Small reactors – new chapter in nuclear energy

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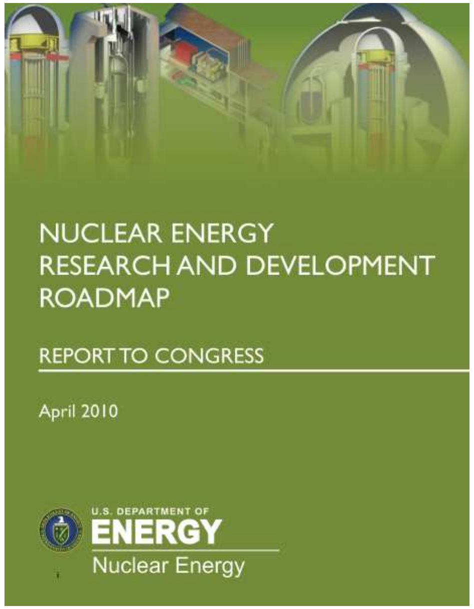
First small, then large and why again small?

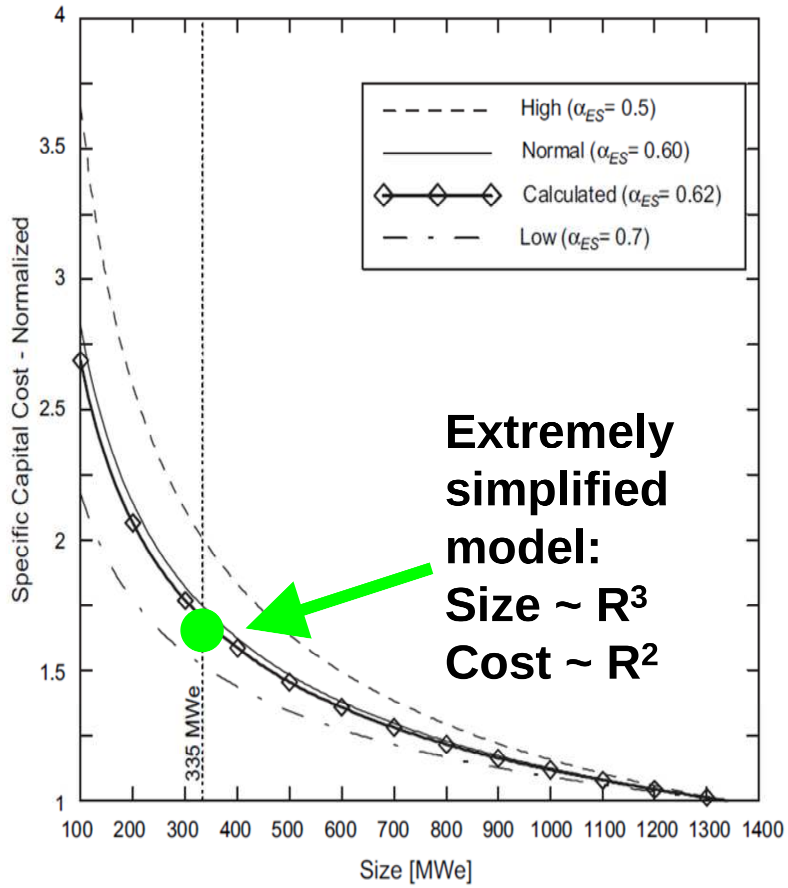
- First nuclear power reactors were small.
  - Even in the 80s of last century one of the typical reactors, WWER-440 had a thermal power below 1500 MWth (thermal megawatts).
- „Scale effect" is common for all technologies, including nuclear, coal, gas and also windmills.
  - Large power plants are more efficient economically than the small,
  - **but „scale effect" limits nuclear energy expansion now**
  - **and small reactors, SMR, can be attractive again**



„The capital cost of new large plants is high and can challenge the ability of electric utilities to deploy new nuclear power plants"

Scale effect - economics

- Strong scale effect[1]
  - Single unite 1340 MW versus 4 small unites each 335 MW
  - Cost of a cluster of 4 small reactors is about 1.7 times higher
- Extremely simplified model:
  - Size ~ R^3,
  - Cost ~ R^2
  - shows the cost of cluster is 1.6 higher
- Small reactors competitiveness could be build on:
  - Standardization, modularity, etc but
  - first of all on innovations that reduce costs
    - ☞ ***Is there a chance to improve safety and reduce safety costs ?***



1) M.D. Carelli, et al., *Economic features of integral, modular, small-to-medium size reactors*, Prog. in Nucl. Ener. 52 (2010) 403–414

Scale effect – decay heat – smaller is safer

- Safety system based on passive cooling of the reactor vessel surface is always attractive
- The same, extremely simplified model:
  - Power, $P \sim R^3$
  - Reactor vessel surface, $S \sim R^2$

$$\frac{P}{S} \propto P^{1/3}$$

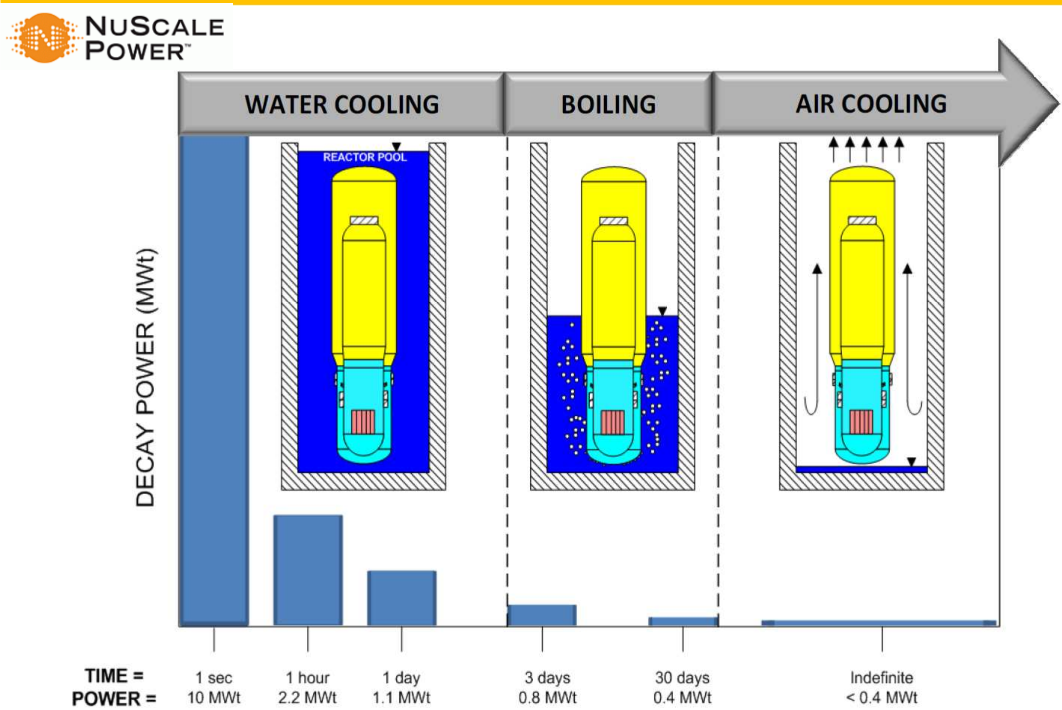
- For a reactor about four times less powerful the decay heat flux density through the surface of the reactor vessel is 1.6 times smaller
  - **Small reactor has greater potential to be safe**

Scale effect – small PWR safety

Kursk - nuclear powered submarine - exploded, sank, but two small PWR reactors safely stayed on the seabed for a year

Stable Long Term Cooling

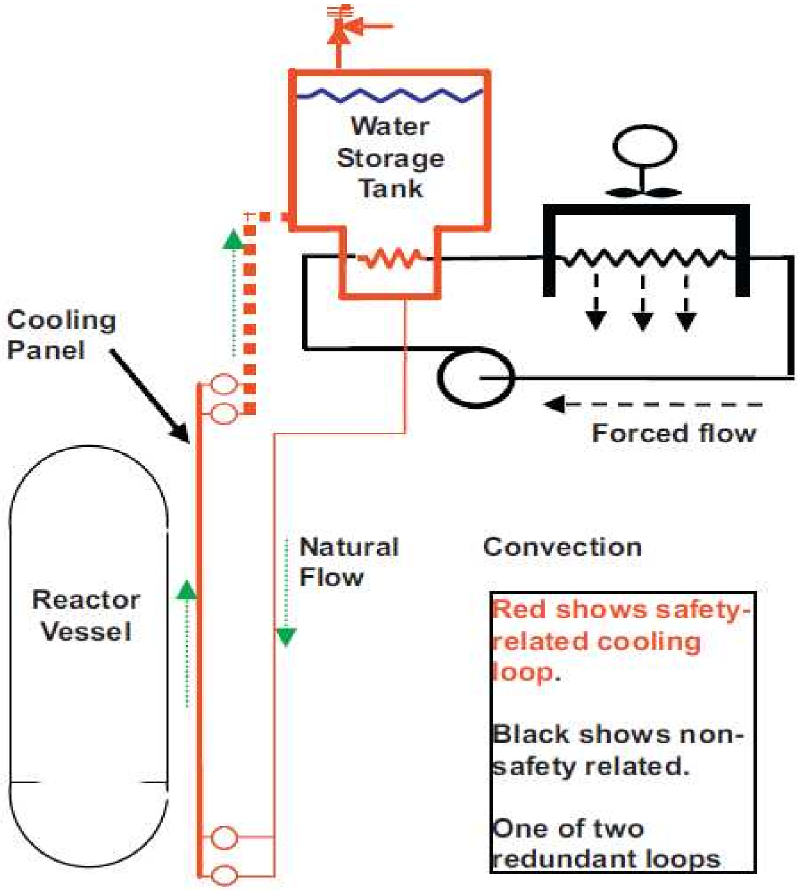
Reactor and nuclear fuel cooled indefinitely without pumps or power



Water is a natural environment for safe, water cooled reactors, assuming that they are small enough

Scale effect – HTR, decay heat

- Helium cooled, graphite moderated High Temperature Reactor (HTR, HTGR) operating at 750 deg C
  - low energy density of the reactor core
  - large heat capacity of the graphite structure
  - ceramic coated nuclear fuel, TRISO, provides the primary containment for radioactive materials up to 1600 deg C
    - ***R&D: ceramic coated fuel for LWR***
- Decay heat - reactor vessel passive cooling system



Lommers, L.J., et al., *AREVA HTR concept for near-term deployment*. Nucl. Eng. Des. (2011), doi:10.1016/j.nucengdes.2011.10.030

SMR – safety

Comparison of Current-Generation Plant Safety Systems to Potential SMR Design

Current-Generation Safety-Related Systems	SMR Safety Systems
High-pressure injection system. Low-pressure injection system.	No active safety injection system required. Core cooling is maintained using passive systems.
Emergency sump and associated net positive suction head (NPSH) requirements for safety-related pumps.	No safety-related pumps for accident mitigation; therefore, no need for sumps and protection of their suction supply.
Emergency diesel generators.	Passive design does not require emergency alternating-current (ac) power to maintain core cooling. Core heat removed by heat transfer through vessel.
Active containment heat systems. Containment spray system.	None required because of passive heat rejection out of containment. Spray systems are not required to reduce steam pressure or to remove radioiodine from containment.
Emergency Core Cooling System (ECCS) initiation, Instrumentation and control (I&C) systems. Complex systems require significant amount of online testing that contributes to plant unreliability and challenges of safety systems with inadvertent initiations.	Simpler and/or passive safety systems require less testing and are not as prone to inadvertent initiation.
Emergency feedwater system, condensate storage tanks, and associated emergency cooling water supplies.	Ability to remove core heat without an emergency feedwater system is a significant safety enhancement.

Interim report of the American nuclear society President's special committee on Small and medium sized reactor (SMR) generic licensing issues, July 2010, http://pbadupws.nrc.gov/docs/ML1100/ML110040946.pdf

What are the challenges?

- Main challenges for energy supply in the 21st Century
  - Securing long term competitive energy supply
  - Reducing greenhouse gas emissions
- Growing nuclear contribution to electricity generation is only addressing 16% of final energy needs

⇒ *Limiting only to electricity, nuclear energy contributes marginally to address these challenges*

- Could nuclear energy also contribute to non-electric energy needs, and **supply the energy-intensive industry?**
- The use of nuclear reactors for industrial applications is the main challenge, never experienced at industrial scale
  - **Only small reactors could be consider**
  - **Typically EII needs: 100MWel or less, usually gas-fired power station**

SMR for massive electricity production?

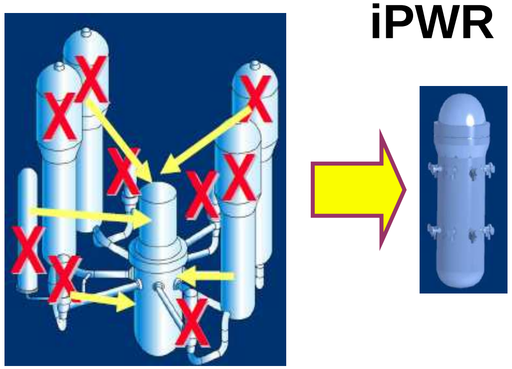
- **Simplicity – one of the main SMR advantage**
- **Power station consisted of many SMR units - inevitable complication**

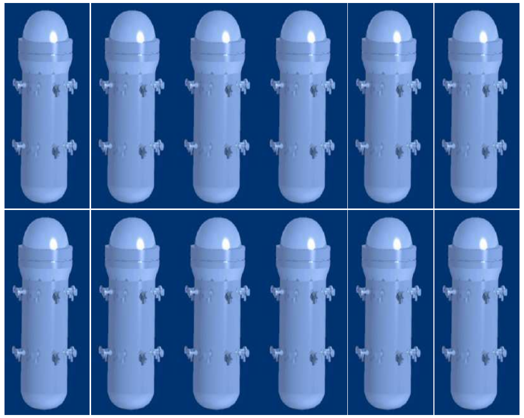
Minimum Requirements[1] Per Shift for On-Site Staffing of Nuclear Power Units by Operators and Senior Operators Licensed Under 10 CFR Part 55

Number of nuclear power units operating[2]	Position	One unit	Two units		Three units	
		One control room	One control room	Two control rooms	Two control rooms	Three control rooms
None	Senior Operator	1	1	1	1	1
	Operator	1	2	2	3	3
One	Senior Operator	2	2	2	2	2
	Operator	2	3	3	4	4
Two	Senior Operator		2	3	[3]3	3
	Operator		3	4	[3]5	5
Three	Senior Operator				3	4
	Operator				5	6

Large PWR

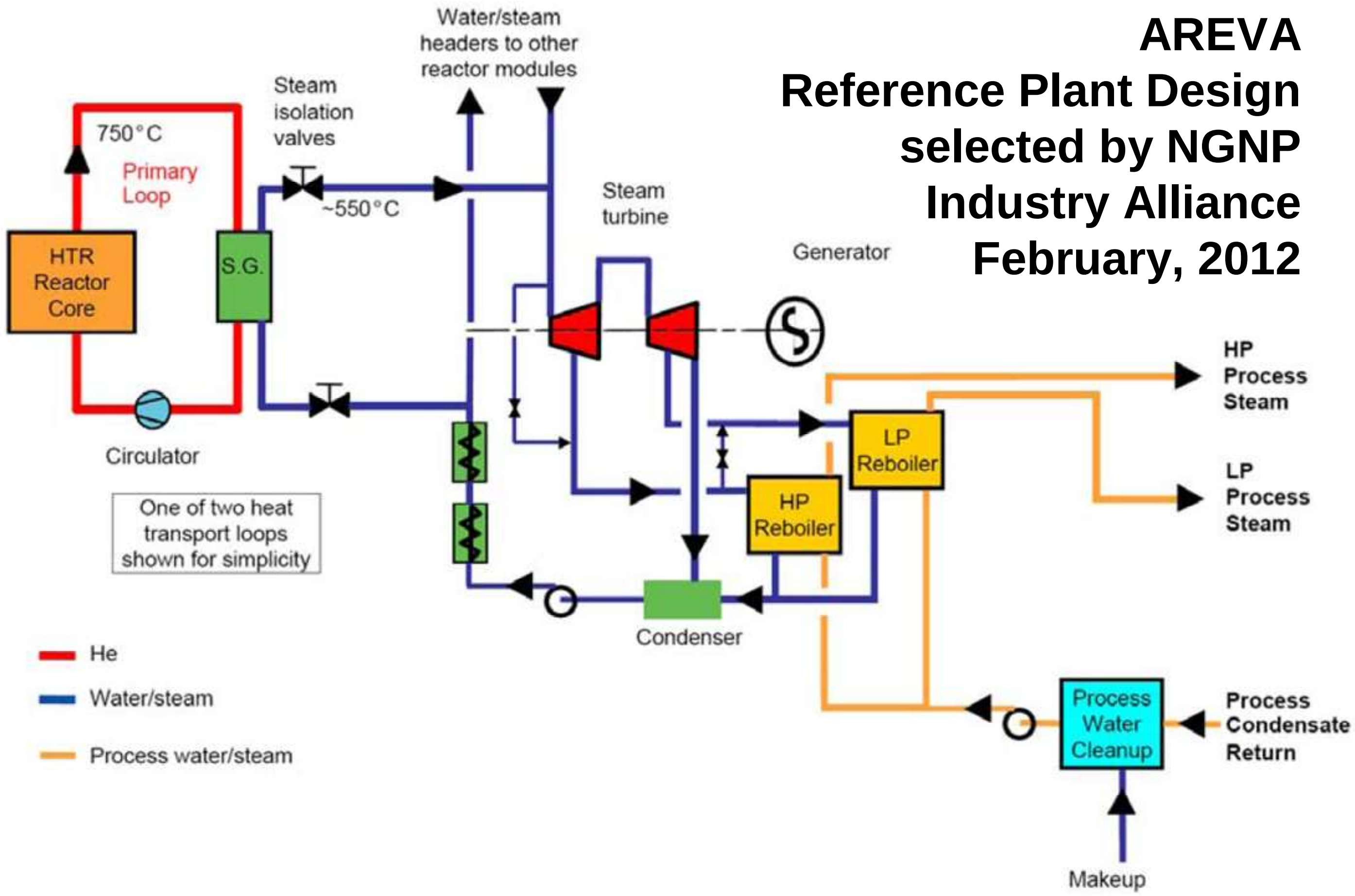
Small iPWR





Is it a simpler system?

US – HTGR (HTR) nuclear cogeneration



AREVA
Reference Plant Design selected by NGNP Industry Alliance
February, 2012

NGNP Industry Alliance

- **AREVA**
- ConocoPhillips
- **DOW – leader NGNP IA**
- Entergy
- PTAC
- SGL Group
- Technology Insights
- Toyo Tanso Co., LTD.
- Westinghouse

Safety:

- **extremely robust, ceramic coated fuel**
- **limited power level, low power density**
- **fundamental simple physics: reactor shuts down if temperature abnormally growing**

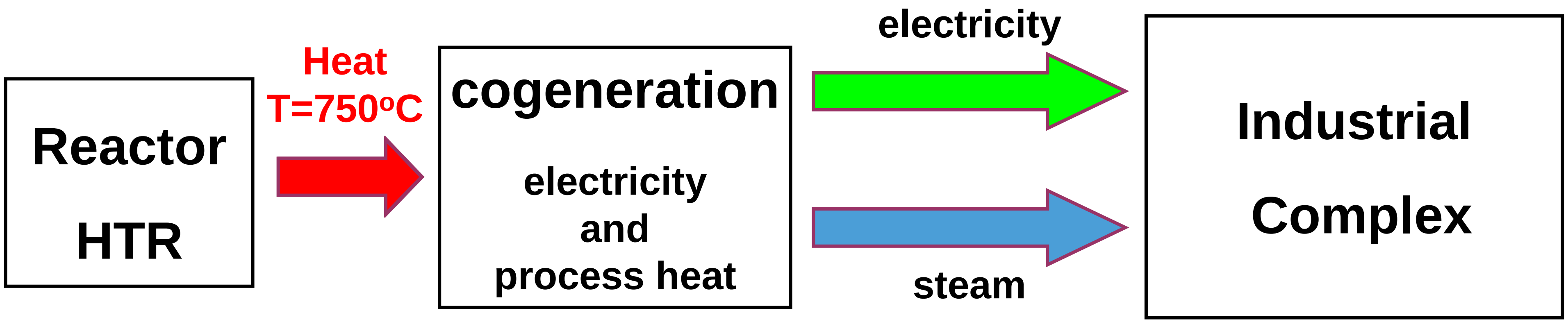
NGNP Project Technology Development Roadmaps:Technical Path Forward for 750–800℃ Reactor Outlet Temperature, INL/EXT-09-16598, August 2009, http://nextgenerationnuclearplant.com/

http://www.ngnpalliance.org/

europairs

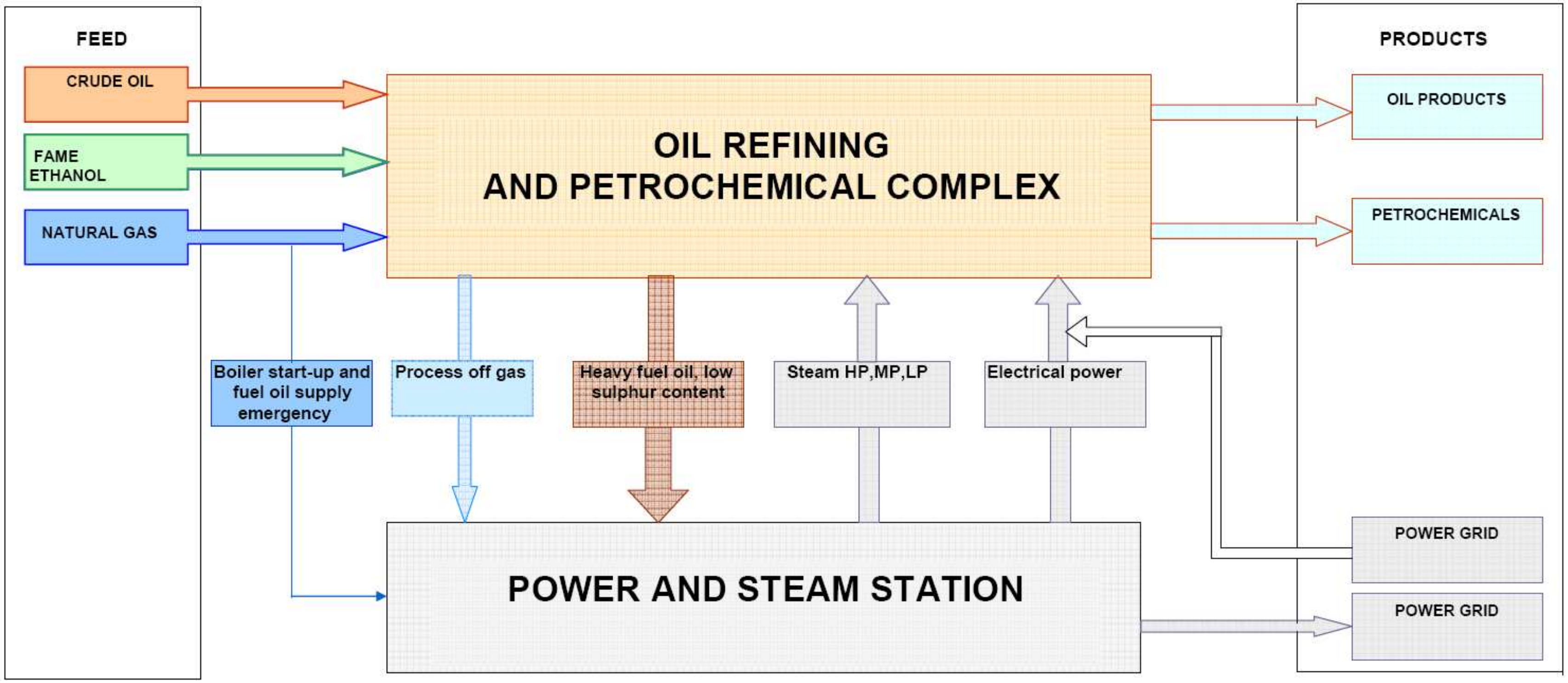
End-User Requirements fOr industrial Process heat Applications with Innovative nuclear Reactors for Sustainable energy supply

European programme 2009 - 2011



- EUROPAIRS sketched conditions for **<u>industrial emergence of nuclear cogeneration</u>**
- ARCHER – currently running EURATOM R&D programme
  - RAPHAEL and PUMA terminated EURATOM projects

Petrochemical industry now
→ nuclear cogeneration perspective



Steam description	Pressure, kPa (g)			Temperature, °C		
	Min.	Norm.	Max.	Min.	Norm.	Max.
High Pressure Steam, HP	3000	3100	4000	236	260	320
Medium Pressure Steam, MP	1300	1600	1850	196	220	280
Low Pressure Steam, LP	400	580	850	152	170	230

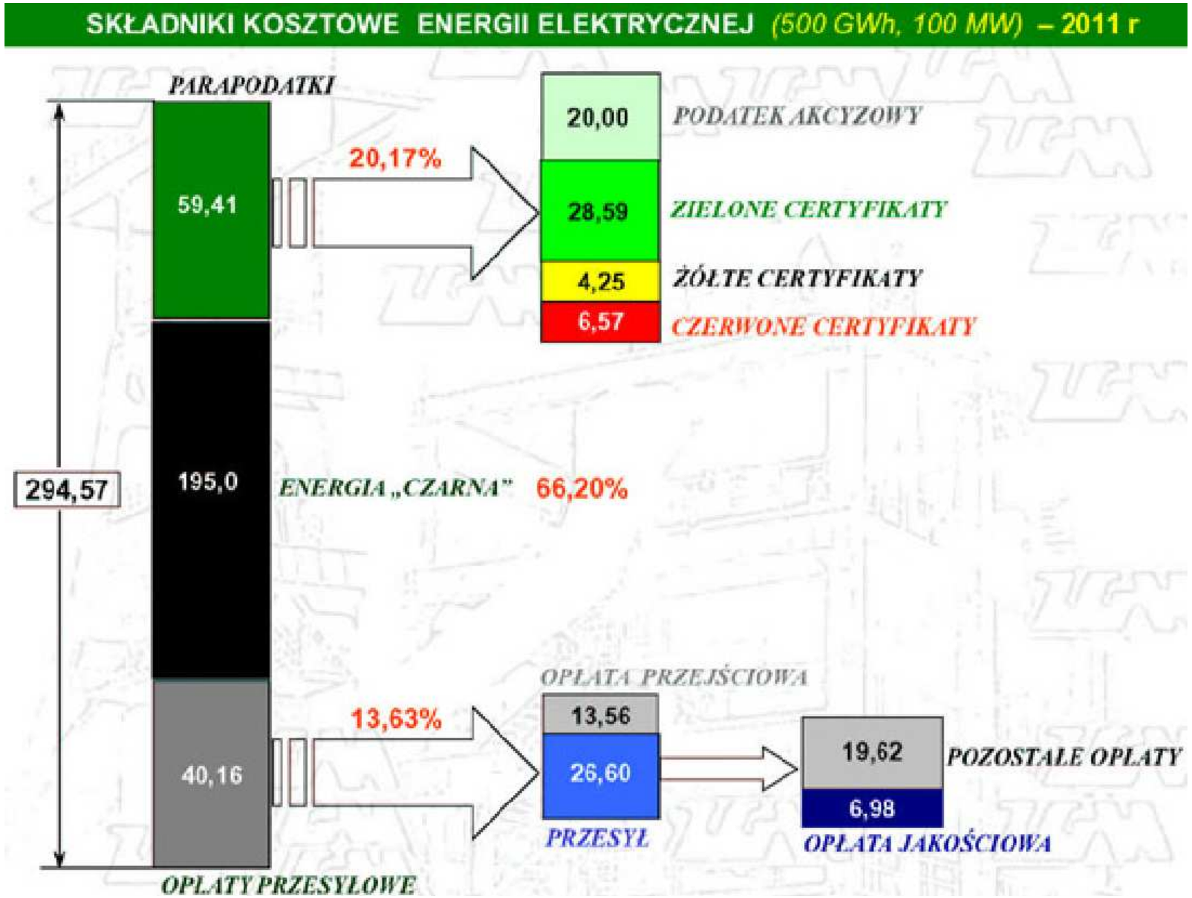
Stem critical point:
T=374 deg C
P=22 MPa

- electricity and steam production consume ~10% of oil
- HTR, **nuclear cogeneration** to improve productivity

Energy Intensive Industry (EII) – electricity

- EII electricity needs can be roughly characterized by:
  - 100 MW or higher power
  - 500 GWh/year or more
- Cost of electricity, case of Poland, 2011
  - **300 PLN/MWh** – total cost
    - ***200*** *– electricity*
    - ***60*** *– para-taxes*
    - ***40*** *– transmission*
- EII often use their own power plants, usually gas-fired

1 EUR ≈ 4.3 PLN



H. Kaliś, „Odbiorca przemysłowy na nowym rynku energii",
Forum Odbiorców Energii Elektrycznej i Gazu
http://www.prezentacje.cire.pl/st,42,285,item,57205,1,0,0,0,0,0,prezentacja-odbiorca-przemyslowy-na-nowym-rynku-energii.html

HTRPL synergistic approach towards industry
a new, strategic programme in Poland

The National Centre for Research and Development (NCBiR)

AGH

- Project: „***Development of high temperature reactors for industrial applications***” was accepted by NCBiR on May 14, 2012
  - AGH University of Science and Technology – HTRPL consortium leader
    - *NCBJ, INS, GIG, IChPW, PŚ, UW, PSSE – universities and research institutions (including nuclear, fertilizes and coal processing R&D)*
    - *PROCHEM S.A. – engineering company*
    - *KGHM S.A. – energy intensive industry*
    - *TAURON PE S.A. – power plant operator (utility)*
  - 30 months, 5 millions PLN (about 1.15 millions EUR)
  - Goals:
    - *Pre-feasibility study of the HTR industrial demonstration*
    - *International cooperation: Nuclear Cogeneration Industrial Initiative in Europe (SNETP, EURATOM), bilateral agreements*
    - *Nuclear reactors for industry, process heat applications*
    - *Coupling of the nuclear and classical systems*

Conclusion

- Large water cooled reactors are great reactors
  - They are just too expensive for many potential investors
  - *Please don't wait for SMR if you are able to arrange project*
- Small reactor challenges
  - Start industrial scale projects
    - *R&D limited to minimum*
  - License
    - *iPWR and HTR are in preferable position today*
  - Energy intensive industry, nuclear cogeneration is potentially the great market for small reactors today
    - ***New market, new chapter in nuclear energy***