Aspects of nuclear process heat application of very high temperature reactors (VHTR)

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Abstract – The different processes of high temperature process application require new concepts for heat exchangers to carry out key process like steam reforming of light hydrocarbons, gasification of coal or biomass, or thermo-chemical cycles for hydrogen production. These components have been tested in the German projects for high temperature development. The intention was always to test at original conditions of temperatures, pressures and gas atmospheres. Furthermore the time of testing should be long as possible, to be able to carry out extrapolations to the real lifetime of components. Partly test times of around 20 000 hours have been reached. Key components, which are discussed in this paper, are:

Intermediate heat exchangers to separate the primary reactor side and the secondary process side. Here two components with a power of 10 MW have been tested with the result, that all requirements of a nuclear component with larger power (125 MW) can be fulfilled. The max. primary helium temperature was 950°C, the maximal secondary temperature was 900°C. These were components with helical wounded tubes and U-tubes. In the test facility KVK, which had been built to carry out many special tests on components for helium cycles, furthermore hot gas ducts (with large dimensions), hot gas valves (with large dimensions), steam generators (10 MW), helium circulators, the helium gas purification and special measurements installations for helium cycle have been tested. All these tests delivered a broad know how for the further development of technologies using helium as working fluid. The total test time of KVK was longer than 20 000 h.

In a large test facility for steam reforming (EVA II 10 MW, $T_{He}=950^\circ$C, $p_{He}=40$ bar, $T_{Reform}=800^\circ$C) all technical details of the conversion process have been investigated and today the technical feasibility of this process is valuated as given. Two reformer bundles, one with baffles and one with separate guiding tubes for each reformer tube have been tested successfully. The test time in totally was longer than 10 000 h.

A hot steam generator with a power of 10 MW ($T_{He}=950^\circ$C, $p_{He}=40$ bar) for application in different processes has been tested over a long time with good success too. For the steam gasification of coal or other C-containing substances a special gasifier has undergone long time testing with great success. This component ($T_{He}=950^\circ$C, $p=40$ bar) for application in different processes has been tested over a time of more than 10 000 h. This component ($P \approx 3$ MW, $T_{He}=1000^\circ$C, $p_{He}=40$ bar, $T_{gasif}=800^\circ$C) represented a characteristic part of a large fluidized bed gasifier.

The development work additionally contained a broad material program for alloys applied at helium temperatures of around 950°C. All mechanical relevant data till 30 000 hours, data of corrosion, Tritium- and hydrogen permeation have been measured for some promising candidates.

Special experiments related to reaction kinetics, heat transfer, pressure drops, vibration, friction and wear, behavior on special components in helium have been carried out and delivered a broad know how on helium technologies. During the planning work for different reactor concepts all questions of coupling nuclear reactors and processes have been analyzed in detail and partly have undergone steps of a nuclear licensing process. It was shown, that extreme safety requirements of the nuclear heat source and the total plant could be fulfilled.
I. REQUIREMENTS OF THE FUTURE WORLDWIDE ENERGY ECONOMY

Future worldwide energy strategies estimate, that the primary energy supply has to be raised up to more than \(20 \times 10^9\) t of hard coal units (HCU) in 2020 for around \(8 \times 10^9\) people. This would just correspond to the today reached average value of \(2.5 \times 10^9\) t HCU/(person\cdot year) and no progress in standards of life in many country's would be realized [1 till 3]. All primary energy carriers have to be used, especially those, which don't cause CO\(_2\)-emission. Nuclear energy and the renewable energy carriers in different forms fulfill this fundamental requirement of future climate protection.

Some problems of future energy economy, which have to be solved, are as follows:

- CO\(_2\)-emissions must be reduced; the separation of CO\(_2\) from the plants technically can be carried out by washing the flue gases, by burning the coal with nearly pure oxygen or by coal gasification with subsequent burning a clean gas (H\(_2\)) in a combined cycle. These processes reduce the efficiency and cause higher production costs.
- The transport of CO\(_2\) is estimated as unacceptable by many people and the final storage is valuated as an unsolved problem today.
- to solve the problems of strong changing conditions of production of electricity by wind and photo-voltaic already now is very difficult, because not enough storage systems for electricity (as example pumping storage) are available.
- the use of coal and biomass as C-carriers requires processes with high as possible usage factor. This favours the application of nuclear energy. Using CO\(_2\) as feed stock for methanol production a double use of C becomes possible.
- modular HTR-plants like the pebble bed reactor with high efficiency allow a good regulation of power and the energy can be distributed flexible for the production of electricity and for heating chemical processes as example.
- If nuclear energy shall play a role in the future world energy economy, extremely high safety standards for reactors and all steps of the nuclear fuel cycle have to be realized. This will be possible realizing a suited layout and design of nuclear power plants.

Especially the production of electricity by wind energy and by photovoltaic causes problems with the electrical grid, because of the strong changing conditions of production. New solutions for storage of electric energy have to be established. Beside the very well known and worldwide introduced storage via pumping storage systems of water, the storage of methanol, methane or hydrogen can be considered. Corresponding to fig. 1 these technologies could be introduced to realize a storage for relatively short time to flatten the load curve of the electrical grid.

Additionally to this possibilities of storage as example a liquid fuel for the chemical industry or for refineries can be produced. The ratio of electrical energy delivered from a storage related to the input to the storage can be defined as recovery factor.

Principally the recovery factor for electrical energy is relatively small in case of production, by renewable concept without the case of hydro pumping systems. Therefore new storage concepts are necessary if in future large capacities of renewable energies shall be realized.

![Fig. 1: Possibilities of storage of electrical energy by different energy carriers](image)

II. APPLICATION OF NUCLEAR PROCESS HEAT

If the requirements explained before shall be fulfilled nuclear energy must be available for the market of heat supply and transportation too. The secondary energy carriers for these applications are district heat, process steam, gases and liquid fuels.

Applying cogeneration processes the production of electricity and heat on a level till around 350°C is possible. This allows the supply of district heat systems, seawater desalination, delivery of steam for industrial purposes (chemicals, refineries, paper, food, pulp and further products). The production of oil by
steam flooding (enhanced oil recovery) is a further important future application of process steam, which favours the use of nuclear energy. In all cases the emission of CO₂ is avoided.

The production of gases and liquids requires partly new technologies, if nuclear energy shall be introduced into this part of the energy market [4 till 7]. Temperatures till 1000 °C will be necessary to cover this part of the energy economy.

Some high temperature processes, which will be relevant for these new energy systems, are included in Table 1.

Table 1: Overview on process heat applications of nuclear energy

<table>
<thead>
<tr>
<th>process steam generation</th>
<th>hot steam production (evaporation + super-heating)</th>
<th>500°C</th>
<th>700°C</th>
<th>different applications; IHX because of Tritium permeation</th>
</tr>
</thead>
<tbody>
<tr>
<td>process heat for seawater desalination</td>
<td>-</td>
<td>150°C</td>
<td>700°C</td>
<td>combination of osmosis and evaporation</td>
</tr>
<tr>
<td>steam for EOR-processes</td>
<td>-</td>
<td>350°C</td>
<td>700°C</td>
<td>combination with refinery and hydro cracking</td>
</tr>
<tr>
<td>steam reforming</td>
<td>( \text{CH}_2+\text{H}_2\text{O} \rightarrow \text{CO}+3\text{H}_2 )</td>
<td>700...800°C</td>
<td>850...950°C</td>
<td>suited for many other applications (*)</td>
</tr>
<tr>
<td>coal gasification</td>
<td>( \text{C}+\text{H}_2\text{O} \rightarrow \text{CO}+\text{H}_2 )</td>
<td>750...850°C</td>
<td>900...950°C</td>
<td>lignite, hard coal</td>
</tr>
<tr>
<td>biomass gasification</td>
<td>( \text{C}_n\text{H}_m\text{O}_x+\text{H}_2\text{O} \rightarrow \text{H}_2, \text{CO}, \text{CH}_4 )</td>
<td>650...700°C</td>
<td>800...900°C</td>
<td>different mixtures of biomass possible</td>
</tr>
<tr>
<td>olefine production</td>
<td>( \text{C}_n\text{H}_m+\text{H}_2\text{O} \rightarrow \text{C}_2\text{H}_4, \text{C}_4\text{H}_8, \text{H}_2 )</td>
<td>700...800°C</td>
<td>850...950°C</td>
<td>broad product spectrum</td>
</tr>
<tr>
<td>oil shale/oil sand conversion</td>
<td>( \text{C}_n\text{H}_m\text{O}_x+\text{H}_2\text{O} \rightarrow \text{H}_2, \text{CO}, \text{CH}_4, \text{C}_n\text{H}_m )</td>
<td>600...700°C</td>
<td>800...900°C</td>
<td>broad product spectrum</td>
</tr>
<tr>
<td>thermo-chemical water splitting</td>
<td>( \text{H}_2\text{O} \rightarrow \text{H}_2+\frac{1}{2}\text{O}_2 )</td>
<td>900...950°C</td>
<td>950...1000°C</td>
<td>several process steps necessary</td>
</tr>
</tbody>
</table>

(*: hydro-gasification of coal, hydro-cracking of heavy oil fractions; direct reduction of iron ore; coal hydrogenation; application of methanation (long distance energy); oil shale and oil sand retorting; synthesis of methanol and ammonia; Fischer-Tropsch-synthesis)

In all high temperature applications the process energy for conversion can be substituted by nuclear heat. This amounts to be around 50% of the total energy balance. Fossil resources are spared. The emission of CO₂, which is produced during the production of the process heat, is avoided. Additionally the expectation is, that in the future nuclear heat is cheaper than the substituted fossil fuel. Especially the fact, that the share of Uranium is a relatively small part of costs of nuclear heat, makes nuclear energy attractive for future applications.

Principally a process heat plant consists from different parts as Fig. 2 shows. These are a modular HTR as heat source, an intermediate heat exchanger (IHX), a process unit (for example steam reformer and steam generator), a gas purification and following processes for use of the gas. A characteristic example is a methanol synthesis based on natural gas and nuclear heat, as indicated in the figure.

Methanol is easy to storage and could be applied in the energy economy in many sectors, especially for transportation, if it is burned in Diesel- or OTTO-engines. In the future methanol can be applied in fuel cells for mobile application too.

The coupling of a modular HTR with different processes has been analysed in detailed work. The final results for the processes is put together in Table 2. Here the total balances are shown.

These principal processes can be combined with other energy systems, as example the systems for production of electricity by wind energy converters and photovoltaic systems. As example the production of methanol in large quantities opens a new option for storage of energy.

Fig. 3 shows a possible combination of energy carriers and technologies to produce methanol from different raw materials and energy sources. Methanol could then be applied in the future in the transportation sector and promises advantages regarding storage and emissions.
steam reforming: \[ \text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 \] endothermic

shift reaction: \[ \text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 \] exothermic

methanol synthesis: \[ \text{CO} + 2\text{H}_2 \rightarrow \text{CH}_3\text{OH} \] exothermal
\[ \text{CO}_2 + 3\text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O} \]

Fig. 2: Principal concept of the production of methanol on the basis of natural gas and nuclear heat

Table 2: Some possible combinations of a modular HTR with processes

<table>
<thead>
<tr>
<th>process</th>
<th>integral balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>cogeneration plant</td>
<td>170 MW $\rightarrow$ 23 MW_{el} + 174 t steam/h (265°C)</td>
</tr>
<tr>
<td>refinery of crude oil</td>
<td>170 MW $\rightarrow$ + 200 t crude oil/h $\rightarrow$ products/h</td>
</tr>
<tr>
<td>enhanced oil recovery</td>
<td>170 MW $\rightarrow$ 106 t steam/h + 30.6 MW_{el} $\rightarrow$ 200 t products/h</td>
</tr>
<tr>
<td>oil from oil shale</td>
<td>170 MW + 180 t oil shale/h $\rightarrow$ 60 t liquid hydro carbons/h</td>
</tr>
<tr>
<td>methanol from natural gas and CO₂</td>
<td>170 MW + 20350 m³CH₄/h + 6170 m³CO₂/h $\rightarrow$ 42.4 t CH₃OH/h + 14.15 MW_{el}</td>
</tr>
<tr>
<td>nuclear long distance energy system</td>
<td>170 MW $\rightarrow$ 100 MW NLE* + 17 MW DH** + 6.8 MW_{el}</td>
</tr>
<tr>
<td>ammonia from natural gas</td>
<td>170 MW $\rightarrow$ 24800 m³ CH₄/h $\rightarrow$ 41.7 t NH₃/h</td>
</tr>
<tr>
<td>methane from hard coal</td>
<td>170 MW + 24.65 t coal/h $\rightarrow$ 32380 m³CH₄/h</td>
</tr>
<tr>
<td>hydrogen from coal</td>
<td>170 MW + 18.26 t coal/h $\rightarrow$ 57580 m³H₂/h</td>
</tr>
<tr>
<td>methanol from coal</td>
<td>170 MW + 9.4 t coal/h $\rightarrow$ 18.2 t CH₃OH/h</td>
</tr>
<tr>
<td>hydrogen and oxygen by water splitting</td>
<td>170 MW $\rightarrow$ 22680 m³H₂/h + 11340 m³O₂/h</td>
</tr>
</tbody>
</table>

(* NLE: nuclear long distance energy; **DH: district heat)

Fig. 3: Concept of conversion and storage of energy using methanol as a new energy carrier
The system includes short term storages for CO, H₂ and CO/H₂-mixtures too. A long term storage system for CH₃OH can be realized for this liquid fuel with some advantages. This concept offers the following positive aspects:

- The CO₂ emitted from fossil fuel power plants or industrial processes partly can be used.
- Electrical energy, produced by wind- or solar energy today partly cannot be used in the grid and partly must be exported with negative costs. Following this proposal this energy can be applied in the electrolysis plants.
- Liquid fuel (CH₃OH, C₂H₅OH) allows a storage about long time and especially a supply of the transportation sector.
- Coal or biomass can be converted into energy alcohol with high efficiency of carbon utilization.
- The heat of the nuclear reactor can be distributed to the steam reforming process and to the electrolysis following the demand.

In general form a future energy system can contain grids for electrical energy, for CH₄, for CO₂, for CO/H₂-mixtures and for CH₃OH (Fig. 4). The input of primary energy carriers and some products are indicated in the figure too.

This concept can help to reduce the problems of storage of electrical energy, to use surplus electrical energy from wind energy converters and photovoltaic systems and in totally to reduce CO₂-emissions.

Additionally the production of methanol and long term storage of this energy as a future fuel for the transportation sector is possible and promises economic advantages. Very well known technologies can be applied.

In a more detailed explanation a flow sheet for a combination of nuclear heat, CO₂, and electricity from other sources is given in fig. 5.

The combination explained here is suited to deliver electrical and methanol corresponding to the time dependent conditions of energy economy. Basic primary energy carriers are produced by wind energy converters, photovoltaic systems and nuclear energy. Methanol is the main product of the process, can be long time stored in liquid form and used in all sectors of energy economy.

Fig. 4: Combined energy system with different storage capabilities for electricity and fuels.

Fig. 5: Principle flow sheet of production of electricity and methanol from different primary energy carriers - concept for storage of electrical energy.
To establish a nuclear process heat system, as explained before requires the realization of different new components and process units:

- A nuclear reactor as heat source with high helium temperature and extremely high safety
- An IHX-system including a heat exchanger, hot gas valves and hot gas ducts
- A steam reformer/steam generator-unit integrated into the IHX-circuit
- A steam gasifier for conversion of coal or biomass
- An olefins cracking process-unit
- A hot electrolysis
- A thermo chemical water splitting process system
- Methanation plants
- Improved methanol/ethanol-synthesis plants

Different combined processes like coal hydrogenation, hydro cracking of heavy oil fractions, oil shale- and oil sand-conversion, direct reduction of iron core, ammonia- and methanol synthesis as well as Fischer-Tropsch-synthesis are available in commercial sizes.

### III. GENERAL ASPECTS OF TECHNICAL CONCEPT

Very high temperature reactor (VHTR) concepts are valued today as an attractive option for the future application of nuclear energy in the heat market. As Table 1 already explained different applications are possible and promise a broad application of these technologies. The basic nuclear heat source is the modular HTR [8 till 11].

Fig. 6 shows a simplified flow sheet for an interesting process, here as example for the steam reforming of methane combined to a modular HTR by an intermediate heat exchanger (IHX).

The principle concept of an IHX-circuit contains the primary heat exchanger itself, hot gas ducts, hot gas valves, cold gas ducts and helium circulators. Naturally the process reactor and the steam generator are part of the chain too.

In connection with this type of technologies different technical questions have to be discussed and solutions have to be found. Some important technical topics are:

- Realization of high helium temperatures in a modular HTR
- Realization of heat exchangers (IHX) for very high temperature applications
- Realization of process reactors (steam reformer, steam generator, steam gasifier)
- Availability of materials for high temperature applications
- Fulfilling requirements of safety of VHTR-plants even in case of extreme accidental situations (practical total retention of radioactive substances in the reactor system)

The following chapters contain some details on these questions.

![Fig. 6 IHX-circuit coupled with a modular HTR](image)

**IV. CONCEPT OF A VHTR**

The modular HTR with spherical fuel elements and TRISO-coated particles fuel is a well suited solution for the VHTR required in generation IV and is capable of controlling the accident spectrum shown in Fig. 7. This includes cases of accidents, which today not at all are assumed in the normal licensing process for nuclear power plants worldwide.

Fig. 8 shows a draft of the system that can meet these high future safety demands [12]. Because of application of the concept of self-acting decay heat removal core melting is completely ruled out and the retention of the fission products in the fuel elements is ensured as long as the accident temperatures remain below 1600°C. The key component for safety performance is the coated particle with excellent retention of the fission products in normal operation and in cases of accidents up to the temperature value mentioned above. Furthermore a totally prestressed, burst safe primary enclosure and a tight inner concrete cell together with an efficient filter system form an independent barrier concept against the release of radioactive substances into the environment. In this case three independent barriers are available.
The plant proposed here has a thermal power of 200 MW, uses a cylindrical core, and has a core power density of 3 MW/m³. This concept allows a heating up of the helium coolant from 250 to 700°C if a steam generator is coupled to the reactor and till 950°C, if an IHX is applied as a heat exchanger to supply high temperature processes.

In designing the reactor and the inner concrete cell it is essential that the decay heat can be transported in a self-acting manner by heat conduction, heat radiation and free convection alone without exceeding the maximum temperature of the fuel elements specified before. For accidents with a complete loss of active cooling of the reactor, a simple surface cooling system is provided on the inner surface of the concrete cell, which operates with water cooling. If this also fails, the heat is transported into the concrete structures. The maximal temperature in the fuel elements practically is not changed in this case.

Table 3 contains some important data for nuclear heat sources suited for process heat production. The 200 MW\textsubscript{th} reactor mainly is applicable to cogeneration plants and the 170 MW\textsubscript{th} design can serve as heat source for high temperature applications.

The entire primary circuit is arranged according to Fig. 8 in a prestressed and thus burst-safe cast steel vessel. The total primary system is contained in a tight inner concrete cell, whose size allows a self-acting limitation of the amount of air, that would be available for corrosion pro-esses on the graphite after depressurization accidents. The inner concrete cell is connected to an accident filter with a stack. Self-acting mechanism such as a flap, which closes under gravity or a silo for granular material flowing out after depressurization accidents hermetically seal the inner concrete cell completely after an assumed depressurization of the primary circuit.
Reactor concept for the VHTR (example: production of process steam)

Fig. 8 Reactor concept for the VHTR (example: production of process steam, use of an IHX)
Fig. 9 shows the arrangement of the reactor containment building. The protection of the reactor plant against external impacts is additionally ensured by an outer thick-walled concrete containment building, which however must not be tight in the sense of an LWR-containment. For protection against very strong impacts from outside, in future, nuclear plants could be constructed underground and covered by a hill of rock and other structures. This will enable precautions against terrorist attacks too, which could become even more serious in a few decades. A fast discharge of fuel elements by gravity is an additional possibility to protect the fuel against terrorism and war.

Fig. 9: Underground arrangement of reactor containment building (example: production of process steam, use of an IHX)

<table>
<thead>
<tr>
<th>parameter</th>
<th>dimension</th>
<th>plant for cogeneration</th>
<th>plant for very high temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>thermal power</td>
<td>MW</td>
<td>200</td>
<td>170</td>
</tr>
<tr>
<td>helium temperature in primary circuit</td>
<td>°C</td>
<td>250—700</td>
<td>250—900-950</td>
</tr>
<tr>
<td>helium pressure</td>
<td>MPa</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>helium temperature in secondary circuit</td>
<td>°C</td>
<td>200—650</td>
<td>200—850-900</td>
</tr>
<tr>
<td>helium pressure</td>
<td>MPa</td>
<td>~ 6</td>
<td>~ 4</td>
</tr>
<tr>
<td>steam conditions</td>
<td>°C/MPa</td>
<td>530/12</td>
<td></td>
</tr>
<tr>
<td>process temperature</td>
<td>°C</td>
<td></td>
<td>700-850</td>
</tr>
<tr>
<td>average core power density</td>
<td>MW/m³</td>
<td>3</td>
<td>2.55</td>
</tr>
<tr>
<td>core diameter</td>
<td>m</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>core height</td>
<td>m</td>
<td>9.4</td>
<td>9.4</td>
</tr>
<tr>
<td>loading of fuel elements</td>
<td>g/FE</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>average enrichment</td>
<td>%</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>average burnup</td>
<td>MWd/t</td>
<td>80000</td>
<td>80000</td>
</tr>
<tr>
<td>Particles</td>
<td>-</td>
<td>TRISO</td>
<td>TRISO</td>
</tr>
<tr>
<td>maximal temperature in accident LOCA</td>
<td>°C</td>
<td>&lt; 1600</td>
<td>&lt; 1600</td>
</tr>
</tbody>
</table>
The nuclear reaction is switched off by shutdown elements solely arranged in the reflector. The reactor has a strong negative temperature coefficient of reactivity; this coefficient causes an always self-acting limitation of nuclear power and fuel temperatures during reactivity accidents. Loading with fresh fuel elements and the discharge of spent fuel elements take place continuously during operation with the aid of known simple lock systems. Excess reactivity for burn-up compensation is practically avoided by this continuous loading. This is a further important aspect of inherent safety.

The spent fuel elements are interim-stored in air-cooled dry storage containers in an interim store at the site for long periods of time. Because the decay heat is very small, natural convection and radiation are sufficient to cool the vessels and to limit the temperatures of fuel elements to small values (< 200°C). The additional improvement of effective heat conductivity of the pebble arrangement by a two grain structure makes this possible.

The reactor concept follows 4 fundamental safety principle of stability, which are forcible to establish a reactor, which cannot be destroyed by accidents and in which the radioactivity will be retained practical totally. These principles are nuclear, thermal, chemical and mechanical stability. An analysis of accidents, including “design basis accidents” and “beyond design basis accidents” is added in section 8.

V. REALIZATION OF HIGH HELIUM TEMPERATURES IN MODULAR HTR-SYSTEMS

The main precondition to realize processes connected to the VHTR is, that very high helium temperatures can be realized with HTR-fuel elements including still high safety factors. This can be either done by the MEDUL cycle (multipasses through the core) or by the OTTO-cycle. One very interesting possibility is the OTTO-cycle (Once Through Then Out) [13 till 16]. The fuel elements and the cooling gas pass the core in a parallel flow. This procedure of fuel management results in an axial asymmetric flux- and power density distribution. The differences between fuel- and gas temperature will be very small at the outlet from the core (around 50°C), which is the hottest part of the system. Fig. 10 shows the principle of this fuel handling concept.

By this method very high temperatures can be realized. It should be mentioned that the OTTO-cycle allows a simplification of the fuel handling too. One disadvantages of the OTTO-cycle is, that the fast neutron dose at the grafitic structures has higher values at around 600°C compared to MEDUL-cores. A limitation of the average core power density to values of around 3 MW/m² is senseful. Furthermore the thermal power of cores with OTTO-cycle should have values smaller by around 20% compared to cores with MEDUL-cycle in case of cylindrical core geometries to limit the maximal fuel temperature in loss of cooling accidents to values below 1600°C.

Annular cores using OTTO-cycle can be realized, obeying these boundary conditions, till a thermal power of 210 MWth if additionally the limits of diameter of forged steel vessels are considered. Prestressed vessels allow much higher thermal power with the same safety behaviour in case of severe accidents. Several 100 MWth can be realized in prestressed vessels made from concrete, cast iron or cast steel.

There is a lot of experience on the use of high helium temperatures in the HTR-technology. The AVR has been operated during 10 years with an average helium outlet temperature of 950°C with high availability [17]. Many important safety experiments were carried out during operation at these very high temperatures. There is no doubt, that cores of pebble bed reactors can be designed for these high temperatures and be operated far away from technical limits of the fuel.
VI. ASPECTS OF SAFETY OF VHTR-PLANTS EVEN IN CASE OF EXTREME ACCIDENTAL SITUATIONS

Related to the safety of modular HTR the following aspects are important [8 till 11]:

- if the core parameters, mainly core power density and diameter of the core are chosen adequately, the core never can melt and the fuel elements cannot be overheated above allowed values. After an accident "total loss of active cooling" the decay heat is removed just by processes of heat conduction, radiation and free convection. If the maximal fuel temperature is chosen as 1600°C (fig. 11), the fission products mainly stay inside the fuel elements.

- The histogram of fuel temperatures makes clear, that just some percent of fuel elements get relative high temperatures, as example between 1400 and 1500°C, for a short time. Therefore the integral fission product release of important isotopes (as example I 131, Cs 137, Sr 90) stays very limited too during the whole accident. Values of less than $10^{-4}$ of the inventory are characteristic [18 till 21]

- even if all structures outside the reactor pressure vessel would be destroyed as shown in fig. 11c) as example by the influence of an extreme strong earthquake, or as a consequence of a terrorist attack with a large air plane, the decay heat would be removed from the reactor, again by the self-acting processes of conduction, radiation and free convection would act [22]. The maximal fuel temperature would stay below a value of 1600°C in this case too, however the histogram of fuel temperatures would be changed. There would be much time, to initiate simple interventions and to cool the system by nitrogen or by water.

Some results of measurement of fission product release from spherical fuel elements under accident conditions are given in Fig.12.
VII. RETENTION OF RADIOACTIVE SUBSTANCES IN THE REACTOR SYSTEM

So far as the retention of radioactive substances in the plant is considered, the concept of barriers and their behaviour in accidents are important.

- Regarding the fission product release from the reactor to the environment one gets the principle result shown in Fig.13. Just a share of around $10^{-5}$ of the inventory of the fission products in the core would be released via the stack (example Caesium 137). An efficient system of independent barriers and an efficient simple filter system would allow this strong reduction of release. As a consequence even after extreme accidents there would be no early fatalities, no land contamination outside plant and a very limited, not detectable number of late facilities [23, 24].

- This safety behaviour of modular HTR can be verified by large suited experiments. In the AVR already some very important safety experiments have been carried out. It was shown that the strong negative coefficient of reactivity can stop the chain reaction without any action of active shut down systems. Furthermore the principal of self-acting decay heat removal just by conduction, radiation and free convection has been demonstrated in AVR under pressure and at normal pressure.

The today introduced TRISO-coated particles show an excellent retention of fission product till temperatures of around 1600°C. Fig.12 showed measurements on spherical fuel elements during heating tests over a long time. There is the expectation that the retention capability will be similar for prismatic fuel elements using the same type of coated particles.

Further progress in the field of coated particles possible. Improvements of coatings or additional layers promise a further reduction of release rates.

- later after the accident has happened the gas mixture can be given off to the environment via a stack. The self-acting closures just use gravity or spring energy and will close the inner cell, after the depressurization phase is finished. In any case by using this principle of closure, the volume of air, if available at all, would be limited to values below 5000 m$^3$ and therefore the graphite corrosion would be limited to 500 kg. Using an inert gas filling of the cell corrosion would be avoided in any case. Simple interventions after a longer grace time would be possible, to stop any air ingress.

- the ingress of water into the primary system is practically impossible in concepts, where IHX-circuits are applied. In any case, in solutions
without IHX the amount of water inside the core would be limited to tolerable values by the arrangement of the steam generator geodetically below the core. The total amount of water in the primary circuit would be limited by suited systems for depressurization of the reactor circuit in time.

- Overall the detailed analysis of the safety behaviour of modular HTR delivers the result compiled in table 6.

VIII. REALIZATION OF HEAT EXCHANGERS (IHX) FOR VERY HIGH TEMPERATURE APPLICATIONS

The key component for the use of nuclear process heat, especially at high temperatures, is the intermediate heat exchanger (IHX). It allows a total separation of the primary circuit from the process, in which the nuclear heat is used. Fig.14 shows a concept for the IHX, which has been developed in the PNP-project [25 till 29] and tested with success in the KVK-facility.

Normally the intermediate circuit uses helium as working fluid. Helical type heat exchangers have been developed and tested for temperatures of 950°C on the primary side and 900°C at the secondary side. The power was 10 MW. It used a central sampler for the secondary hot helium and the tests were carried out corresponding to a component of 125 MW for this sensitive part. Fig. 13 shows a flow sheet of the IHX,

---

Table 4 Valuation of the safety behaviour of modular VHTR

- the core can never melt; no overheating of the fuel above 1600 °C is possible
- the self-acting decay heat removal can never fail
- the reactor would also sustain extreme reactivity transients without being damaged
- the primary circuit pressure boundary can never fail by bursting
- the ingress of air is meaningless from a safety-related point of view
- the ingress of water does not cause any serious damage either in the primary system
- the plant withstands the normal external impacts to be assumed
- there is also protection of the fuel elements against extreme external impacts (terrorism, extreme earthquakes)
a $T$-$Q$-diagram for the component and the component itself. In the table there are the data of the test component and for comparison that of a commercial plant. The component has been tested under stationary and extreme transient conditions about a time period of 10 000 hours. The behaviour was excel-lent. A lot of qualification tests of sensitive parts of the component (hot sampler, supports, insulation, and of the IHX-circuit (hot gas valves, pipes, helium-circulators) accompanied the integral test in the KVK-plant. Especially the central hot sampler with large dimensions has been tested to the 125 MW component, using a special device to simulate the original flow conditions. As an alternative an IHX with U-tubes has been tested in the KVK too (10 MW, $T_{He}=950$ °C, $P_{He}=40$ bar). The component contained sampling systems, which had the size as necessary in a component with a power of 125 MW. This heat exchanger has been tested with good success for nearly 10 000 hours. In both components fast transients of temperature and pressure have been applied, with values much larger than to be expected in a real plant. All these loads were tolerated.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimension</th>
<th>KVK-test</th>
<th>IHX-comp.</th>
<th>IHX comp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>MW</td>
<td>10</td>
<td>85</td>
<td>170</td>
</tr>
<tr>
<td>Temperature (primary)</td>
<td>°C</td>
<td>950...300</td>
<td>950...300</td>
<td>950...300</td>
</tr>
<tr>
<td>Temperature (secondary)</td>
<td>°C</td>
<td>200...900</td>
<td>200...900</td>
<td>200...900</td>
</tr>
<tr>
<td>Pressure (primary)</td>
<td>bar</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Pressure (secondary)</td>
<td>bar</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Heat transfer area</td>
<td>m²</td>
<td>300</td>
<td>2500</td>
<td>5000</td>
</tr>
<tr>
<td>Max. wall temperature</td>
<td>°C</td>
<td>930</td>
<td>930</td>
<td>930</td>
</tr>
<tr>
<td>Material</td>
<td></td>
<td>Inconel 617</td>
<td>Inconel 617</td>
<td>Inconel 617</td>
</tr>
</tbody>
</table>

Fig. 14: Concept of the IHX
a) Helical tube heat exchanger (85, 170 MW)
b) Principle flow diagram
c) $T$-$Q$ -diagram
d) Data of test in KVK-facility and of components
IX. HELIUM HEATED STEAM REFORMERS AS A KEY TECHNOLOGY

The helium heated steam reformer [30 till 36] is a key component for several high temperature process heat applications. This component can be arranged directly into the primary system or indirectly in an intermediate heat exchanger cycle operated with helium, too. The flow diagram of the primary circuit of a modular HTR directly combined with a steam reformer and a steam generator is shown in Fig.15.

Fig.15: Primary circuit of a steam reformer plant with HTR as a heat source
a) Principle flow diagram (direct coupling of heat exchangers)
   (1: reactor; 2: steam reformer; 3: steam generator; 4: helium circulator)
b) Reformer tube (with outer helium ducting tube)
c) Temperature-diagram for the helium and the process gas

It contains main data of such a plant as designed for H₂-production on the basis of a HTR with a cylindrical pebble bed core of a thermal power of 170 MW. Today it is thought, that an IHX would be advantageous for the steam reformer application too.

The main argument for an IHX are the easier licensing process, more freedom in component design, avoidance of contamination and further reduction of Tritium permeation. Naturally the investment costs of the plant are higher.

As compared to former HTR designs with steam cycles and coolant temperatures of 700...750°C, the thermal power of modular HTR for Nuclear Process Heat (NPH) is reduced by the requirements of self-acting decay heat removal in the reactor, i.e. to stay with the maximum fuel temperature in accidents of total loss of cooling below 1600°C for a reactor with a helium temperature of 950°C. Thus, the thermal power of a reactor for this type of process heat application is only 170 MW. Without IHX, the helium coolant is directly fed to the steam reformer which consumes 71 MW and to the steam generator which is operated with a power of 99 MW. One promising technical concept for a steam reformer/steam generator loop is shown in Fig.16.

There are small pressure differences of less than 2 bar between helium- and process side in the hot part. The mechanical strength properties of the relevant materials to be used in these components, Incoloy 617, Incoloy 800H are high enough at 900°C. With regard to the tube wall thickness of 10 mm, a high safety factor also for the long-term stability (10⁵ h lifetime) of the component is ensured. The heat stresses resulting from the heat fluxes during normal operation are significantly reduced by creeping processes. Additional transient stresses during start up and shut down of the plant are reduced to tolerable values with a limitation of the allowable transients to a few °C/min. In the course of the research and development program-me, technically feasible concepts for the evaluation of stresses of reformer tubes as well as concerning the damage accumulation and failure models have been worked out.

Heat fluxes of 50 till 60 KW/m² can be realized in these components; the power density in the reformer bundle can reach around 1 MW/m³. Two bundles with a power of 6 MW (baffle concept, system with single helium ducting tubes) have been tested over more than 10 000 hours with great success in the EVA II-plant with helium heating till 950°C at 40 bar. The extrapolation to a technical component (factor 10 of power) is valuated as feasible, because just the number of reformer tubes will be larger.

The arrangement of the component in an intermediate cycle, as this is preferred today, makes all conditions easier. Furthermore a maximal heating temperature of 850 till 900°C is sufficient to carry out the process with high conversion rate of methane and suitable data of heat transfer.
X. AVAILABILITY OF MATERIALS FOR HIGH TEMPERATURE APPLICATIONS

High alloyed materials [37 till 42] have to be used for the tubes of IHX and of steam reformers, for hot samplers and supporting structures. The maximal temperatures will be around 950°C for the design of IHX, as explained in chapter 6. The heat fluxes are in the order of 30 KW/m² and the pressure difference between the primary and secondary circuit is nearly 1 bar in normal operation in this component.

In the tubes of the heat exchanger the heat fluxes cause thermal stresses, which are compensated by creep at the applied high wall temperatures. In case of start-up and shut down and during load following thermal stresses partly appear and have to be covered in the stress analysis.

Additionally in case of depressurization accidents on the primary or on the secondary side large additional stresses can occur, however just for a very short time. Therefore detailed stress analysis has to cover a complicated history of the component, which has to be assumed as a basis for the design. The total shares of stress for all these situations can be described by summing up all these effects.

A broad material program has been carried out, to qualify materials for high temperature process heat- and gas-turbine applications. It contained tests of all mechanical properties, corrosion effects and aspects of fabrication and necessary proof test. Fig.17 shows some results of important strength values dependent

<table>
<thead>
<tr>
<th>parameter</th>
<th>dimension</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>thermal power of reactor</td>
<td>MW</td>
<td>170</td>
</tr>
<tr>
<td>helium temperature</td>
<td>°C</td>
<td>250 → 950</td>
</tr>
<tr>
<td>helium pressure</td>
<td>bar</td>
<td>40</td>
</tr>
<tr>
<td>helium mass flow</td>
<td>Kg/s</td>
<td>70</td>
</tr>
<tr>
<td>power of steam reformer</td>
<td>MW</td>
<td>71</td>
</tr>
<tr>
<td>power of steam generator</td>
<td>MW</td>
<td>99</td>
</tr>
<tr>
<td>pressure in reforming process</td>
<td>bar</td>
<td>40</td>
</tr>
<tr>
<td>H₂-production</td>
<td>m³/h</td>
<td>30 000</td>
</tr>
</tbody>
</table>

Fig. 16: Helium heated steam reformer
a) component
b) reformer tube with gas ducting tube sheet around the reformer tube
c) horizontal section through the reformer bundle
(1: supporting plate; 2: reformer tube; 3: internal recuperator; 4: catalysts bed; 5: tube bundle; 6: gas duct; 7: pressure vessel; 8: sampling chamber for feed gas and process gas; 9: guiding tube for a reformer tube; 10: hot helium inlet structure)
d) data of a reformer furnace
from time and temperature. It was concluded, that Incoloy 800H and Inconel 617 would be suited candidates to fulfil the requirements of an IHX-design for a 10⁵ hours life. Especially Inconel 617 was the candidate for the hottest parts of the component.

Another important question is the availability of design rules and qualified codes for the analysis of components in the licensing process. There are further steps necessary to establish design codes above 800°C material temperatures. Work has been done to a large extent in the HHT- and PNP-project to establish rules for designing components at high temperatures, but for practical application there is still work needed. The design codes for high temperature application of component have to be extrapolated above temperatures of 900°C. At the moment just the ASME - Code case N47 is applicable to material temperatures of around 800°C in nuclear applications.

![Fig. 17: Materials for high temperature applications](image)

- a) overview on different candidates
- b) creep rupture of Inconel 617
- c) 1% strain values of Inconel 617
- d) Fatigue values of Inconel 617
XI. COMPONENT DEVELOPMENT IN LARGE TEST FACILITIES IN GERMANY

In the course of development of nuclear process heat worldwide already until now large progress has been reached. As example during the period from 1960 to 1992 the financial effort of the HTR development in Germany reached a value of 2 billion Euro [43 till 49].

The R&D work was performed as well in large test facilities, in tests fields for material development and many small test installations. Some very important large test facilities are listed up in Table 6.

During the years of operation from 1982 to 1990 of the KVK nearly all the time several test components have been tested simultaneously. These tests delivered very positive experience and confirmed that IHX-concepts, can be realized.

As an example in Table 7 the total operating times of KVK and the periods at temperatures above 900°C are listed. The experiences gained for these components is an excellent basis for the design of VHTR-plants. Especially the partly very long test times were estimated as essential preconditions for the design of real components.

Table 6: Some information on large helium test facilities in German HTR-projects

<table>
<thead>
<tr>
<th>aspect, parameter</th>
<th>dimension</th>
<th>facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>purpose</td>
<td>-</td>
<td>test of total plant (gas turbine)</td>
</tr>
<tr>
<td>location</td>
<td>-</td>
<td>Oberhausen</td>
</tr>
<tr>
<td>project</td>
<td>-</td>
<td>HHT</td>
</tr>
<tr>
<td>electrical power</td>
<td>MW</td>
<td>50</td>
</tr>
<tr>
<td>thermal power</td>
<td>MW</td>
<td>150</td>
</tr>
<tr>
<td>max. helium</td>
<td>°C</td>
<td>750</td>
</tr>
<tr>
<td>temperature</td>
<td>Bar</td>
<td>28.7</td>
</tr>
<tr>
<td>helium pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>helium mass</td>
<td>kg/s</td>
<td>84</td>
</tr>
<tr>
<td>flow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>operation time</td>
<td></td>
<td>50 000</td>
</tr>
<tr>
<td>specific aspects</td>
<td>-</td>
<td>fossil burner to heat up helium</td>
</tr>
</tbody>
</table>

(EVO = Energie Versorgung Oberhausen = Energy Utility Oberhausen
HHV = Hochtemperatur Helium Versuchsanlage = High temperature helium experimental facility
EVA II = Einzelrohr-Versuchs Spaltanlage II = Steam reformer plant (bundle)
KVK = Komponenten Versuchs Kreislauf = Components experimental facility
WKV = Wasserdampf Kohle Vergasung = Facility for coal gasification with steam)
The EVO power plant has been built to demonstrate the possibility to operate the Brayton cycle. It consisted of a high and a low pressure turbine, two compressors, a recuperator, a precooler and an intercooler. The total thermal power of the plant reached 150 MW and the net electrical power was designed as 50 MW. The gas was heated by burning fossil fuel. Because of some problems with vibration the first version of the turbine did not reach the specific electricity energy. In the HHT-project a very large helium test facility was built to test the first stage of a helium turbine and the hot gas ducts under real conditions.

For this purpose the mass flow corresponded to a 300 MWel turbine and the helium was heated up to 850°C at 60 bar. Furthermore many important components of helium technology have been tested like large valves, gas purification, helium circulator and measurement installations. The WKV-plant was built and operated to test the process of coal gasification. It had a maximum temperature of 1000°C and a total thermal power input of 10 MW. The measurement of reaction velocities, coal conversion and a large test of an allo-thermal gasifier system were the main topics and results in this large facility.

EVA II was a large plant to test helium heated steam reformer systems with a maximal power at a helium temperature of 950°C at 40 bar and a total power of the helium cycle of 10 MW. The total operating time of the EVA II reached 13000 h with 7750 h at temperature > 900°C. During 10150 h the reformer facility was connected to a methanation plant (power: 6 MW) in which the reversible exothermal process \( \text{CO} + \text{3H}_2 \rightarrow \text{CH}_4 + \text{H}_2\text{O} \) was performed.

Parallel to this project an extensive program to qualify high temperature alloys above wall temperatures of 900°C was carried out with great success. The development of IHX-circuits including all necessary components was carried out as already described in the KVK-plant. This facility with a power of 10 MW and a maximal helium temperature of 950°C at 40 bar allowed the tests of different large (10 MW) IHX-components, gas ducts, valves, steam generators, helium circulators, gas purification and measurement installation.

### XII. CONCLUSIONS

The work, which has been carried out in the field of HTR-technology until now, can be characterized by the following statements:

- **nuclear reactors**, mainly modular high temperature reactors till a power of 170 to 200 MWth can be designed for helium temperatures of 850 till 950°C dependent on the planned application
- **Intermediate heat exchanger systems** can be realized till maximal temperatures on the secondary side of 900°C, based on the experience available from the past
- **high temperature alloys** for the temperatures mentioned before are available and already qualified for a first phase of operation (5 to 10 years)
- **important conversion processes** like steam reforming of methane, gasification of coal or biomass, have been tested in large scale (till 10 MW); they can be extrapolated to larger power

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### Table 7: Times of testing of large components (example: KVK) [26]

<table>
<thead>
<tr>
<th>component</th>
<th>max. helium temperature (°C)</th>
<th>total operation time (h)</th>
<th>operation at temperature &gt; 900 (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 MW helical heat exchanger</td>
<td>950</td>
<td>4700</td>
<td>2100</td>
</tr>
<tr>
<td>10 MW U-type heat exchanger</td>
<td>950</td>
<td>5300</td>
<td>2200</td>
</tr>
<tr>
<td>hot samplers for both components</td>
<td>900</td>
<td>7100</td>
<td>1700</td>
</tr>
<tr>
<td>central return duct for U-type comp.</td>
<td>900</td>
<td>4250</td>
<td>2100</td>
</tr>
<tr>
<td>10 MW steam generator</td>
<td>950</td>
<td>16000</td>
<td>6075</td>
</tr>
<tr>
<td>primary hot gas duct</td>
<td>950</td>
<td>10100</td>
<td>2260</td>
</tr>
<tr>
<td>primary compensator</td>
<td>950</td>
<td>5300</td>
<td>2450</td>
</tr>
<tr>
<td>hot core connection</td>
<td>950</td>
<td>1700</td>
<td>470</td>
</tr>
<tr>
<td>secondary hot gas duct</td>
<td>900</td>
<td>10600</td>
<td></td>
</tr>
<tr>
<td>bending in secondary hot gas duct</td>
<td>900</td>
<td>10100</td>
<td>4200</td>
</tr>
<tr>
<td>hot gas valve DN 200</td>
<td>900</td>
<td>12000</td>
<td>5300</td>
</tr>
<tr>
<td>hot gas valve DN 700</td>
<td>900</td>
<td>5300</td>
<td>2450</td>
</tr>
<tr>
<td>hot gas valve (sphere.)</td>
<td>900</td>
<td>5300</td>
<td>2450</td>
</tr>
<tr>
<td>10 MW decay heat cooler</td>
<td>950</td>
<td>4000</td>
<td>1260</td>
</tr>
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</table>
modular HTR can be realized with a safety concept, which does not cause high release rates of radioactive substances even in case of very extreme accidents

large test facilities have delivered a broad know how on helium technology, which is necessary to realize future VHTR-plant

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