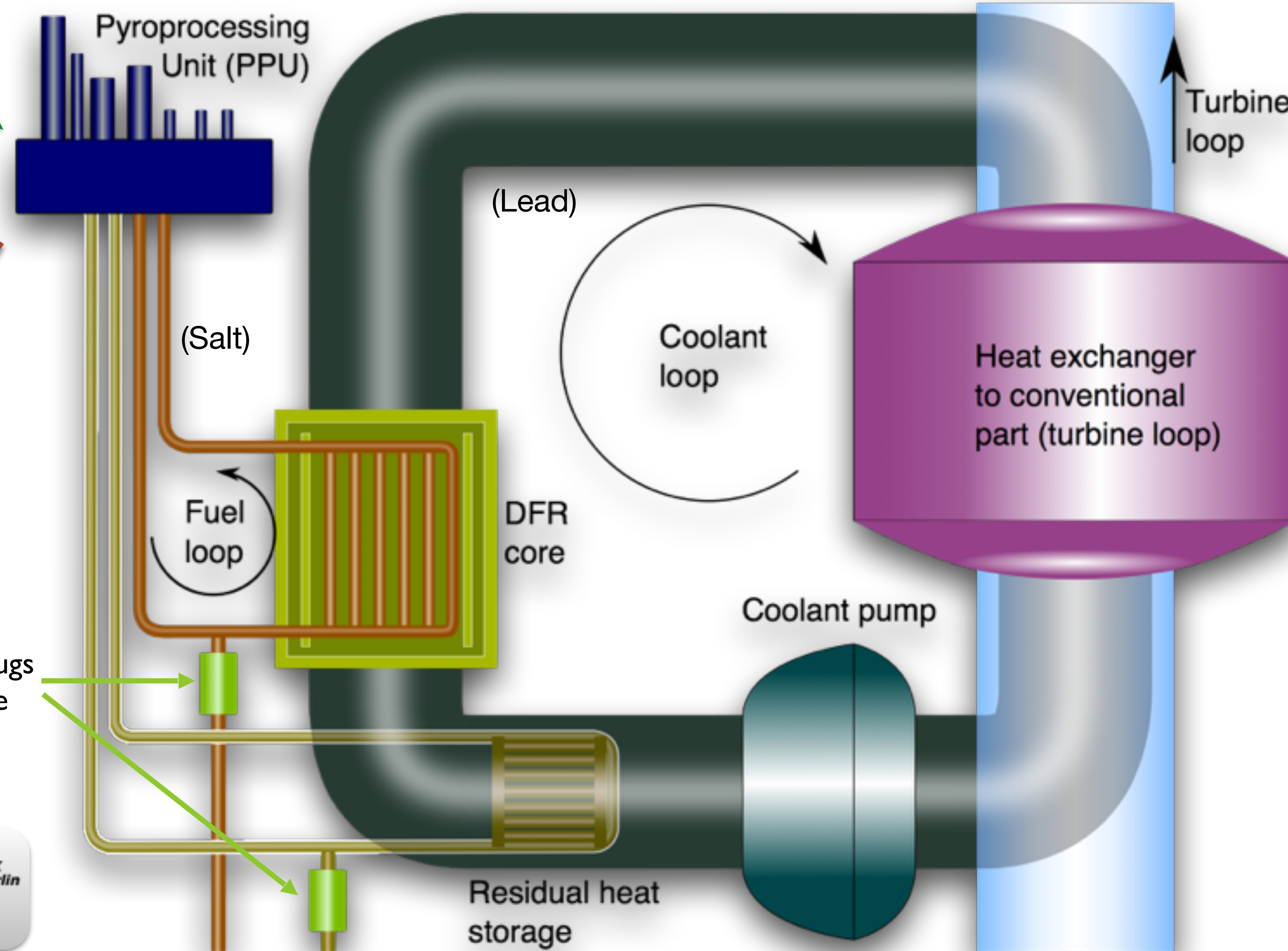
It is better than fluid fuel Molten-Salt Fast Reactor (MSFR), because it allows optimization of the working parameters for both fuel and coolant independently.

DFR (main properties):

- fuel: undiluted molten salts - DFR/s (chlorides UCl3, ThCl3, PuCl3) or molten metal - DFR/m (eutectic e.g. Cr-U)
- coolant: lead
- fast reactor
- heterogenic (inhomogeneous)
- very high temperature (up to 1300°C in the upper core)
- breeding fuel cycle (Pu239 from U238 or U233 from Th232)
- reprocessing by destillation/rectification

DFR/s (300-1500 MW)

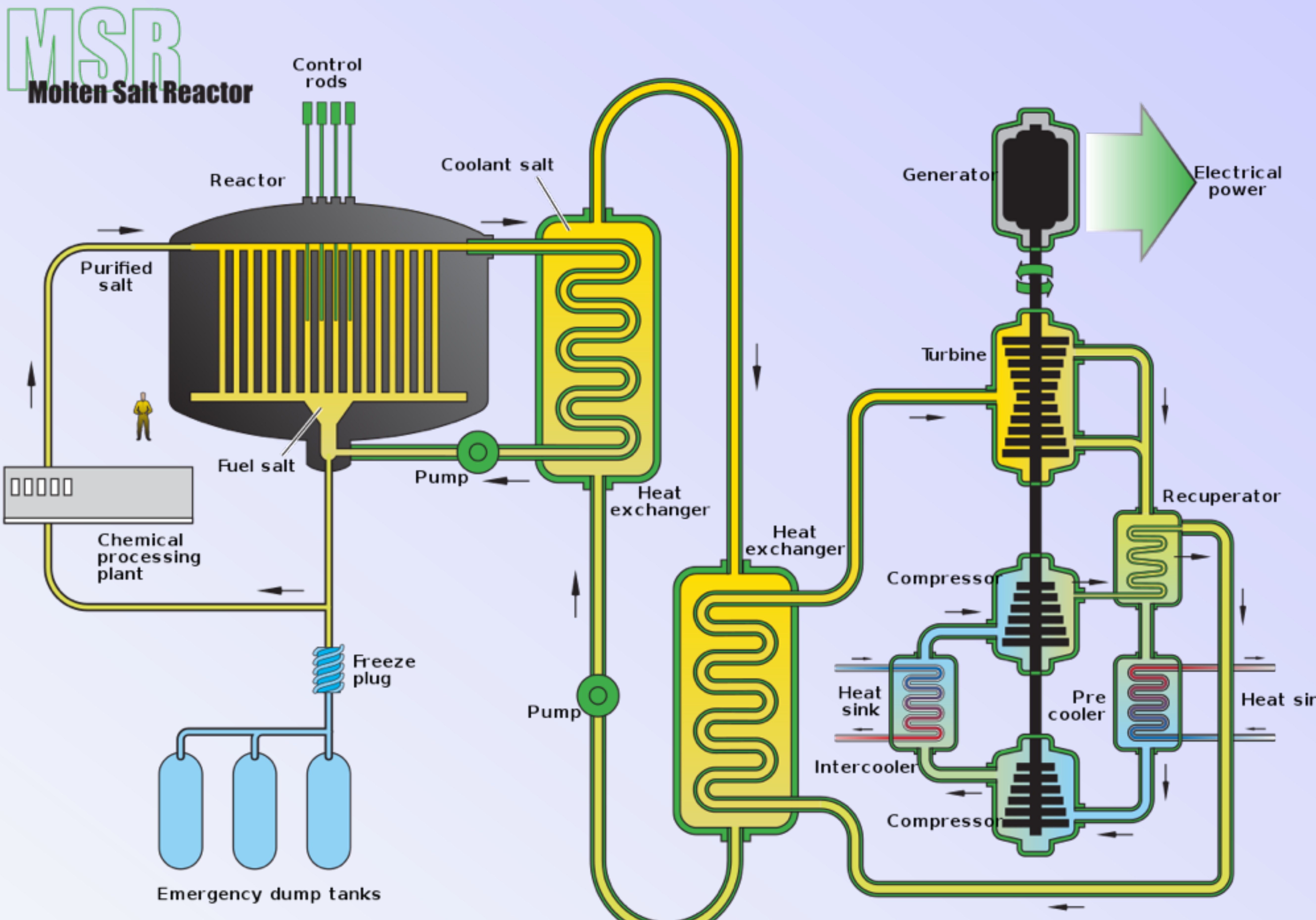
- Natural Uranium
- Depleted Uranium
- Thorium
- Used fuel elements



- Fission products
- Med. radioisotopes
- Fissile material

International patent protection for the Dual Fluid principle since Sep. 2011

IFK Berlin


MSR
Molten Salt Reactor
Control rods
Reactor
Coolant salt
Generator
Electrical power
Purified salt
Turbine
Fuel salt
Pump
Heat exchanger
Recuperator
Chemical processing plant
Heat exchanger
Compressor
Freeze plug
Heat sink
Pre cooler
Heat sir
Pump
Intercooler
Compressor
Emergency dump tanks

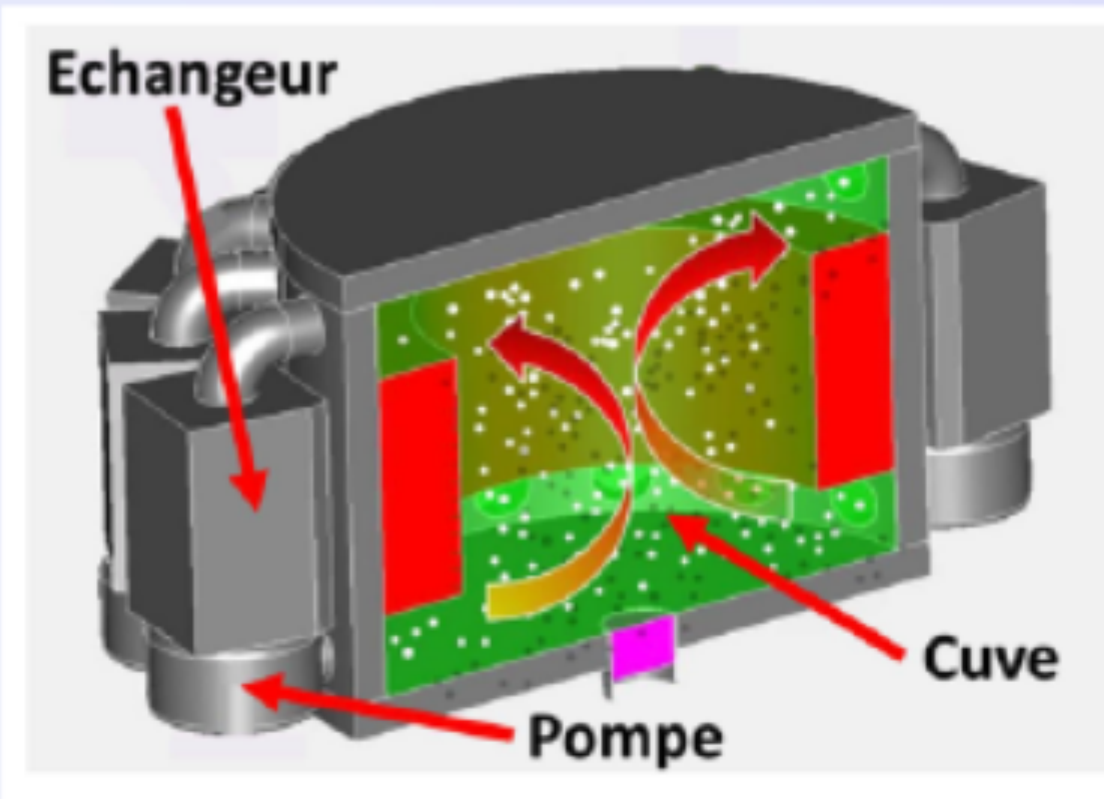
Why is the DFR not an MSR?

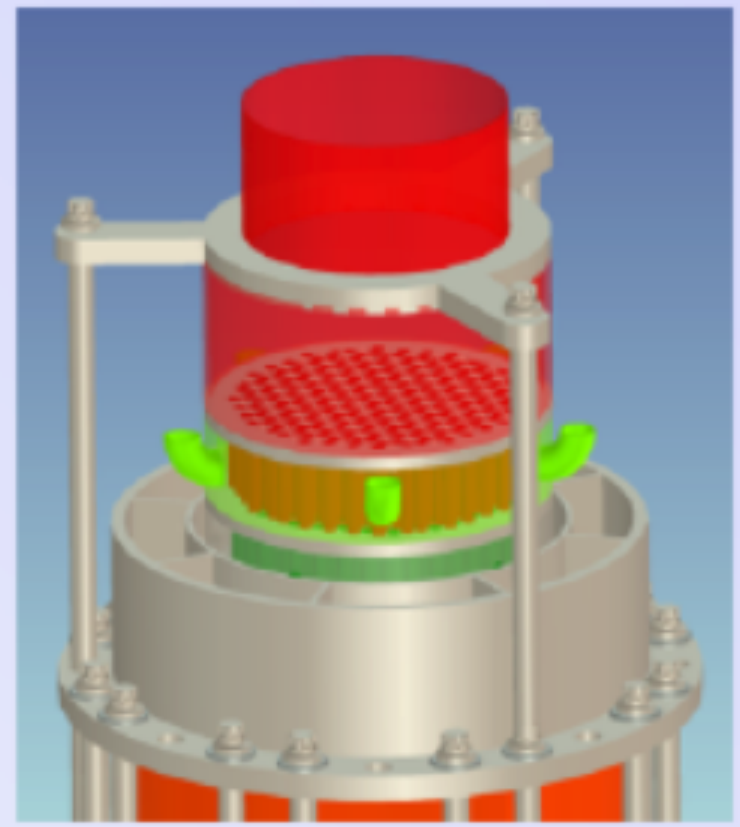
Molten Salt Reactor (MSR)

- Homogeneous core
- Fuel limited to salt
- Heat removal by salt

Dual Fluid Reactor (DFR)

- Heterogeneous core
- Fuel not „restricted", just fluid
- Heat removal by second fluid



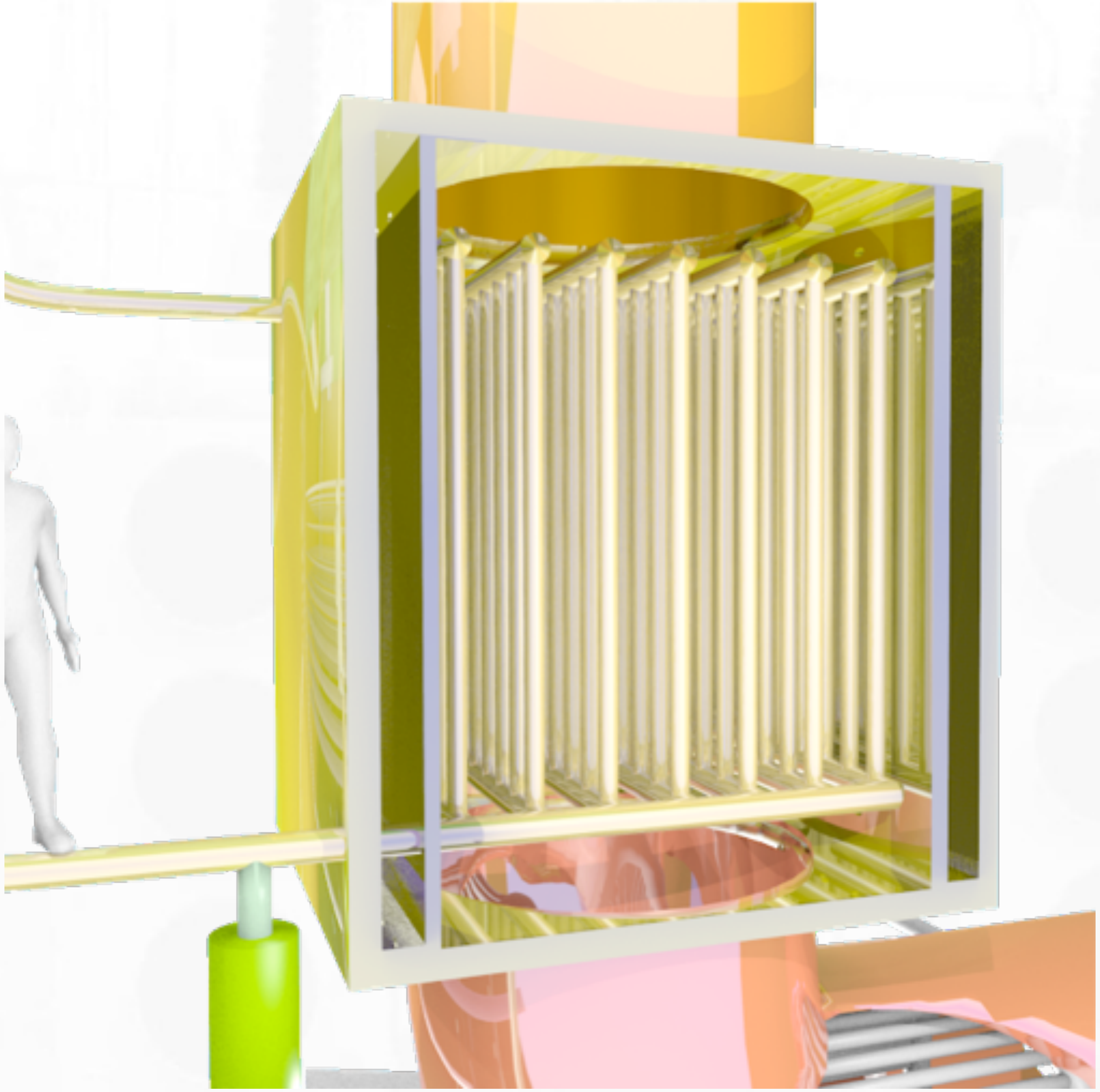


The double function of fuel providing and heat removal in the MSR limits its power density. **This limitation is not present at the DFR.**

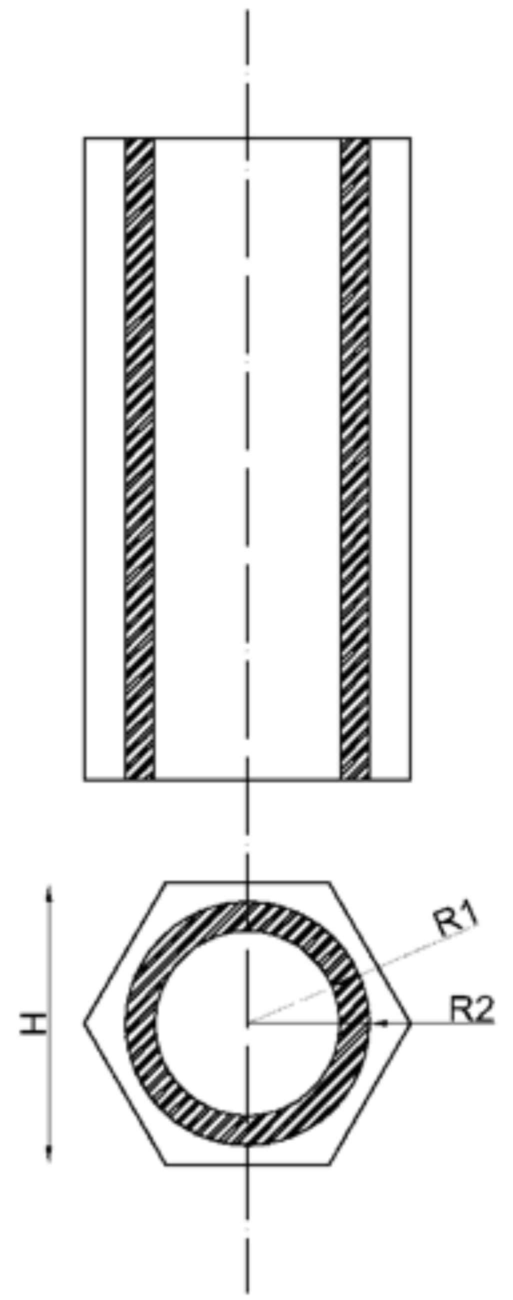
DFR technical data

	DFR/s (hexag.)	DFR/m (hexag.)
Fission zone D x H (m)	2.8 x 2.8	2.5 x 2.5
Outer/inner tube diameter (mm)	18/15	22/18
Pitch-to-diameter ratio	1.25	1.25
Mean linear power density (W/cm)	900	1800
Melting point/boiling point of fuel (K)	1100/1950	1080/ > 3500
Mean temperatures fuel inlet/outlet (K)	1270/1540	1330/1600
Temperatures coolant inlet/outlet (K)	1030/1300	1000/1270
Conversion ratio U-Pu/Th-U cycle at start	>1.2/1.1	1.7/1.1
\forall {^{234}U, ^{240}Pu, ^{242}Pu} k_{inf} . 1 & (resp. CR)	False (1.2/1.1)	True (2.1/1.3)
^{238}U fast fission/all fission	6%	20%
Fission zone volume without reflector (m^3) (fuel fraction)	17.5 (39%)	12.3 (39%)
Fuel processing, coarse/complete (kg/a)	400,000/12 x 28,000	0/4 x 65,000
Fresh fuel/coolant 1 reflector reactivity coefficients (pcm/K)	-8 to - 40/ < +0.25	-5/ 0
Inner core pressure at nominal power, fuel/ coolant (MPa)	<0.2/ < 0.5	0.1/ < 0.5
Fuel/coolant velocity (m/s)	1.2/3.6	0(.06)/3.7

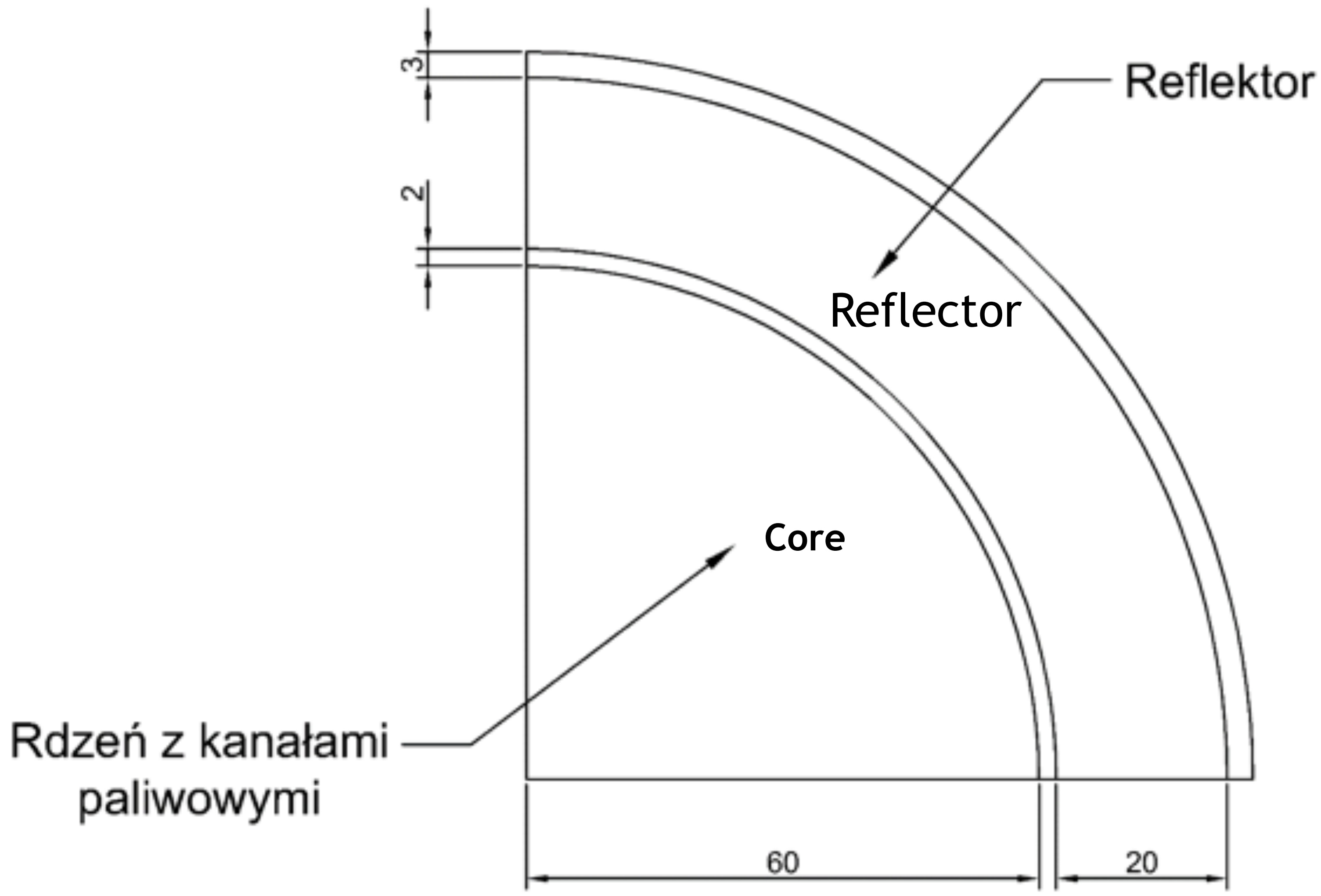
REACTOR DFR - core



REACTOR DFR - example geometry



Fuel element - SiC tube

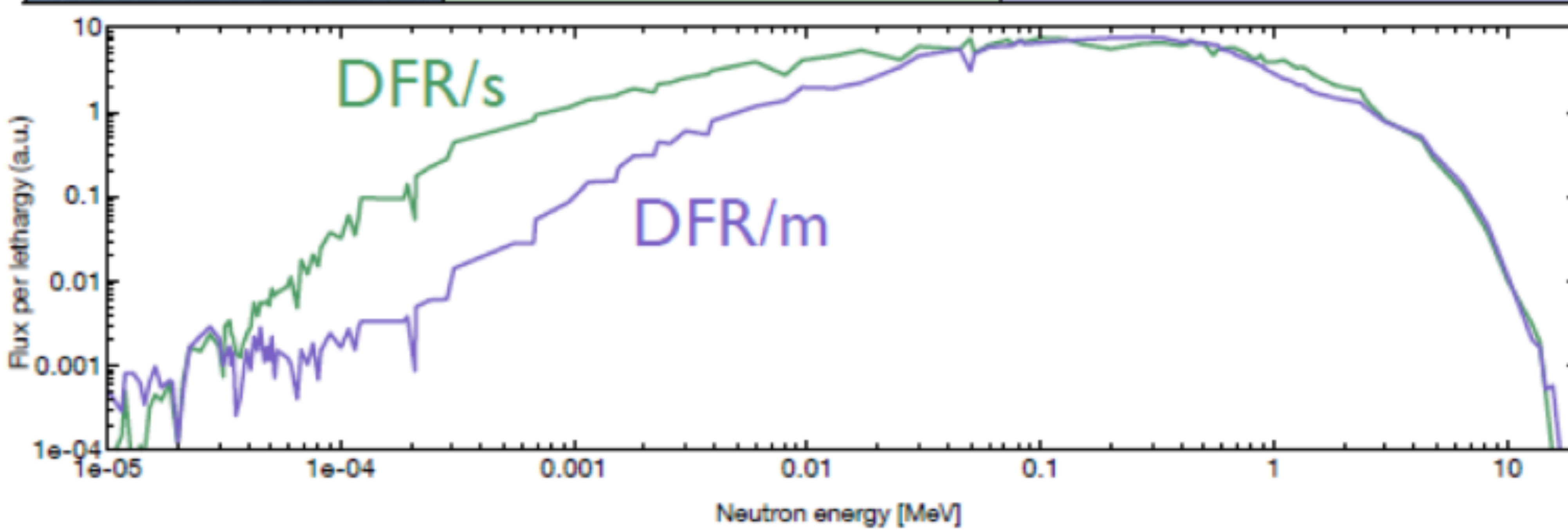


Core geometry and reflector

DFR - some fuel example properties

DFR: Metal vs Salt Fuel

3 GW_{th}, 1.5 GW_{el}	DFR/s	DFR/m
Fuel	Undiluted Act.-Cl3 salt, density 3500 kg/m³	Pure eutectic U-Cr/Th-Fe density 16500/9500 kg/m³
Critical with	20.5/18.3/15 HM mass-% reactor-Pu/^{235}U/^{233}U	8.4/8.8/8.8 HM mass-% reactor-Pu/^{235}U/^{233}U
Blanket	cylindrical, thickness 1 m, height 5.5 m (100 m³)	No blanket, thicker reflector (Pb coolant) 0.5 m
Structural Material	pure high-density SiC, 3210 kg/m³	ZrC-20mass%TiC, 6100 kg/m³



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REACTOR DFR – lead coolant properties

- Lead melting temperature: 327°C.
- Lead boiling temperature: 1749°C.
- Small cross-section for fast neutron capture.
- Practically each actinide isotope created as a result of lead-neutrons interaction decays back into the stable lead isotope.
- Good reflector for fast neutrons.
- High heat conductivity $\lambda = 9.32 + 0.0108 \cdot T$
- Mass density at T= 1000 °C: $\rho = 9.8416\ g/cm^3$

$$\rho = 11441 - 1.2795 \cdot T \qquad (2)$$

- Flow of coolant velocity will be optimized to get most effective heat removal.

REACTOR DFR - materials

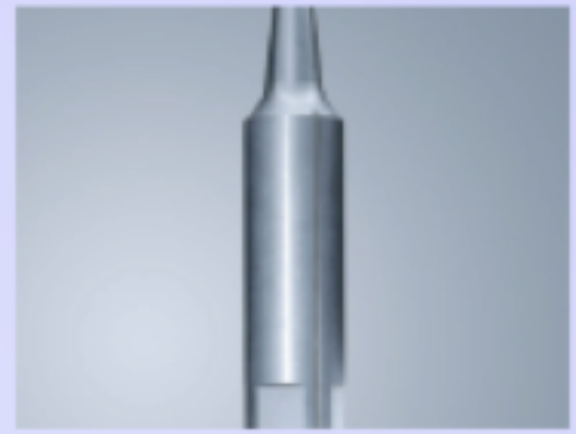
Operates at very high temperature > 1000 °C

Refractory (heat resistant) metal alloys and ceramics are needed

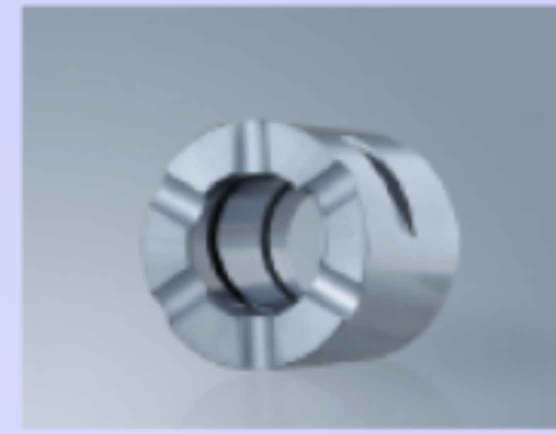
Such materials are known outside nuclear industry - SiC (silicon carbide)

Because of the low consumption of the materials one can afford them despite they are more expensive (usually in nuclear industry one was looking for cheaper corrosion resistant steel alloys)

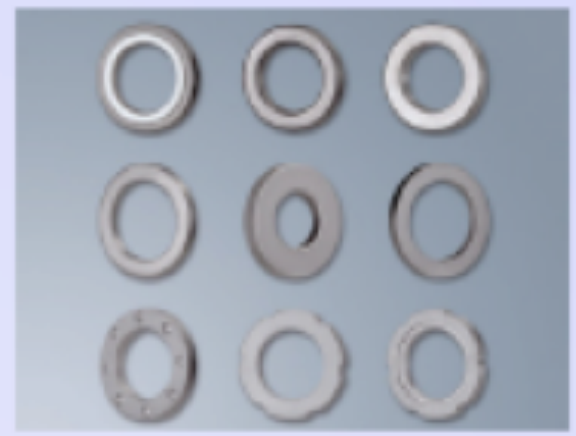
SiC Machined Parts



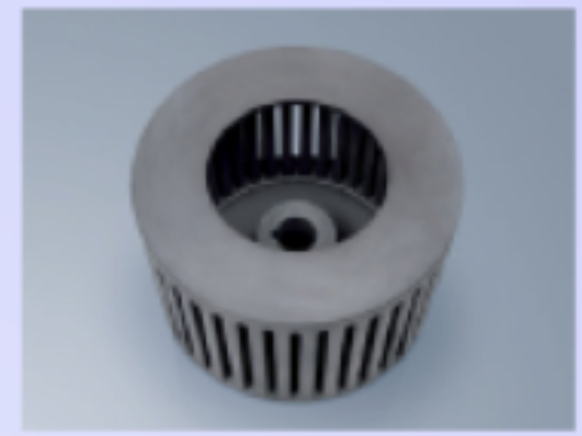
EKasic® Siliciumcarbid Pumpenwellen



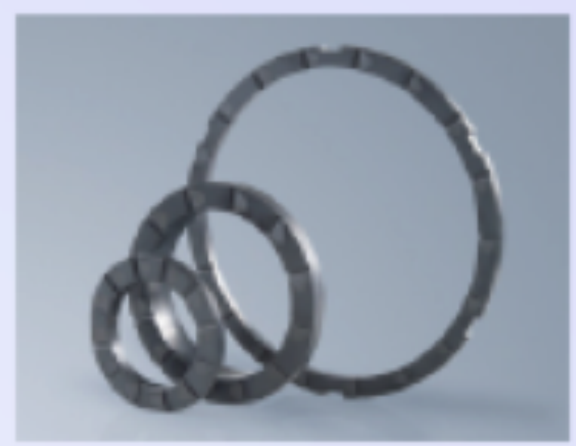
Gleitlager aus EKasic® Siliciumcarbid, werden z.b. in hochwertigen Chemie- und Industriepumpen, sowie r ührwerken für die chemische, pharmazeutische und Lebensmittelindustrie verwendet



Gleitringdichtungen aus EKasic® Siliciumcarbid eignen sich besonders für medien, die stark beansprucht sind, z.b. durch Verunreinigung, abrasion und/oder Korrosion



Sichterräder aus EKasic® Siliciumcarbid finden Verwendung in der chemischen, pharmazeutischen, Lebensmittel-, mineralien-, metall- und r ecycling-Industrie zur Herstellung von Pulvern, Granulat und Schüttgut.

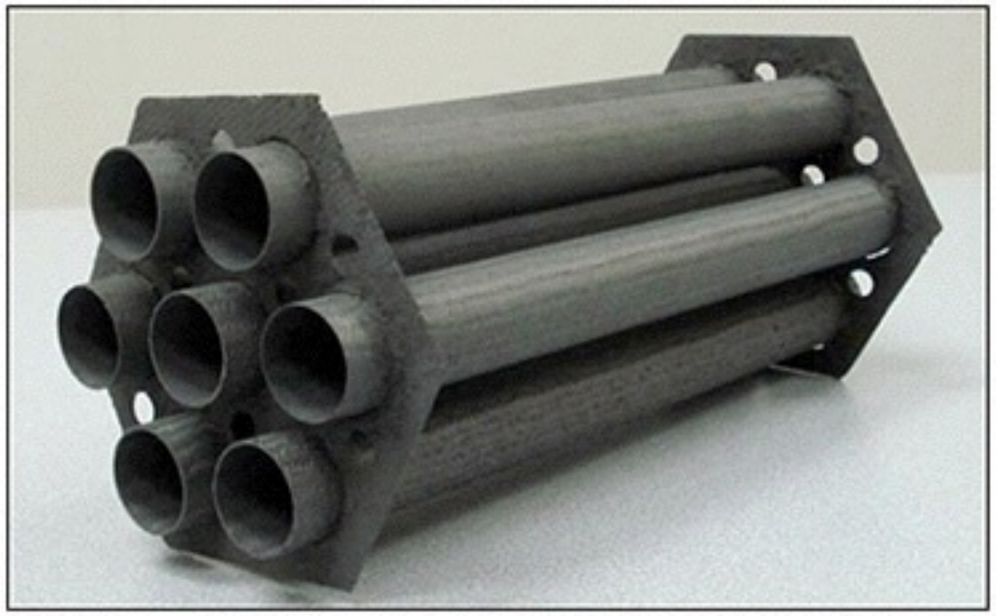


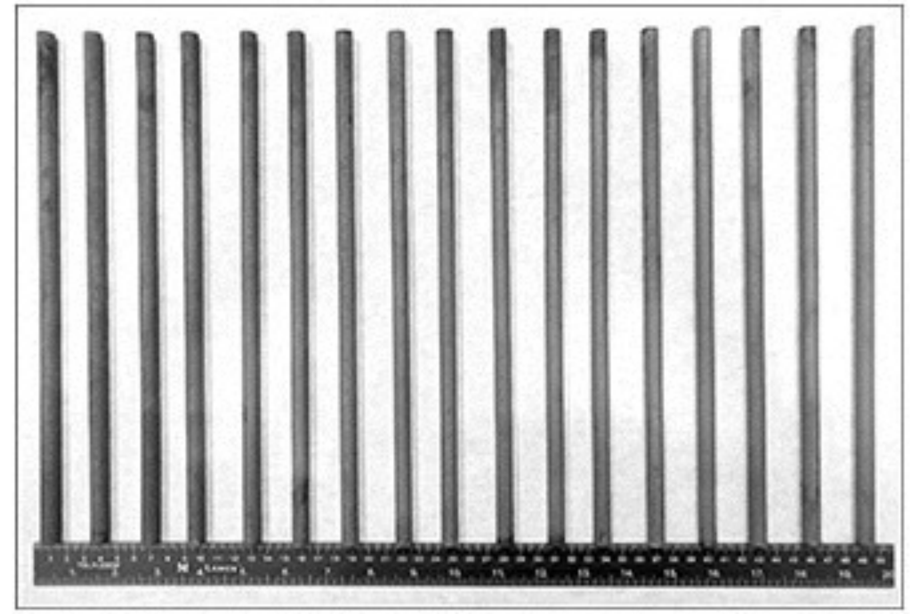
Laserstrukturierte Gleitringdichtungen aus EKasic® Siliciumcarbid (links: r adiallager, rechts: axiallager), werden z.b. in hochbeanspruchten Chemiepumpen, in magnetkupplungen für hermetisch dichte Pumpen sowie in r ührwerke für chemische und pharmazeutische Verfahren verwendet

Gasdichtungsringe aus EKasic® Siliciumcarbid werden zur abdichtung von Kompressoren und r ührwerken für die Erdöl- und Gasverarbeitungsindustrie eingesetzt

GENERAL ATOMICS (GA)

www.ga.com/siga-sic-composite





SiGA™ composite components are available in tube diameters from 5 mm to >50 mm, and tube lengths up to 1 m. Hot-Pressed structures with thickness >25 mm can be produced, and both blind and thru-hole features can be manufactured near net-shape without machining.

Finished SiGA™ composites maintain their strength and stability under high levels of irradiation and can retain strength at temperatures well above 1600°C

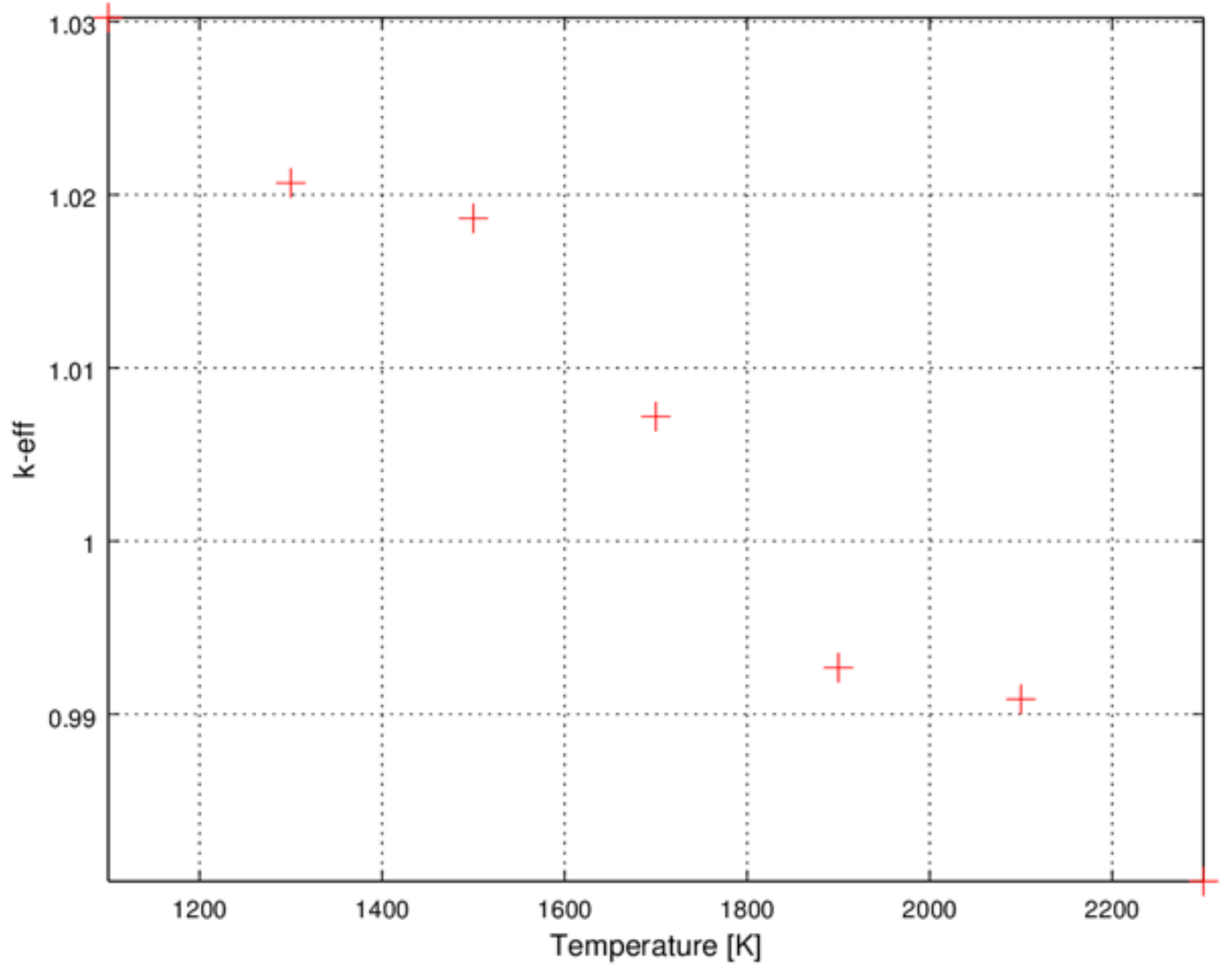
REACTOR DFR - safety

Passive safety reacting on the temperature increase:

- Melting “fuse” allows fuel to fall into the subcritical tank below the reactor.
- Decay heat removal by natural air convection.
- Decrease of fuel density accompanies decrease of the amount of actinides.
- Decrease of coolant density weakens lead properties as reflector.
- Doppler effect - resonant capture of neutrons grows.

Strongly negative temperature coefficient: $dk/dT < 0$
($dk/dT = -0.0005/k$; Huke et. al 2015; Wang 2017).

NEGATIVE TEMPERATURE COEFFICIENT



REACTOR DFR - startup

To start the reactor one needs to:

- Pre-heat to liquid phase fuel and coolant.
- Pump in the fuel from the storage tanks to the reactor.
- Criticality when the salt (900 C) is pumped in the reactor core - equilibrium temperature reached.
- Strong negative temp. coefficient does not allow to freeze the fuel out (melting at 800 C).

REACTOR DFR - operational

- Initially power production minimal.
- Coolant pump starts accelerating circulation of lead.
- Heat discharged to the heat exchanger - decrease of temperature.
- Reactor supercritical till nominal temperature and the power output is reached.
- Coolant pump starts decelerating circulation of lead.
- Temperature in the reactor increases - then subcritical.

- The reactor fission rate is steered by the power extraction.
- Actively: changing the lead pumping speed;
- Passively: feedback from turbine's electricity generation.
- No need of control rods in DFR!

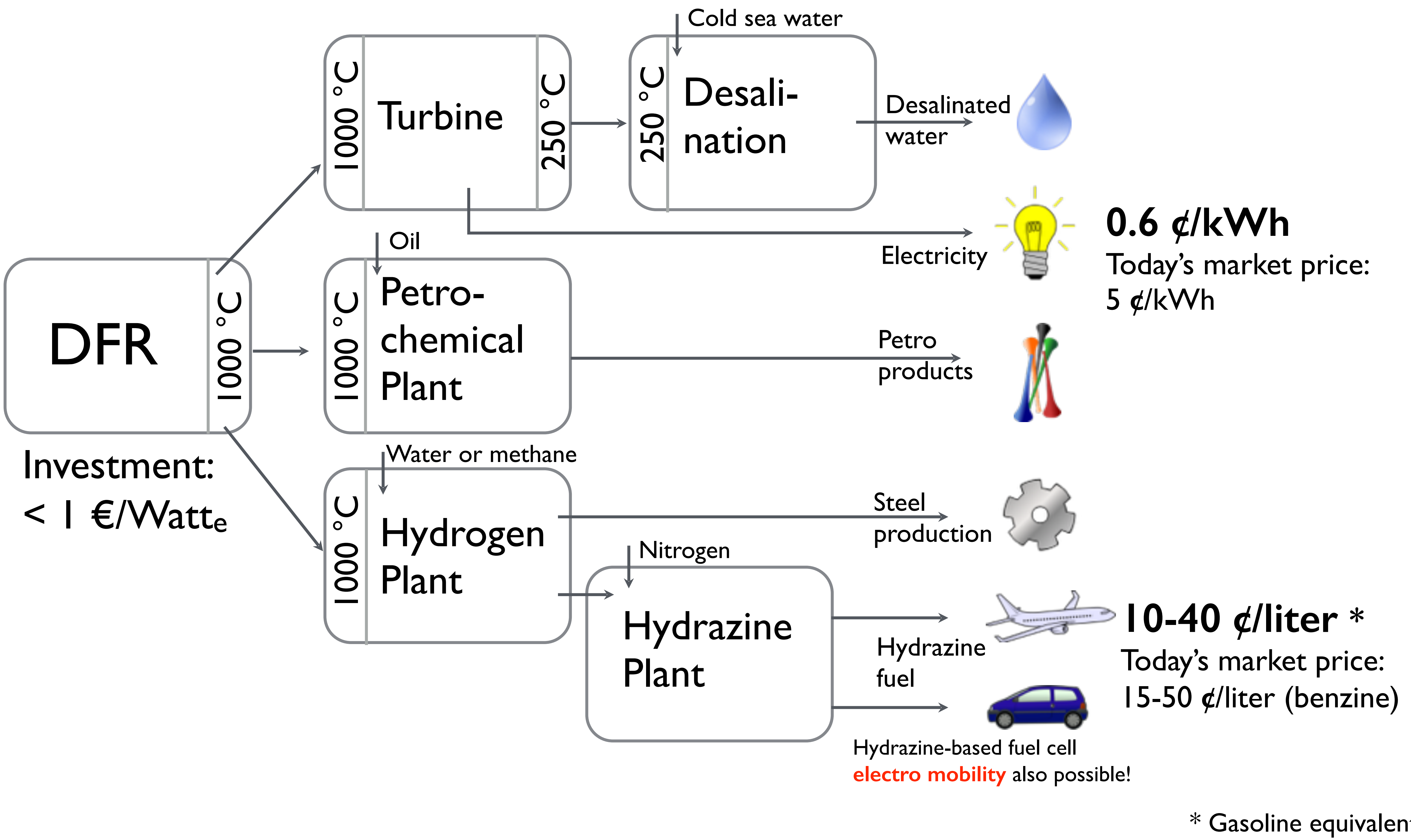
REACTOR DFR - shutdown

To shutdown the reactor one needs:

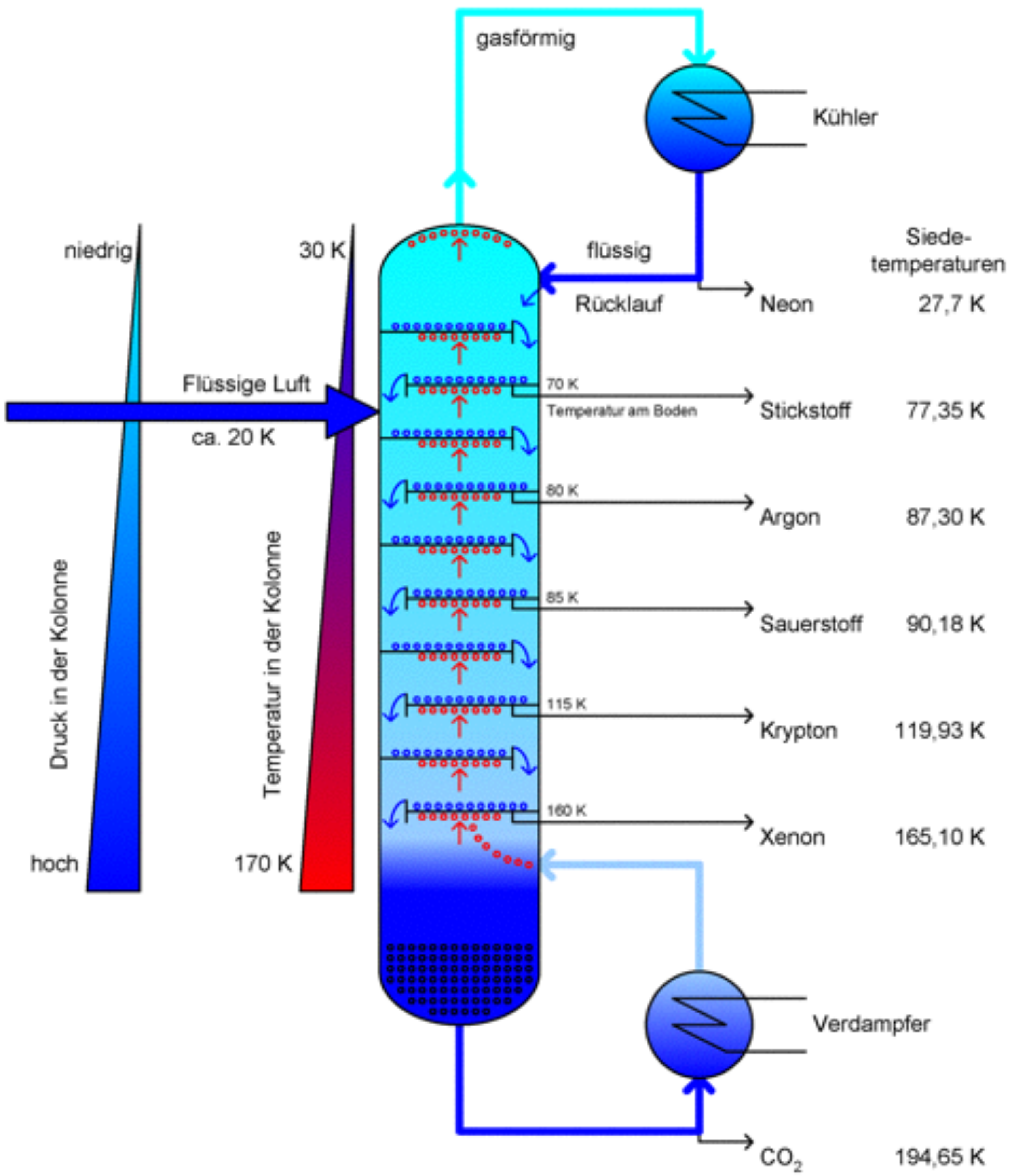
- Stop the coolant circulation.
- Stop the fuse cooling - fuel is emptied to the storage tank.
- Any malfunction increasing the equilibrium temperature would result in fuse cooling stop.
- Emergency shutdown is same as regular shutdown in DFR!

- No need of control rods in DFR!

Potential DFR applications



Salts reprocessing with the PPU

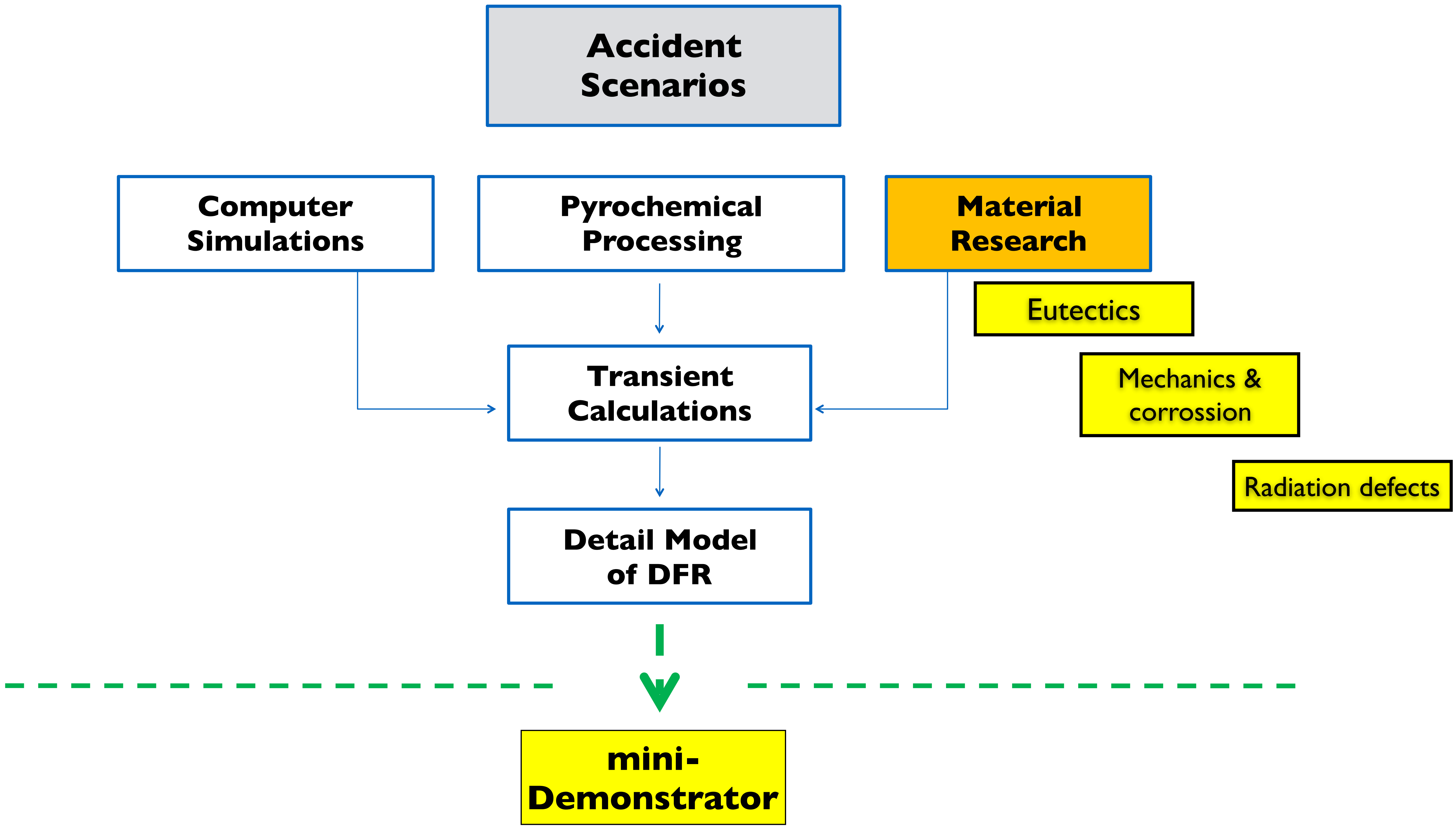


Well-known technics from chemistry:

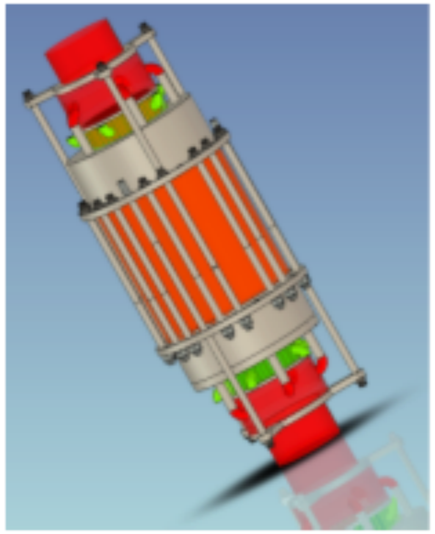
Partitioning of the salt components by the distillation

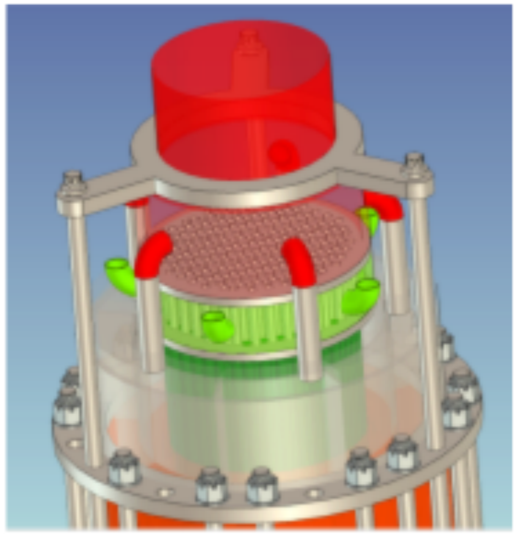
No wet chemical techniques with large amounts of medium-active chemical waste

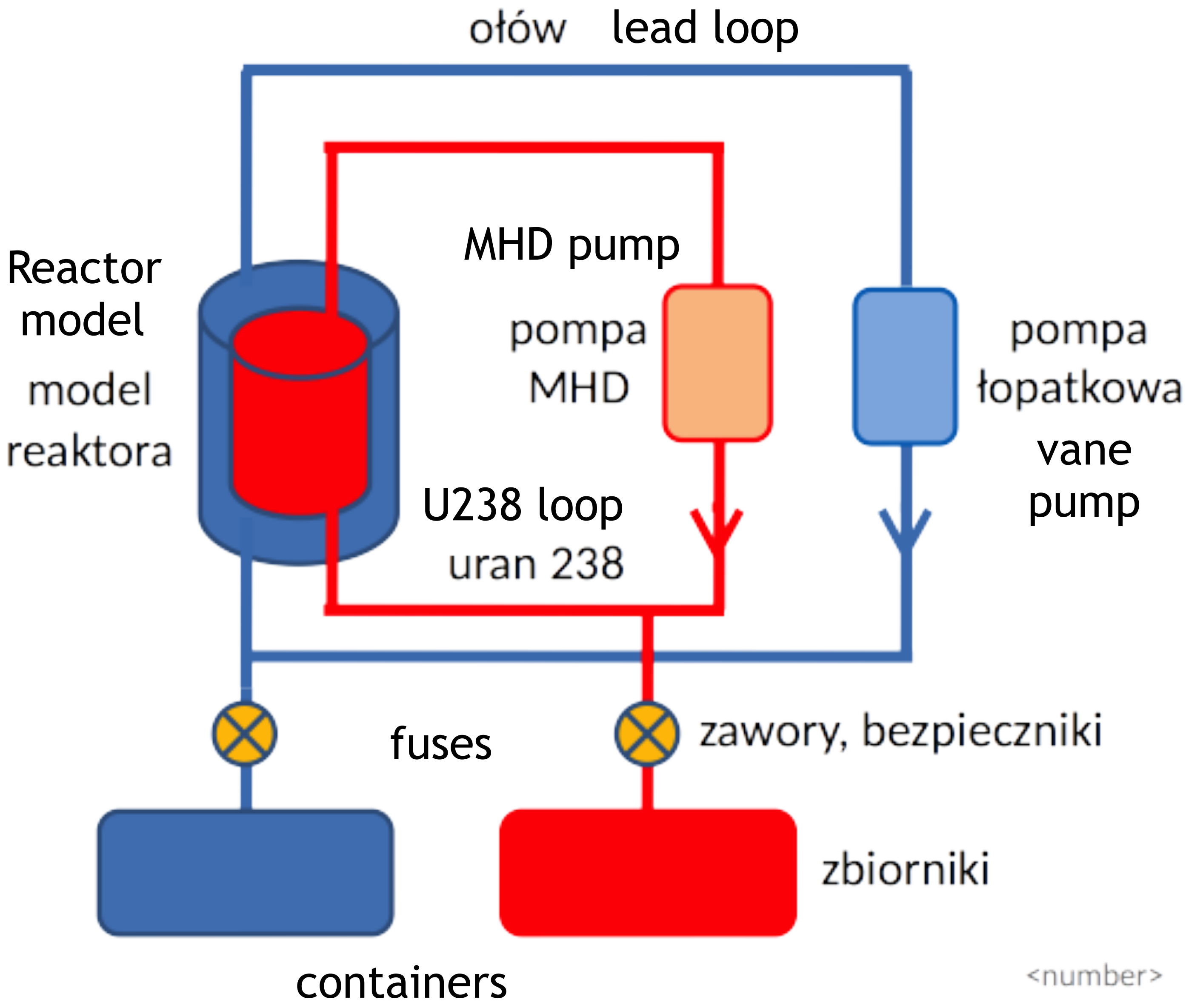
Current DFR state-of-the-art



Minidemonstrator - a depleted loop (NCBJ)

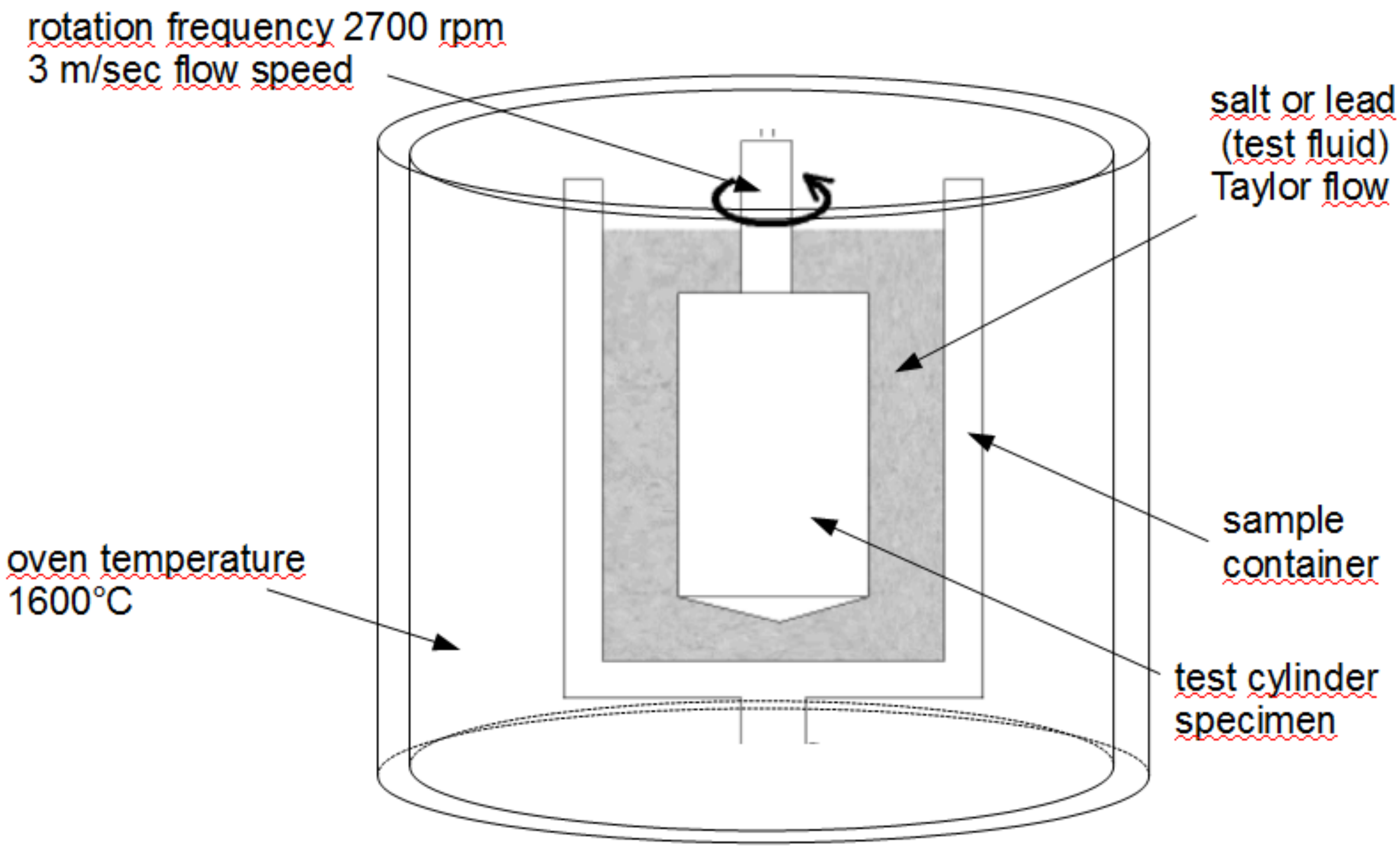






Material Experiments, NCBJ

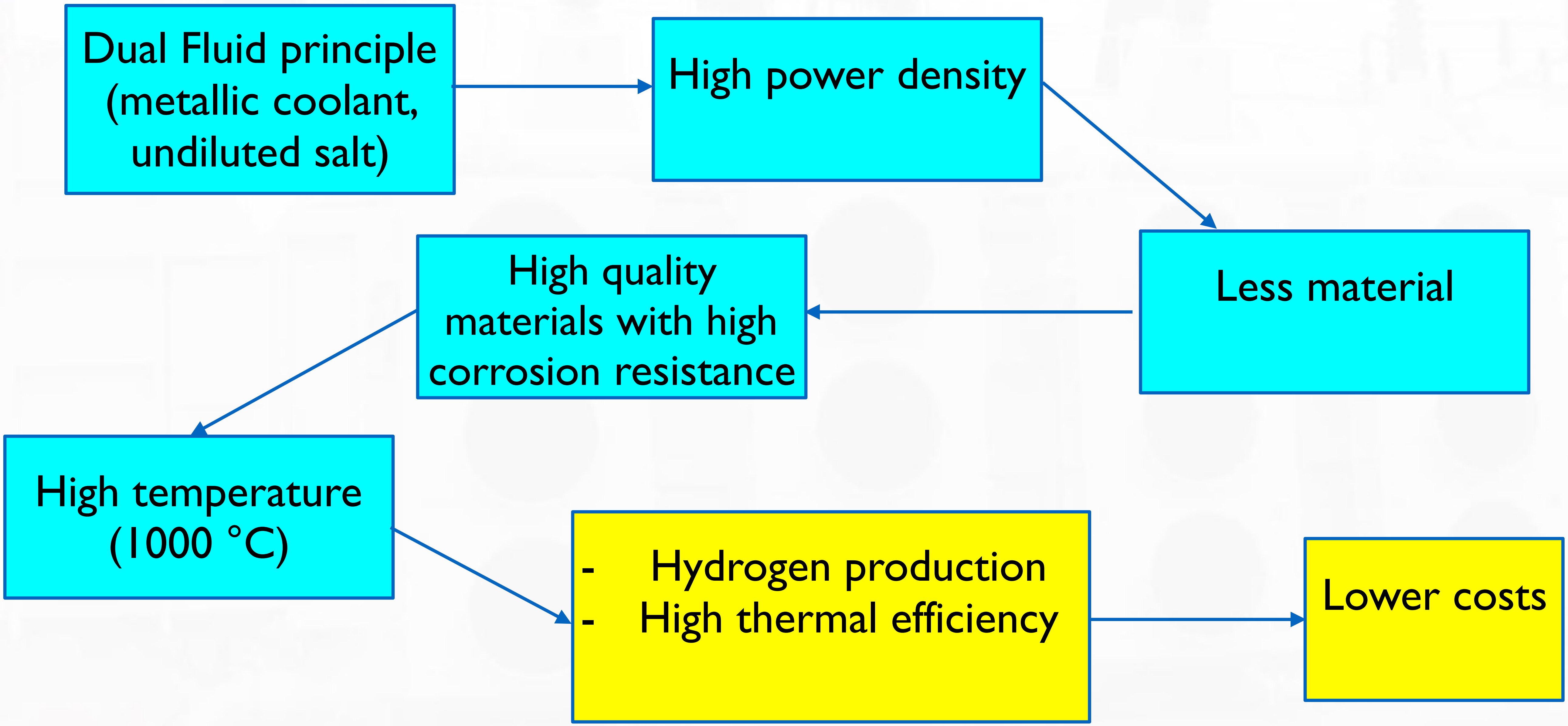
Experimental Setup: Corrosion Oven



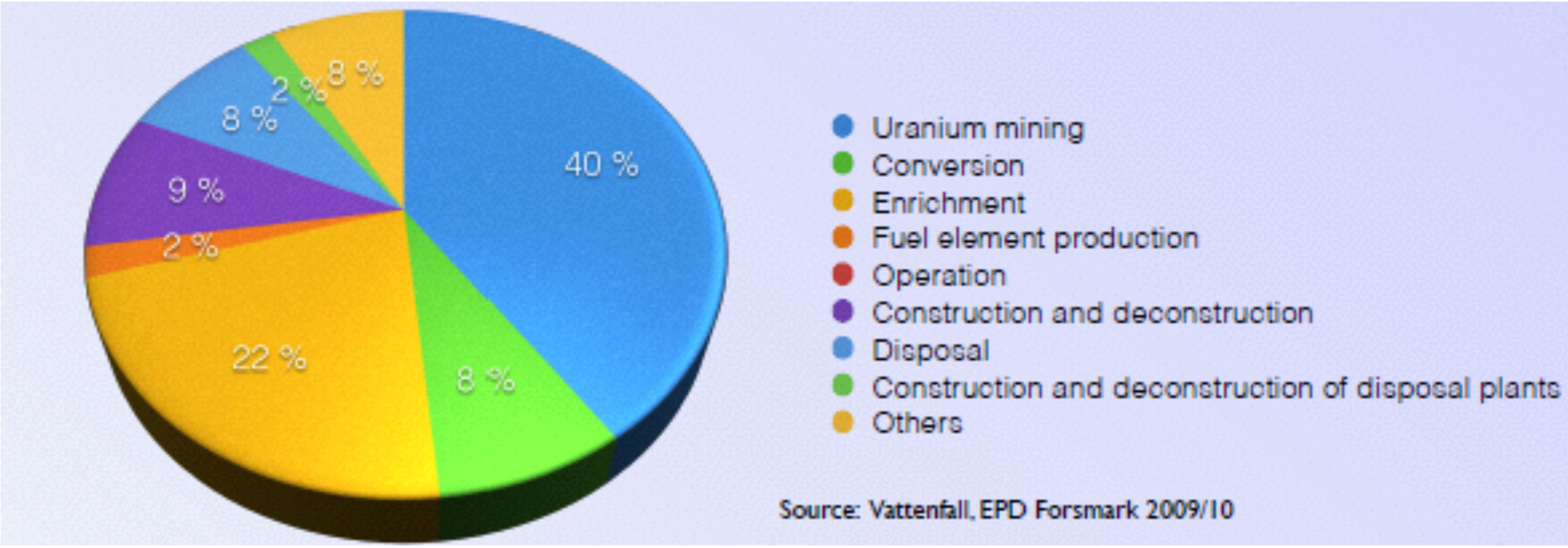
4. Is DFR generation IV or V and why?

DFR – optimization

Fluid fuel with a high density of actinides together with fluid coolant with a very good heat removal properties leads to a significant growth of the power density in the core.



Economy of current NPPs:



Today's nuclear reators are more effective than other power generating systems, but **nuclear power can do much better!**

- Expensive external fuel cycle
- Using only 1% of the mined Uranium
- 99% waste that needs geological storage
- Low power density

Energy Return on Invested - EROI

The EROI describes the efficiency of a power plant by comparing the electricity output with all the expended exergy input.

$$\text{EROI} = \frac{\text{Total energy output}}{\text{Total energy input}}$$

All „produced" energy during lifetime of a power plant

All expended energy to construct and operate the plant, including indirect processes like mining and fuel provisioning („from the cradle to the grave")

Better efficiency means

- Smaller impact/footprint on nature
- Lower costs

EROI:=R;

E_R = usable energy;

E_I = invested energy

R = E_R/E_I

E_fix = *energy fixed* for construction and deconstruction

P_I = energy demand per time (e.g. maintenance, fuel)

E_I = E_fix + t x P_I

P = average power

E_R = t x P

After the plant's lifetime T we have:

R = T x P / (E_fix + T x P_I)

Solving for R=1 (energy returned covers invested)

one finds *energy payback time*

T_a = E_fix / (P - P_I)

Small maintenance approximation ($P\_I << E\_fix$; $P\_I << P$):

$R \sim T \times P / E\_fix = T/T\_a$

(works for all the plants except gas-fired since for them P_I dominates P)

Net energy: $E\_net = E\_R - E\_I = E\_I (R - 1)$

EMROI:= R_em - energy money returned on invested is often mistaken with EROI

$R\_em = w\, E\_R/(E\_th + w\, E\_el)$,

where $w = 3$ is the ratio of thermal to electric energy, $E\_I = E\_th + w\, E\_el$ and E_R is reduced only to the electric output energy.

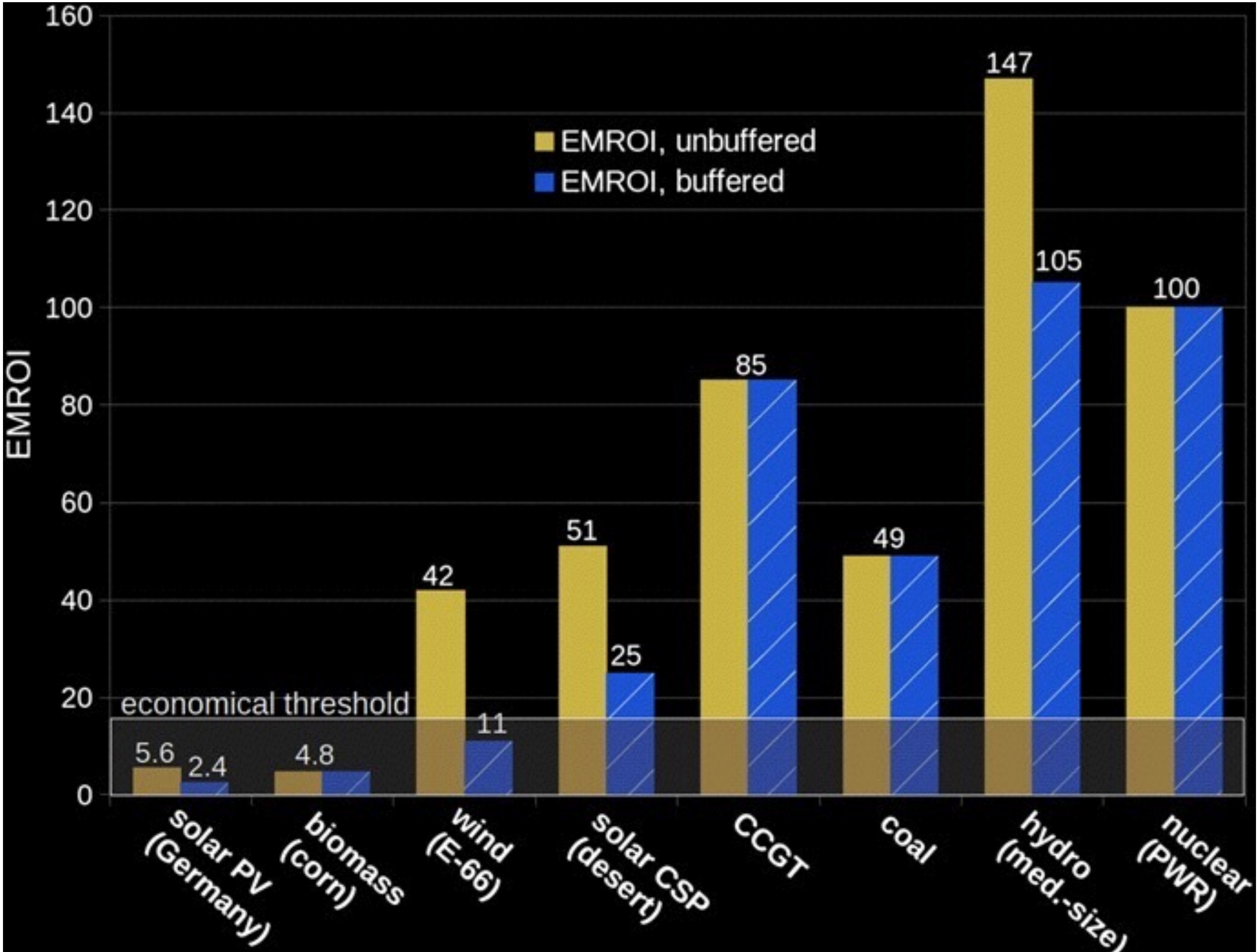
It counts only money return for energy and excludes the labor costs.

“Buffering” sources of energy:

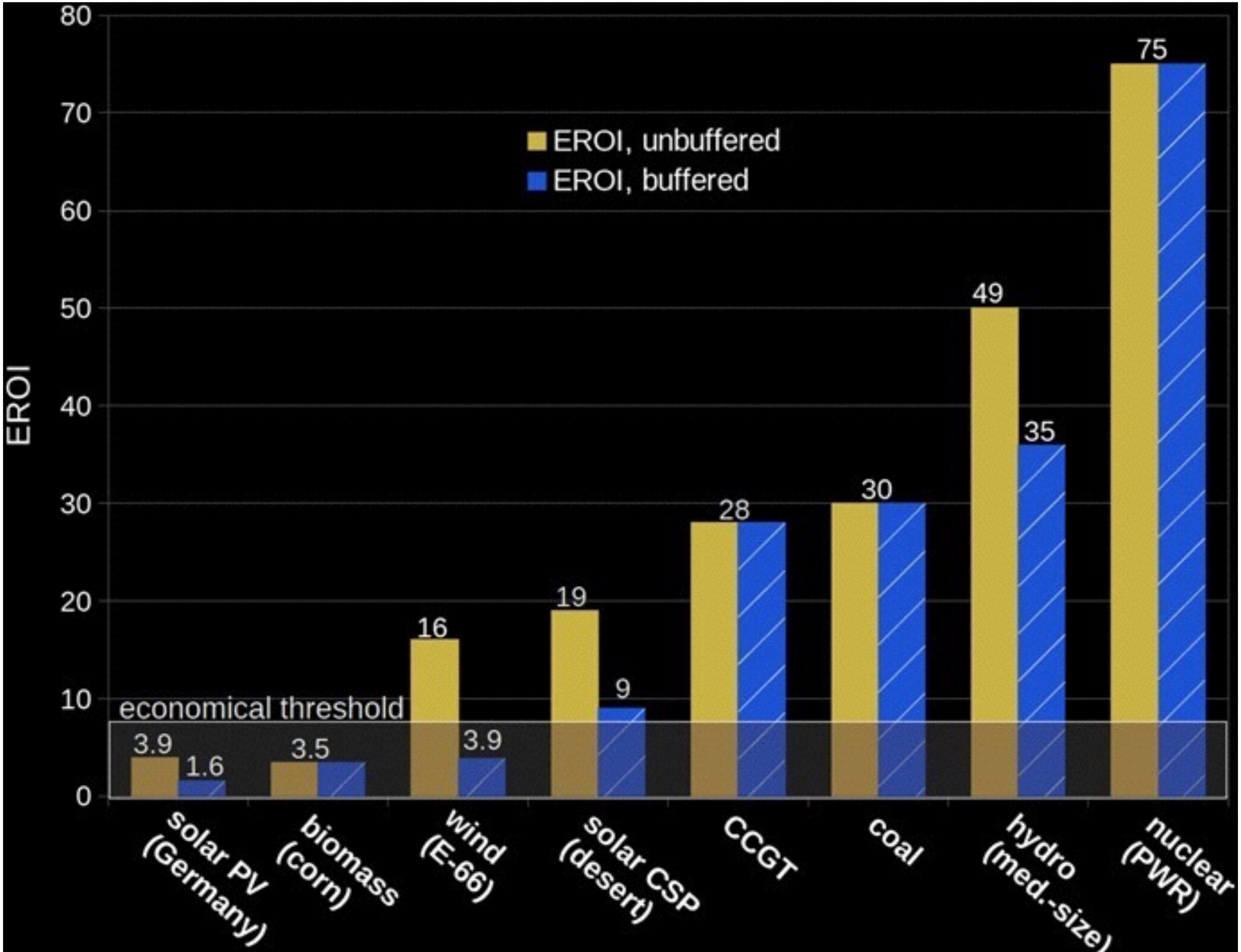
“availability” of energy - connected to a grid
“usability” - consumer must need it/should be available when needed
3 options:

- **ignore output peaks and installing multiple times of the necessary capacity as a backup**
- **Buffering: installing storage capacities to store the peaks, reducing over-capacity plant installations**
- **Adapting the demand to the output (unrealistic)**

Buffering small for fuel based units. Large for renewables (including hydro-plants).
Enlarges E_I to $E\_IS = f\_0 \times E\_I + E\_S$ (reduces R)
(f_0 - “over-capacity” factor, E_S - storage energy)



EMROI, unbuffered
EMROI, buffered
EMROI
160
140
120
100
80
60
40
20
0
147
105
100
85
51
49
42
25
11
5.6
2.4
4.8
economical threshold
solar PV (Germany)
biomass (corn)
wind (E-66)
solar CSP (desert)
CCGT
coal
hydro (med.-size)
nuclear (PWR)



80
70
60
50
40
30
20
10
0
EROI
EROI, unbuffered
EROI, buffered
75
49
35
30
28
19
16
9
economical threshold
3.9
1.6
3.5
3.9
solar PV (Germany)
biomass (corn)
wind (E-66)
solar CSP (desert)
CCGT
coal
hydro (med.-size)
nuclear (PWR)

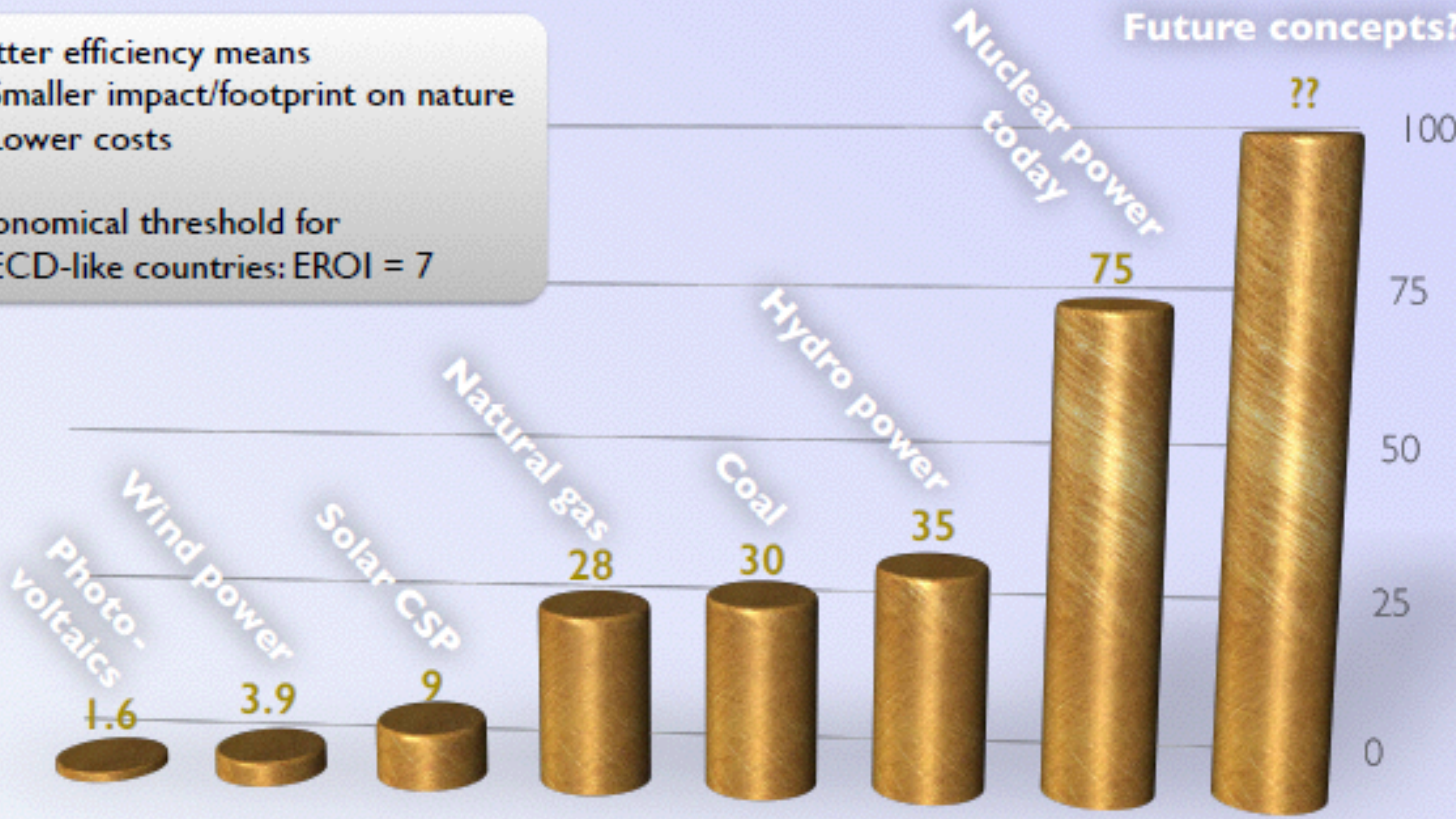
Energy Efficiency of Power Plants

Efficiency by **EROI** (Energy Return on Energy Invested)

see Weißbach et al., *Energy*, vol. 52 (2013), pp. 210–221

Better efficiency means
- Smaller impact/footprint on nature
- Lower costs

Economical threshold for OECD-like countries: EROI = 7

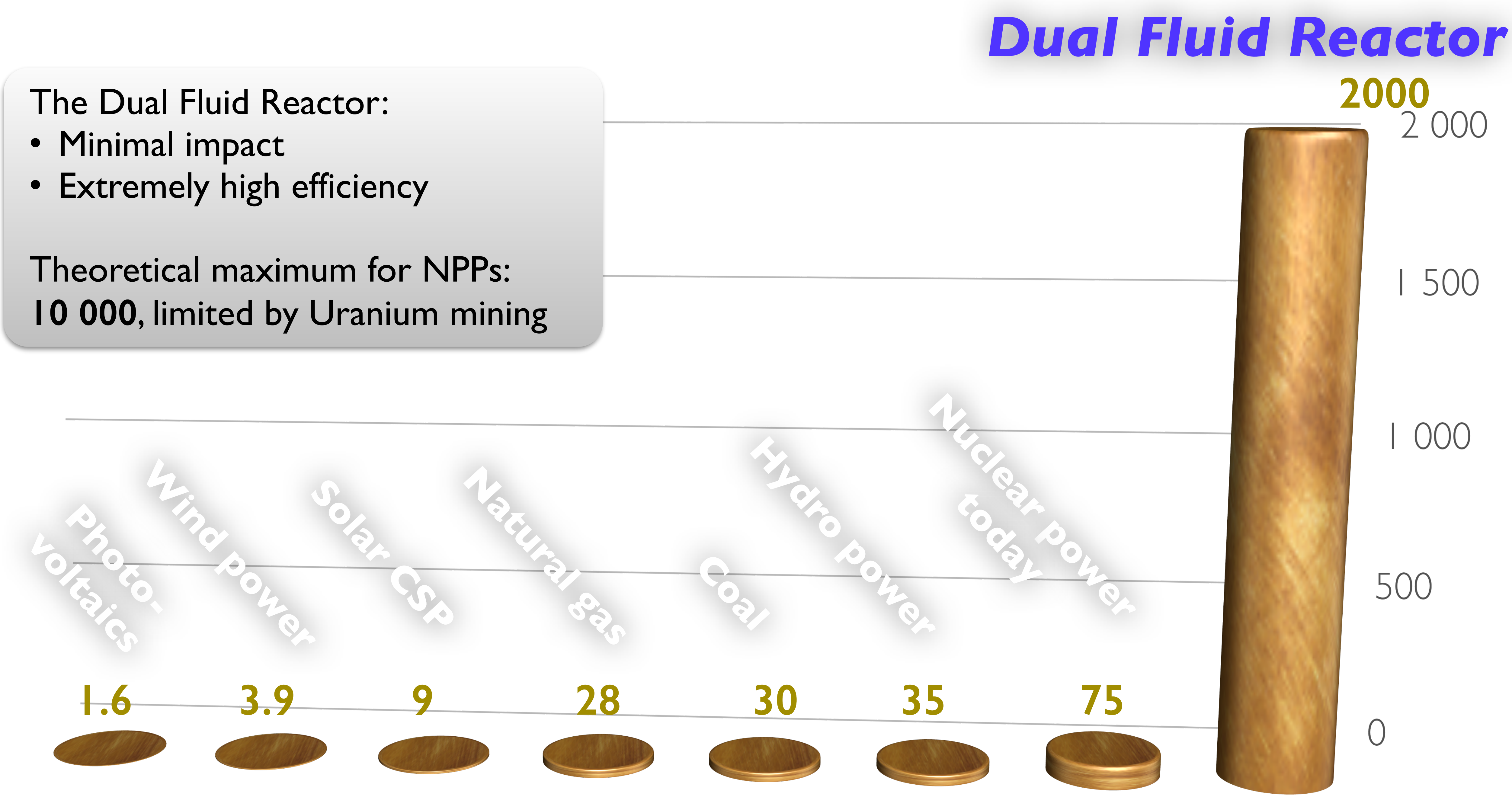


Efficiency by **EROI** (Energy Return on Energy Invested)

see Weißbach et al., *Energy*, vol. 52 (2013), pp. 210–221

The Dual Fluid Reactor:
- Minimal impact
- Extremely high efficiency

Theoretical maximum for NPPs:
10 000, limited by Uranium mining

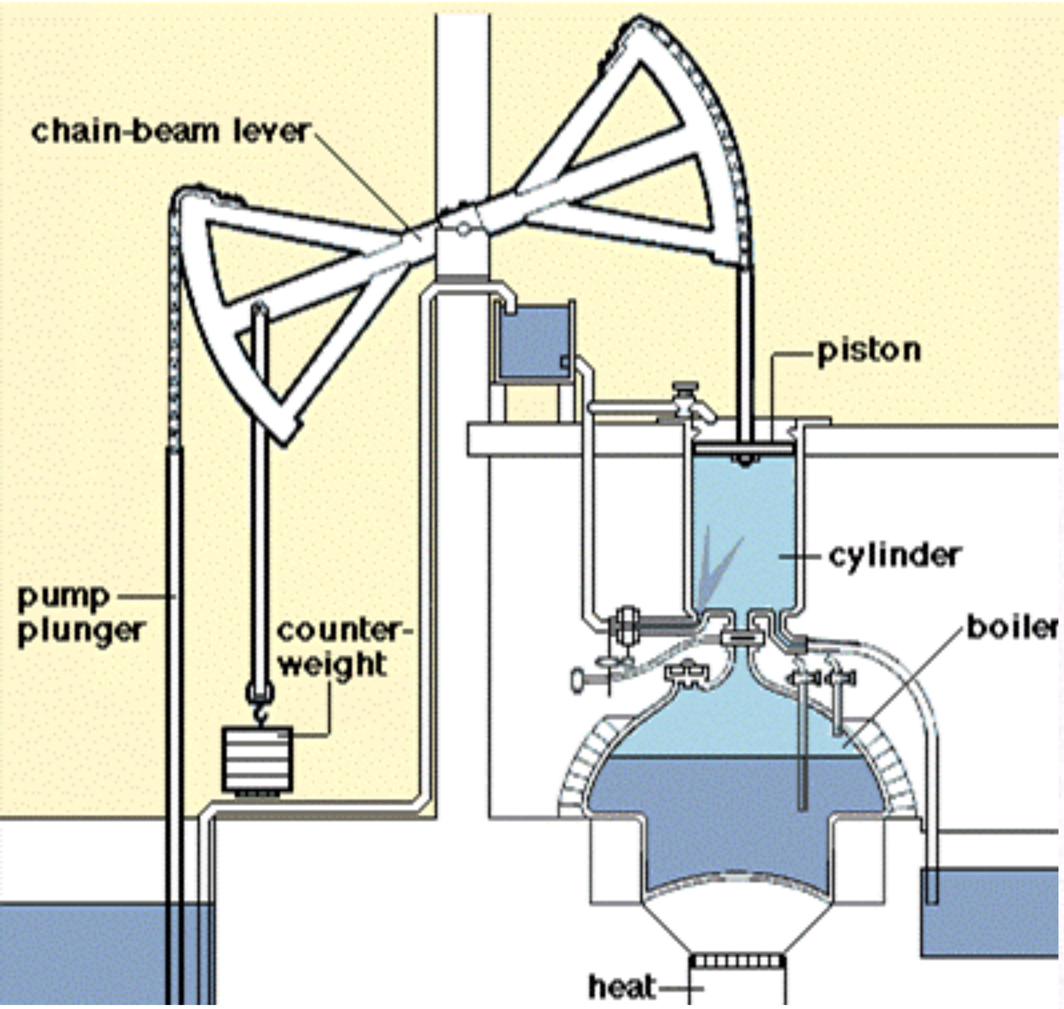


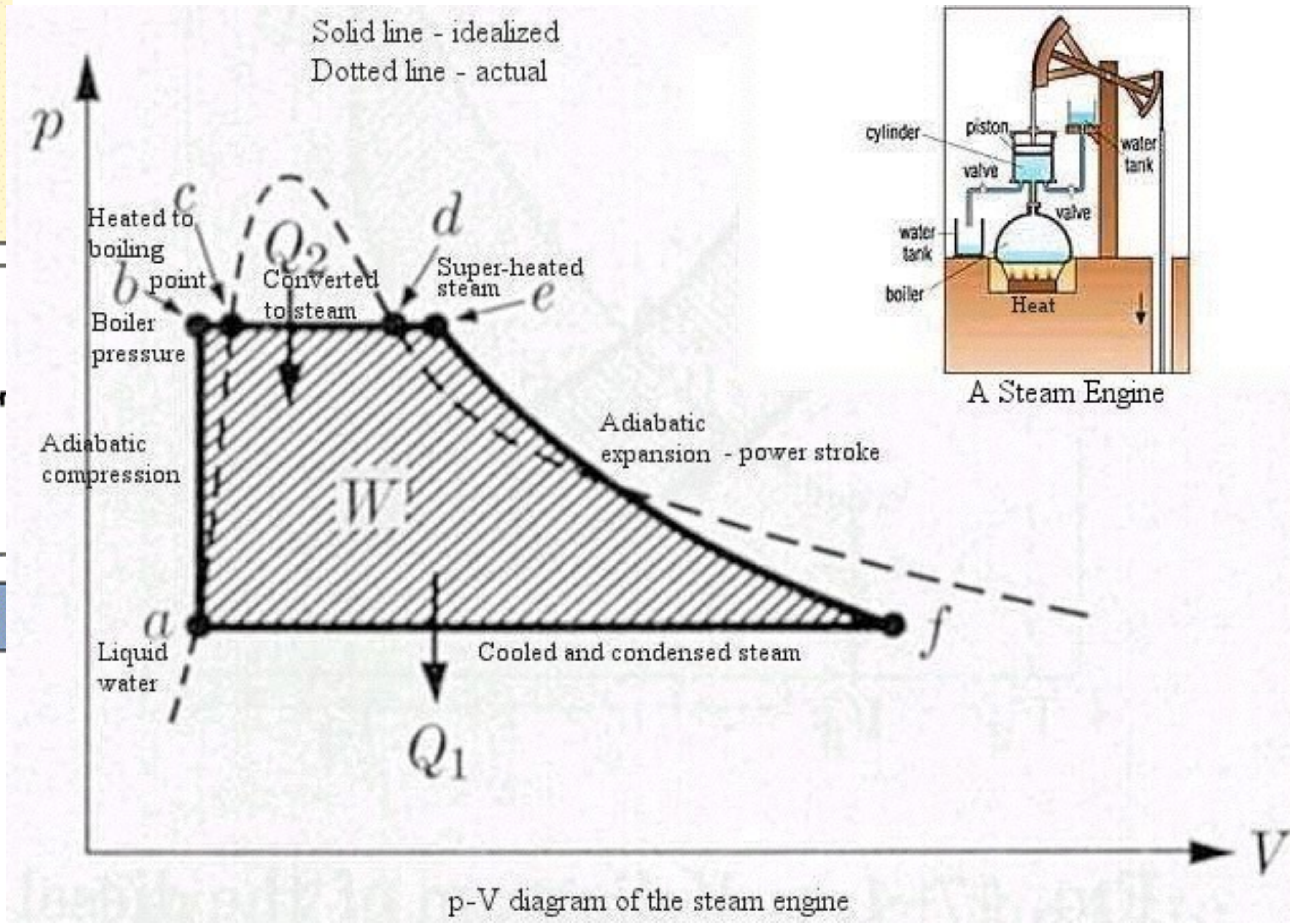
How such a large EROI is gained?

1. The loss of costly external fuel processing infrastructure (about 3 x LWR) - no need for costly enrichment (EROI: diffusion - 25; centrifuge - 75-105; laser - 115)
2. Much higher compactness and simplicity of construction (about 6 x LWR)
3. Lower maintenance efforts
4. Much less fuel consumption
5. Lower disposal needs
6. Reduction of refractory material for construction (1000 tons in LWR to 100 tons in DFR)
7. For the EROI input one counted: construction, fuel supply expense, maintenance, decommissioning

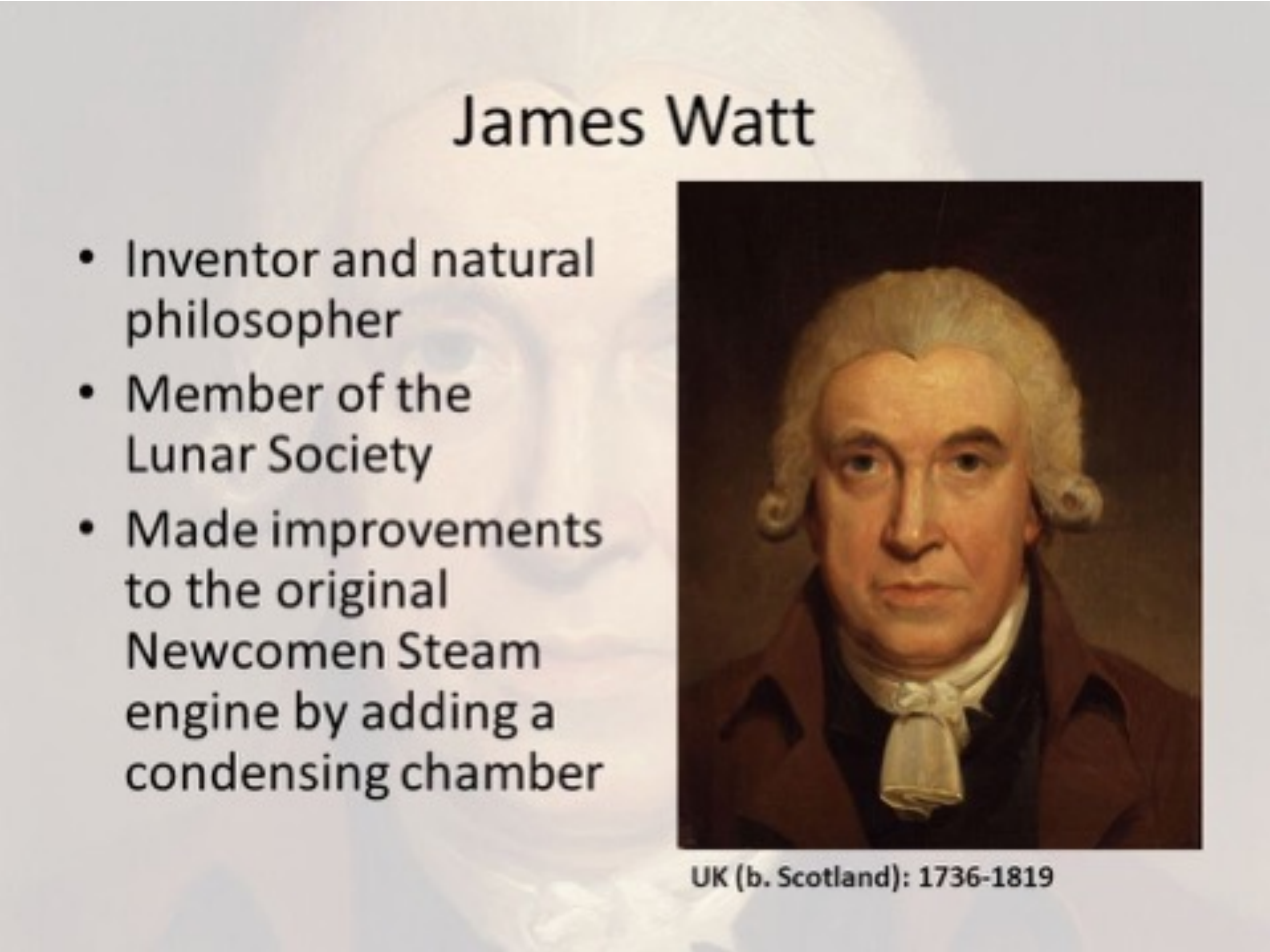
James Watt's type "revolution" in nuclear power?

Newcomen steam engine (1712) thermal efficiency extremely low (0.5-1.0 %) and could practically only be used to pump flood water out of the coal mines



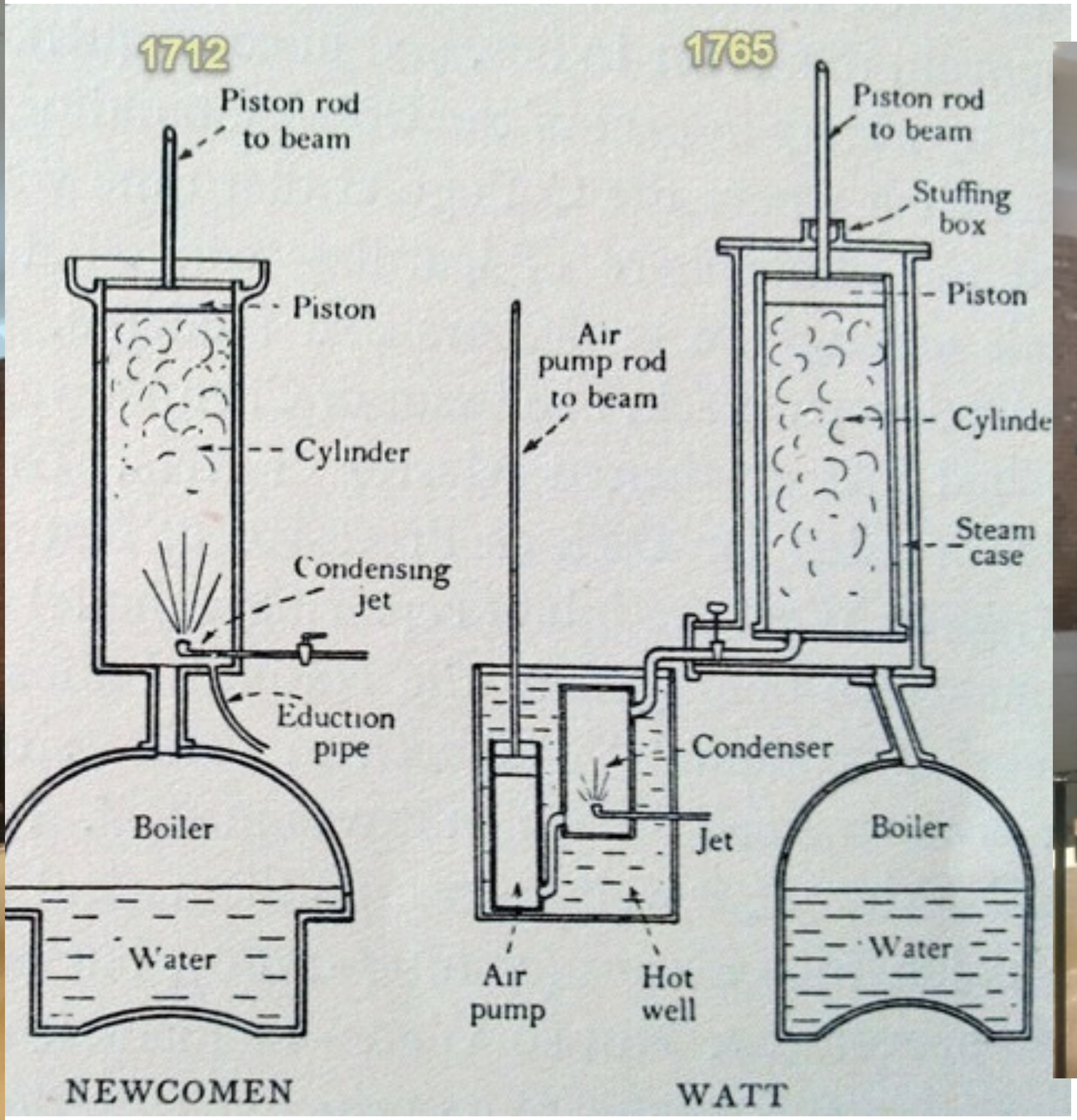


James Watt's invention.



- College of Glasgow scientist - in 1764 given a task to repair a classroom teaching scale model of Newcomen engine - "stopped after a few cycles"
- realised that most of the energy was used to heat the piston-cylinder unit
- small size of the engine made the efficiency lower

The major breakthrough was that Watt separated condenser chamber and so the piston-cylinder unit would not have to be reheated during each cycle and steam consumption was greatly reduced.



Watt steam engine (1765) thermal efficiency increased enough high (4.0-5.0 %) making steam engines practical to drive machinery in factories ("industrial revolution")

Watt patented his engine in 1769 and then after entering business partnership with Matthew Boulton to manufacture it, they dominated steam-engine design and improvement. They (and Britain as the country) made vast profit out of it before in 1800 the patent expired and new generation of engineers (e.g. C.R. Trevithick) "waiting in the wings" were able to take up the challenge.

Why is this the boost?

1. It is a technology not motivated by military applications (nuclear bomb, propulsion of naval vessels) as it was for PWR etc. (but not for HTGR).
2. Main problem of Gen III+ - safety competes with economics - i.e. it can be improved but at higher cost.
3. High power density (despite low for HTGR which prevents core meltdown there).
4. DFR - combines high power density and economic efficiency.

Energy: exergy and anergy

1. The invention of Watt lead to the formulation of the theory of thermodynamics (energy law, entropy law).
2. Not all forms of energy are of equal value - only those which can do work i.e. exert force (the case of Watt).

Energy (1st law)

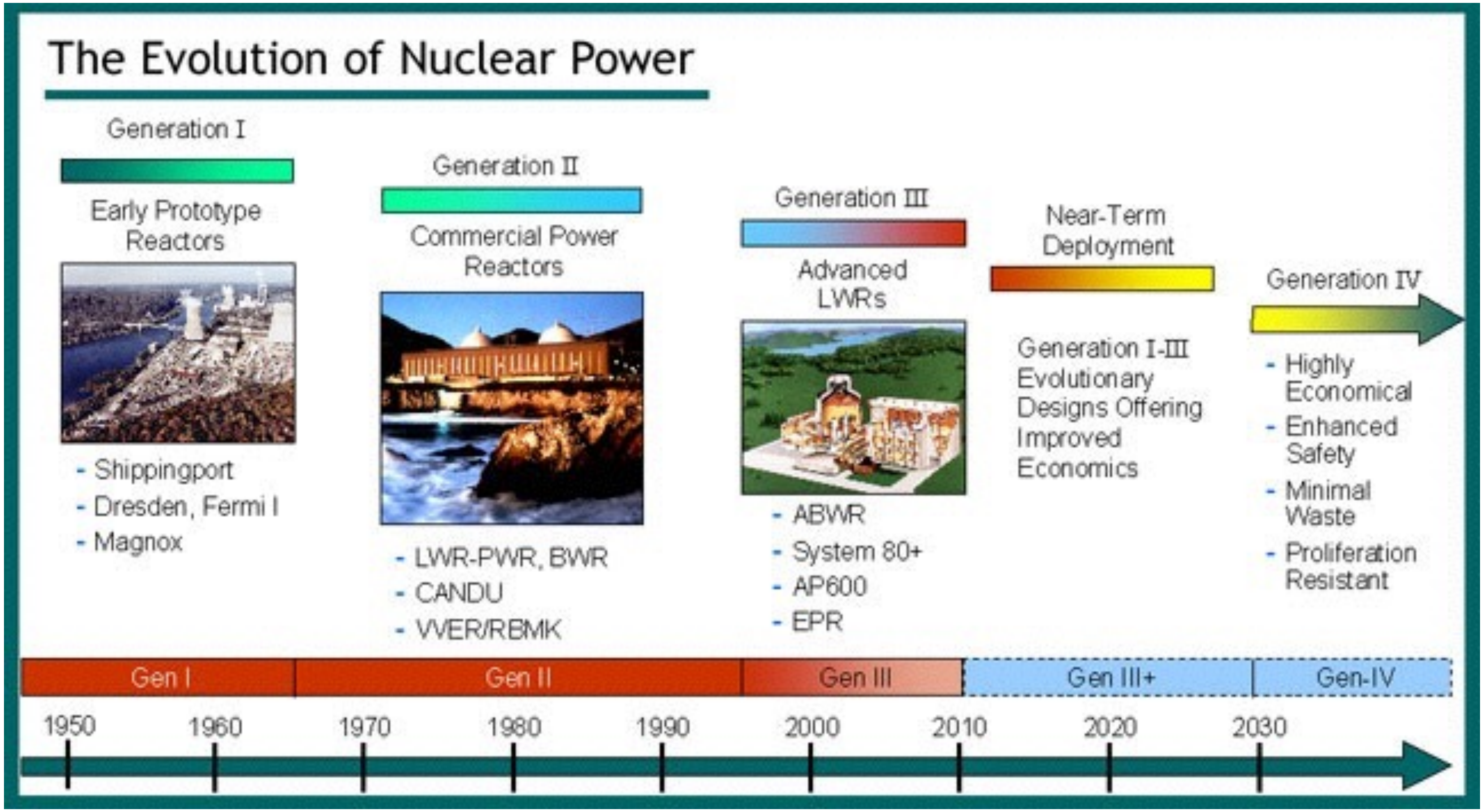
Exergy
(can do work, e.g. rotational, electric)

Anergy (no use except heating e.g. low temperature heat, radiation, cycling low gear)

According to the inventors, the major breakthrough of DFR - separation of the fluid and coolant (both liquid) flows could possibly be an analogous advance in the nuclear power technology.

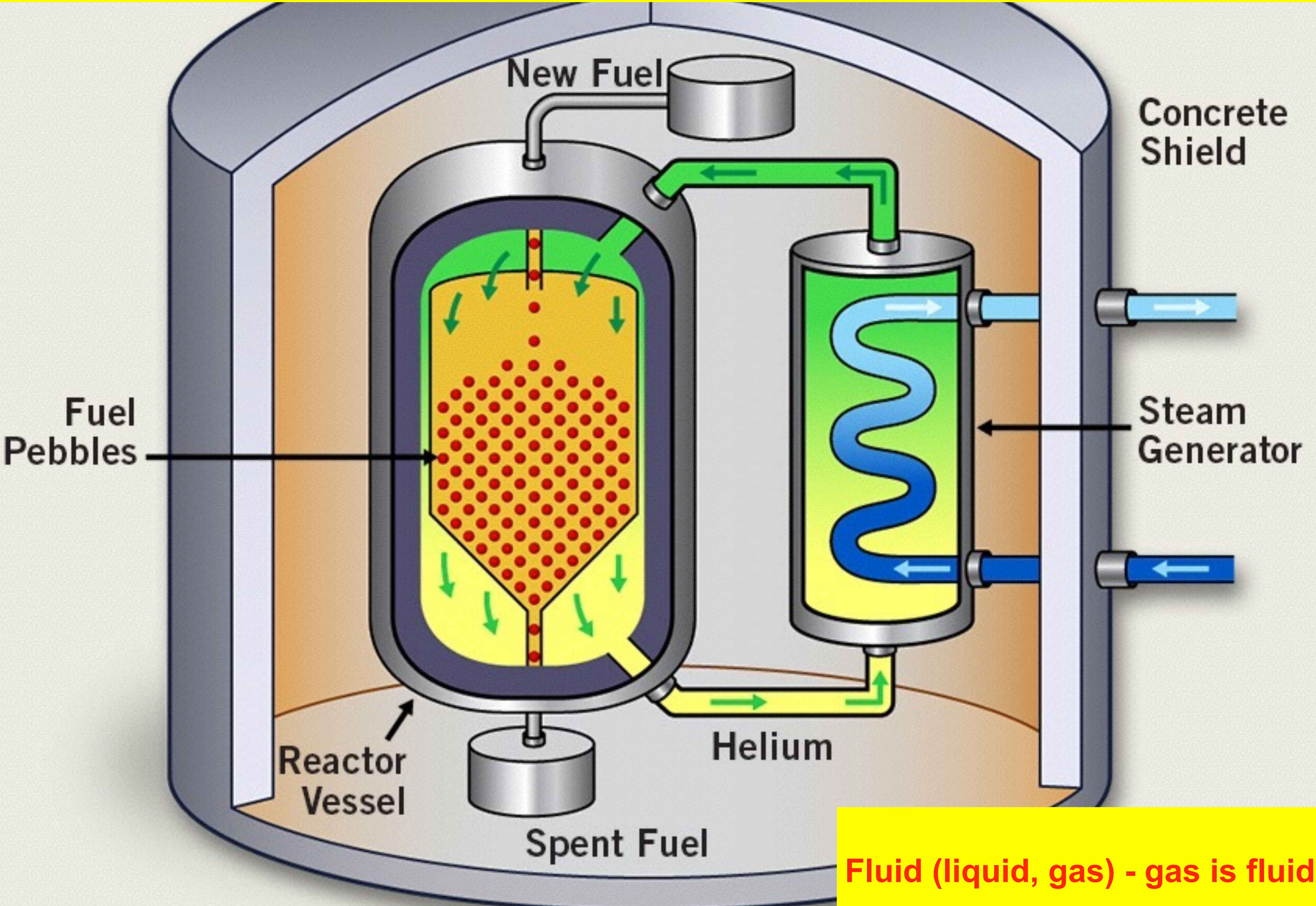
This is because of optimization of the working parameters for both fuel and coolant independently.

DFR as generation V of nuclear technology?



Generation V
- Very Highly Economical (EROI 2000-10000 against 75 for PWR)
- extremely safe (checks needed!)

Pebble bed HTGR technology - can also be counted as kind of "two-fluid" - though the "fluid" pebbles flow very slowly - an analogy with the tar which is a fluid flowing extremely slowly



Fluid (liquid, gas) - gas is fluid

Pebble bed technology - can also be counted as kind of "two-fluid" - though the "fluid" pebbles flow very slowly - an analogy with the pitch (tar) which is a fluid flowing extremely slowly

**Pitch drop experiment - started by Thomas Parnell (University of Queensland, Australia) in 1927 - Ig Nobel Prize 2005
(T. Parnell (1881-1948),
John Mainstone - photo left) - proven that viscosity is 2.3x10^11 times that of water**

9 drops fell so far in periods reaching from 8.1 years to 13.4 years (the period enlarges)

NCBJ - Ph.D. study program - phd4gen.pl (HTGR, DFR) "New reactor concepts and safety analyses for PPEJ"

1. 5-year program, includes internships at Univ. Illinois Urbana/Champaign and a topical school (June 2019, Kazimierz Dolny)
2. Research in new reactor technologies (HTGR and DFR)
3. Supervisors: prof. prof. J. Cetnar (AGH, Kraków), K. Czerski (IFK, USzczecin), M. Dąbrowski, W. Gudowski (KTH, Stockholm), T. Kozłowski (Illinois and NCBJ), R. Macian-Juan (TU Munich).

Summary:

1. Generation IV research on the construction of reactors for heat generation are going in parallel to the generation III and III+
2. However, both generation III and IV have still EROI (about 75) which is not competitive with fossil and other sources of energy. Besides, GIF GIV technologies have been known since decades.
3. A new DFR reactor concept is beyond the classification of GIF to GIV because of its outstanding economical (and safety) properties expressed in terms of EROI - this is why we claim it is Generation V!
4. Concept promising - experimental checks are necessary!