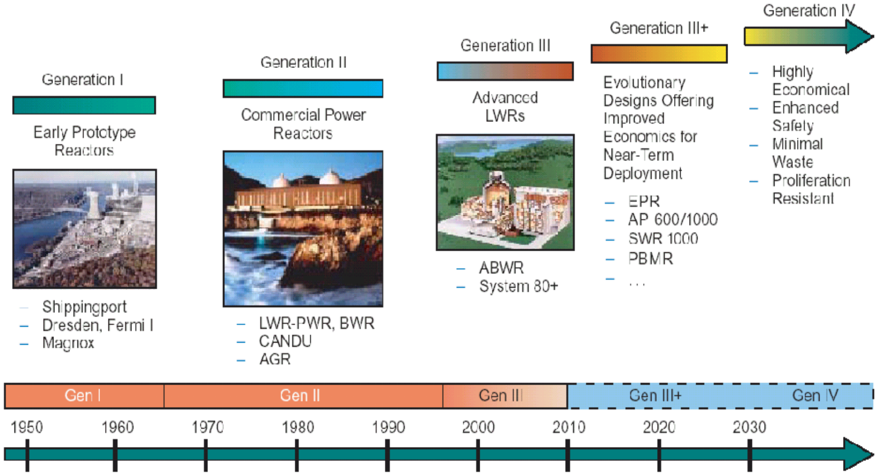
Safety of Nuclear Power Plants

EPR, GIF, HTR

Generation I to Generation IV



Generation I

Early Prototype Reactors

- Shippingport
- Dresden, Fermi I
- Magnox

Generation II

Commercial Power Reactors

- LWR-PWR, BWR
- CANDU
- AGR

Generation III

Advanced LWRs

- ABWR
- System 80+

Generation III+

Evolutionary Designs Offering Improved Economics for Near-Term Deployment

- EPR
- AP 600/1000
- SWR 1000
- PBMR
- . . .

Generation IV

- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant

A Technology Roadmap for Generation IV Nuclear Energy Systems

EPR Overall Safety Philosophy

- These objectives, motivated by the continuous search for a higher safety level, involve reinforced application of the defense in depth concept:
  - by improving the preventive measures in order to further reduce the probability of core melt, and
  - by simultaneously incorporating, right from the design stage, measures for limiting the consequences of a severe accident.

EPR Plant Parameter

Thermal power	4250/4500 MW
Electrical power	1600 MW
Efficiency	36%
No. of primary loops	4
No of fuel assemblies	241
Burnup	> 60 GWd/t
Secondary pressure	78 bar
Seismic level	0.25 g
Service live	60 years

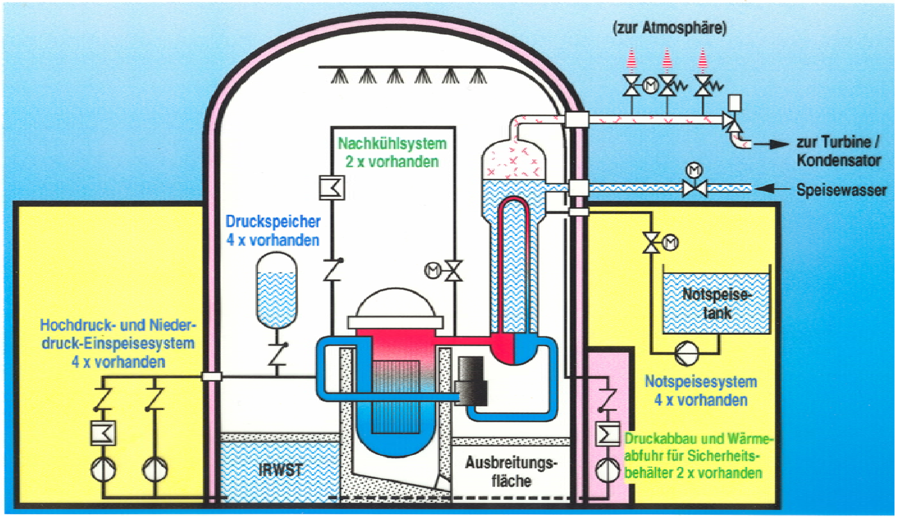
Risk Reduction – EPR Approach

Reinforced protection in the unlikely event of core meltdown

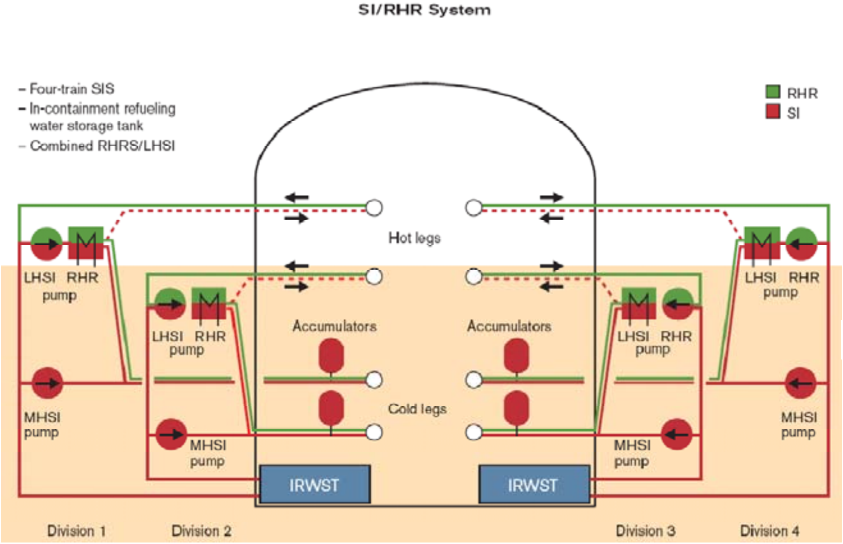
- Preventive features include safety devices which further reduce the probability of a severe accident
  - enlarged water inventory of the main primary system and of the steam generators; increased reliability of safety systems through
  - 4-fold 100% redundancy (4-train concept);
  - use of diversified technologies for each train of these systems.
- Features to mitigate the consequences of such an event:
  - the extremely robust, leaktight containment around the reactor is designed to prevent radioactivity from spreading outside;
  - the arrangement of the blockhouses inside the containment and hydrogen catalytic recombiners (passive devices) prevent the accumulation of hydrogen and the risk of deflagration;
  - molten core escaping from the reactor vessel would be passively collected and retained, then cooled in a specific area inside the reactor containment building (“core catcher”)

Enhanced protection against external hazards

EPR – Safety Systems



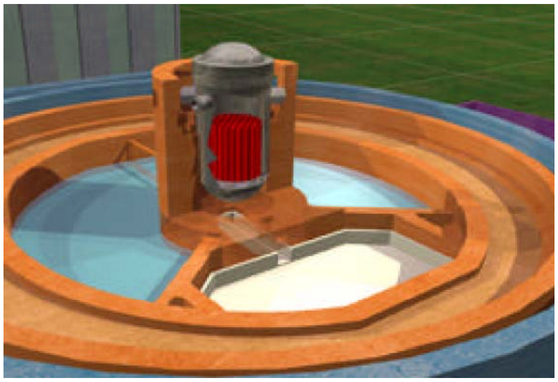
EPR Safety Injection / Residual Heat Removal (SIS/RHRS)



Risk Reduction - EPR Containment

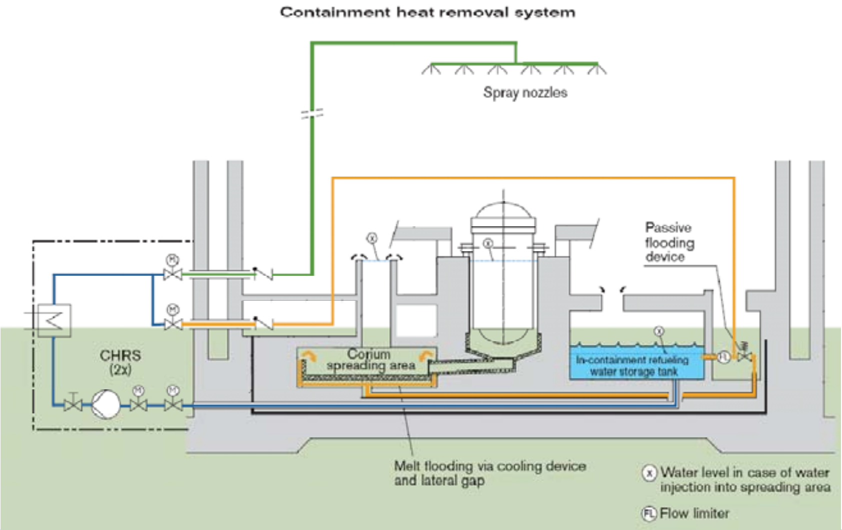
The unique building housing the reactor is extremely robust. It rests on a 6 m thick concrete base mat and is enclosed by a double shell: the inner is made of leaktight, prestressed concrete and the outer one of reinforced concrete, each 1.30 m thick. This total to 2.60 m concrete thickness, capable of withstanding external hazards such as an aircraft crash.

EPR Core Catcher



Even in the event of the core melting, and piercing then escaping from the steel reactor vessel in which it is housed, it would be contained in a dedicated spreading compartment. This compartment is then cooled to remove the residual heat.

EPR Containment Heat Removal System



Generation IV International Forum (GIF)

- To meet future energy needs, ten countries have agreed on a framework for international cooperation in research for an advanced generation of nuclear energy systems, known as Generation IV.
- Euratome joined as 11th full member; Switzerland joined in February of 2002

Generation IV – Overall Goals

- **Development of one or more nuclear energy systems**
- Deployable by 2030
- With significant advances in:
  - Sustainability
  - Safety and reliability
  - Proliferation and physical protection
  - Economics
- Competitive in various markets
- Designed for different applications:
  Electricity, Hydrogen, Clean water, Heat

Generation IV Initiative – Aims (1/2)

Nuclear energy-systems including fuel cycles of the 4th generation should ...

SR-1 ... be excellent regarding safety and reliability while in operation.

SR-2 ... have very low core damage frequency and little consequences.

SR-3 ... eliminate the need for emergency planning outside of the plant.

EC-1 ... clear lifecycle-cost advantages over other energy sources.

EC-2 ... comparable financial risk to other energy projects.

Generation IV Initiative – Aims (2/2)

Nuclear energy-systems including fuel cycles of the 4th generation should ...

SU-I ... produce sustainable energy, following regulations for air pollution prevention and enhancing the long term availability of the system and efficient usage of fuel.

SU-2 ... minimise the nuclear waste and disposing it, especially they will reduce administration efforts on a long term scale and hence improve the protection of health and environment.

SU-3 ... increase the certainty that they are an undesirable and difficult source to obtain dangerous materials for usage in weapons.

Selected Generation IV Concepts (out of 21)

GEN IV Concepts	**Acronym Pressure**	**Spectrum**	**Fuel cycle**	**Temperature**	
				[° C]	[bar]
Sodium Cooled Fast	SFR	Fast	Closed	530-550	1
Lead Alloy-Cooled	LFR	Fast	Closed	550-800	1
Gas-Cooled Fast	GFR	Fast	Closed	490-850	90
Very High Temperature	VHTR	Thermal	Once-Through	640-1000	70
Supercritical Water Cooled	SCWR	Th.&Fast	Once/Closed	280-510	250
Molten Salt	MSR	Thermal	Closed	565-850	< 5

The Roadmap Addresses Viability and Performance R&D Phases

- Viability
  - Key feasibility and proof-of-principle decisions
- Performance
  - Engineering-scale demonstration and optimization to desired levels of performance

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- Demonstration
  - Mid- to large-scale system demonstration
- [Commercialization]

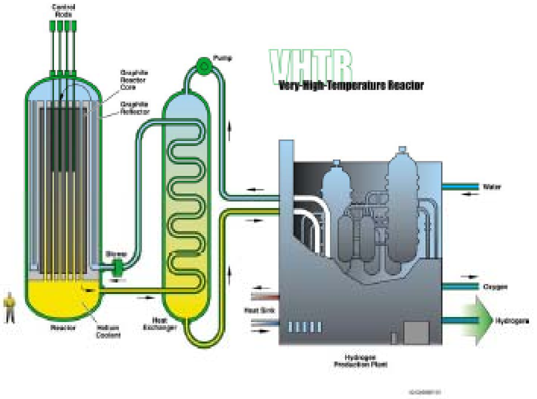
VHTR - Technology gaps

Process-specific R&D gaps exist to adapt the chemical process and the nuclear heat source Qualification of high-temperature alloys and coatings.

Producing hydrogen using the I-S process

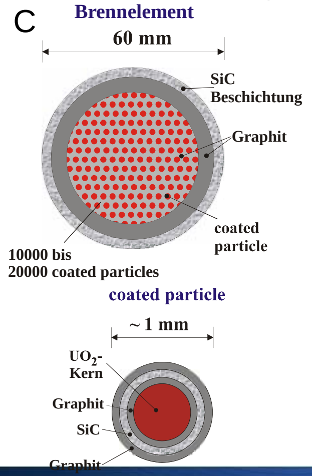
Performance issues include development of a high-performance helium turbine.

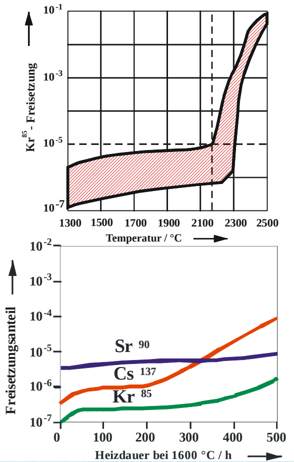
Modularization of the reactor and heat utilization systems is another challenge for commercial deployment of the VHTR.



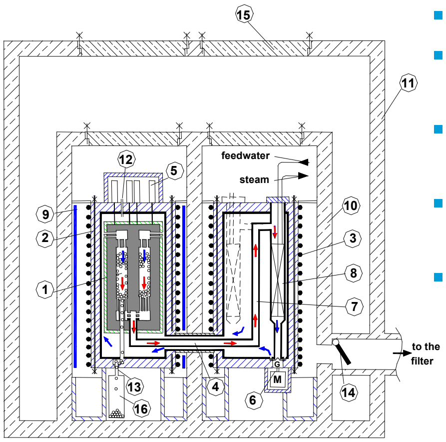
Concept of a modular HTR (1/3)

Fuel element and restraining the fission products up to 1600° C





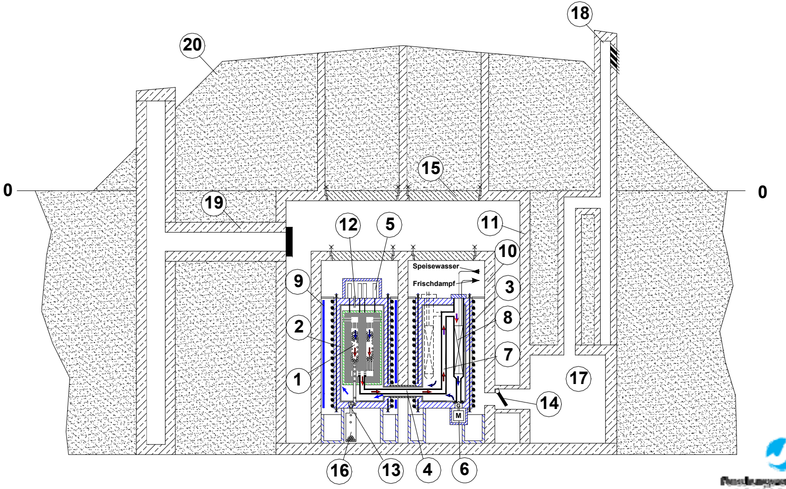
Concept of a modular HTR (2/3)



- Thermal power 300MW
- Circular core
- Pre stressed primary loop as an burst prove inclusion
- Interior concrete cell with a limitation on air amount
- Underground arrangement of the reactor building
- Use of the primary loop to steam production, gas turbines and process heat applications (with in-between heat exchanger)

Concept of a modular HTR (3/3)

Underground arrangement of the reactor



Accident behaviour of a modular HTR (1/10)
Accident assumptions

internal Causes

- Full loss of coolant
- Full loss of the active residual heat removal
- Massive water ingress into the primary system
- Massive air ingress into the primary system
- Extreme reactivity disturbances
- Massive damage of reactor components

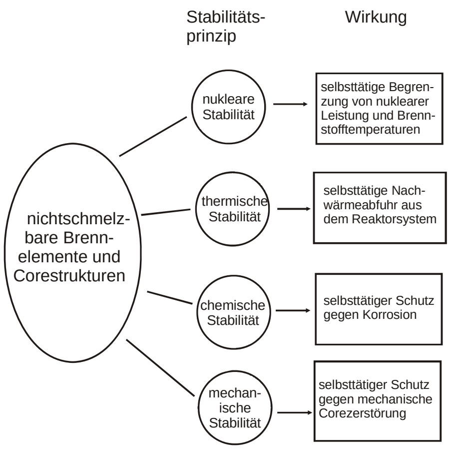
external Causes

- Crash of a plane (phantom)
- Gas cloud explosion
- Earthquake (b < 0,3 g)
- Fire
- Tornados, hurricanes and floods

external causes (beyond licensing)

- Terrorist attacks with planes (Booing 747)
- Sabotage
- Impacts of war (missiles)
- Extreme earthquakes (b > 0,3 g)
- Meteorites

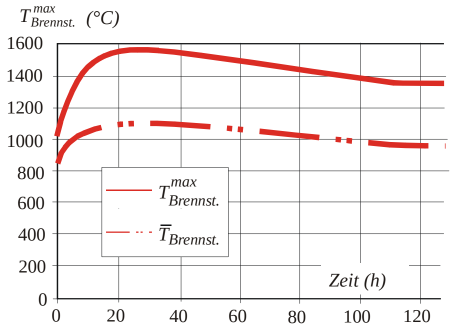
Accident behaviour of a modular HTR (2/10)



Requirements for a non melting inherent safe modular HTR

- Fulfilment of the principles for all accidents due to internal and foreseeable external cause (requirements from licensing)
- Fulfilment of the principles for all accidents including unforeseeable occurrences such as terrorist attacks or extreme earthquakes

Accident behaviour of a modular HTR (3/10)



Automatic removal of the residual heat in the case of failing of all active heat removal (for example: PBMR, additionally the total failure of the first shut down system was assumed)

- Fuel elements can never melt
- Maximum fuel temperature remains below 1600° C
- Most fuel elements stay far below this temperature
- Total fission product release stays below 10^{-5} of the inventory

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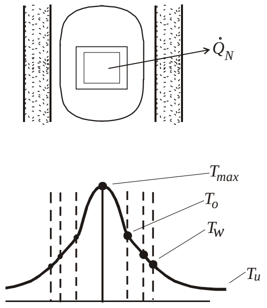
Accident behaviour of a modular HTR (4/10)

Biological analogue for the automatic residual heat removal and limitation of accident temperature



$T_{max} < 1600$ °C

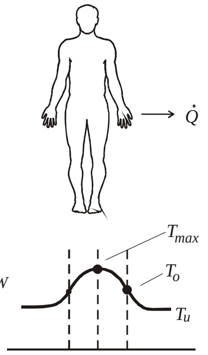
$T_W < 400$ °C

$\dot{Q}_N \approx \alpha_a \cdot A\,(T_w - T_u)$

$T_{max} - T_o \approx \frac{\dot{Q}_N/H}{4\pi\lambda_c}$

$\dot{Q}_N \approx 600\ kW$

(entspricht der Nachwärme eines Cores mit $P_{th} = 300\ MW$ nach etwa $30\,h$)



$T_{max} < 38$ °C

$T_o < 37$ °C

$\dot{Q} \approx \alpha_a \cdot A\,(T_o - T_u)$

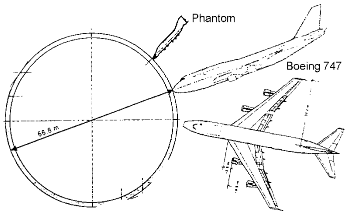
$T_{max} - T_o \approx \frac{\dot{Q}/H}{4\pi\lambda_i}$

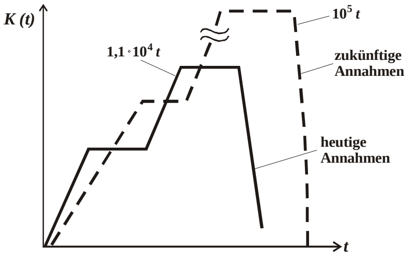
$\dot{Q} \approx 60\ W$

(entspricht der Wärmeabgabe eines Menschen unter "normalen" Bedingungen)

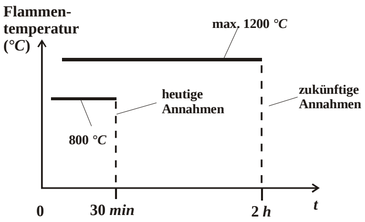
Accident behaviour of a modular HTR (5/10)

New safety requirements for nuclear technology





Schutz der Gebäude gegen Penetration und Zerstörung



Schutz gegen langandauernde Flammeneinwirkungen mit hohen Temperaturen bei Kerosinbrand

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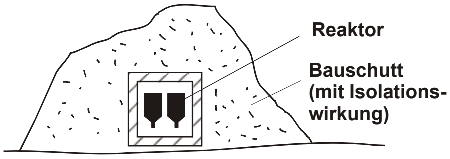
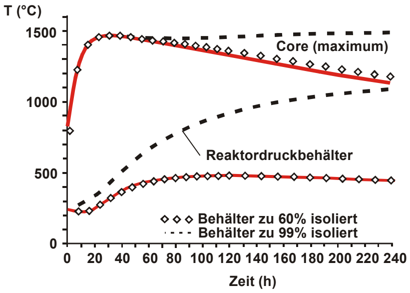
Accident behaviour of a modular HTR (6/10)

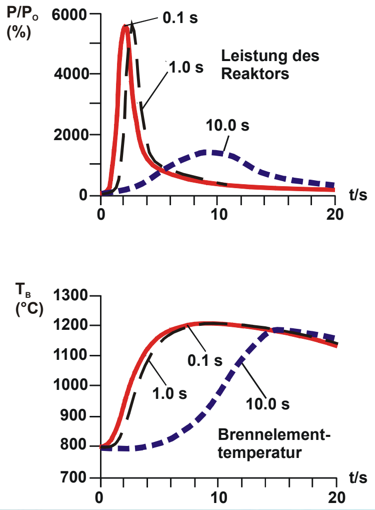




Automatic removal of the residual heat after the destruction of the reactor building (for example caused by an extreme earthquake or a plane crash caused by terrorists)

- Reactor totally covered with rumble
- Residual heat is still removed automatically, but slowed down
- Maximum fuel temperature stays below 1600° C
- Total fission product release stays below 10^{-5} of the inventory

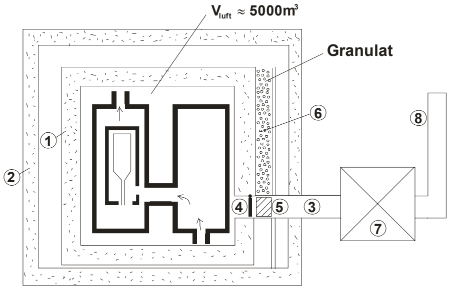
Accident behaviour of a modular HTR (7/10)



Automatic limitation of nuclear power and fuel temperature when faced with extreme reactivity transient (total loss of the first shut down system: ρ = 1,2 % in a short period of time)

- Strongly negative temperature coefficient ends the excursion
- Transient heat is quickly and for the most part stored in the fuel element graphite
- Maximum fuel temperature stays below 1600° C

Accident behaviour of a modular HTR (8/10)



1) Internal concrete cell (sealed against outside air)
2) Reactor building
3) Draining channel
4) Sealing flaps (gravity)
5) Sealing plug
6) Granulate silo
7) Filter
8) Flue

Concepts for minimising the consequences of an air ingress accident:

- Draining the primary Helium through pipes over a filter
- Automatic limitation on the amount of air within the concrete cell (V < 5000 m^3) by automatic closing mechanisms (flaps and pouring granulate)
- Limitation of possible graphite corrosion to < 500 kg C and therefore no radiological consequences
- Limitation of possible graphite corrosion to < 100 kg by simple intervention methods (protection of investment)

Accident behaviour of a modular HTR (9/10)

Begrenzung der Menge an Luft

↓

- Volumen der inneren Betonzelle ist begrenzt (<5000m³)
- nach erfolgter Druckentlastung schließt eine Klappe oder ein Granulatvorrat den Kanal ab
- innere Betonzelle wird mit Inertgas gefüllt

Begrenzung der Mengenrate an Luft

↓

- Vorgespannter Reaktordruckbehälter mit kleinen Öffnungen
- Berst-Schutz für die Behälter
- Intervention in innerer Betonzelle

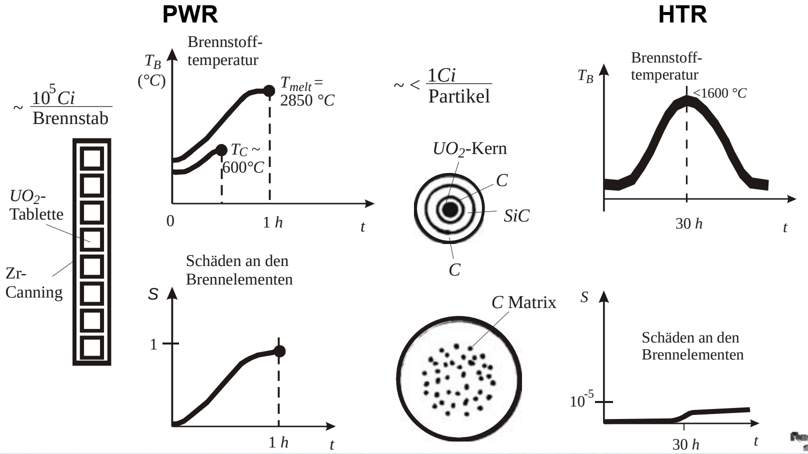
Verhinderung der Korrosion von Brennelementen

↓

- Korrosionsbeständige SiC-beschichtete Brennelemente
- innere Betonzelle ist mit Inergas gefüllt

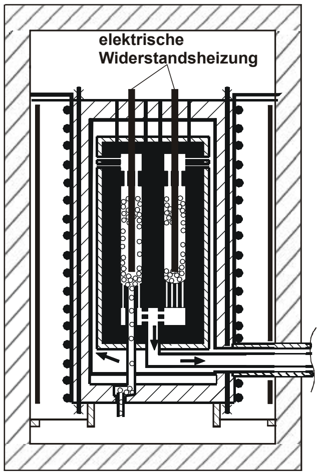
Accident behaviour of a modular HTR (10/10)

Comparison of the fuel behaviour after loss of the active residual heat removal.



Total Assessment of Safety (1/2)

Integral proof of safety behaviour



- Simulation of the residual heat in a graphite-sphere-pile by electrical resistance heating. (~ 2 MW for a 300 MW_{th} - Core)
- Analysis of all assumable accidents (total loss of coolant, air ingress, water ingress, pressure discharge, mechanical impacts on the elements of the shut down system, component damage when pressure relief)
- Validation of all calculating programs for extreme accidents (heat transfer throughout all structures, flow phenomena, acts of pressure discharge).

Total Assessment of Safety (2/2)

- Fuel elements can never melt; there is no heating up of the fuel elements to a temperature above 1600° C
- The principal of automatic residual heat removal can never fail, even after the destruction of the reactor building it stays intact.
- The reactor would even stay resistant against extreme reactivity transient. There is no temperature raise of the fuel elements to above 1600° C
- The pre-stressed reactor containment can not burst; It is impossible that an unacceptable amount of air enters the primary loop, graphite corrosion is minimal.
- The ingress of larger amounts of water into the primary loop will not lead to unacceptable states of the reactor; in the case of gas turbines operating this accident is not applicable.
- Against extreme, in future even more severe external impacts, the underground way of building with covering mound, and fast removal of spherical fuel elements as protection
- There is no accident in which case a significant amount of radiation is released