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Overview of Nuclear Cogeneration in High-Temperature Industrial Process Heat Applications

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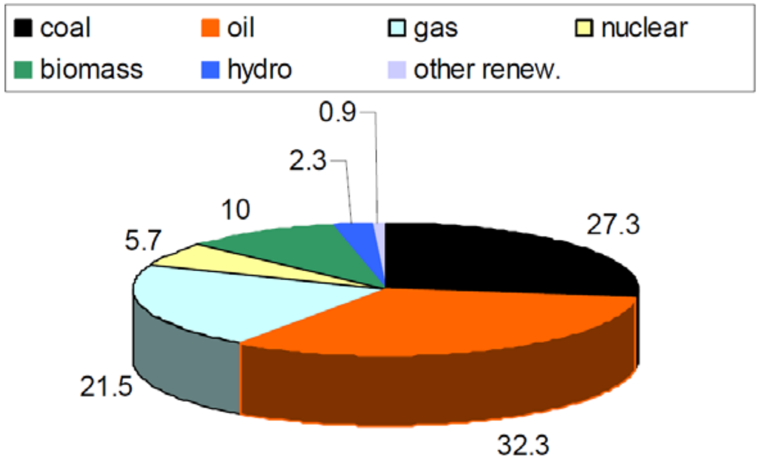
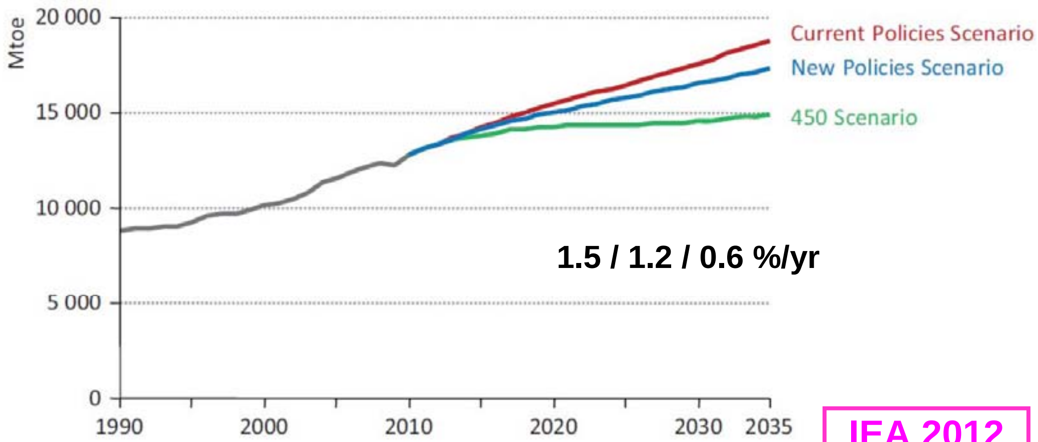
World Energy Situation

- World primary energy demand steadily increasing in each scenario
- Fossil fuels were 81% in 2010 and will remain dominant contributor through 2035



Total: 12 730 MTOE



IEA 2012

Current Policies:	business-as-usual, no implementation of policies beyond those adopted by mid-2012
New Policies:	existing policy commitments and assuming that those recently announced are implemented (targeted use of renewables, nuclear phase-out) , global temperature increase by 3.6 K
450 Scenario:	assuming policy actions having a 50% chance of limiting the long-term global temperature increase to 2 K ("450" = long-term concentration in atmosphere of 450 ppm CO_2-eq)

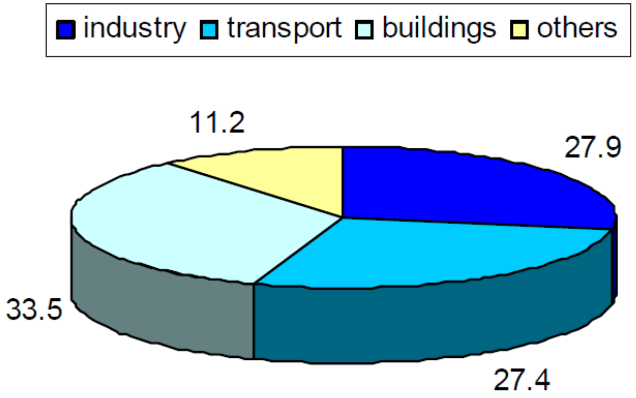
World primary energy demand in 2010 and projection by scenario

Status of Nuclear Energy

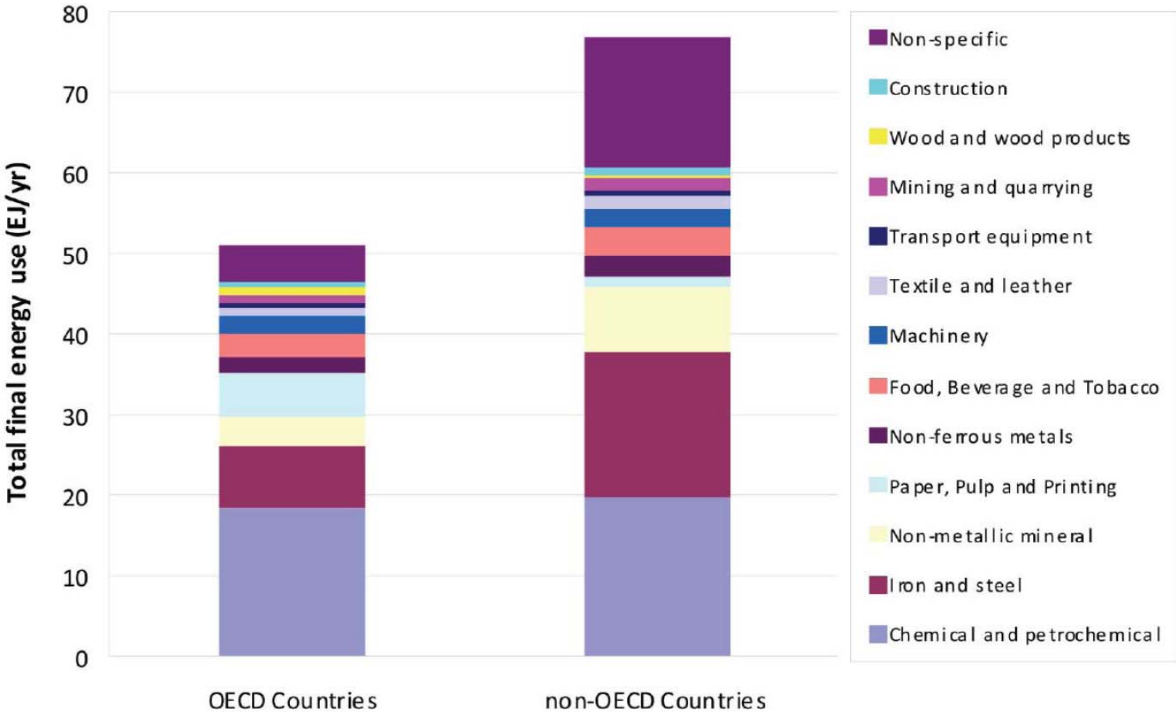
- Of global final energy, 17.7% is used for electricity generation, of which 12.9% comes from nuclear energy (= 2756 TWh)
- As of March 2013, total 437 nuclear power plants with 372 GW(e) capacity in operation with 82% being LWR providing 89% of all nuclear electricity
- 68 NPP with 65 GW(e) capacity under construction, of which 48 GW(e) was started after 2006 (of which 85% accounted for by China and India)
- Majority of operating NPP will be shut down within the next two decades
- Primary uranium production in 2010 was 54 000 t, barely enough to even meet the NEA low-case scenario for the next 10-20 years [EWG 2013]

Industrial Heat Demand

- Of global final energy consumption, 28% was in industrial sector



IEA 2012



Data include feedstock use for petrochemicals, coke ovens and blast furnaces, and exclude petroleum refineries' energy use.

UNIDO 2010

Strong Points of (Nuclear) Combined Heat and Power

- **Minimize heat losses**
- **Improve energy (fuel) efficiencies**
- **Reduced CO_2 emissions**
- **Enhance energy security**
- **CHP since long applied in many industries**

Nuclear Non-Electric Energy

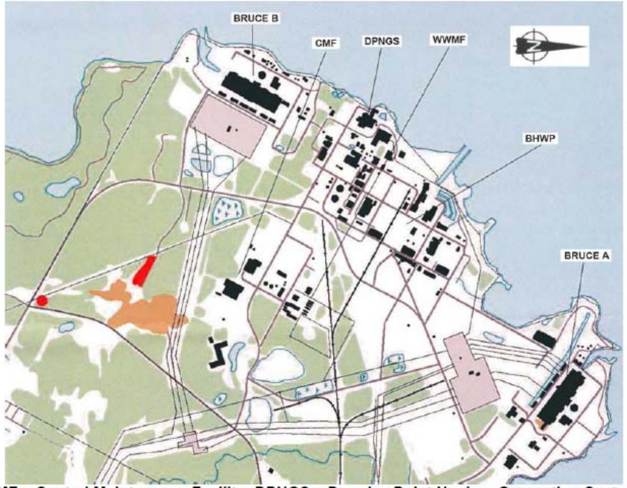
- Nuclear electricity generation means that two thirds of the heat produced is wasted.
- Potential for utilization of nuclear heat/steam in four areas:
  - desalination
  - district heating in residential/commercial areas
  - industrial process heat
  - fuel synthesis
- Less than 1% of the nuclear heat used for non-electric applications
- Nuclear heat/steam experience of ~750 reactor operation years from 74 NPP (mainly district heating and desalination)

Experience from Nuclear Industrial Non-Electric Applications

Country / reactor type	Power (MW(th) / MW(e)net)	Heat delivery (MW(th))	Temp. at interface feed / return (°C)	Distance to industry	Industrial application	Operation period of application
Norway / Halden BWR	20 / -	20		adjacent site	Paper mill	1964 –
Switzerland / Gösgen PWR	2806 / 985	45	220 / 100	1.8 km	Cardboard factory	1979 –
Canada / Bruce CANDU	4 x 848 4 x 860	5350		on-site	D_2O production and others	1981 – 1997
Germany / Stade PWR	1892 / 630	30	190 / 100	1.5 km	Salt refinery	1984 – 2003

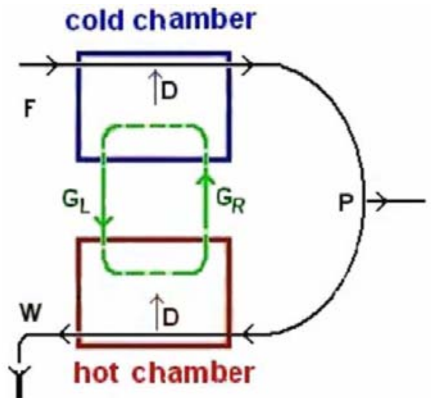
Heavy Water from Nuclear Process Heat

- Canada, Bruce NPP, 6232 MW(e)
- BHWP provided with medium-pressure steam from steam supply plant (one of the largest process steam systems with 5350 MW)
- BHWP operated until 1997, max. capacity ~700 t/yr, total D_2O production was ~16 000 t



CMF = Central Maintenance Facility; DPNGS = Douglas Point Nuclear Generating System, WWMF = Western Waste Management Facility; BHWP = Bruce Heavy Water Plant

$$H_2O(l) + HDS(g) \underset{130°C}{\overset{30°C}{\rightleftarrows}} HDO(l) + H_2S(g)$$



Girdler process

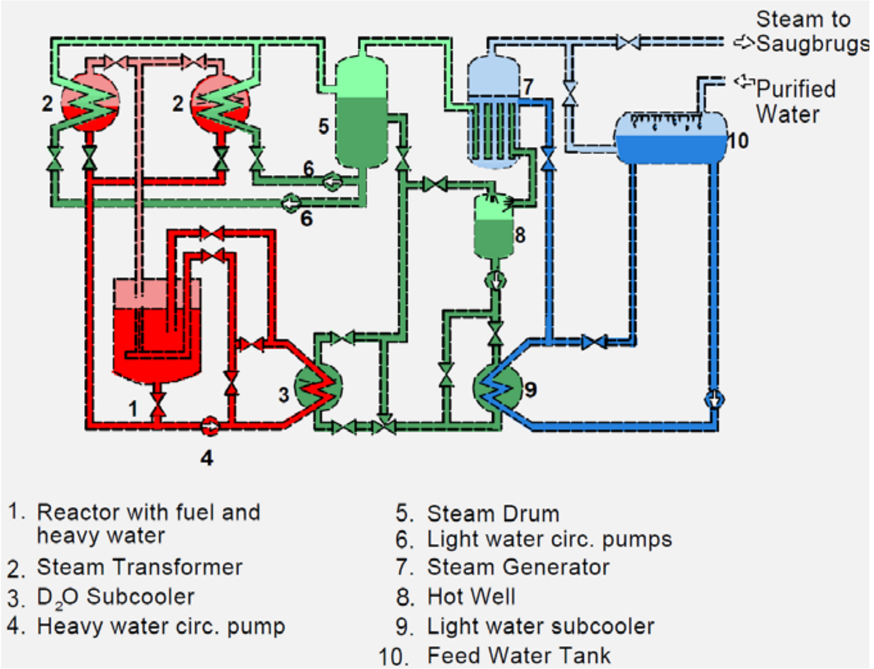
D = deuterium
F = feed water
G = gaseous H_2S
P = product
W = waste water
L = lean
R = rich

OPG 2002

Required: 35 t of H_2O, 25 GJ of thermal, 700 kWh of electric energy per 1 kg of D_2O

Steam from Nuclear Process Heat

- Norway, Halden NPP
  since 1964: 30 t/h of process steam
  to adjacent paper mill



- Switzerland, Gösgen NPP
  since 1979: 1% of lifesteam diverted
  to heat a water/steam cycle
  70 t/h of process steam
  @ 200°C and 1.2 MPa
  to cardboard factory;
  since 1996: district heating
  since 2007: 2nd water/steam cycle
  with 10 t/h to another paper factory

Gen-IV Nuclear Reactor Systems

Reactor type	Thermal power (MW)	Coolant outlet (°C)
Gas-Cooled Fast Reactor	600	~ 850
Lead-Cooled Fast Reactor	2400	~ 800
Sodium-Cooled Fast	2000-4000	~ 550
Molten Salt Reactor	2250	~ 800
Supercritical Water Reactor	900-3800	~ 550
Very High Temperature Reactor	250-600	~1000

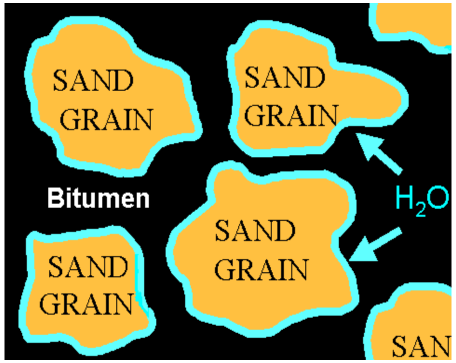
Requirements for Nuclear Process Heat Plants

- Secure and economic supply of power, heat, steam to guarantee continuous and reliable operation
- Smaller-scale units to match with needs of industries
- 2-6 units, practicable in terms of redundancy, reliability, reserve capacity
- To be easily switched between electricity and process heat production mode
- Intermediate heat exchanger to minimize tritium migration to industrial product
- Sufficient safety distance between nuclear island and industrial application

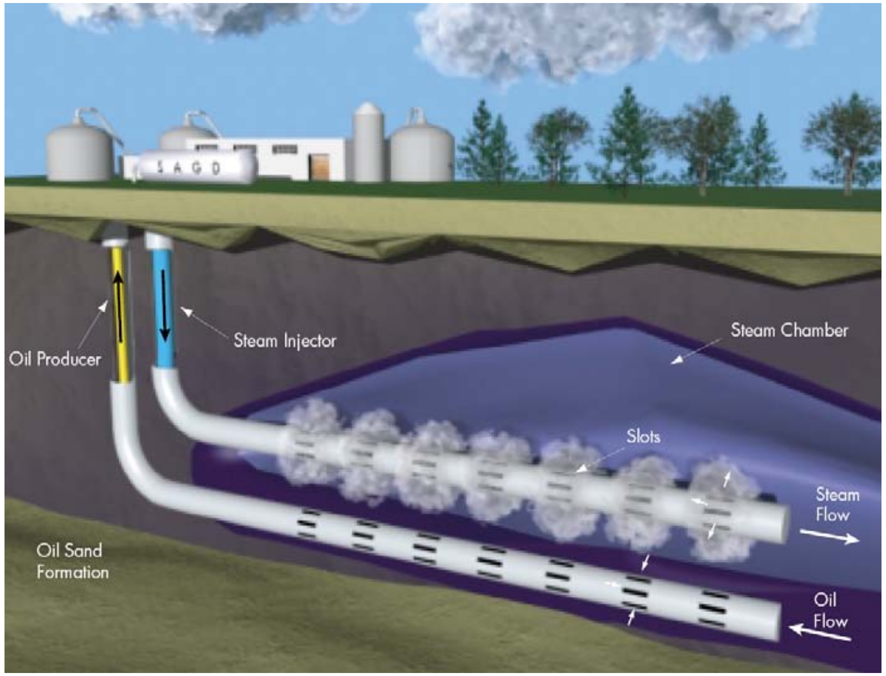
Recovery of Unconventional (Tertiary) Oil

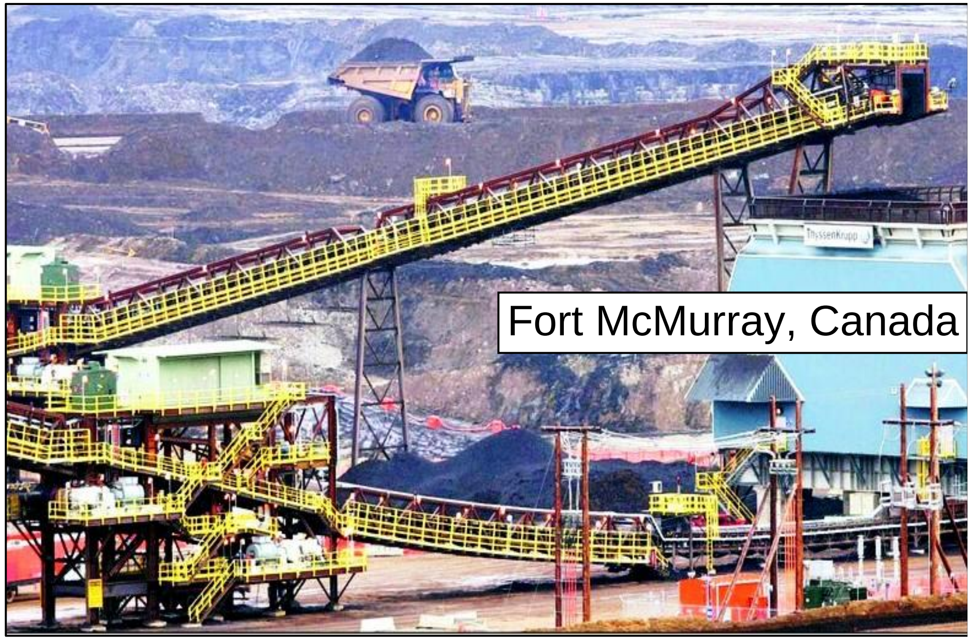
Flooding with steam
@ 200-340°C, 10-15 MPa

(makes more nuclear concepts applicable)



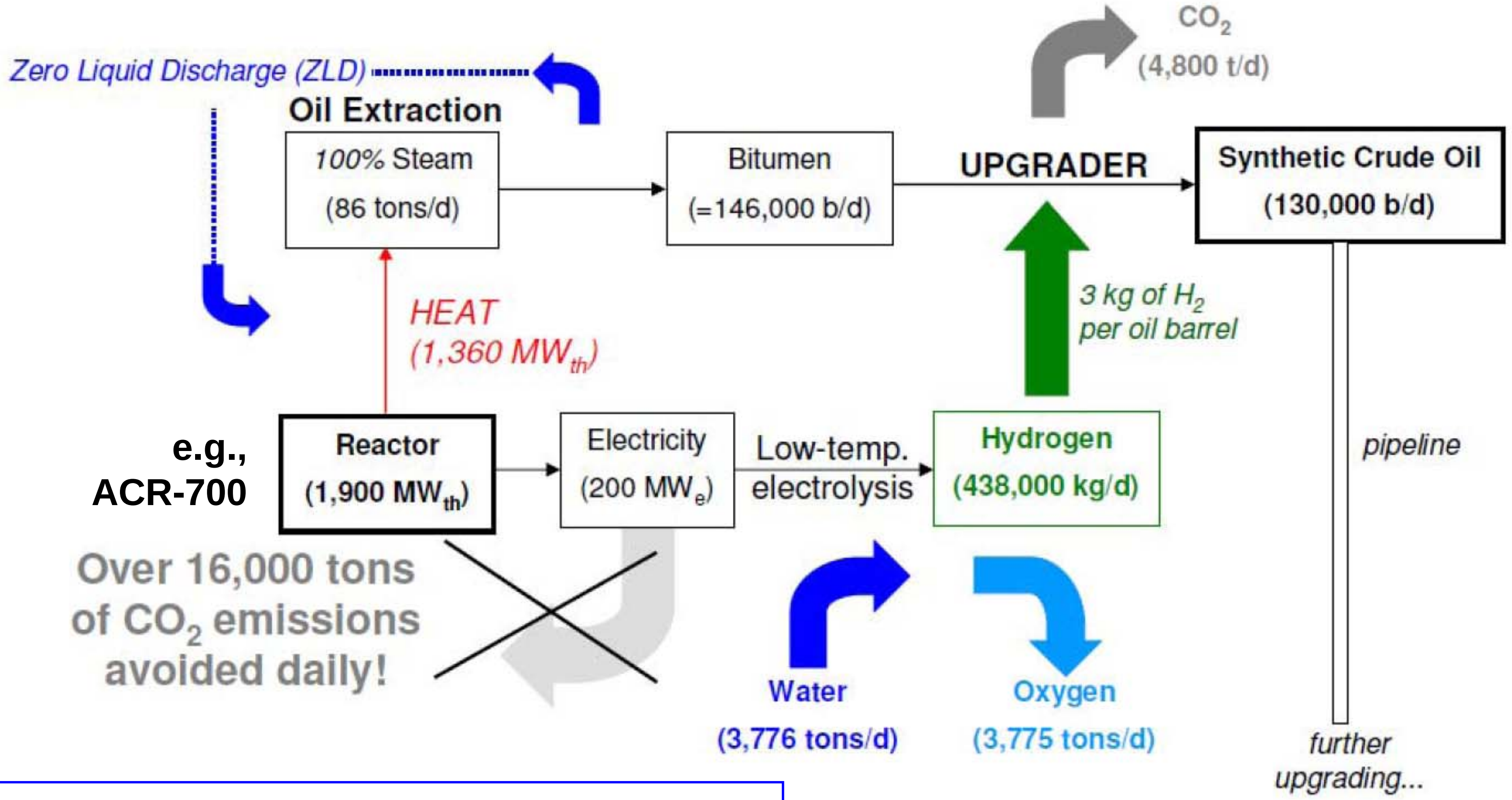
Steam-Assisted Gravity Drainage





one well for steam injection, one for production

Nuclear Production of Synthetic Crude Oil

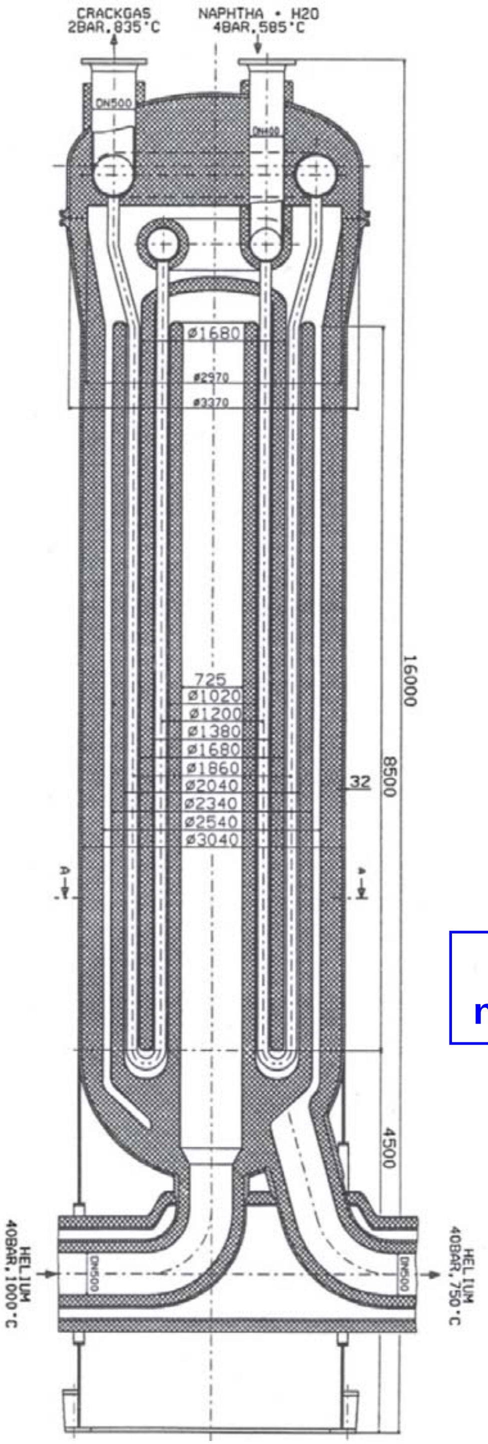


Large centralized steam source

Fluctuations met by cogeneration of electricity

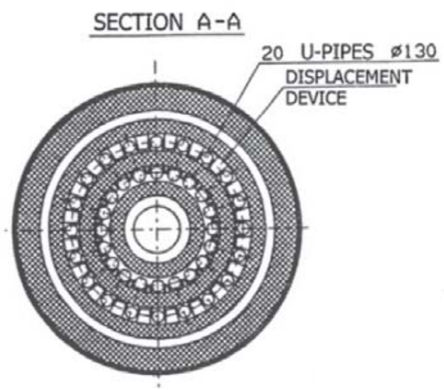
Coupey 2006

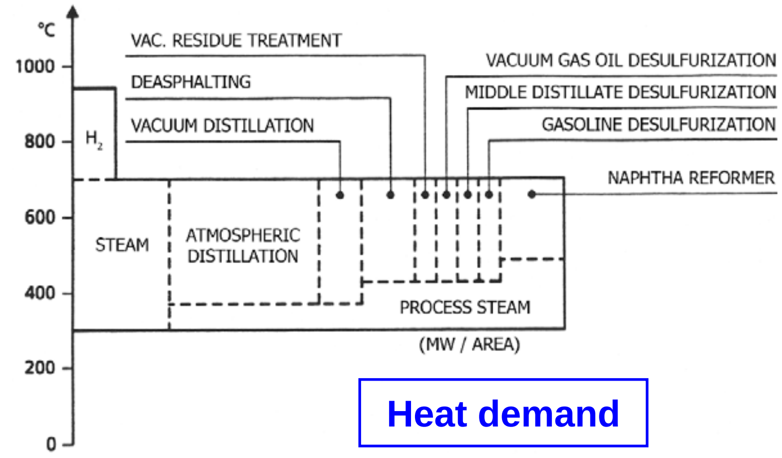
Crude Oil Refinery



Schad 1988
Reimert 2010

Helium-heated naphtha cracker





Heat demand

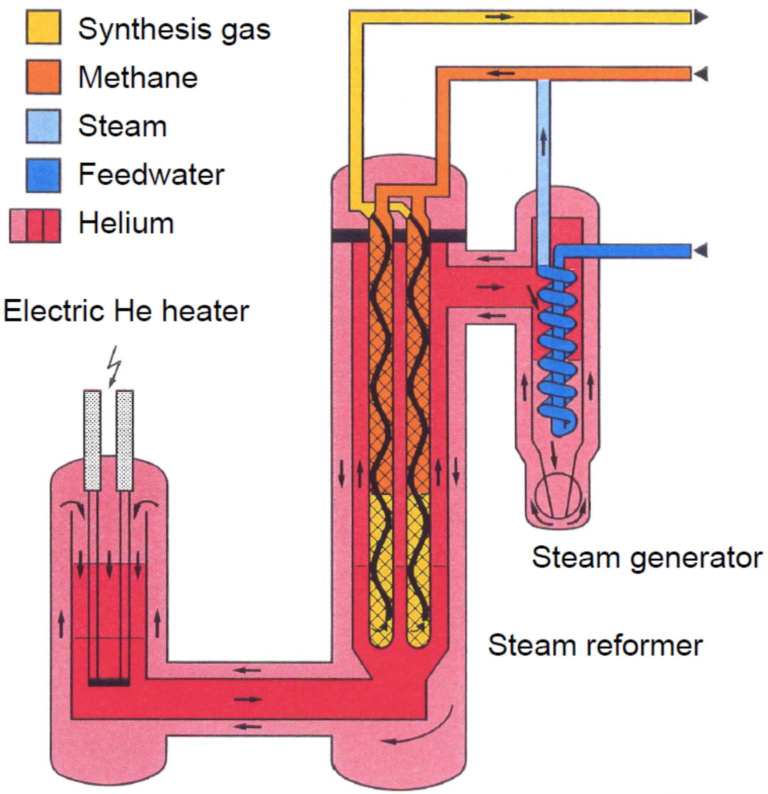
LURGI study in 1988:

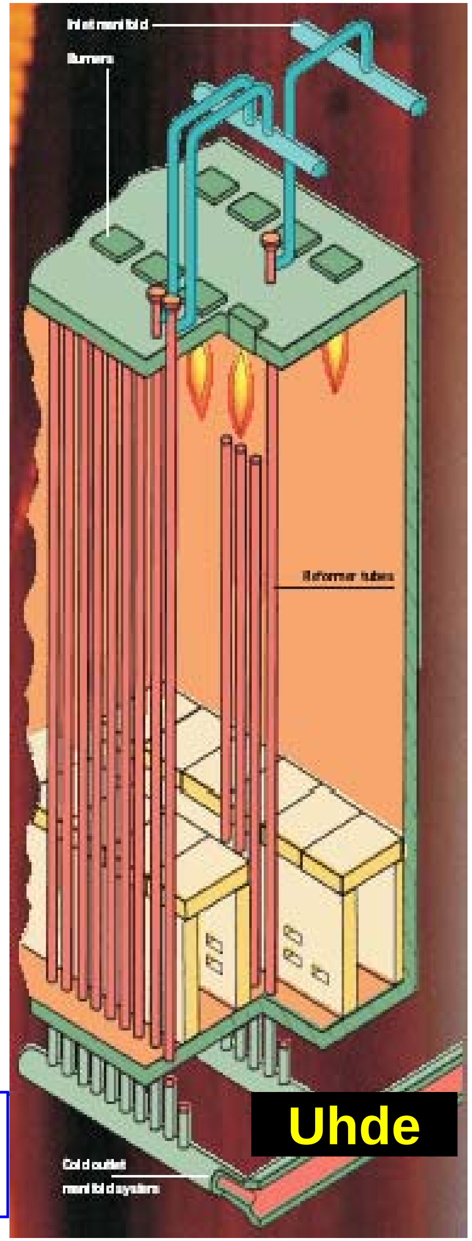
Integration of process heat from HTR-M is possible in different refinery components with heat demand < 540°C

- separation (e.g., distillation)
  most energy-intensive processes
- conversion (e.g., cracking)
- finishing (e.g., hydrotreating)

Reforming of Natural Gas

Nuclear-simulated steam reforming
tested at 10 MW pilot plant scale
in Germany and Japan





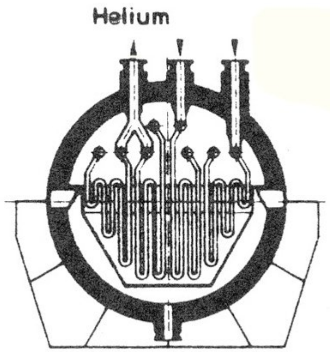
Capacity: 13.8 t/h or 153,000 Nm³/h
corresponding to 550 – 630 MW (HHV)

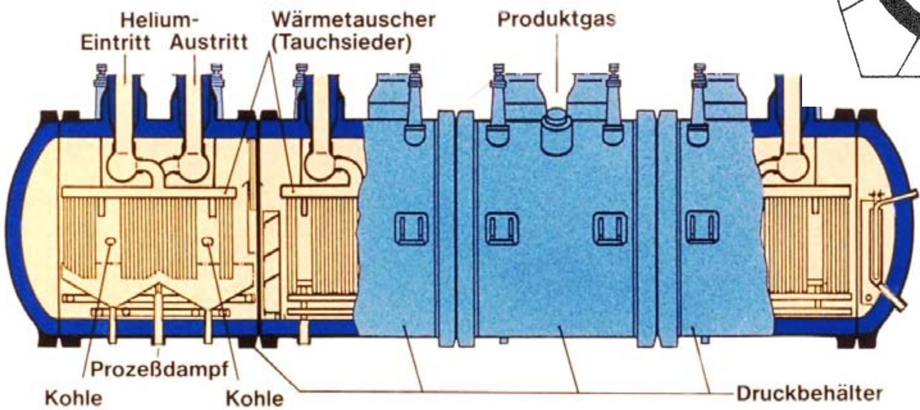
Coal Gasification

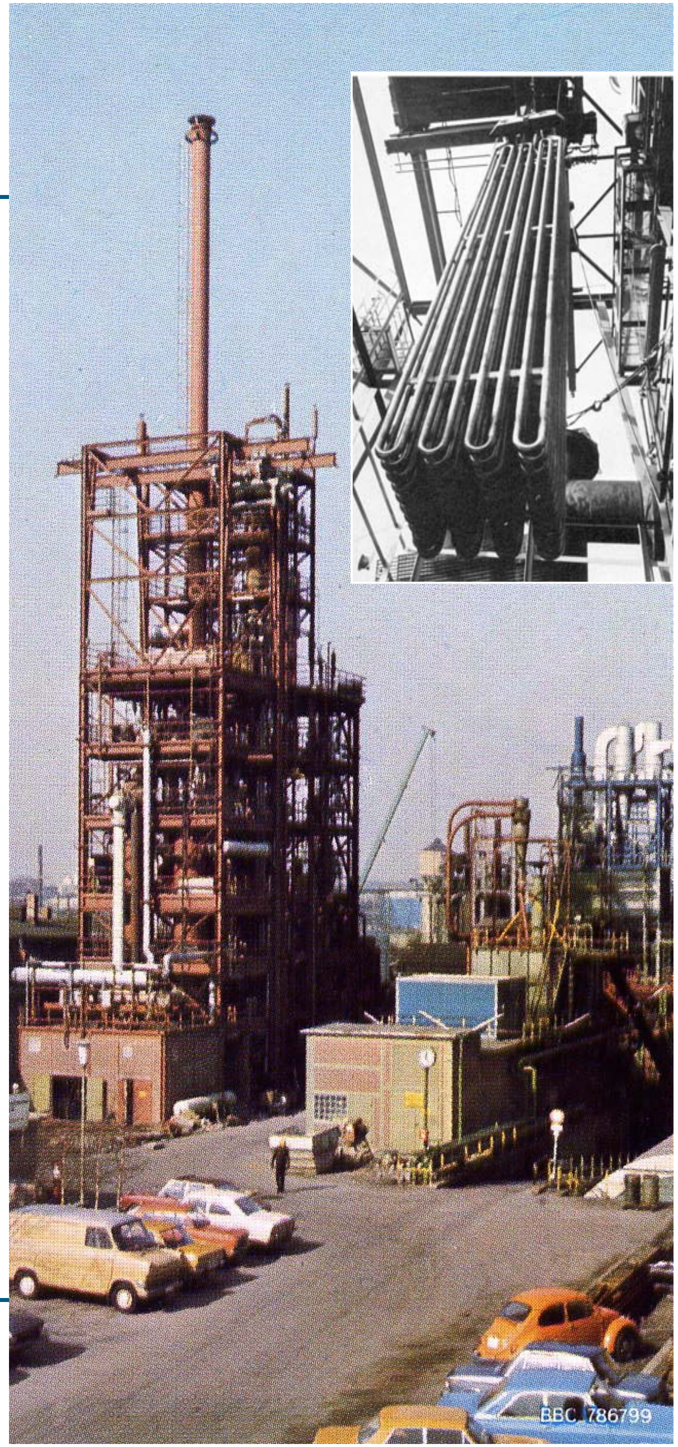
Nuclear-simulated coal gasification
tested at semi-technical scale
in German PNP project

Feedstock savings up to 35%

Concept of steam-coal gasifier for 340 MW(th), 50 t/h



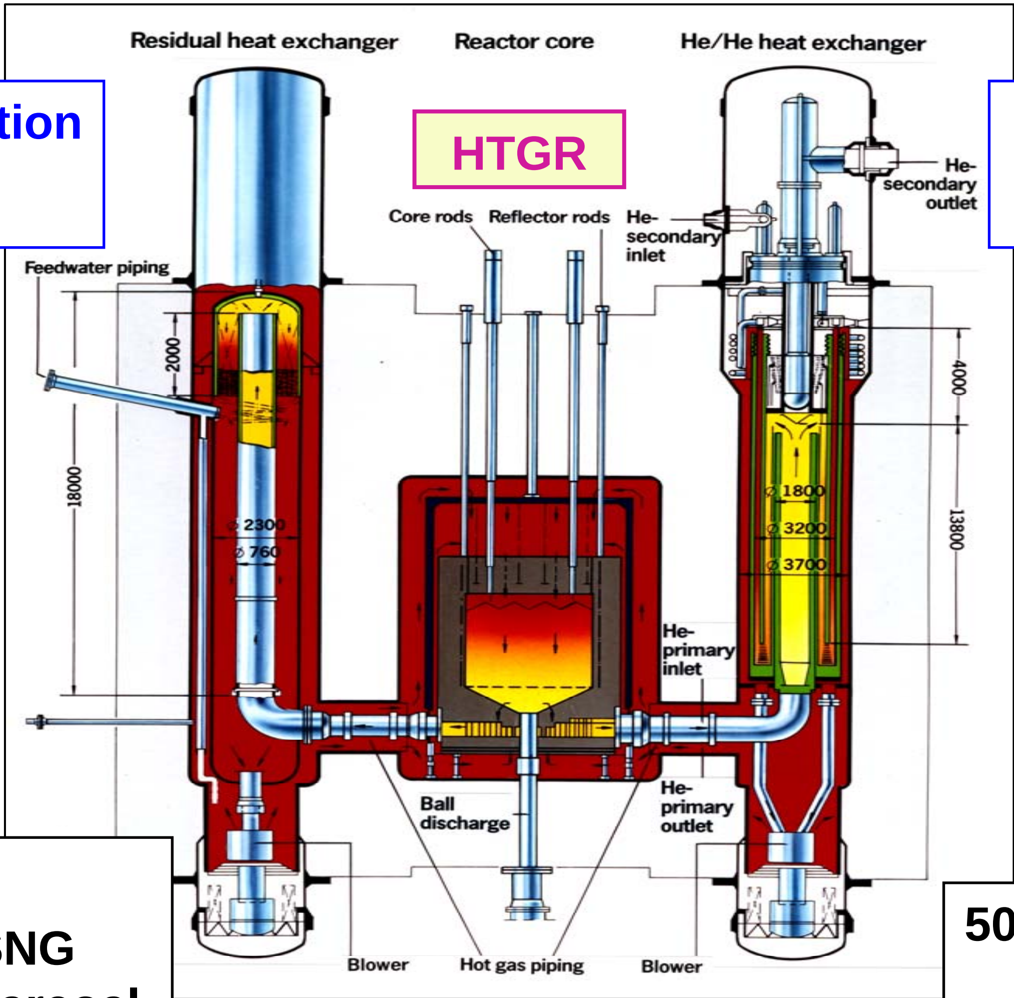




Prototype Plant PNP-500

Hydro gasification of lignite

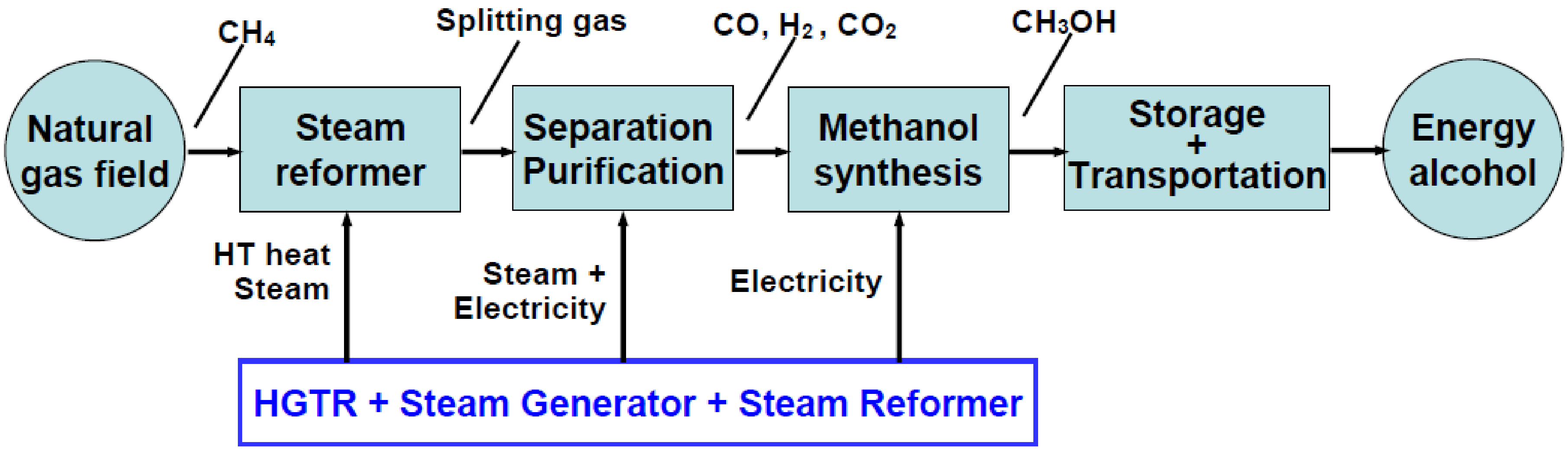
Steam gasification of hard coal



166 t/h coal
→ 26,500 m³ SNG
+ 18.4 t/h charcoal

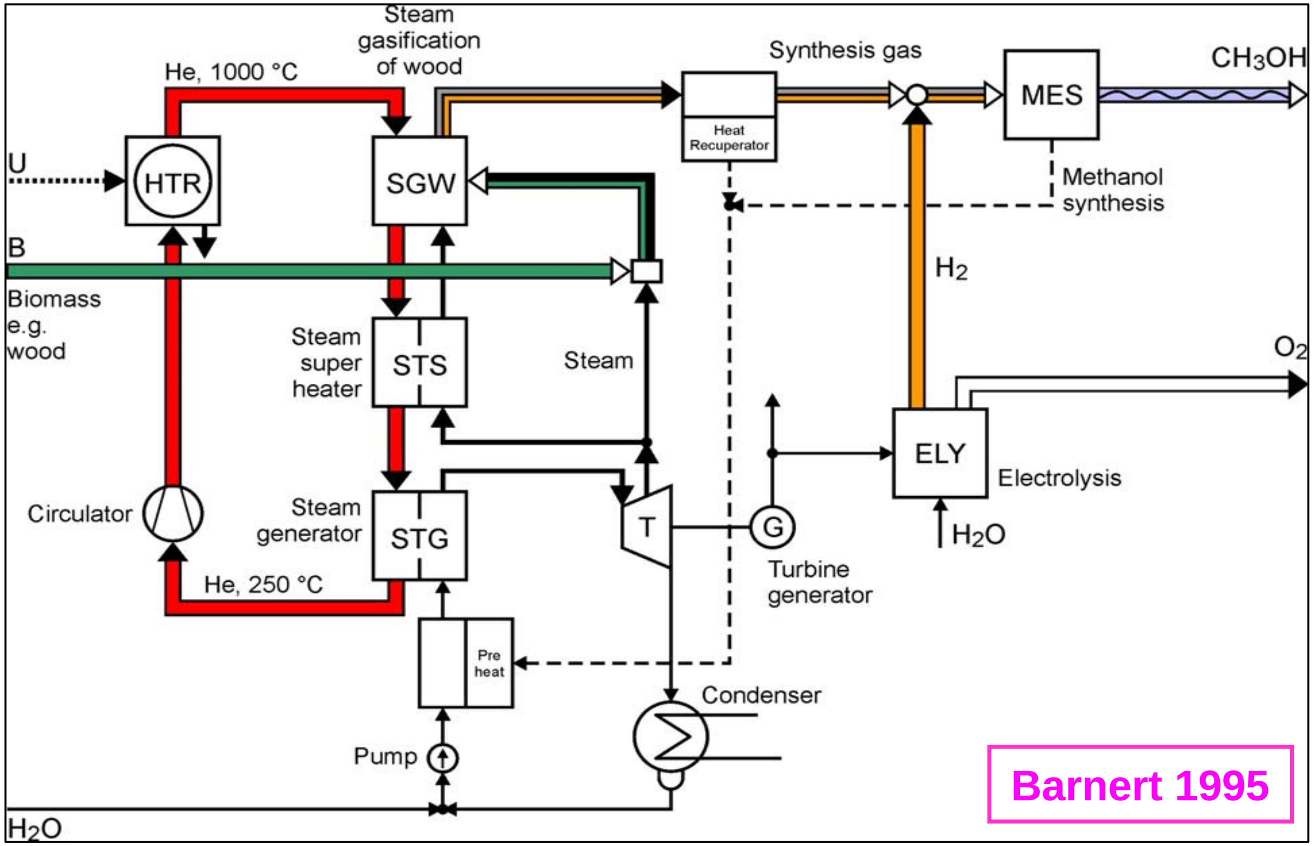
50 t/h coal
→ 41,000 m³ SNG

Methanol from Natural Gas



Conv.:	1000 m³ natural gas	⇒ 1 t methanol + 1.5 t CO_2
Nuclear:	1000 m³ natural gas + 10 MWh_{th}	⇒ 2 t methanol

Liquid Fuels from Biomass and Nuclear

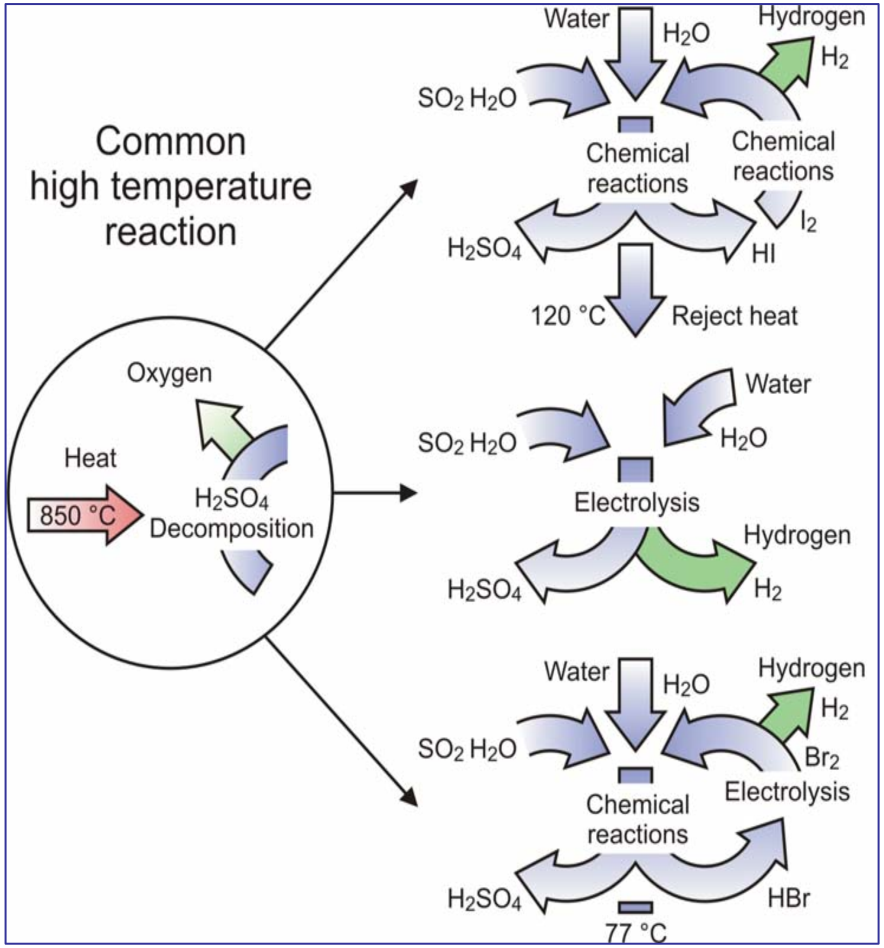


CO_2-neutral

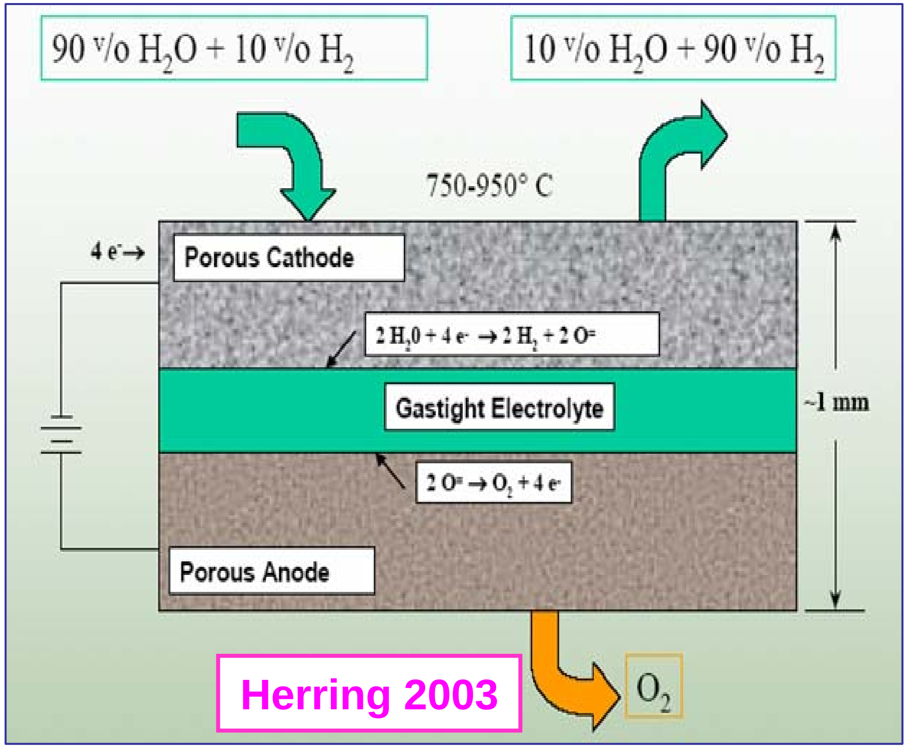
Conv.:	12 t Biomass	⇒ 1 t liquid HC (e.g., CH_3OH)
Nuclear:	12 t Biomass + 10 MWh_{th}	⇒ 2 t liquid HC (e.g., CH_3OH)

Nuclear Hydrogen from Water-Splitting

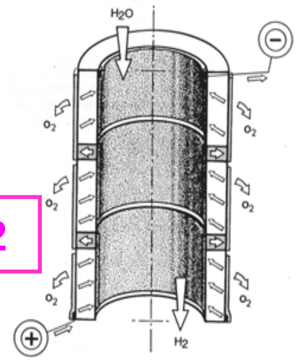
S-based Thermochemical Cycles



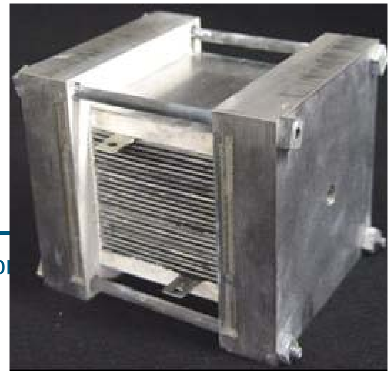
High-Temperature Electrolysis



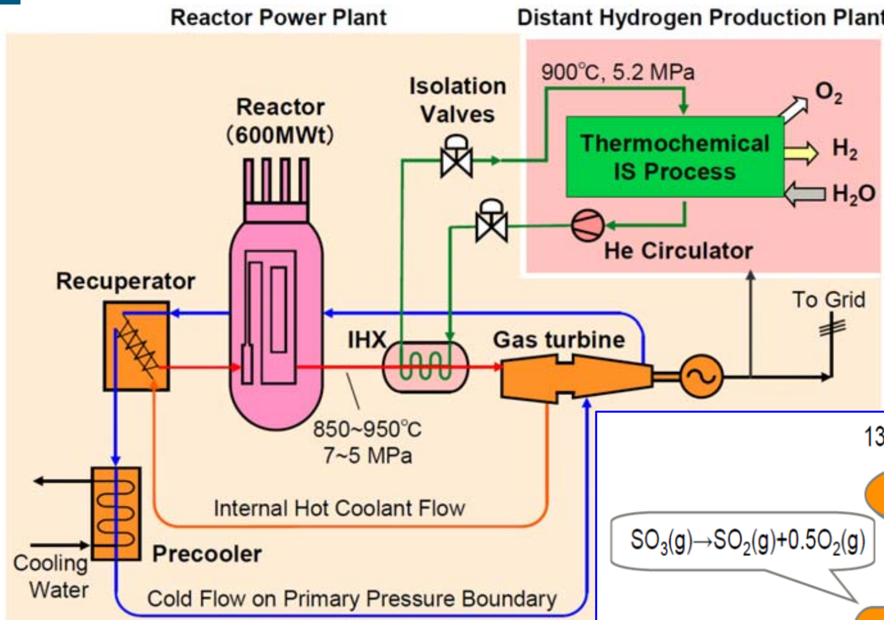
Herring 2003



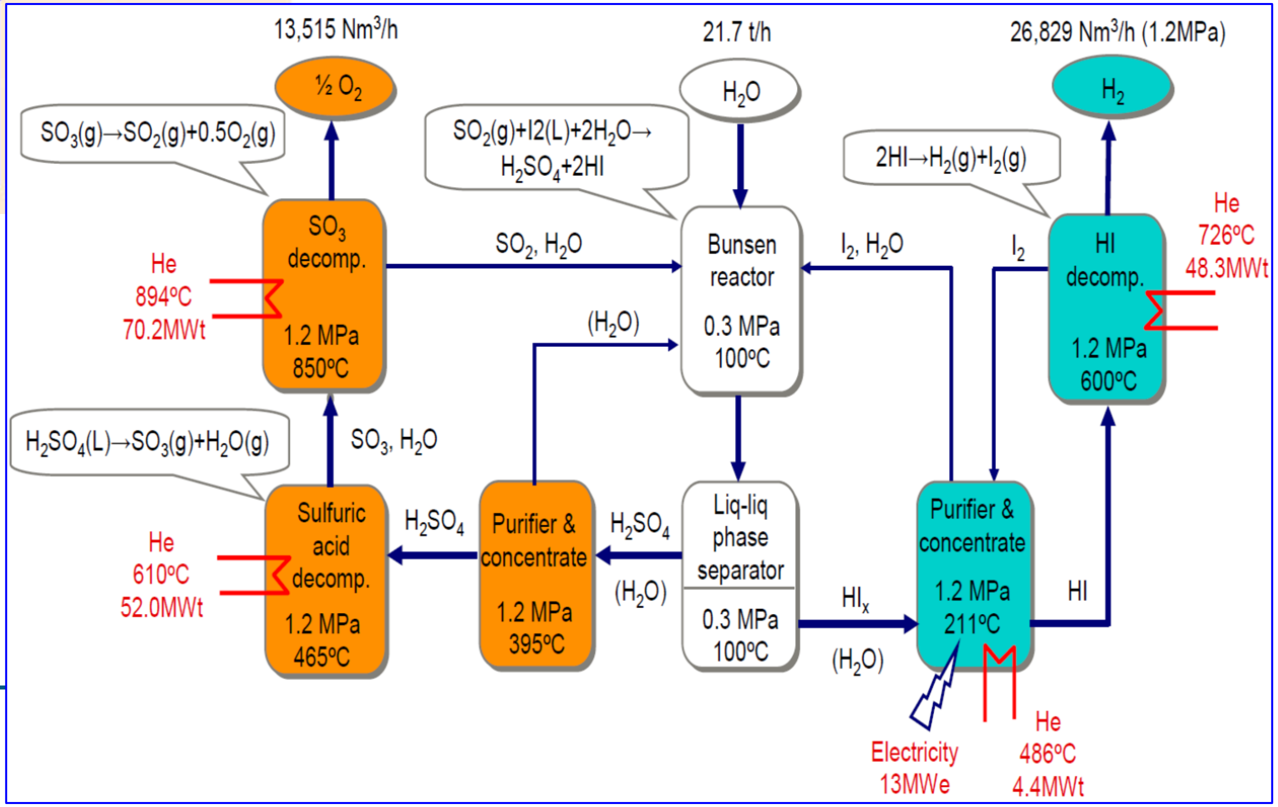
Dönitz 1982



Nuclear H_2 Production with GTHTR300C

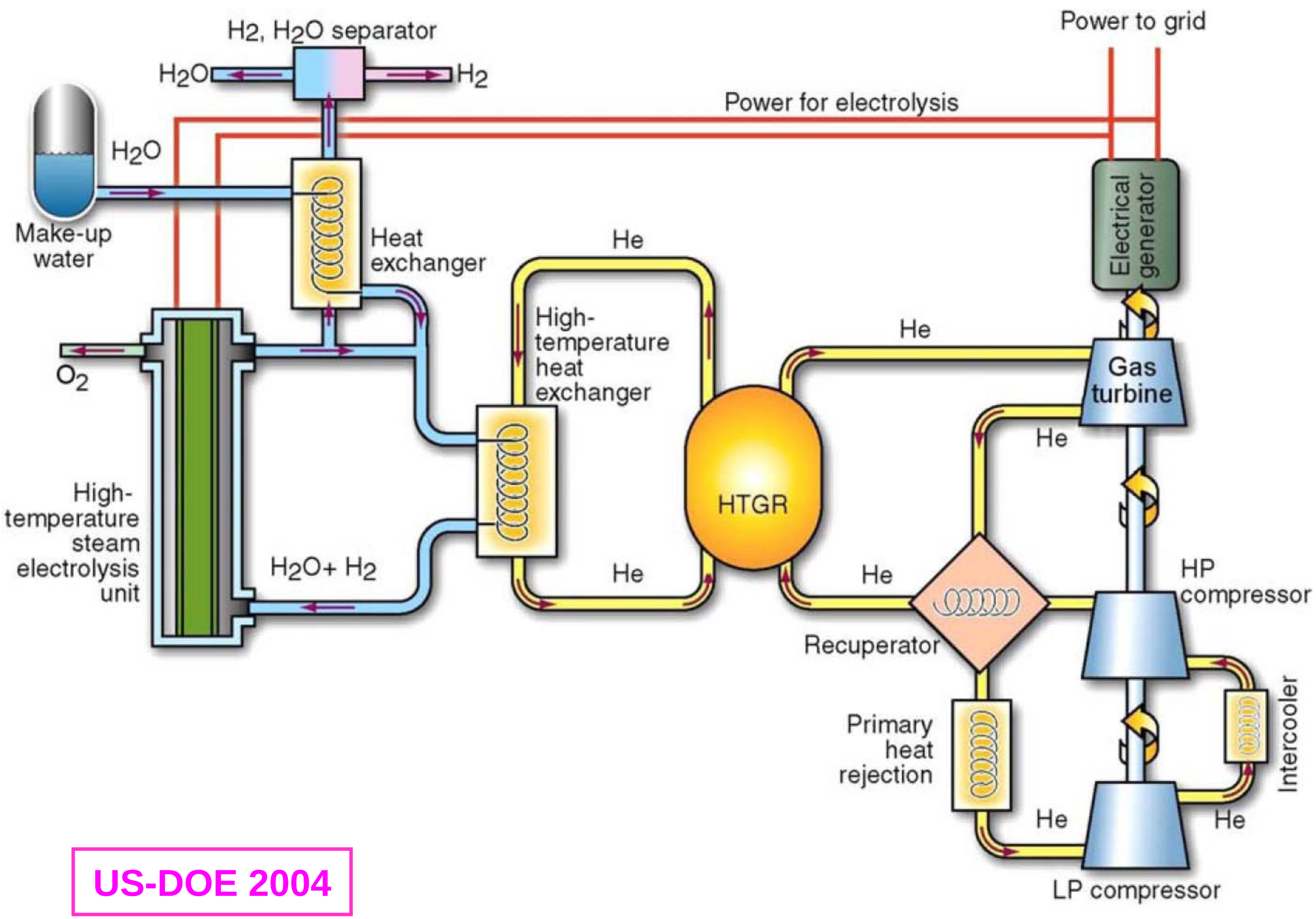


Heat-mass balance in S-I process



Yan 2012

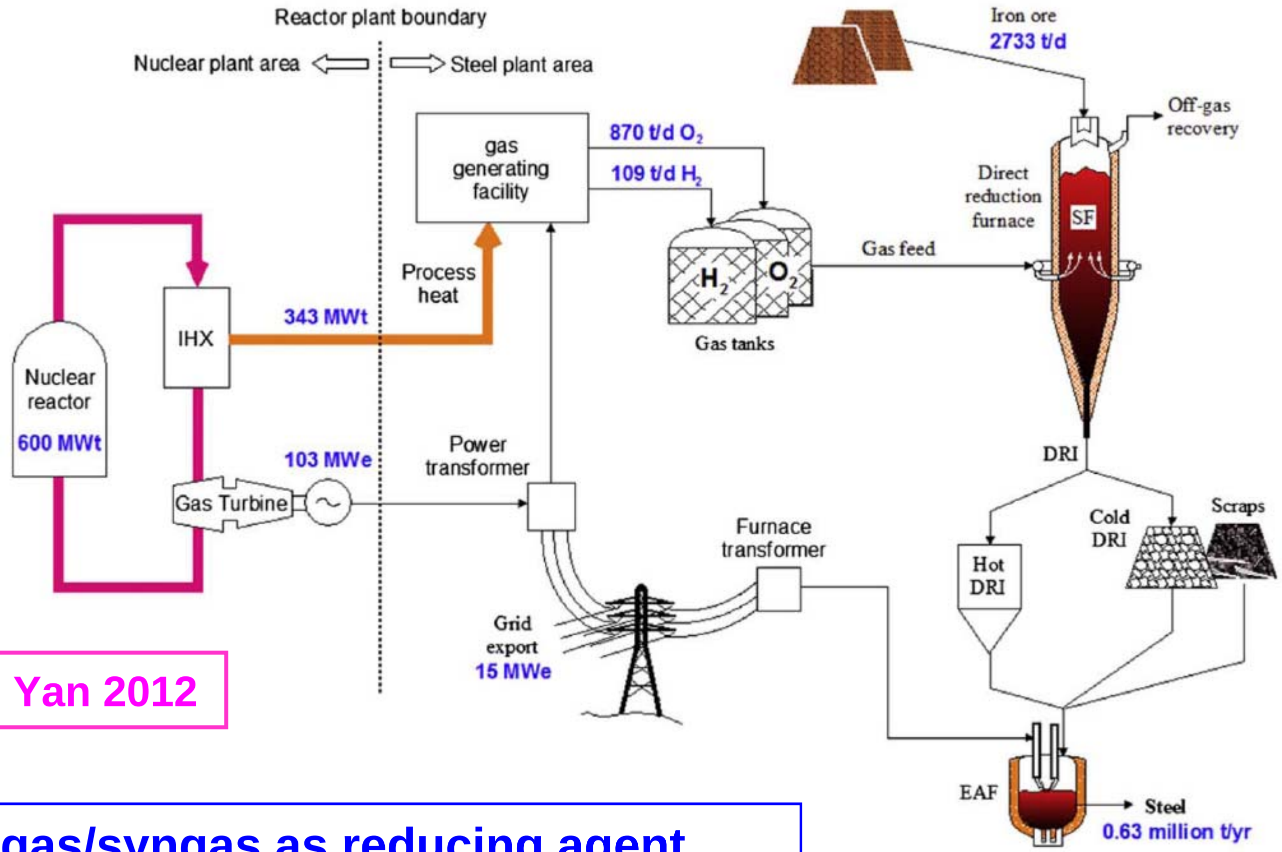
Nuclear H_2 Production with H2-MHR



US-DOE 2004

Nuclear-Assisted Steel Production

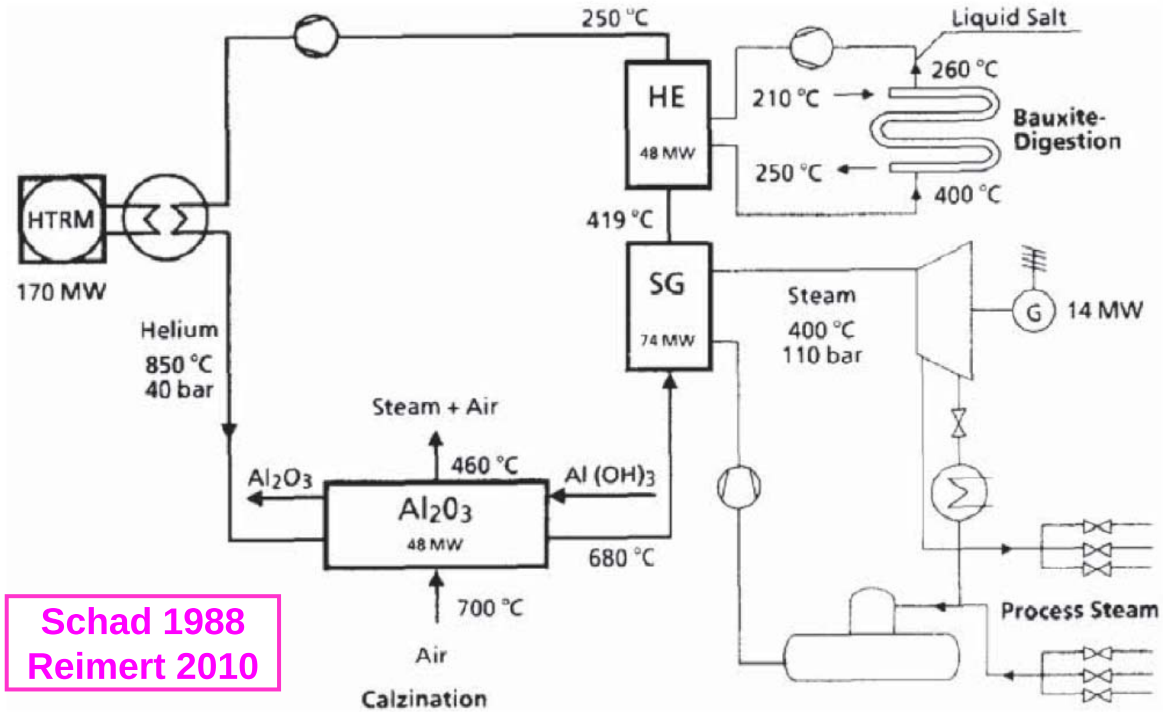
Direct reduction of iron ore



Yan 2012

H_2 to replace natural gas/syngas as reducing agent
CO_2 emission reduction are minimal (comsumption of graphite electrode)

Nuclear-Assisted Aluminum Production



Schad 1988
Reimert 2010

Process steps:

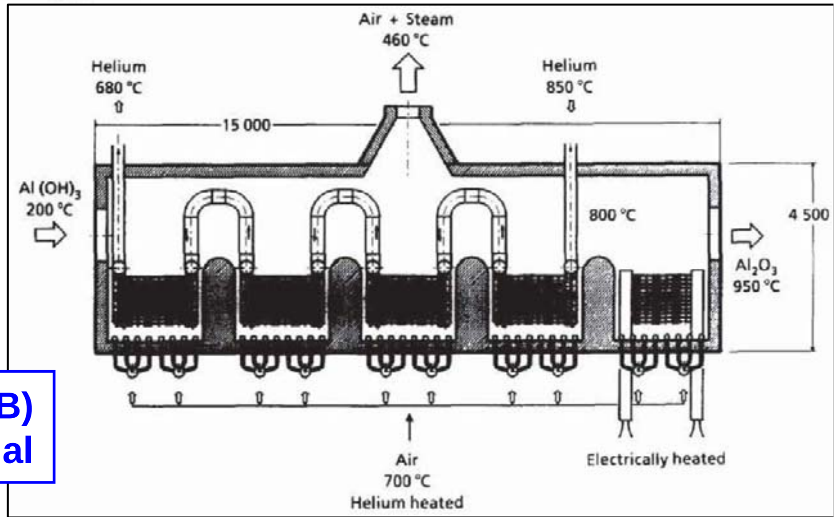
(i) Leaching Al_2O_3 from bauxite with liquid salt @ ~250°C, 10 MPa to produce $Na[Al(OH)_4]$; upon cooling, crystallization to $Al(OH)_3$

(ii) Calcination to Al_2O_3

(iii) Electrolytic reduction in a smelter to Al

Calcination @ up to 1100°C
exceeds current capability of HTGR

→ Process modification to lower temperatures



Circulating Fluidized Bed (CFB)
heat exchanger for fine-grained solid material

Summary and Conclusions

- Significant potential for nuclear energy to penetrate the huge heat market existing
- Potential for utilization of nuclear heat in 4 areas:
  - desalination
  - district heating in residential/commercial areas in cold countries
  - industrial process heat
  - fuel synthesis
- Nuclear reactors to supply energy (apart from power) in form of
  - low-temperature heat (low-quality steam) ← **demonstrated in practice**
  - high-temperature heat (high-quality steam)
- Gen-IV concepts promise ability to deliver process heat / steam for industrial applications (VHTR as dedicated system)
- HT industrial processes with integrated nuclear heat (like steel or aluminum or fuels production) might not be economic at the moment, but represent promising candidate applications