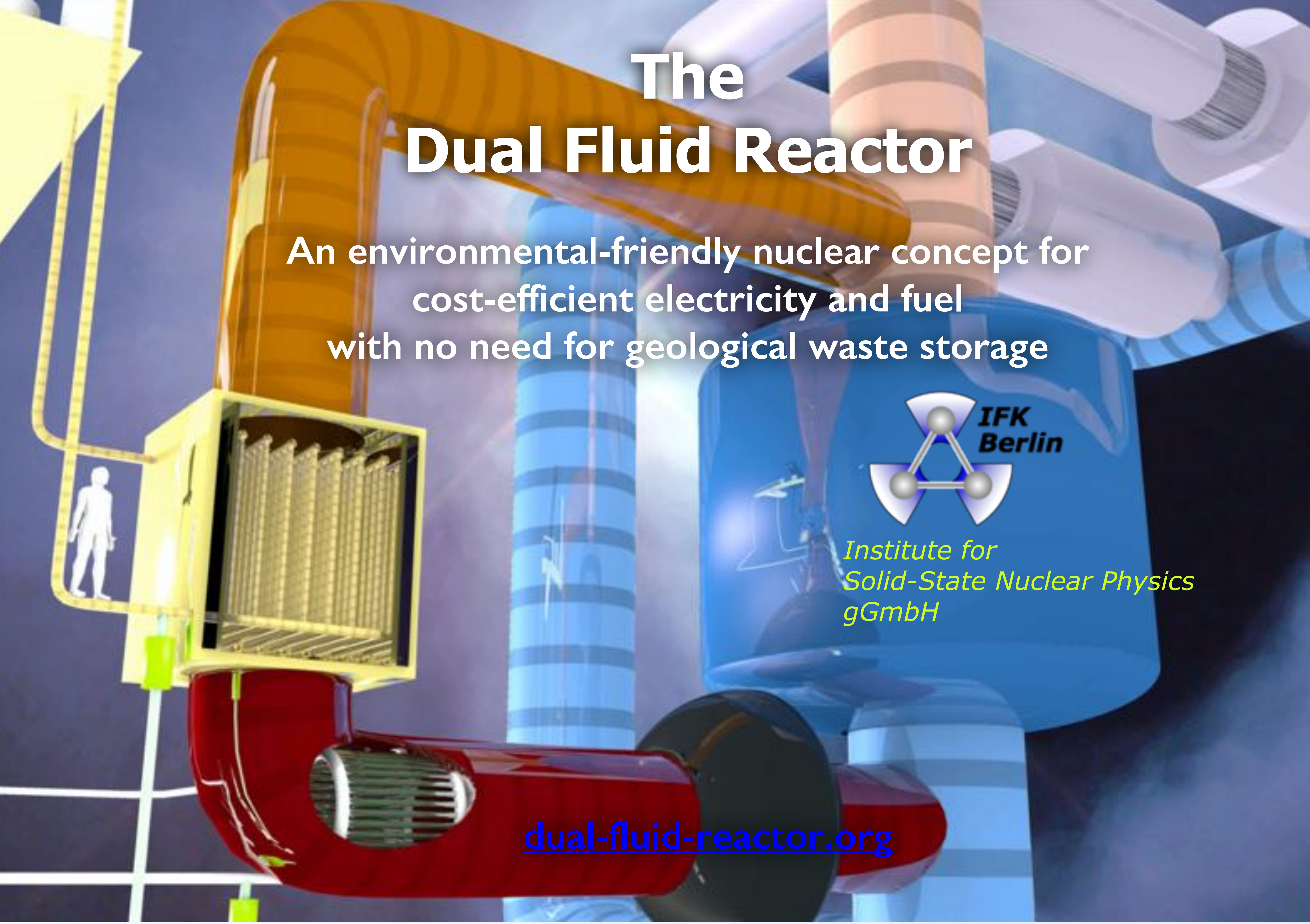

The Dual Fluid Reactor

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

IFK Berlin

Institute for
Solid-State Nuclear Physics
gGmbH

dual-fluid-reactor.org

Institute for Solid-State Nuclear Physics gGmbH

http://festkoerper-kernphysik.de

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Dipl.-Ing. Nico Bernt


Dr. rer. nat. Götz Ruprecht

Technische Universität München

Department for Nuclear Technology
Prof. Dr. Rafael Macián-Juan

Reactor development - where we are

Generation I

Early Prototype Reactors

- Shippingport
- Dresden, Fermi I
- Magnox

Generation II

Commercial Power Reactors

- LWR, PWR, BWR
- CANDU
- WWER/RBMK

Generation III

Advanced LWRs

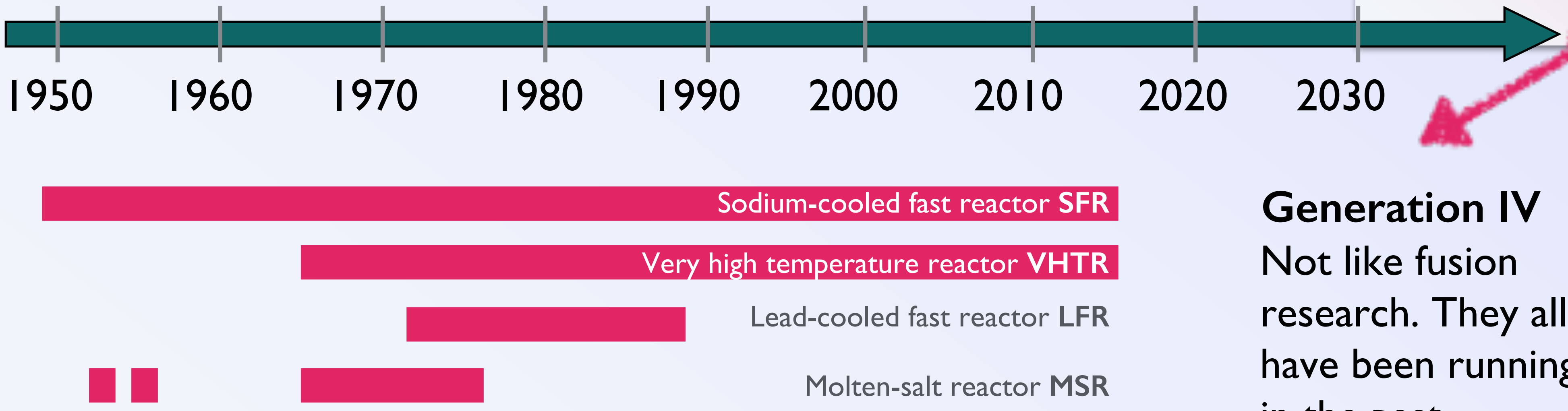
- ABWR
- System 80+
- AP600
- EPR

Generation III+

- Near-term deployment
- Evolutionary designs, offering improved safety

Generation IV

- New designs
- Inherently safety
- Minimal waste
- Closed fuel cycle
- Proliferation resistant



Sodium-cooled fast reactor **SFR**

Very high temperature reactor **VHTR**

Lead-cooled fast reactor **LFR**

Molten-salt reactor **MSR**

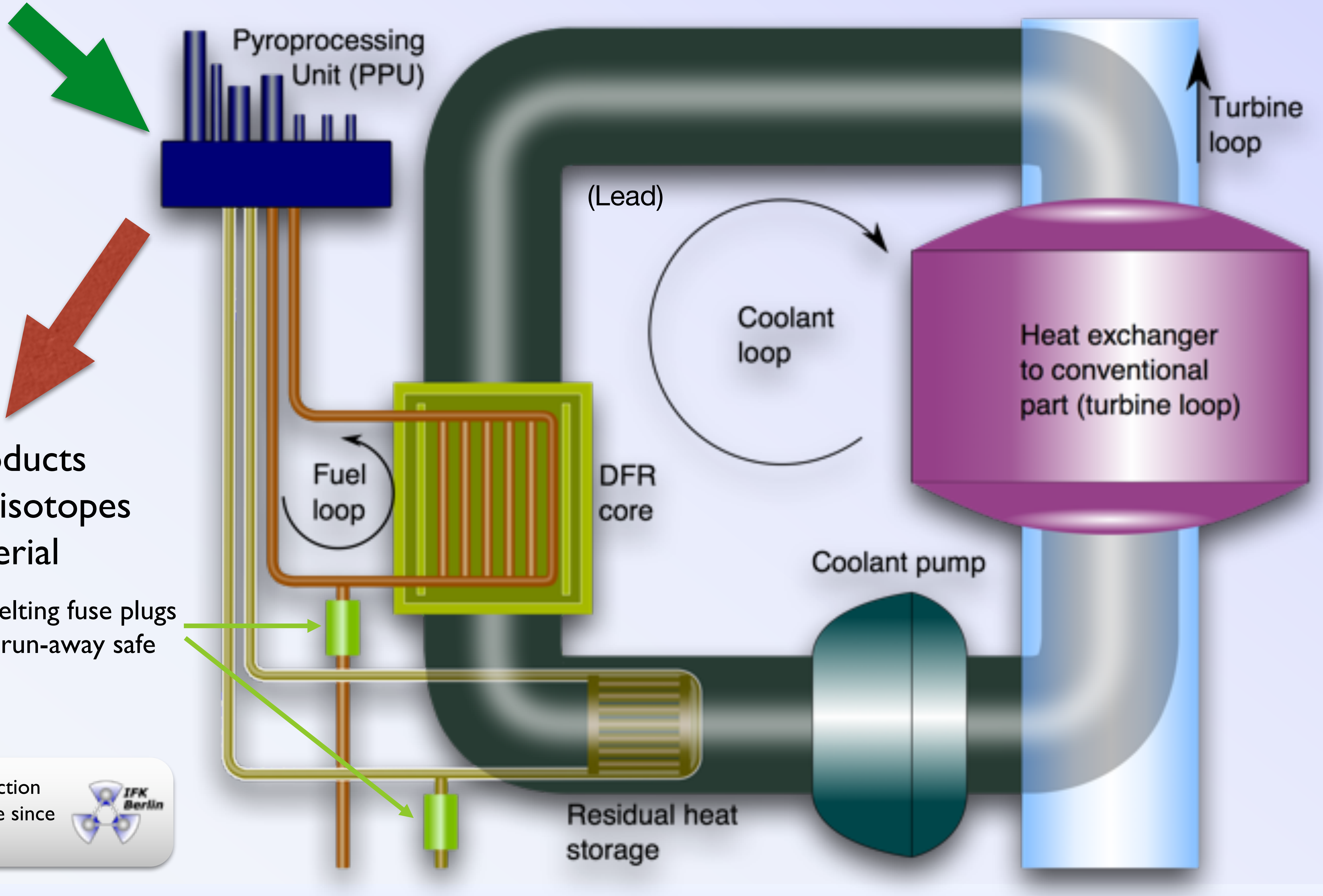
Generation IV
Not like fusion research. They all have been running in the past.

The main problem with Generation IV is the economy: They still use **solid fuel rods** and therefore still require the **expensive fuel cycle**. Only exception: The molten salt reactor **MSR**.

The Dual Fluid Reactor

A concept beyond Generation IV

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

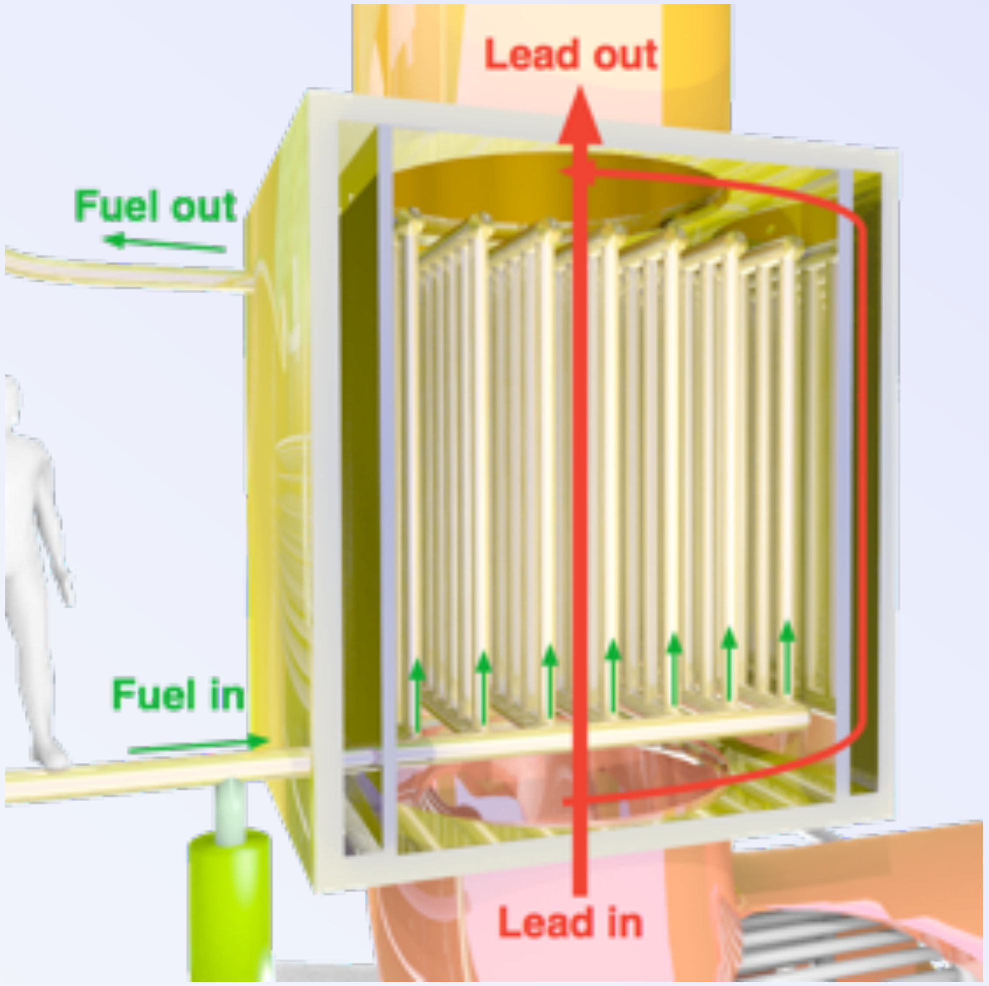


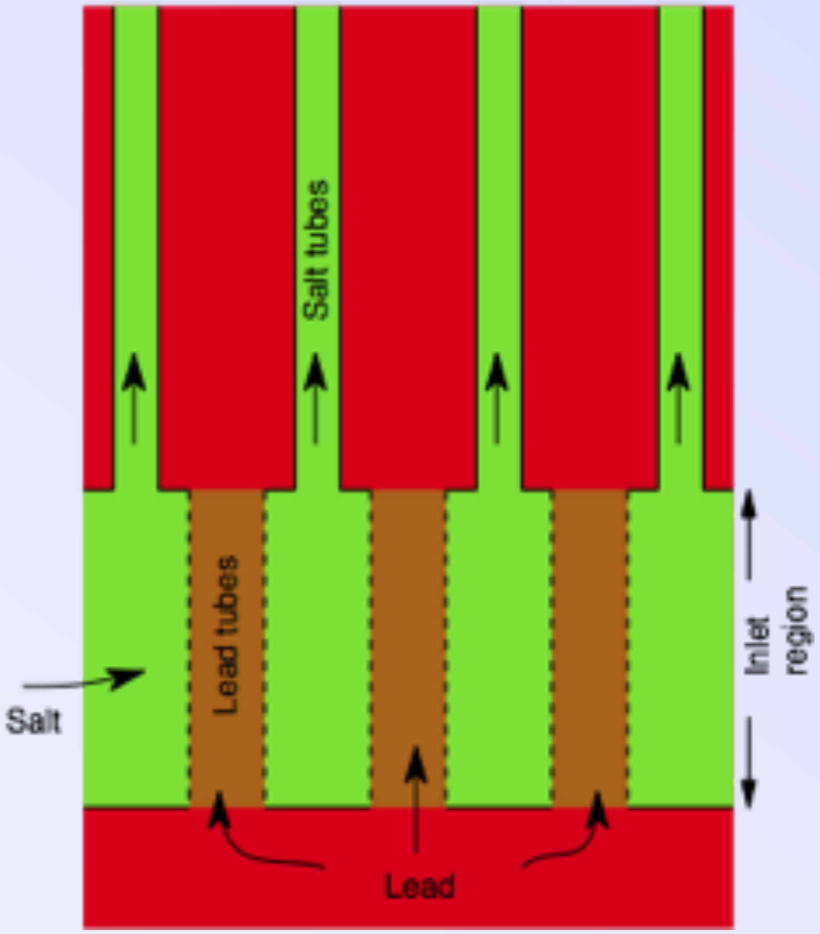
- Fission products
- Med. radioisotopes
- Fissile material

Melting fuse plugs
= run-away safe

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

The Dual Fluid Principle



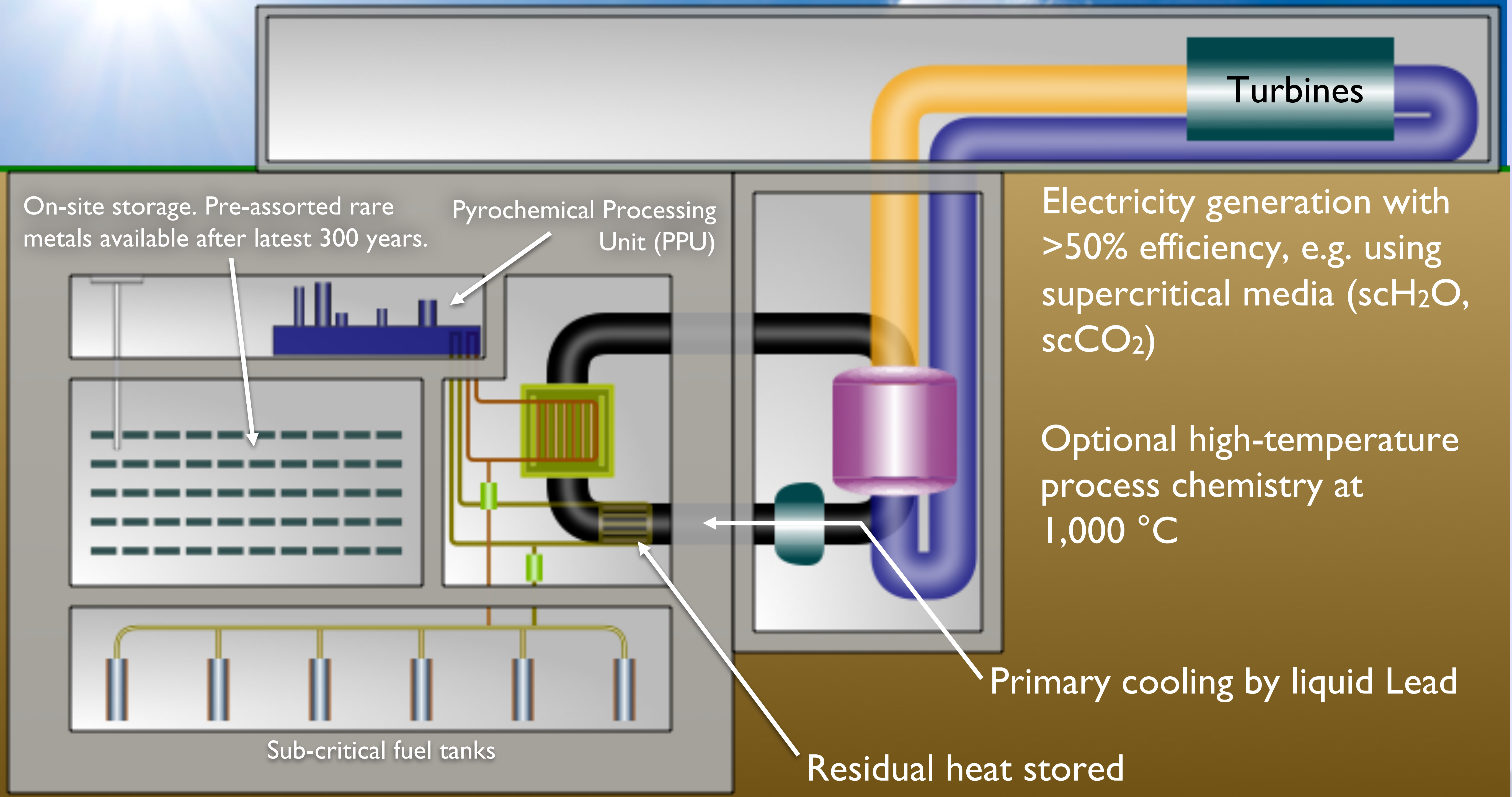


International patent application PCT/DE2012/000957

Nuclear reactor including a primary duct for **continuous** insertion and discharge of liquid fuel into and out of a core vessel wherein the fuel duct is lead through the core vessel, characterized by

- **a secondary duct** for a liquid coolant wherein the coolant enters the aforementioned core vessel via an inlet, **passing and bathing the primary duct** and leaving the core vessel via an outlet.

DFR power plant



On-site storage. Pre-assorted rare metals available after latest 300 years.

Pyrochemical Processing Unit (PPU)

Sub-critical fuel tanks

Electricity generation with >50% efficiency, e.g. using supercritical media (scH_2O, $scCO_2$)

Optional high-temperature process chemistry at 1,000 °C

Primary cooling by liquid Lead

Residual heat stored separated from the core

DFR Control

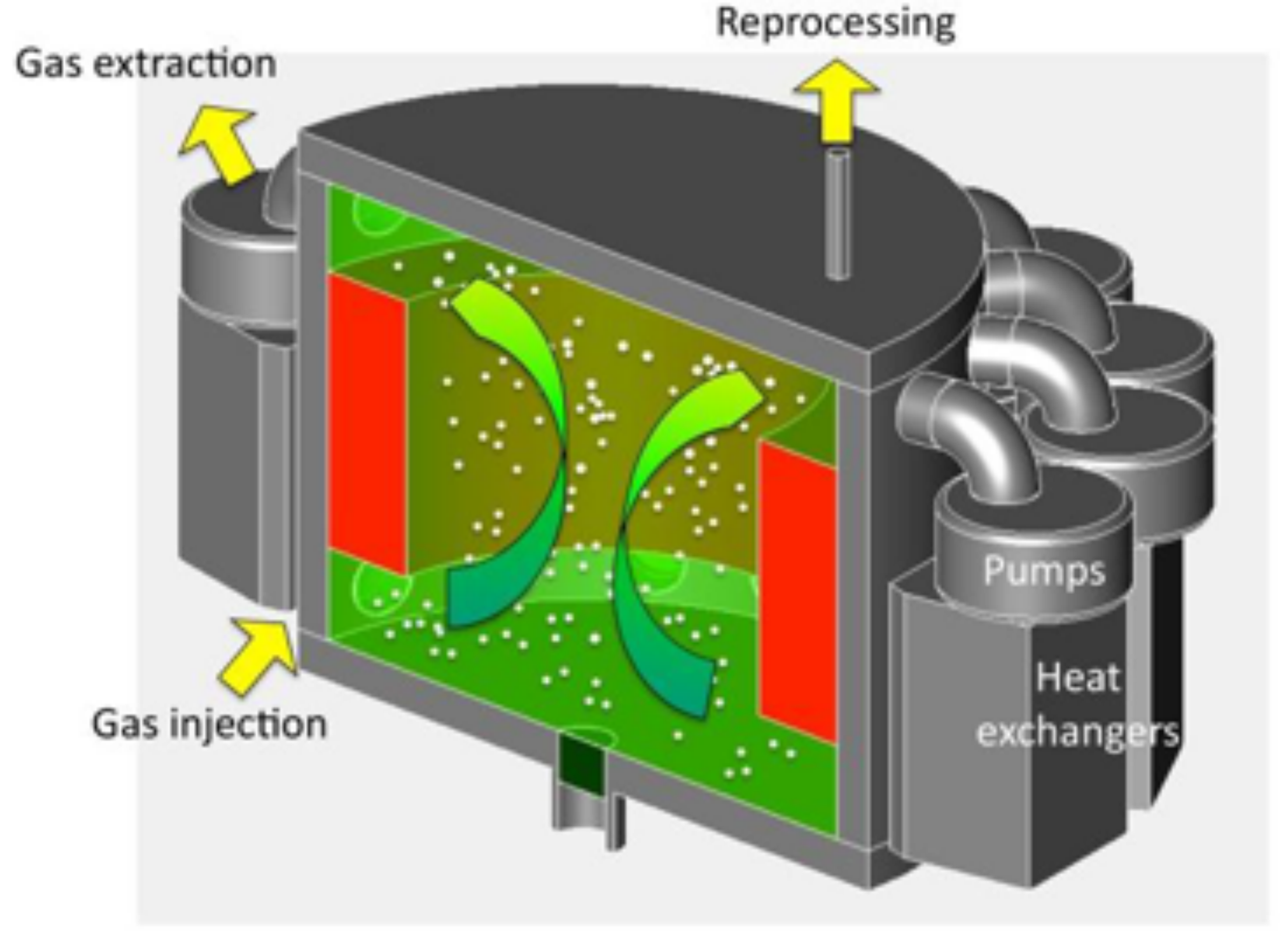
- Highly negative temperature coefficient due to thermal expansion of the liquid fuel
  Temperature rises → Fission rate and heat production drop
  Temperature drops → Fission rate and heat production rise
- Therefore, the temperature is held homeostatic at 1000 °C
  → no material stress on power change
- Therefore, power is fully regulated by heat extraction
  → Load-following operation in the grid
- Therefore, also qualified for rapidly changing power demand in chemical plants (process heat)
- No mechanical regulation equipment needed
- The reactor can be on „stand by" in a critical state at zero power output → Safe operation mode

Why is the DFR not a MSR?

Molten Salt Reactor (MSR) e.g. SAMOFAR

Single fluid

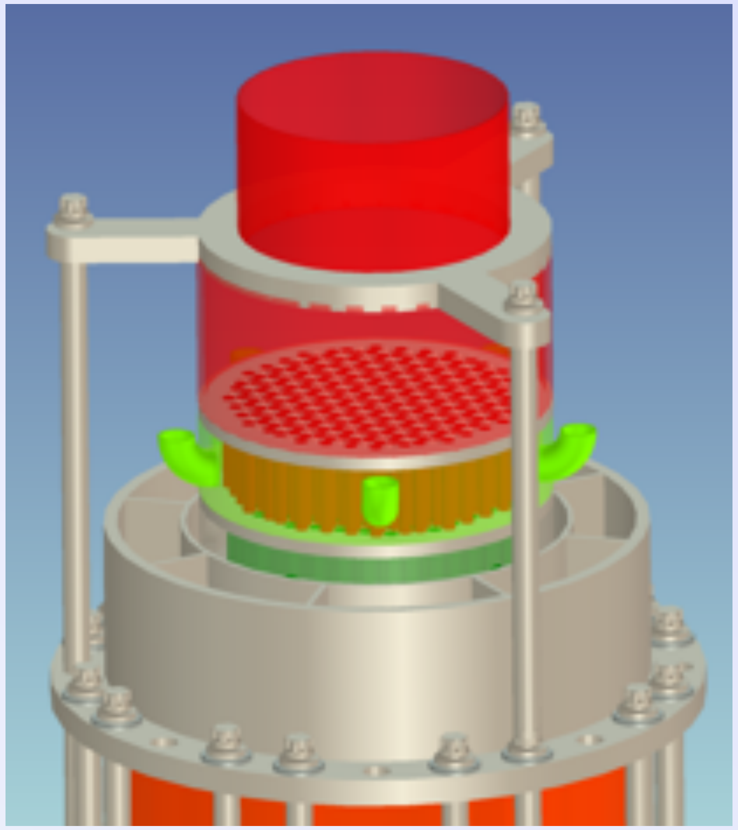
- Homogeneous core
- Heat removal by salt
- Fuel limited to salt



Dual Fluid Reactor (DFR)

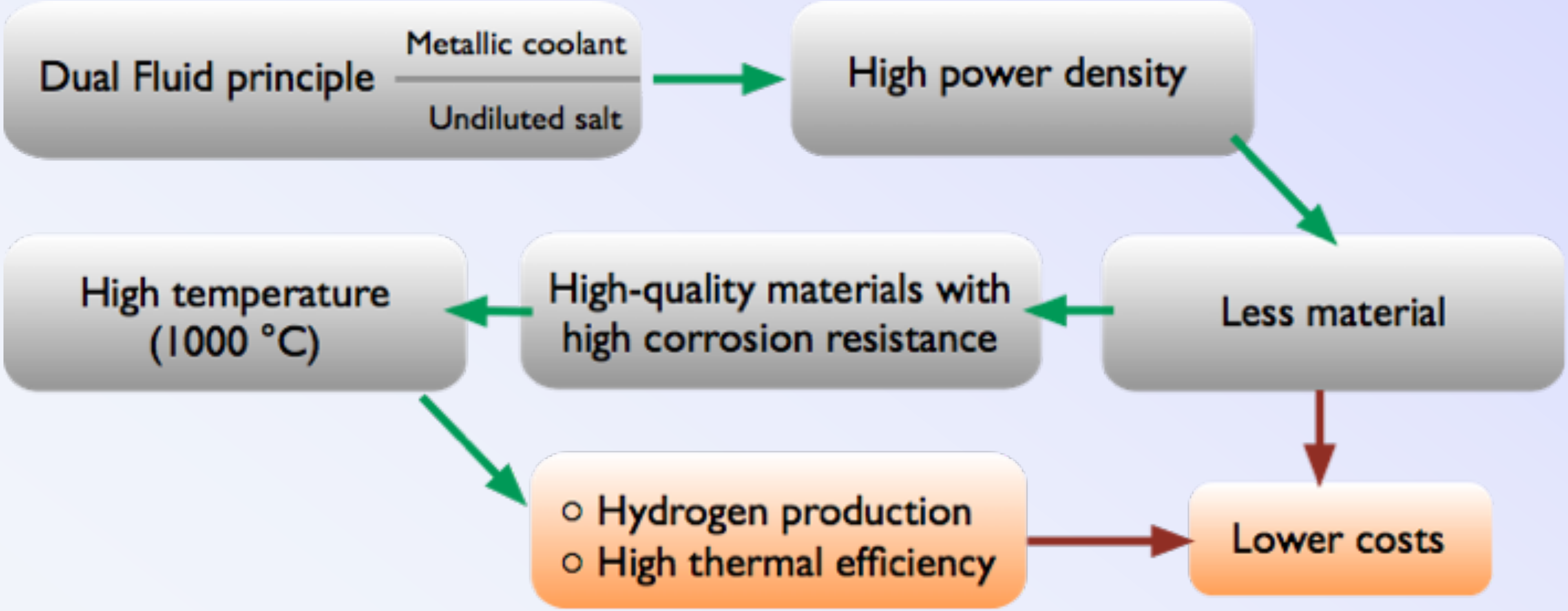
Two fluids

- Heterogeneous core
- Heat removal by second fluid
- Fuel liquid less constrained



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

Why is the DFR so efficient?



Dual Fluid principle

Metallic coolant

Undiluted salt

High power density

Less material

High-quality materials with high corrosion resistance

High temperature (1000 °C)

- Hydrogen production
- High thermal efficiency

Lower costs

Salts and Lead at 1000 °C

How is this possible?

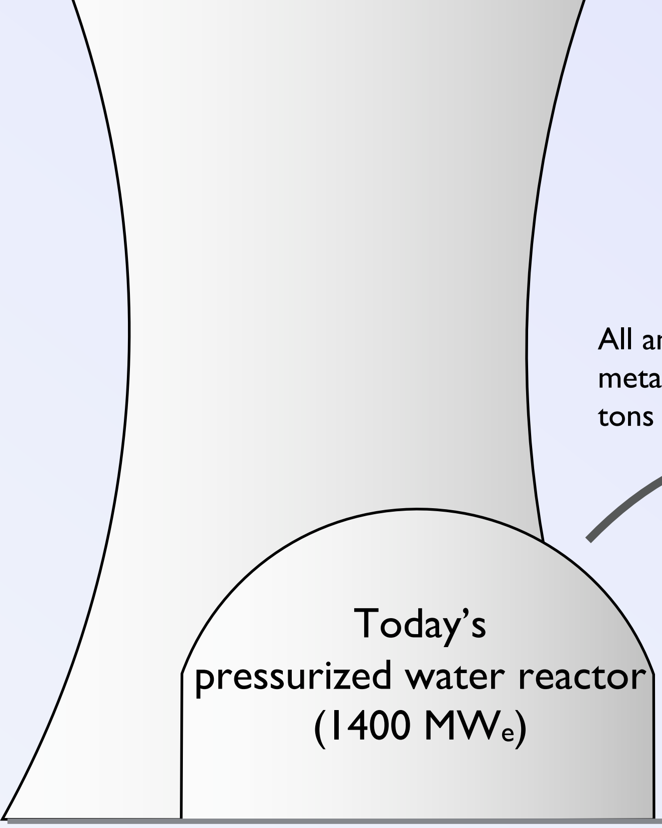
- *Outside* the nuclear industry suitable materials are known since a long time
- Focus of nuclear industry so far was on finding *cheap* materials (usually steel alloys) that are corrosion resistant.
- The DFR can afford *expensive* materials due to the low material consumption

Possible Materials

Silicon Carbide (SiC)

Refractory metal alloys and ceramics

P&T strategy with the DFR



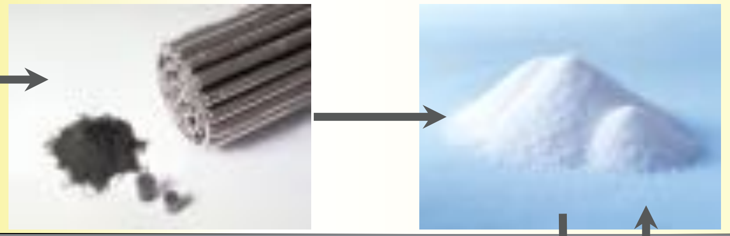
All amounts are for the heavy-metal (HM) part. Tons are metric tons

25 tons / year,
in case the reactor
is still in operation

Per reactor **1,000 tons,**
accumulated
over 40 years

Step 1
Pre-conditioning plant

- Dismantling of the fuel elements
- Chopping of the pellets
- Conversion of the oxides into chlorides



Mass reduction:
Factor 33 within 2 years

Chloride salts

Chlorine (reprocessed)

Step 2
Partitioning plant

Fission product storage

30 tons
Thereof 3 tons long-lived
Max. 300 years of storage time

Energetically **not usable**

PPU

Max. throughput:
500 tons / year

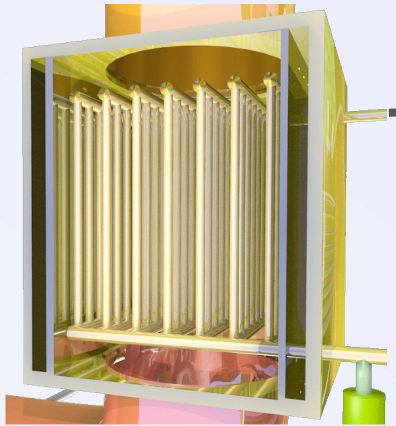
Actinide storage

960 tons Uranium
9 tons Plutonium
1 tons minor Actinides

Energetically **usable**

Step 3
Transmutation plant

DFR core
3 GW thermal



Energetic usage:
- High temperature heat
- Electricity generation

Incineration of actinides
in the DFR core

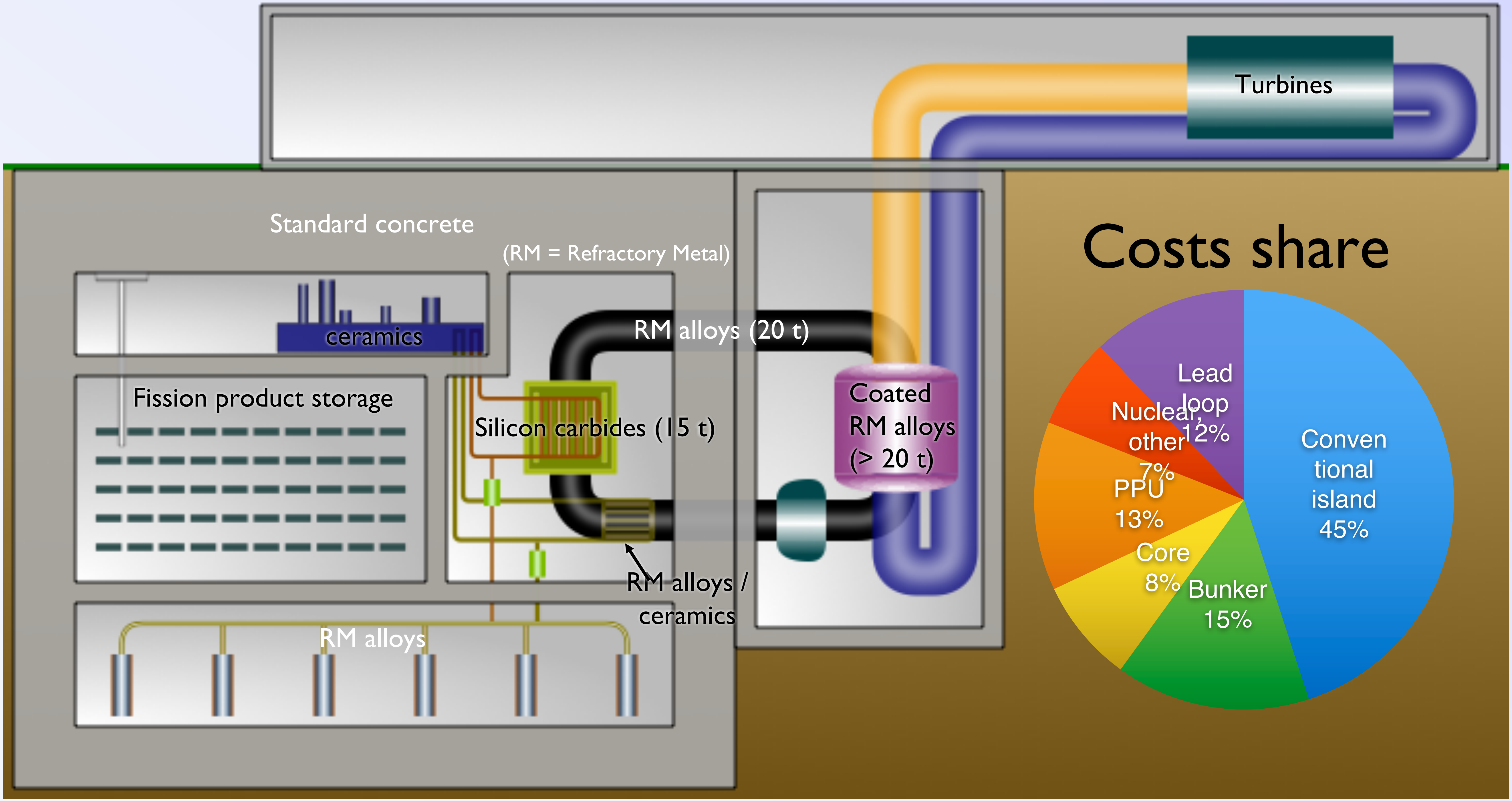
Consumption: 1.2 tons / year
(Range of the waste for many hundred years)

Optional additional transmutation of up to
0.3 tons / year long-lived fission products

Dual Fluid Reactor
Applications, economic and financial aspects

Institut für Festkörper-Kernphysik Berlin
Institute for Solid-State Nuclear Physics Berlin

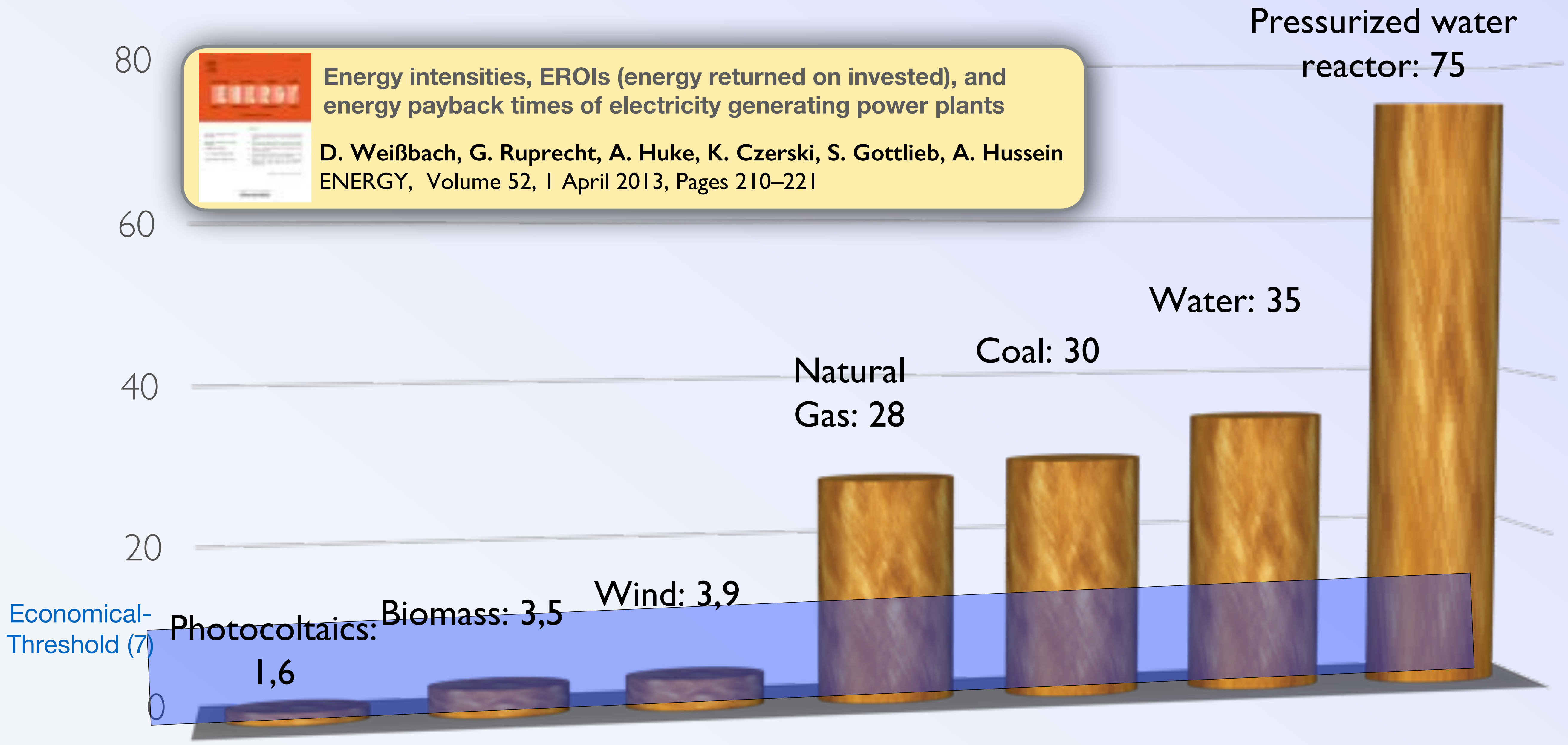
Materials in the DFR Power Plant



Energy Return on Invested - EROI

During the entire life-cycle of the plant:
Produced electricity **E_{out}**
divided by the expended energy (construction, operation, deconstruction) **E_{in}**.

$$\mathrm{EROI} = \frac{E_{out}}{E_{in}}$$



Energy intensities, EROIs (energy returned on invested), and energy payback times of electricity generating power plants

D. Weißbach, G. Ruprecht, A. Huke, K. Czerski, S. Gottlieb, A. Hussein
ENERGY, Volume 52, 1 April 2013, Pages 210–221

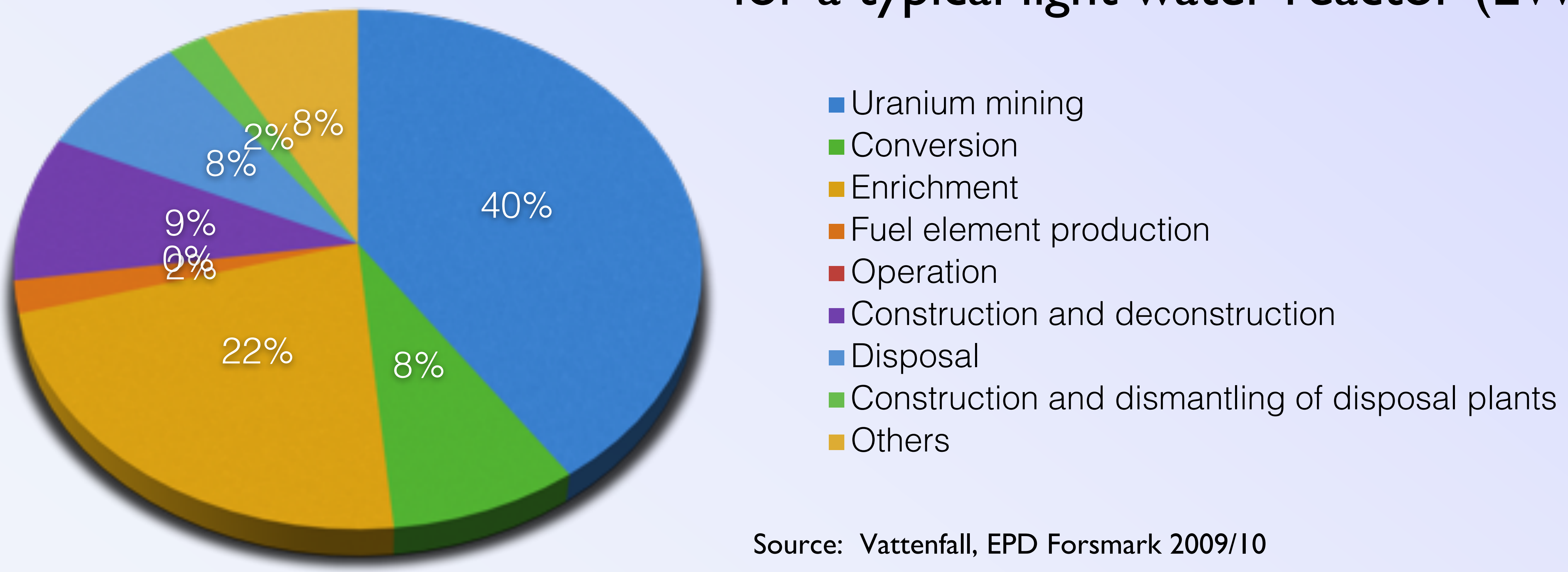
Is the EROI for PWRs large?

EROI	Energy release on combustion/fission
Pressurized water reactor: **75**	Uranium nucleus: **200.000.000 eV**
Factor 2,5	Factor 100 million
Coal power plant: **30**	Hydrocarbon atom: **2 eV**

What’s going wrong here?

The expensive nuclear fuel cycle today

Contributions to the energy demand in the nuclear power production for a typical light water reactor (LWR)



Source: Vattenfall, EPD Forsmark 2009/10

100% Diffusion

17 % Diffusion + Centrifuge (today)

100 % Centrifuge

100 % LASER

EROI: 29 → 75 → 105 → 115

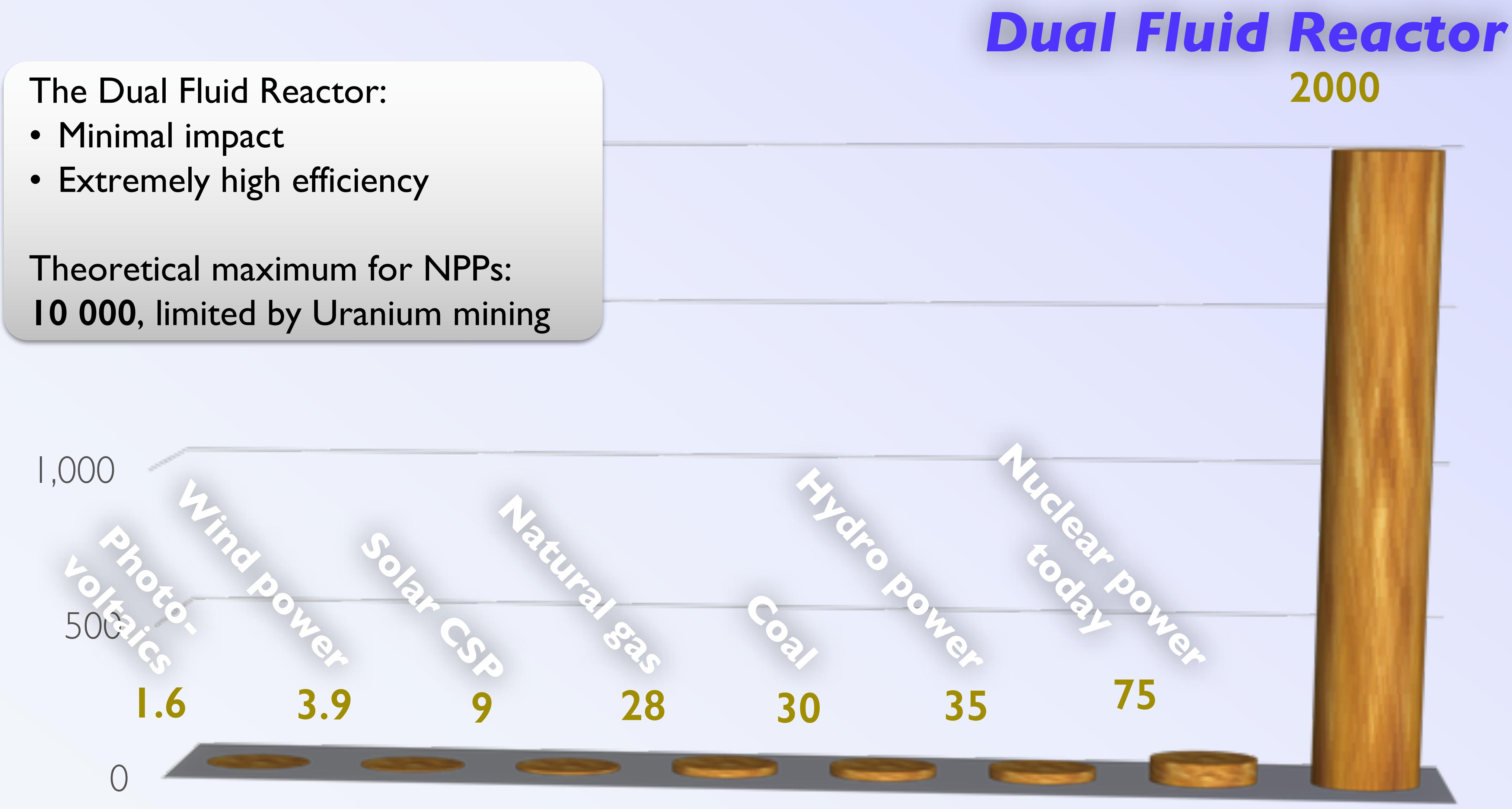
Energy Efficiency of Power Plants

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

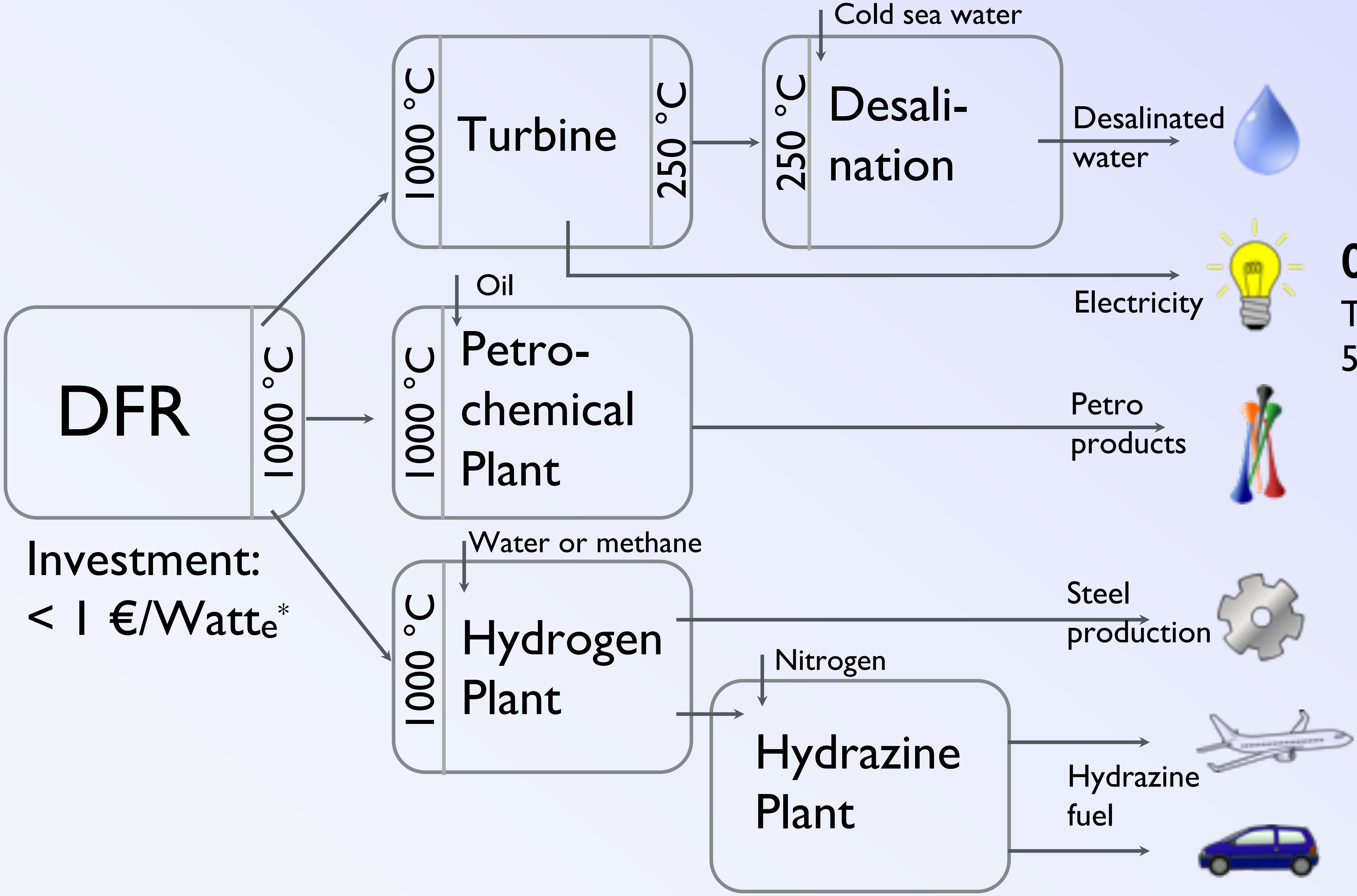
see Weißbach et al., *Energy*, vol. 52 (2013), pp. 210–221

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

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



DFR applications



DFR

1000 °C

Turbine

1000 °C

250 °C

Cold sea water

Desali-
nation

250 °C

Desalinated water

Electricity

Oil

Petro-
chemical
Plant

1000 °C

Petro products

Water or methane

Hydrogen
Plant

1000 °C

Steel production

Nitrogen

Hydrazine
Plant

Hydrazine fuel

0.6 ¢/kWh

Today's market price:
5 ¢/kWh

10-40 ¢/liter **

Today's market price:
15-50 ¢/liter (benzine)

Investment:
< 1 €/Watt$_e$*

Hydrazine-based fuel cell electro mobility also possible with 1.5 ¢/km* and ranges of more than 1,000 km

* Overnight costs
** Gasoline equivalent

Supporters always welcome!

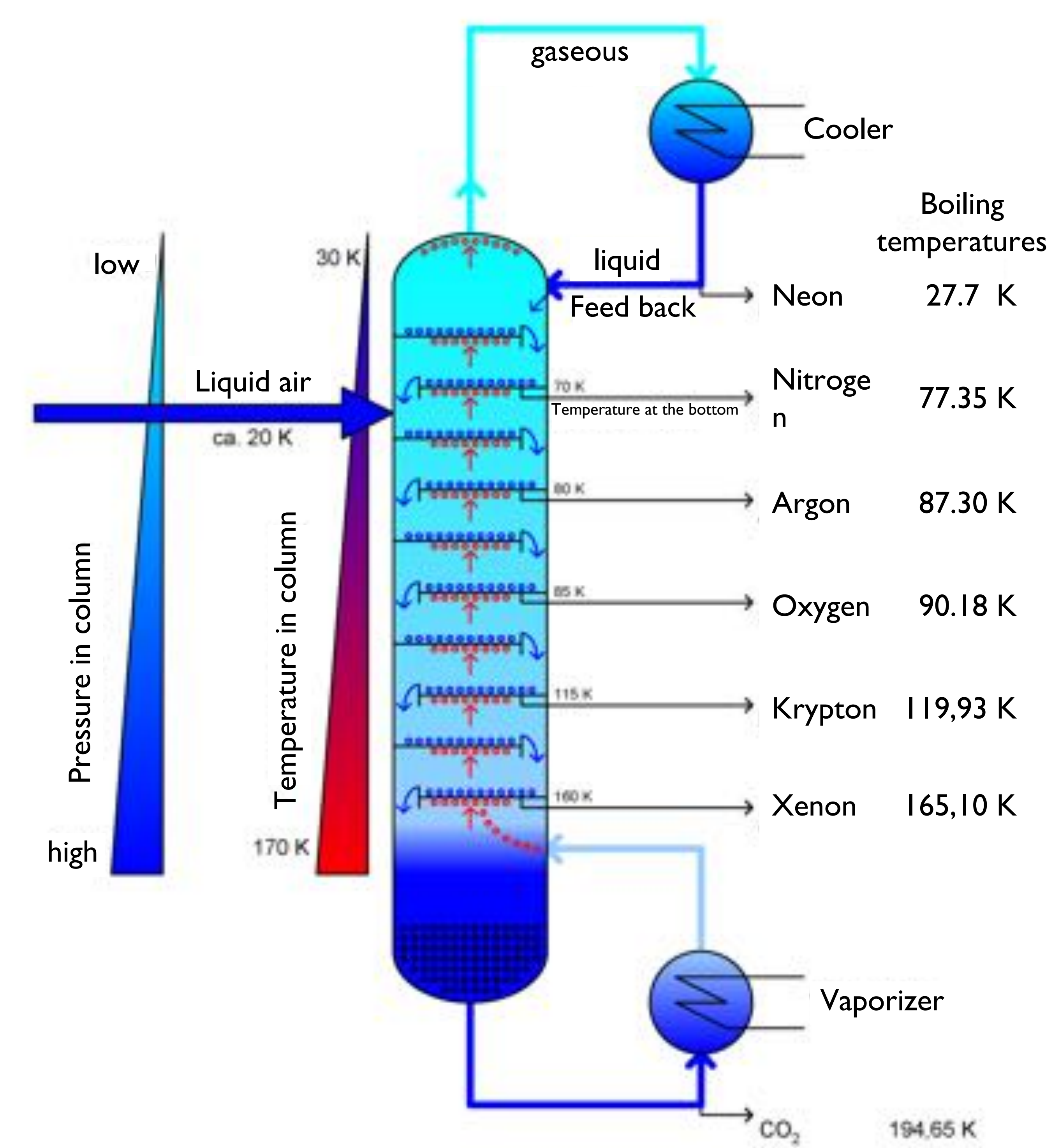
Institute for
Solid-State Nuclear Physics
gGmbH

KASTOGA GmbH

`dual-fluid-reactor.org`

Salt Reprocessing with the PPU

(Pyrochemical Processing Unit)



Example: Rectification of liquid air

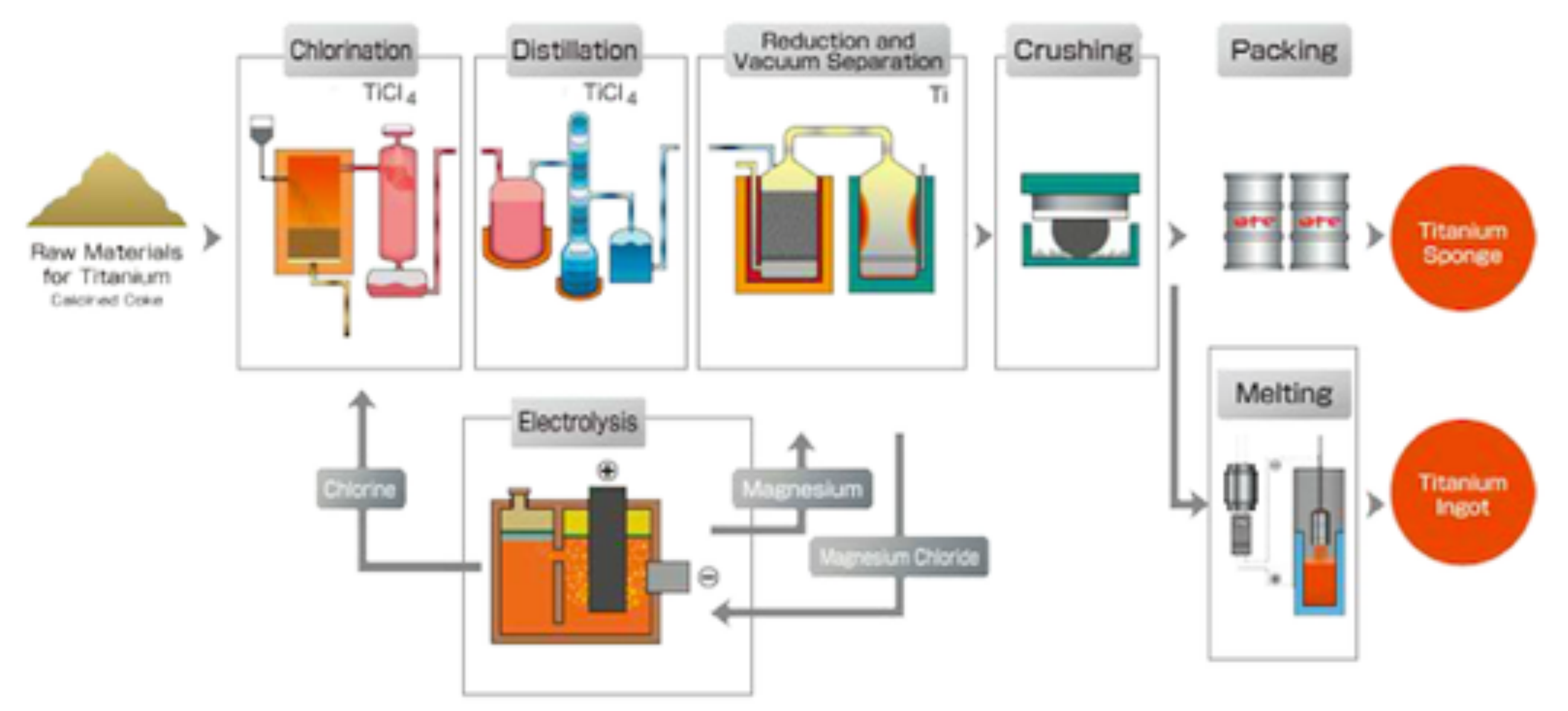
Well-known techniques from the industrial chemistry:

Partitioning of the salt components by distillation.

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

The Kroll Process

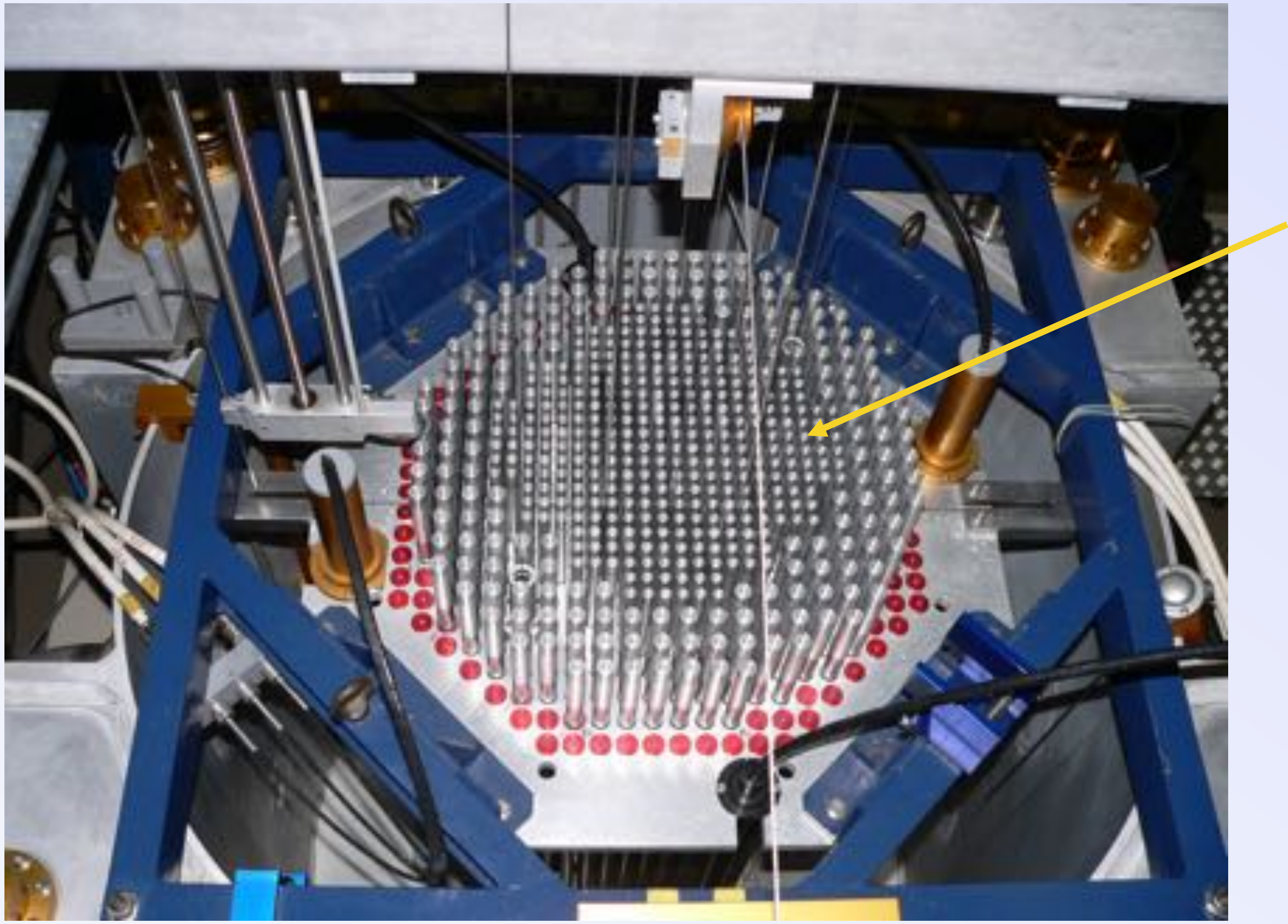
- State-of-art since a long time
- Used for all metals of the Ti group (e.g. Zr, Hf)
- Developed in the 1930ies
- Titanium ore is reduced and chloridized
- Distillation to the single chlorides at clearly above 1000 °C to 1400 °C
- Then reduction of $TiCl_4$ with alkaline metals
- High purity Titanium is sold for 10 $/kg



Ti-Produktion at Osaka Titanium Technologies

http://www.osaka-ti.co.jp/e/

Today’s reactor designs



Almost all are water-moderated and based on **solid fuel rods:**

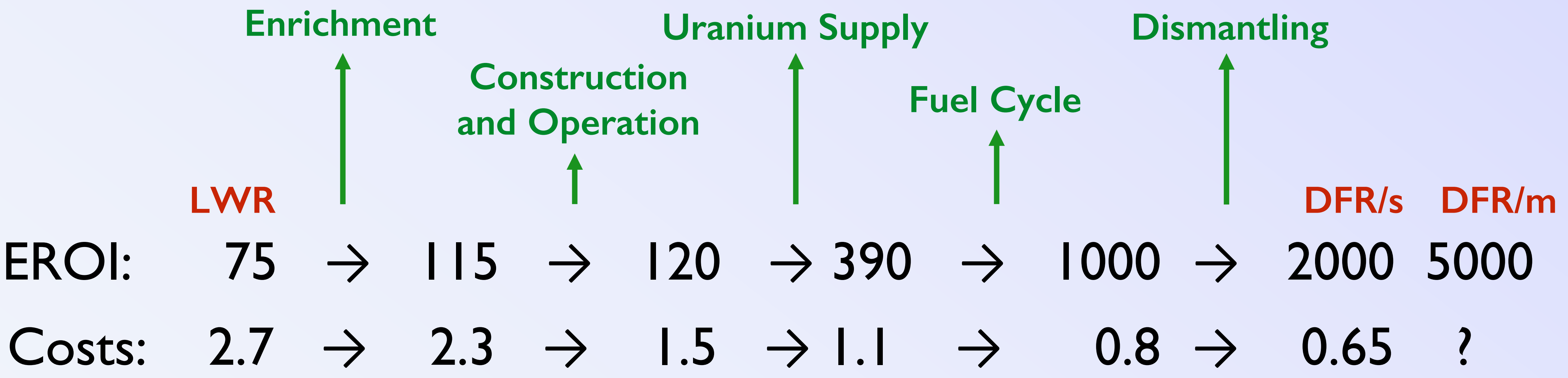
- Expensive external fuel cycle
- Using **only 1%** of the mined Uranium
- **99% waste** that needs geological storage
- Low power density

They also work at **high pressure**

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

How efficient is the DFR

If these expenses are reduced to DFR level, EROI and costs change to...



Enrichment ↑ Construction and Operation ↑ Uranium Supply ↑ Fuel Cycle ↑ Dismantling ↑

	LWR					DFR/s	DFR/m
EROI:	75 →	115 →	120 →	390 →	1000 →	2000	5000
Costs: cent/kWh overnight	2.7 →	2.3 →	1.5 →	1.1 →	0.8 →	0.65	?

From LWR to DFR.
Many steps are repealed or reduced, increasing the EROI and decreasing the costs.
DFR/m comes close to the theoretical limit of nuclear energy, dominated by the Uranium mining expense.

For comparison:

Wind and PV: 1-4
Fossil fuels: 30
Hydro: 35

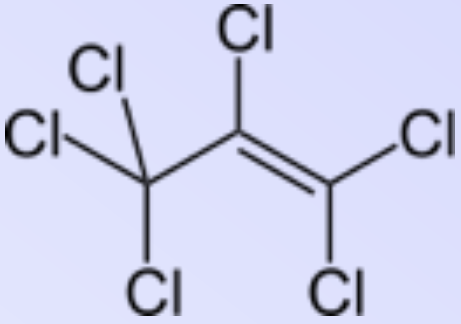
Nuclear:
Today's LWRs: 75
Theoretical limit: 10,000

Waste Pre-conditioning

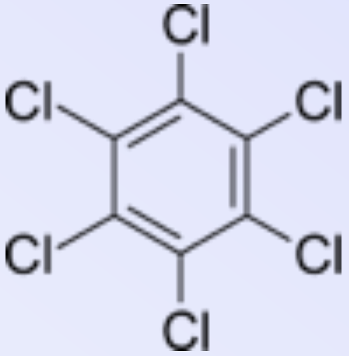
Treatment of fuel elements

- Opening of the bundles and tubes
- Separation of pellets from tube
- Cleaning of the tube material
- Redox reaction with chlorocarbons
- Distillation / Infusion PPU

Hexachloropropene



Hexachlorobenzene



Uranium dioxide

Uran trichloride + carbone oxides

DFR Safety

Safety advantages

- Highly negative temperature coefficient → Self regulation
- Residual heat disposal by natural convection
- Overheat protection by passive melting fuse plugs
- No static overpressure

Problem	Solution
Risk of leakages	No overpressure, survey and containment without much effort
More volatile activity due to high operating temperature and liquid fuel	Will be extracted/absorbed in the online fuel processing, containment
Raised proliferation risk due to online fuel processing	Fixed piping, encapsulation and monitoring is easier to accomplish due to compact size

Difference to MS(F)R concepts

- The DFR concept does not rely on molten-salt.
  There are 2 development threads

DFR/m with **molten-metal** fuel
DFR/s with **molten-salt** fuel

- DFR/s is quite different from MSR
  - The salts are **undiluted** (No Li, Be, or other carrier salts)
  - The salts are **chlorides** (UCl_3, $ThCl_3$, $PuCl_3$…)
  - The reprocessing is based on **destillation/rectification**, a very simple physical separation processes.
    There is no need for liquid/liquid extraction as for fluorbased MSR concepts, or wet-chemical processes.

Hydrogen production

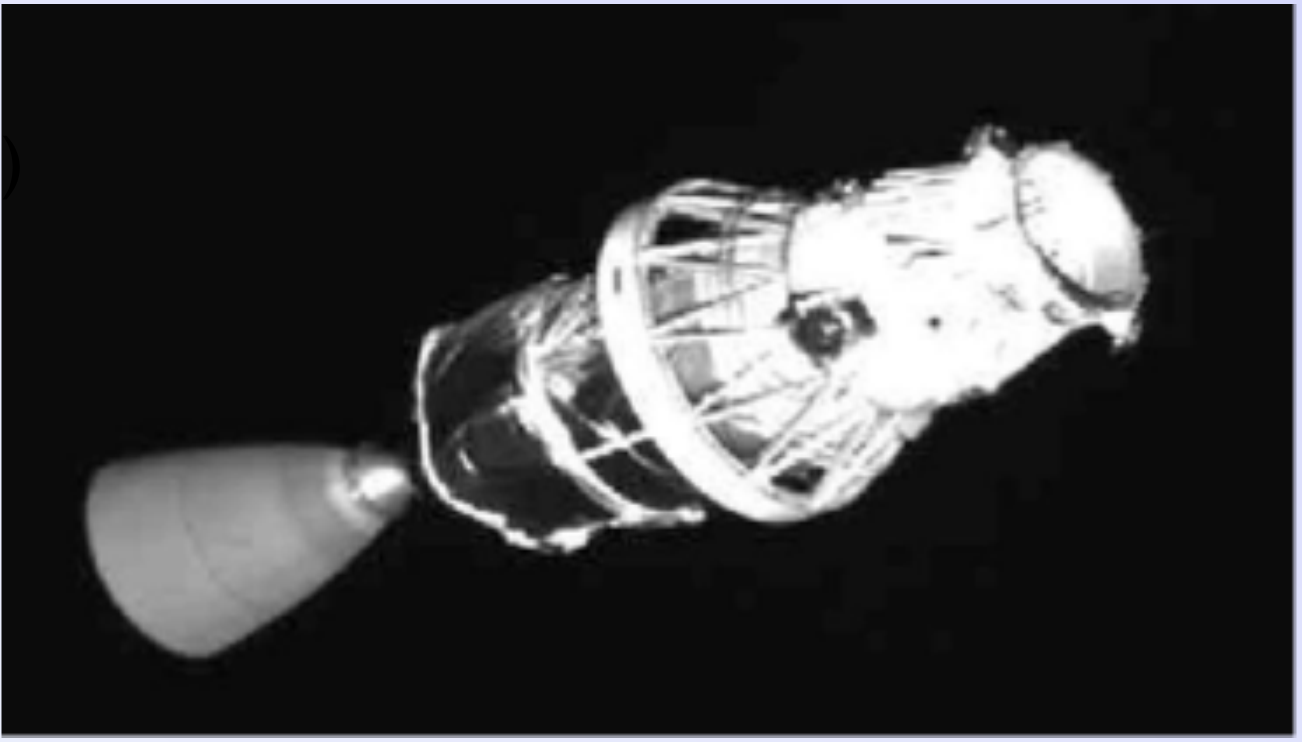
- Water dissociation by high temperature
- Hot-ELLY, KfA Jülich for THTR
- Sulfur Iodine process for VHTR (GenIV)

- Gasoline sysnthesis by coal hydration similar to crude oil reforming

- Lignite transport by ship to the NPP where they are anyway for cooling.
- Process heat by DFR from nuclear waste

- Alternatively CO2 usage from power plant exhaust

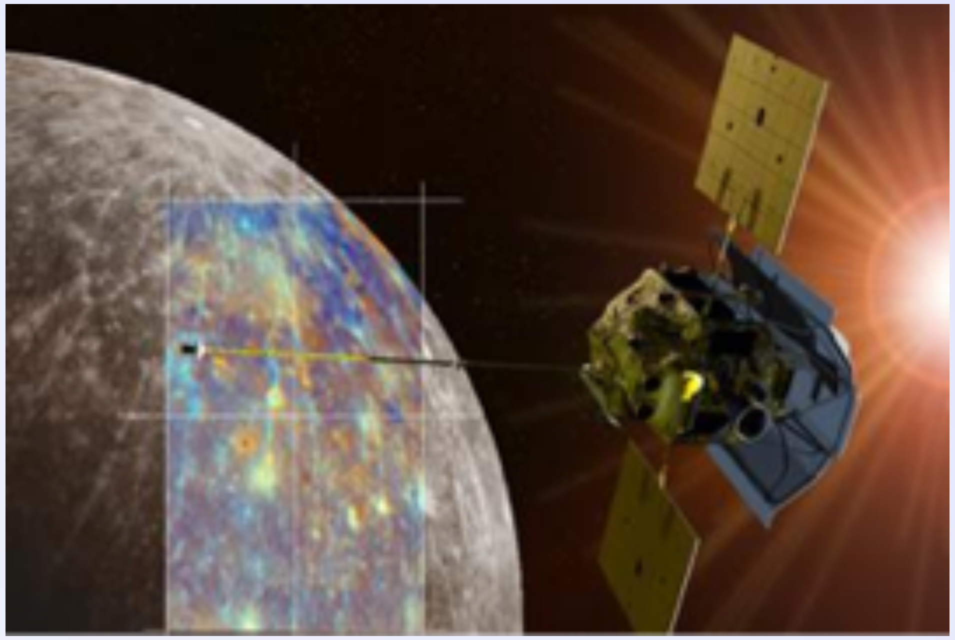
NtL: Hydrazine



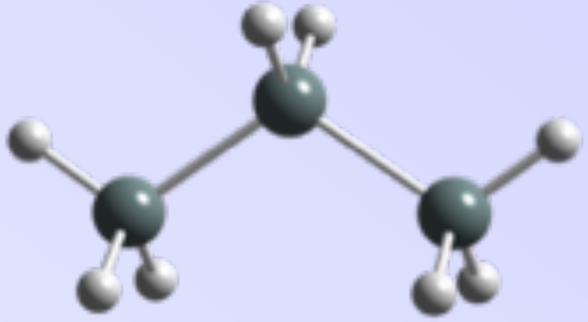
- Synthesis of ammonia from atmospheric nitrogen and water. (Haber-Bosch, SSAS) Hydrazine synthesis (Pechiney-Ugine-Kuhlmann)

- Gasoline equivalent costs:
- Ammonia: 20 c/l
- Hydrazin: 40 c/l

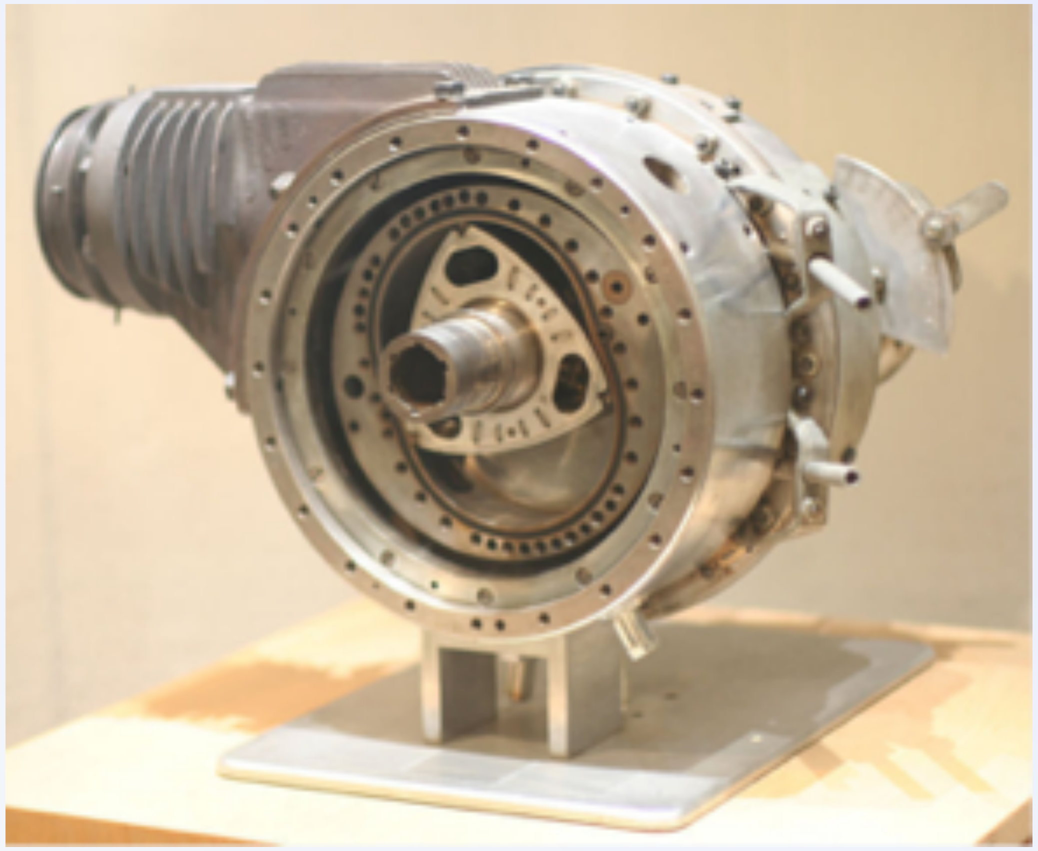
- Fuel cell driven by nuclear-produced hydrazine is the only way of electro mobility with costs advantage against combustion engines:
- Construction costs: Similar to Diesel engine
- Fuel costs: 50% of today's gasoline



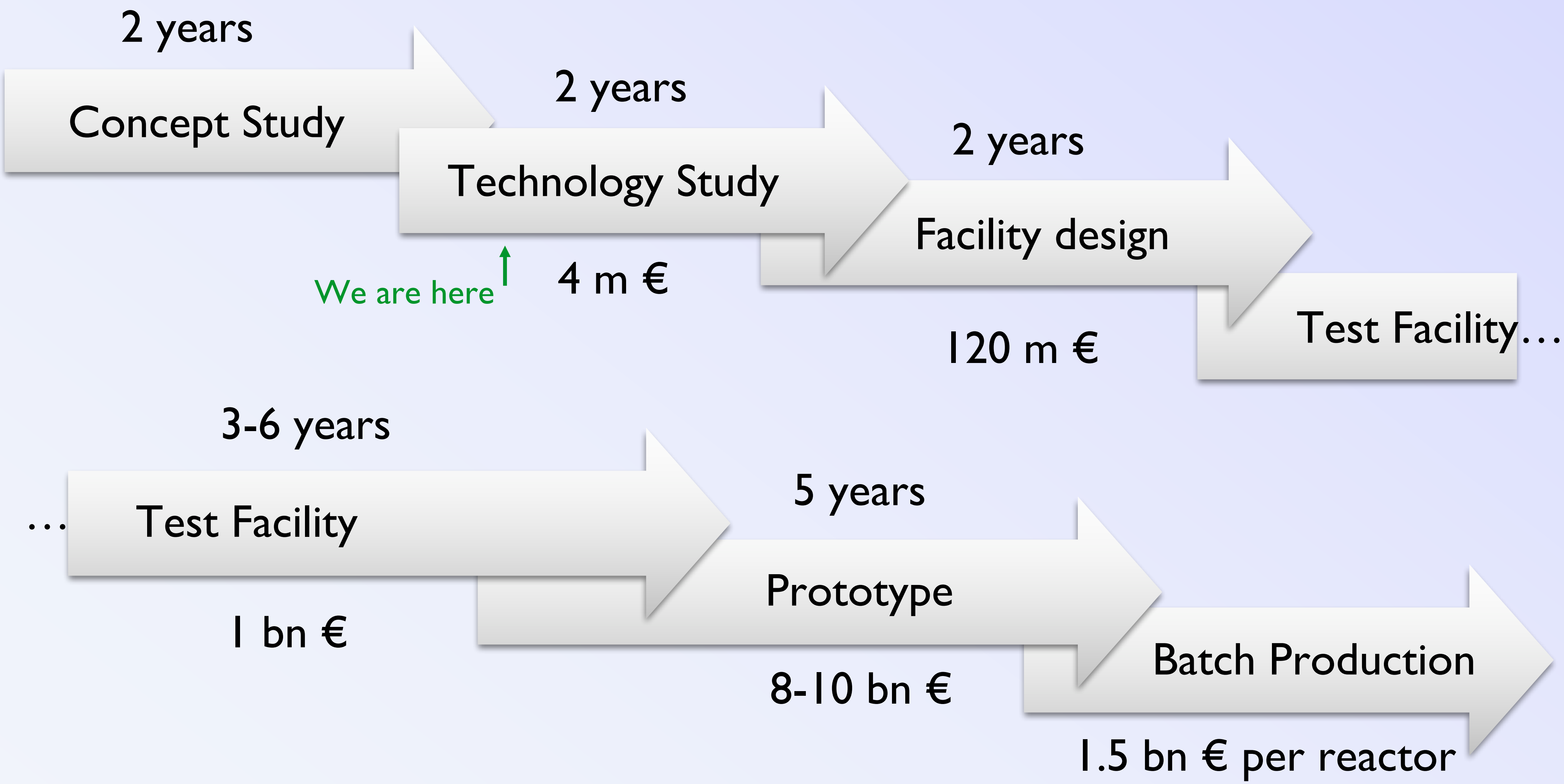
StL: Silane



- Müller-Rochow synthesis from quarz and water
- High power density
- Combusting at 1400 °C with air nitrogen
- Ideal as fuel for hypersonic aircrafts (SCRAM-jet), also for rockets
- Usage in Wankel engines for cars possible



DFR development: Schedule and costs



2 years

Concept Study

2 years

Technology Study

We are here

4 m €

2 years

Facility design

120 m €

Test Facility…

3-6 years

…Test Facility

1 bn €

5 years

Prototype

8-10 bn €

Batch Production

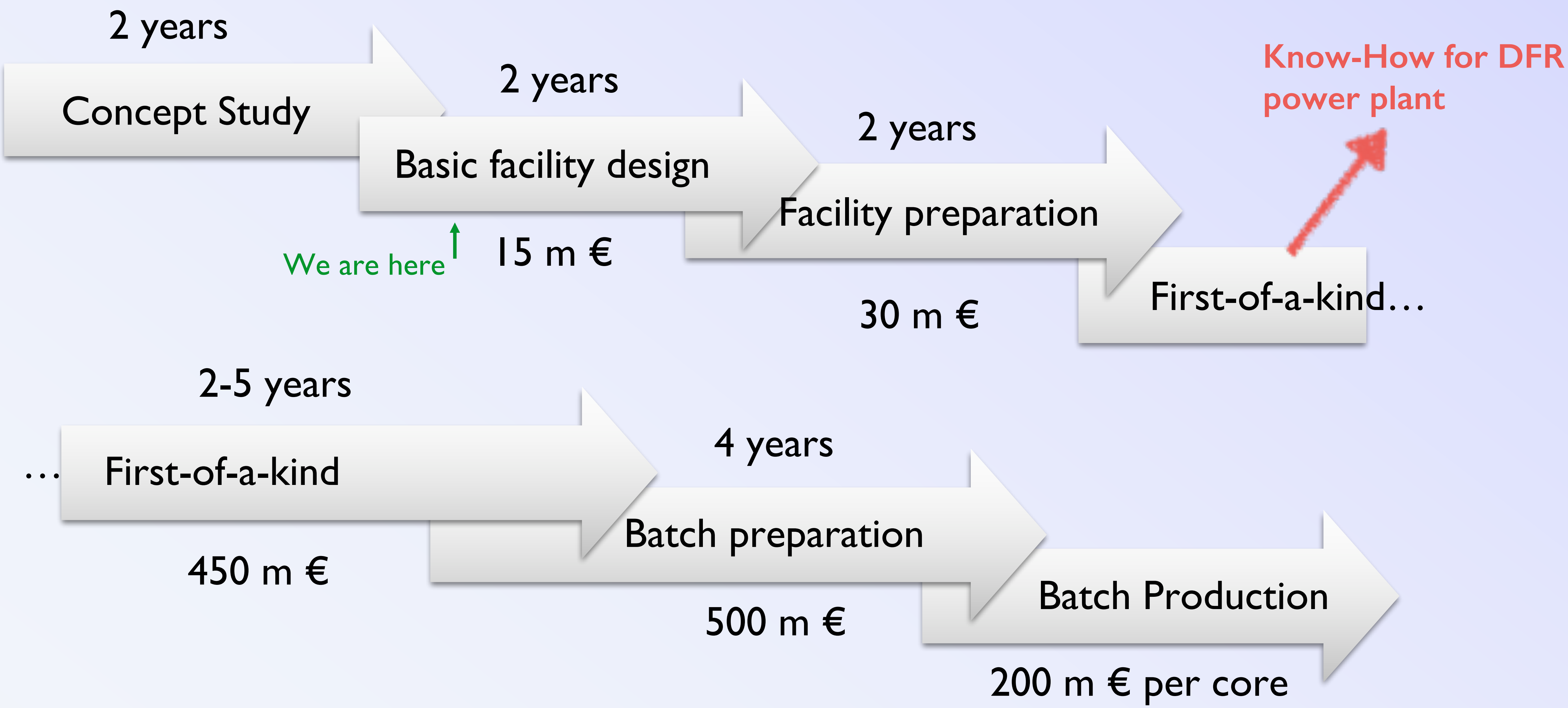
1.5 bn € per reactor

Development of the DFR prototype: 10 years, 10 bn €

Serial type: 1.5 bn €

For comparison: Germany’s Renewable Energy Law (EEG): **25 bn € per year**

DFR process heat plant development: Schedule and costs



2 years

Concept Study

2 years

Basic facility design

We are here ↑

15 m €

2 years

Facility preparation

30 m €

First-of-a-kind…

Know-How for DFR power plant

2-5 years

… First-of-a-kind

450 m €

4 years

Batch preparation

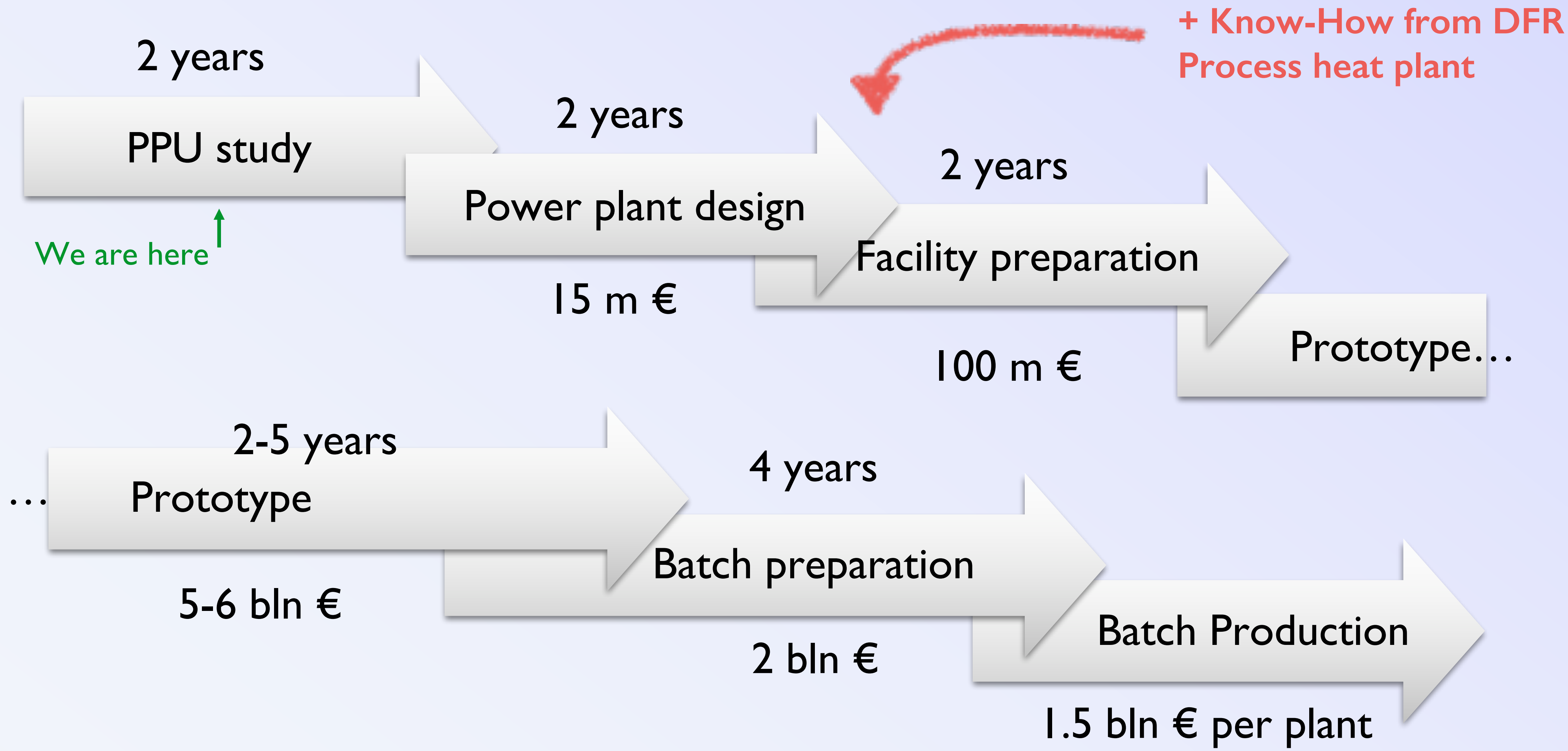
500 m €

Batch Production

200 m € per core

Development of the DFR process heat plant (300 MW_{th}):
(scH_2O @ 1000 °C)
8 years, 1 bln €
Serial type: 200 m €

DFR power plant development: Schedule and costs



+ Know-How from DFR Process heat plant

2 years
PPU study
We are here

2 years
Power plant design
15 m €

2 years
Facility preparation
100 m €

Prototype…

2-5 years
…Prototype
5-6 bln €

4 years
Batch preparation
2 bln €

Batch Production
1.5 bln € per plant

Development of the DFR power plant (1.5 GW_e):
8 years, 8 bln €
Serial type: 1.5 bln €

World Market

	Increase and Replacement*** until 2050 (PWh)	Plants*
Electricity	36	2740
Heat	40	3040
Transportation	42	1600
Process Heat	72	2740
Sum	**190**	**14400**
Investment Costs Process**		**9110** Mrd. €
Investment Costs Electricity**		**17340** Mrd. €
Investment Costs Total**		**26500** Mrd. €

* 3 GW thermal or 1,5 GW electrical

** 2 € per Watt electrical, 0,7 € per Watt thermal

*** For transportation and heat full transition to synthetical fuels (with fuel cells) or electricity, for electricity and process heat 80% replacement of old plants

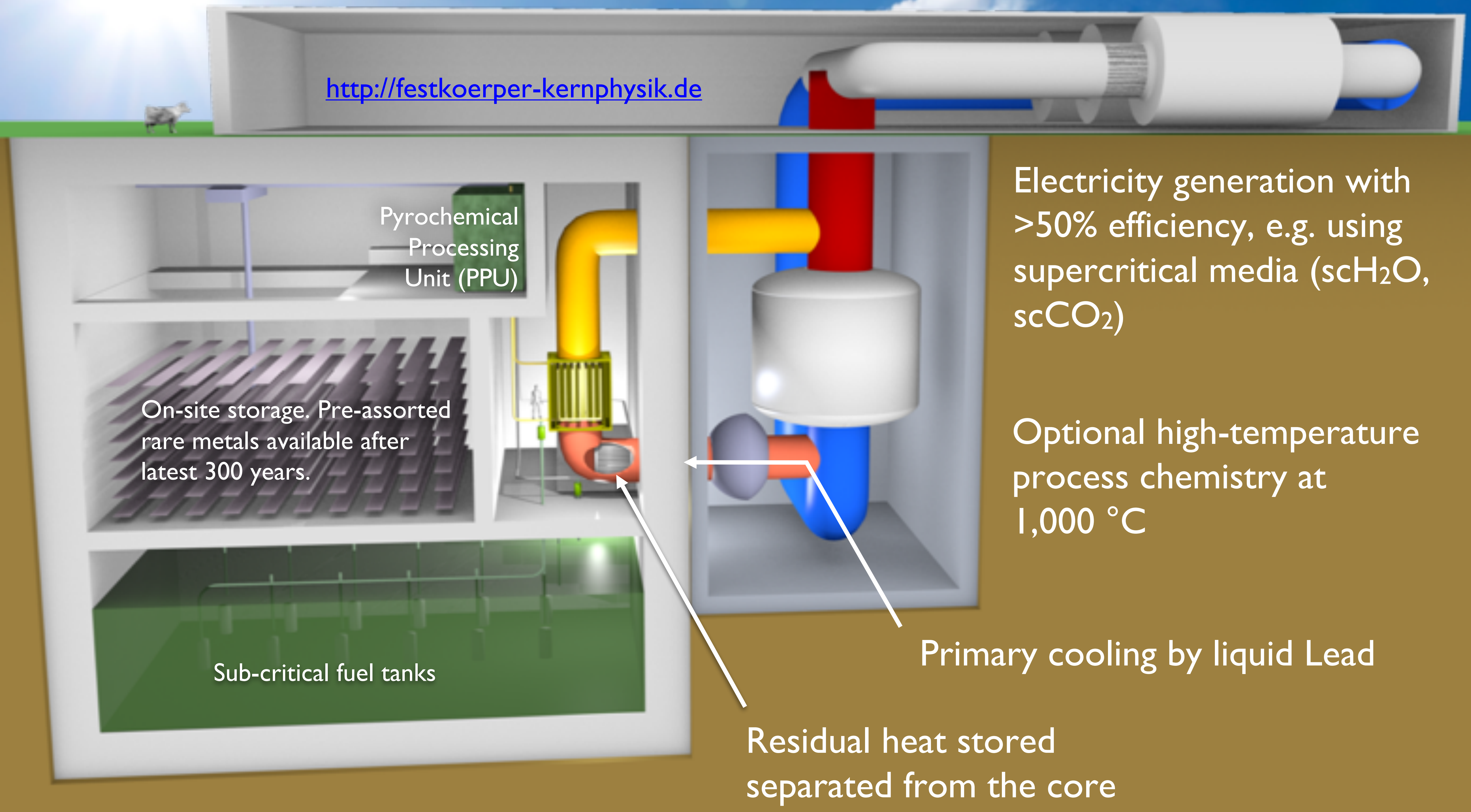
Key properties of the DFR

- Adiabatic power plant: No external fuel cycle needed
- Investment costs: 1 €/Watt[a] → Comparable with coal power plants
- Energy efficiency (EROI) 20 times as high as for pressurized water reactors
- Electricity production costs: 0.6 ¢/kWh[a]. Per serial DFR annual profit of 300 mio. € possible
- Oil-equivalent fuels can be produced for 50 US$/barrel[a,b] (0.3 €/liter[,b])
- Electromobility based on hydrazine fuel cells possible with 1.5 ¢/km[a] and ranges of more than 1,000 km

Alle costs are based on today's energy mix.
When the entire economy changes to DFR technology the costs further drop to the ratio of the EROIs.

a) Overnight costs
b) Energy equivalent

DFR power plant



http://festkoerper-kernphysik.de

Pyrochemical Processing Unit (PPU)

On-site storage. Pre-assorted rare metals available after latest 300 years.

Sub-critical fuel tanks

Electricity generation with >50% efficiency, e.g. using supercritical media (scH_2O, $scCO_2$)

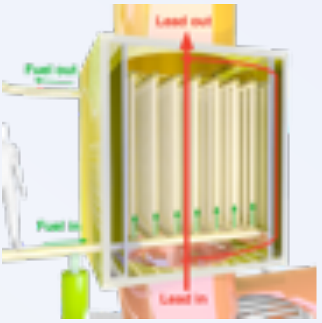
Optional high-temperature process chemistry at 1,000 °C

Primary cooling by liquid Lead

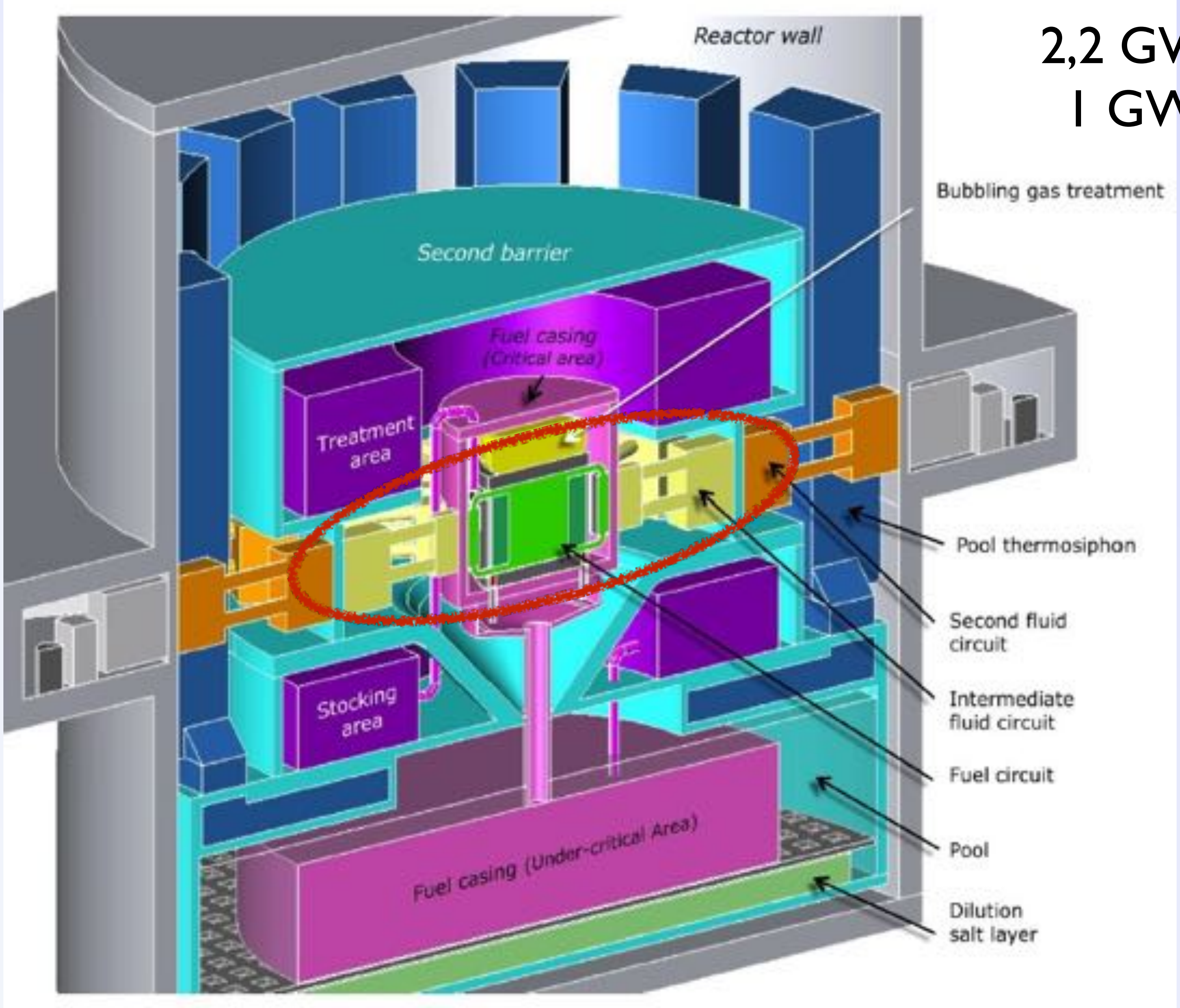
Residual heat stored separated from the core

Power Density: DFR vs MSR

DFR
3 $\mathrm{GW_{th}}$
1,5 $\mathrm{GW_e}$



SAMOFAR
2,2 $\mathrm{GW_{th}}$
1 $\mathrm{GW_e}$

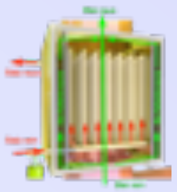


THTR vs DFR

THTR: 300 MW_e

- Infrastructure: Enrichment, fuel element production
- Not thermal and no fuel processing → needs final geological deposit
- The GenIV VHTR concept provides even a second intermediary He loop!
- Scalability: max. 300 MW, otherwise risk of core meltdown
- 3 €/Watt, 5 ct/kWh

DFR: 1.500 MW_e



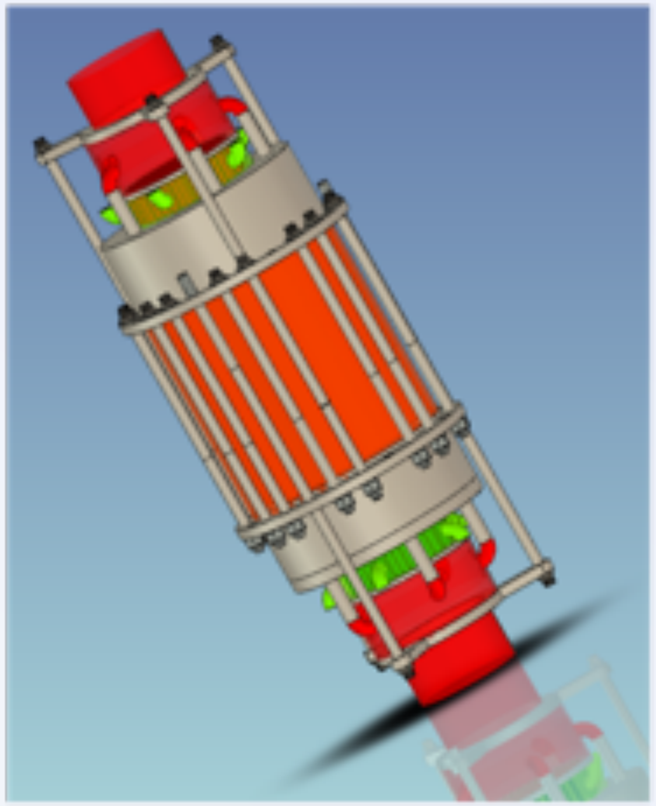
- No further infrastructure
- Fast reactor + online reprocessing → no need for final geological deposit
- 1/8 of the volume and 5-fold power
  → 40-fold power density
  → 1/40 of material expenses
- Much higher scalability
- 1 €/Watt, 0,65 ct/kWh

DFR bei 1000 °C

Umspült von flüssigem Blei und Metall-/Salzbrennstoff in einem Neutronenbad
Gibt es dafür Materialien?

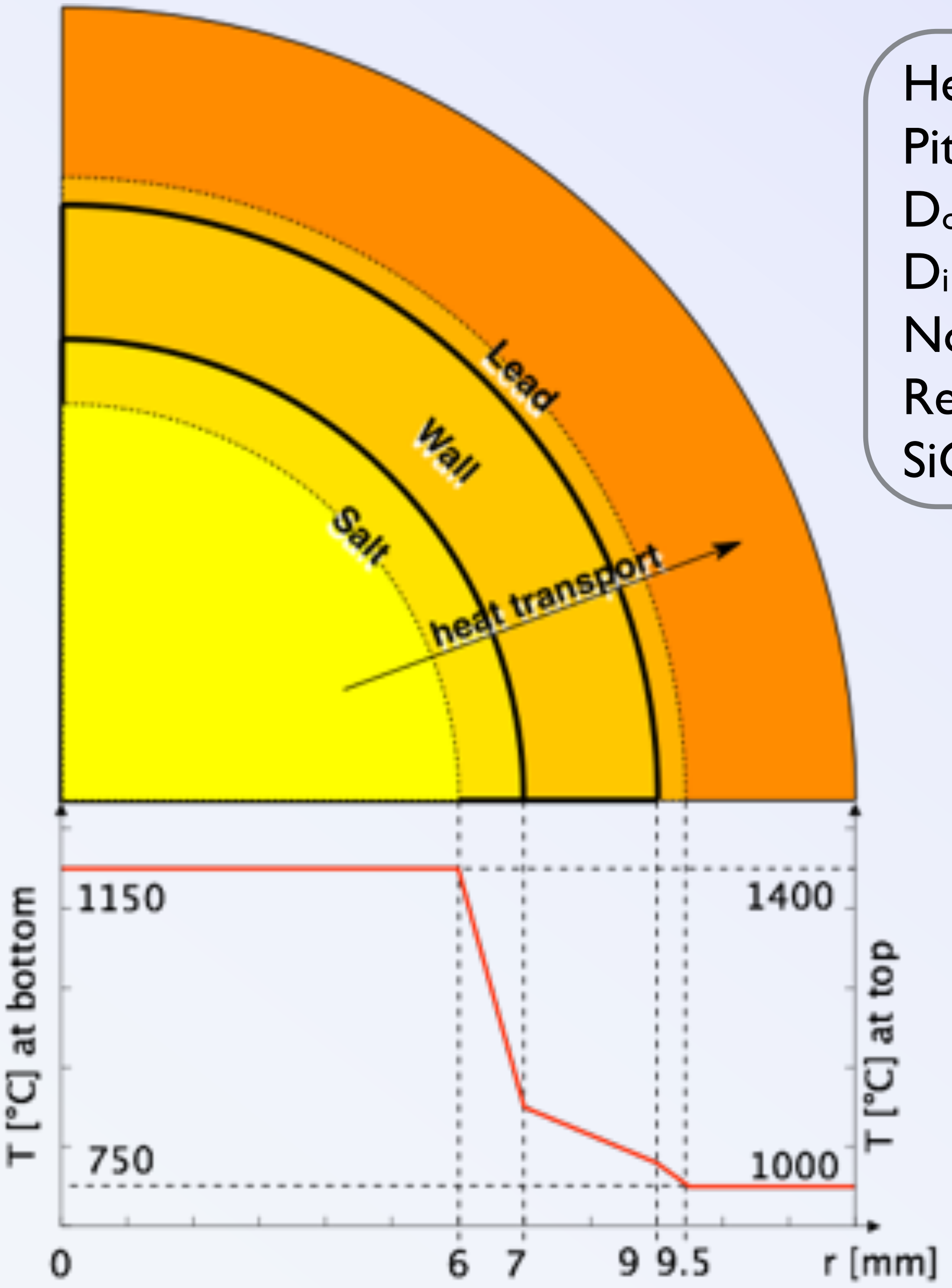
Siliziumkarbid (SiC)

DFR/s-Kern



SiC-Maschinenteile →

DFR/s Thermohydraulics

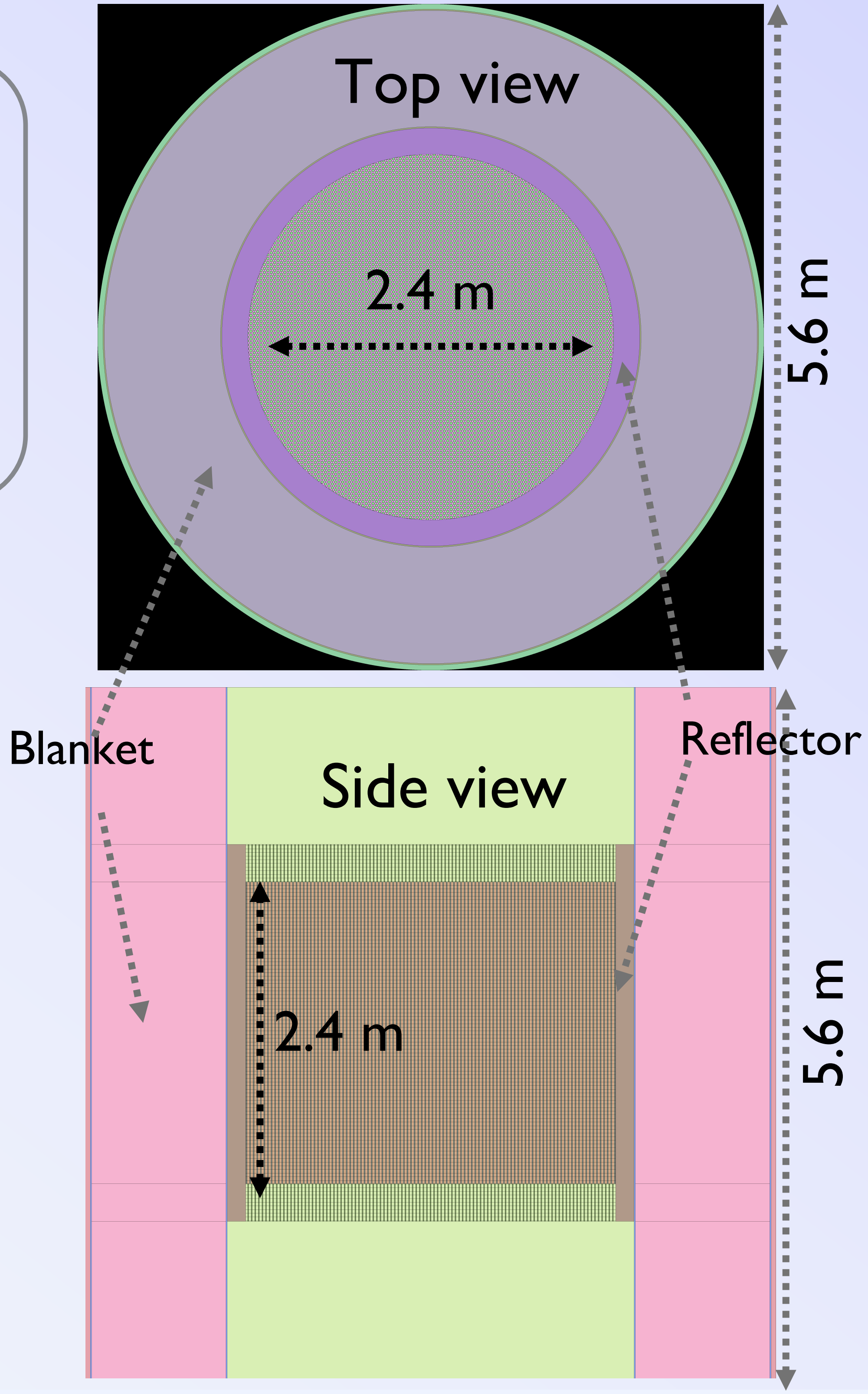


DFR Core

Hexagonal lattice
Pitch-to-diameter (P/D) ~ 1.15
D_o=19(18)mm
D_i=14(15)mm
Nominal power: 3 GW_{th}
Reflector thickness: 0.2m
SiC density 3.2 g/cm^3

UCl3 (theor. !):
3.5 g/cm^3
2 W/(m K)
0.5 mPa s
400 J/(kg K)
v = 1 m/s
Re = 140,000
Pr = 0.09

Lead coolant:
9.7 g/cm^3
23 W/(m K)
1 mPa s
140 J/(kg K)
v = 4 m/s
Re = 360,000
Pr = 0.006



Fuchs-Nordheim and simple reactivity investigations (1st pulse)

Conditions for application:

- $\rho \gg \beta$ → Inserted reactivity much larger than delayed neutron fraction
- Adiabatic fuel heating (always given in fast reactors and high reactivity insertion rate)
- Reactivity coefficients constant over relevant temperature range

	LWR	DFR
Inserted reactivity ρ	0.01	0.01
β (reactor-grade Pu)	0.0035	0.0035
Reactivity coefficient α	-3 pcm/K	-50 pcm/K
Fuel heat capacity C_p	40 MJ/K	9 MJ/K
Prompt neutron lifetime	60 µs	6 µs (!)
Max. temp. change ΔT_{fuel}	400 K	26 K
Temperature after pulse ΔT_{fuel}	200 K	13 K
Pulse duration Δt_{peak}	40 ms	4 ms
Pulse energy E_{peak}	20 GJ	0.2 GJ
Pulse power Δp_{peak}	1 TW	0.1 TW

$\Delta P_{peak} = C_p(\rho-\beta)^2/(2\Lambda\alpha)$

$\Delta T_{fuel} = 2(\rho-\beta)/\alpha$

$\Delta T_{fuel} = (\rho-\beta)/\alpha$

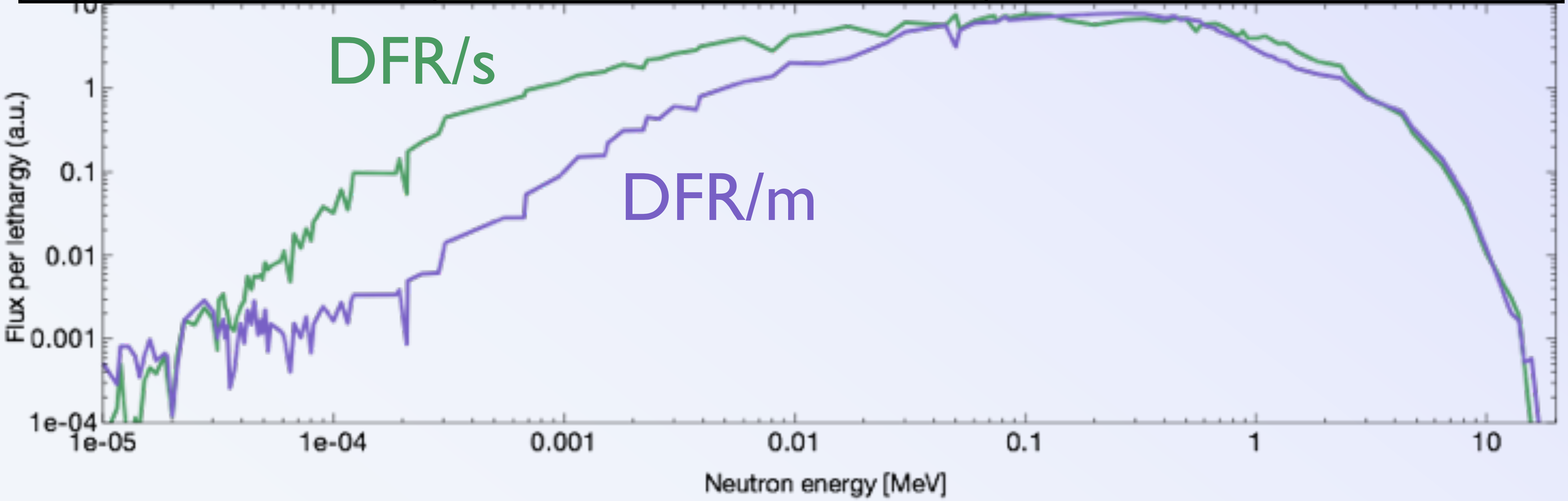
$\Delta t_{peak} = \sim 4\Lambda/(\rho-\beta)$

$E_{peak} = 2C_p(\rho-\beta)/\alpha$

- DFR reactivity coefficient (almost) inde- pendent on fuel composition (liquid fuel)
- LWR temperature changes far too high → control rods needed

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 with >70% actinides, 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



DFR neutronic results

Assumed fuel salt density: 3.5 g/cm^3, no burnup, ^{238}U fast fission ignored for CR calculation
Composition: ^{37}Cl, 68.5 mole-%, actinides balance (material below and ^{238}U/^{232}Th balance)

Fissile Material	Type	Fuel Enrichment	ν	CR
U-235	Salt	~19.5%	2.47	< 0.9
Pu-239	Salt	~17%	2.90	< 1.2
Reactor-grade Pu[a]	Salt	~22%	2.92	1.2 (1.25)
U-233	Salt	15.5%	2.52	1.1
Reactor-grade Pu[a]	Metal	< 9%	2.92	> 1.6

$$\mathrm{CR} = \frac{\mathrm{Cap}(^{238}\mathrm{U}/^{232}\mathrm{Th})+\mathrm{Cap}(^{238}\mathrm{Pu})+\mathrm{Cap}(^{240}\mathrm{Pu})+\mathrm{Cap}(^{242}\mathrm{Pu})}{\text{Total fission and capture } (^{233}\mathrm{U}+^{235}\mathrm{U}+^{239}\mathrm{Pu}+^{241}\mathrm{Pu})}$$

a) 45 GWd/t Pu

DFR: Metal vs Salt Fuel

	DFR/s (hexag.)	**DFR/m (hexag.)**
fission zone DxH [m]	2.8 x 2.8	3 x 2.6
outer / inner tube diameter [mm]	18 / 15	24 / 20
Pitch-to-diameter ratio	1.25	1.25
mean linear power density [W/cm3]	850	1250
mean temperatures fuel inlet / outlet [K]	1270 / 1540	1350 / 1650
temperatures coolant inlet / outlet [K]	1030 / 1300	1070 / 1370
conversion ratio U-Pu / Th-U cycle at start	> 1.2 / 1.1	1.7 / 1.1
^{234}U, ^{240}Pu, ^{242}Pu burnable? (resp. CR)	no (1.2 / 1.1)	yes (2.1 / 1.3)
^{238}U fast fission / all fission	6%	20%
fiss. zone volume [m^3] (fuel fraction)	21 (32%)	23.6 (32%)
fuel / coolant velocity (m/s)	1.2 / 3.6	0 / 2.6