

# **The Pebble Bed High Temperature Reactor as a Source of Nuclear Process Heat**

**Volume 1  
Conceptual Design  
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THE PEBBLE BED HIGH TEMPERATURE REACTOR  
AS A SOURCE OF NUCLEAR PROCESS HEAT

Volume 1  
CONCEPTUAL DESIGN

ABSTRACT

A conceptual design is proposed for a process heat reactor with ball fuel elements and a gas outlet temperature of 950 °C. A short description is given of interesting processes, especially such which utilize a steam reformer. Details are given about the components, in particular the process heat exchangers. A short description of the technical safety problems and the development status follows.

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## Conversion Table

Unit in Metric System	Unit in British/American System
1 m	3.28 ft
$t_c$ (e.g. 950 °C)	$t_F = \frac{9}{5} t_c + 32$ 1742 °F)
1 kg = 0.001 t	2.2 lb
1 b = 1.02 at	14.5 psi
1 kcal	3.97 BTU
$\frac{\text{kcal}}{\text{kg}}$	1.8 $\frac{\text{BTU}}{\text{lb}}$
$\frac{\text{kcal}}{\text{mh}^\circ\text{C}}$	0.67 $\frac{\text{BTU}}{\text{ft hr}^\circ\text{F}}$
$\frac{\text{kcal}}{\text{m}^2 \text{ h}^\circ\text{C}}$	0.205 $\frac{\text{BTU}}{\text{sq ft hr}^\circ\text{F}}$
$\frac{\text{kcal}}{\text{m}^2 \text{ h}}$	$1.02 \cdot 10^{-4} \frac{\text{BTU}}{\text{sq ft sec}}$
1 Nm <sup>3</sup> (0 °C, 760 torr)	37.2 std cu ft (60 °F, 30")
1 DM = 100 Dpf	0.37 %

## 1.1 Summary

Objectives - This report presents a conceptual design of the Pebble Bed Nuclear Reactor (PBR) as a 950 °C helium heat source for process heat and electricity generation. A verification test program is outlined and the technological status is summarized.

### Conclusions

- 1.- The tubular steam reformer (SR) when heated with helium at 950 °C is adaptable to various chemical processes including:
  - o Steam reforming of methane
  - o Hydrogasification of coal
  - o Direct reduction of iron ore
  - o Conversion of heavy fuel oils
  - o Conversion of bituminous coal or lignite to gasoline
  - o Transportation of nuclear heat in form of chemical energy over long distances at low temperature (chemical heat pipe).
  
- 2 - The PR 3000 pebble bed reactor is capable of producing helium at 950 °C. It is ready now for final design. Plant data is listed in table 1.3.1-2.
  
- 3 - The fuel is developed ahead of the rest of the system. The well tested fuel balls of the German THTR may be used in the PR 3000 plant. Very low fission product release rates will ease maintenance. These balls are now being produced by HOBEG at the rate of 200,000 per year.
  
- 4 - The PBR fuel has three unique features, namely, on-line refueling, OTTO fuel loading scheme, and the spherical fuel shape. These may be combined to economic advantage, for example:
  - Plant availability is increased since there is no refueling shutdown. This is important for the process plant which should run continuously. An estimate of 0.5 to 1.0 month is required for annual shutdown for competing HTGR.
  - Versatile fuel management is available through easy changeover in existing plants to other fuel types as economic factors change or high fuel conversion ratio as described
  - Large fuel temperature design margin is available. As the balls pass through the core, their power density decreases, burnup increases and the helium gas temperature increases. The fuel centerline temperature remains approximately the same and close to the helium temperature, see figure 1.3.5.1-1.

## II.

- Reflector control except for cold shutdown, then the control rods must penetrate into the pebble bed.
  - Excess reactivity is minimized by control of fuel addition. Burnable poison is not required. Neutron economy is maximized.
  - The spherical fuel element is inherently stable. No separate core structure is required. Local hot spots are essentially eliminated by helium crossflow through the homogeneous bed. Tolerances within the core are of little concern. The full sized fuel element can be tested in pile. Therefore there are a lot of test results.
  - Increased power in new plants is available at constant fuel cost (mills/kwh) using essentially identical hardware. This standardization can decrease engineering and manufacturing costs and provide plant reliability/availability improvement. This additional degree of design freedom results from the design margin in the fuel and the variable fuel residence time in the core.
- 5 - Design choices are available in the remainder of the plant. Thus, features of the HTGR may be applied. Also, design features introduced at KFA are equally applicable to other high temperature reactors (HTR), for example:
- o Very low fuel power density to further increase safety (but at increased capital cost)
  - o Underground containment structure.
  - o Prestressed cast steel pressure vessel.
- 6 - The conceptual design of the PR 3000 is directly applicable for the all electrical plant with minimum hardware change. Helium core exit temperature would be reduced to 800 °C. Plant efficiencies of 0.4 are possible even with use of dry cooling towers.
- 7 - The total fuel costs in mills/kwh of the pebble bed reactor will be comparable to those of other reactors, including LWR.
- 8 - Safety -- Process heat plants are usually located near populated areas. Also, any reactors site in West Germany is close to a populated area. Therefore, KFA has concentrated on taking fullest advantage of the safety features inherent in the PBR even to the disadvantage of capital costs. For example, the core volume is twice as large as it need be. That is, the power density in the fuel can be doubled without reaching a design limitation. The licensing procedure must be done.
- 9 - Main questions of the fuel cycle are development of reprocessing and refabrication.

## 1.2 Description of Processes

### 1.2.1 Principle of Nuclear Process Heat

Nuclear process heat is a new source of primary energy together with natural gas, oil and coal. All these three raw materials can be converted into hydrogen,  $H_2/CO$ -mixtures, methane or light hydrocarbons by use of high temperature nuclear process heat (see Fig. 1). Furthermore, nuclear heat itself can be transported over a long distance by a chemical heat pipe system. A future possibility to get hydrogen could be to split water by heat using closed chemical processes. The heat source for all these processes is the high temperature gas cooled reactor.

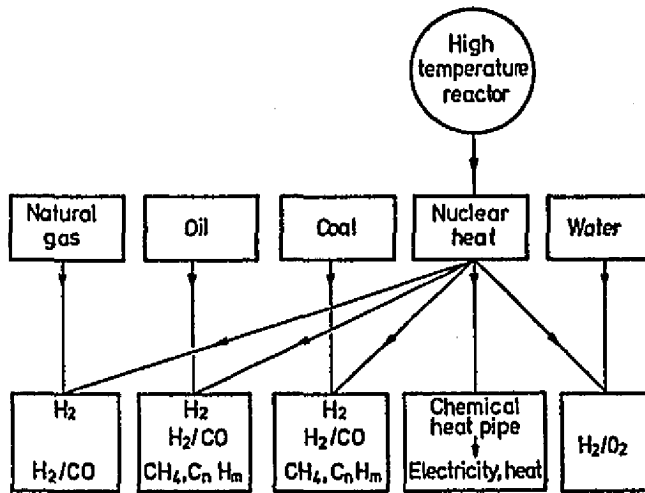


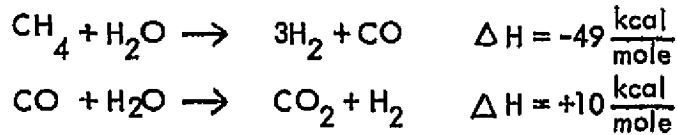
Fig. 1.2-1: Principle of Nuclear Heat

There are two main ways to use nuclear process heat for conversion of raw materials:

- use of helium heated steam reformer, which produces hydrogen in combination with a lot of different processes, which consume hydrogen
- use of a helium heated coal gasifier to convert coal to gas by steam gasification.

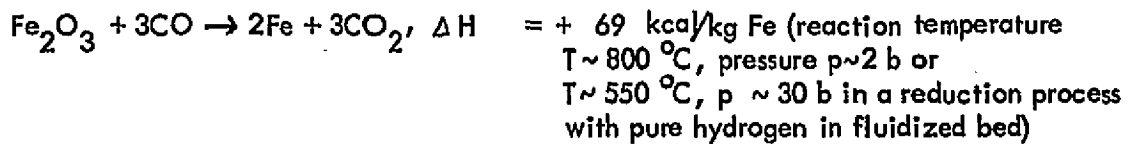
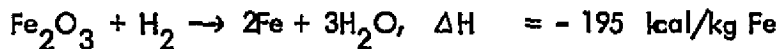
### 1.2.2 Steam Reformer Application

The steam reformer is used to convert all different sorts of light hydrocarbons as natural gas, methane, gasoline, refinery gases with steam to hydrogen or a mixture of hydrogen and carbon monoxide. The steam reformer process itself is an endothermic catalytic process with a large heat demand at a temperature level of  $750...850^{\circ}C$  with pressure of up to 30 b today. There are two main reactions in the steam reforming process. The gas analysis is dependent on temperature, pressure and steam/hydrocarbon ratio in the reformer tube:



The product gas of steam reforming is then inserted in different processes (see Fig. 1.2-2)

- In an exothermic process (hydrogasification) bituminous coal or lignite is converted to methane ( $\text{C} + 2\text{H}_2 \rightarrow \text{CH}_4$ ,  $\Delta H = 20 \text{ kcal/mole}$  (reaction at  $800^\circ\text{C}$ , 50...70 b). A part of the methane is used as feed for the steam reformer and converted to hydrogen and carbon-monoxide. Dependent on the capacity of the steam reformer and on the hydrogasification, the product of this process is  $\text{H}_2$ ,  $\text{H}_2/\text{CO}$  or  $\text{CH}_4$  (ref.1).
- The direct reduction of iron ore with gas is made in an exothermic (CO) or a weak endothermic ( $\text{H}_2$ ) reaction (ref.2):



The reducing gas for this process is produced in the steam reformer using  $\text{CH}_4$ , natural gas, gasoline or refinery gases as raw material.

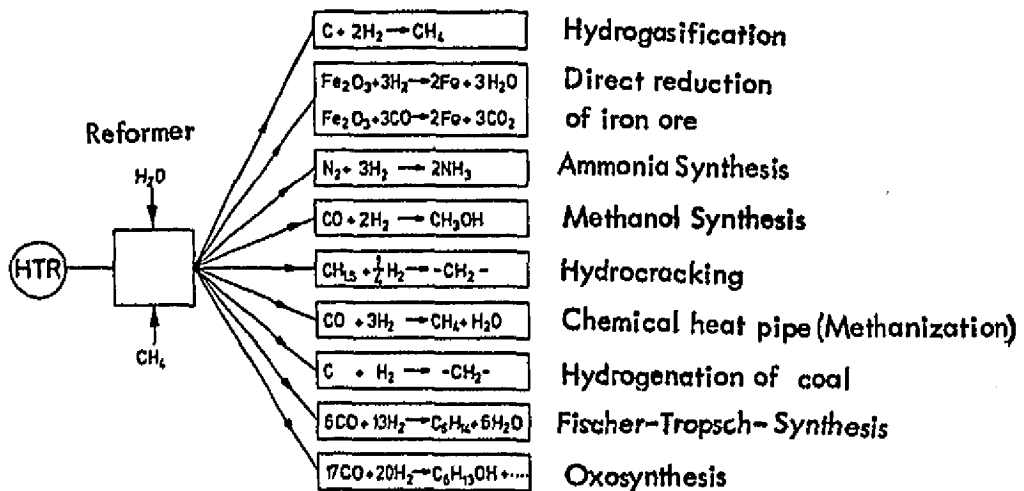


Fig.1.2-2: Products of Nuclear Process Heat

- The production of ammonia is made by synthesis of a mixture of hydrogen and nitrogen ( $H_2/N_2 \sim 3/1$ ). A common process would be to produce a gas with high hydrogen content in the steam reformer and to add air in a secondary reformer to get the needed gas mixture in the synthesis. Raw material is methane or gasoline.
- The methanol synthesis is made by using a mixture of hydrogen and carbon monoxide ( $H_2/CO \sim 2/1$ ). Raw material for this process is natural gas or gasoline, too.
- Hydrogen is used to convert heavy, sulfur containing oils (hydrocracking) to light hydrocarbons or gases such as  $H_2$ ,  $H_2/CO$ -mixtures or  $CH_4$ . The byproducts of the process ( $C_1$ - $C_4$ -hydrocarbons) are used as feed for the steam reformer. The conversion process of the heavy feedstock is made in several hydrocracking stages, these are high pressure catalytic processes, too ( $T \sim 400^\circ C$ ,  $p \sim 100$  b) (ref.3).
- To transport nuclear energy (chemical heat pipe system) the steam reformer process can be connected with a methanation process, which makes the reversible reaction ( $CO + 3H_2 \rightarrow CH_4 + H_2O$ ,  $\Delta H = +49$  kcal/mole). This methanation can be located far away from the steam reformer process. In this way the chemical heat of the process is transported over a long distance. The heat is carried by the chemical potential of the cold steam reformer products  $H_2$  and  $CO$ . Because gas transport with high pressure is very cheap, this can be an interesting way to transport nuclear heat in competition to the transport of electrical energy, which is relatively expensive. Product of the methanation process ( $T \sim 450 \dots 600^\circ C$ ,  $p \sim 40$  b) is heat which is used to make power by a back pressure turbine and steam or district heat. Feed for the steam reformer is methane, which is recycled as a product of the methanation by a further gas pipe (ref.4).
- Hydrogen is furthermore used to convert coal to gasoline (coal hydrogenation). The byproducts of the hydrogenation process ( $C_1 \dots C_4$ -hydrocarbons) are the raw materials for the steam reformer process. The hydrogenation process itself is a high pressure catalytic process ( $T \sim 400^\circ C$ ,  $p > 300$  b) (ref.5).
- The Fischer-Tropsch synthesis produces a broad spectrum of hydrocarbons by a catalytic process. Raw material for the steam reformer could be methane made in a coal hydrogasification process.
- The oxosynthesis is used to produce alcohol from mixtures of  $H_2$  and  $CO$ . These gases are made in the steam reformer too, raw materials are methane or natural gases or other light hydrocarbons.

As a conclusion it can be stated that the steam reformer process can be used for a lot of applications of nuclear process heat. Its function is to transfer the heat of the nuclear reactor from the primary helium circuit to the chemical process. The main advantages of this process are:

- it is a very well known reaction, which is in use since 20 years.
- the process requires a gas-gas heat exchanger, if one thinks of nuclear applications, no corrosion and erosion problems arise.
- the temperatures of the process are relatively low (750...850 °C), such that the materials are very well known ( $T_{\max} \sim 900$  °C) and have proved to have sufficiently high heat fluxes.
- The temperature of the nuclear reactor must not be higher than 950 °C because of the excellent heat transfer behaviour of helium at 40 b pressure. This temperature value is really used in the AVR-reactor during normal operation.
- the reforming process is very flexible from the point of view of temperature (reaction temp. 750...850 °C), pressure (1...40 b) and steam/hydrocarbon ratio (1.5...5). If a reformer pressure  $p=40$  b is used, there is no pressure difference on the reformer tube walls during normal operation.

The following figures 1.2-3-1.2-8 show the principle of the main processes in more detail. The primary helium circuit can be made in the same way for all processes. The flow sheet on the helium side can be changed by using other flow schematics for the process (achieved by use of waste heat of the reformer gas, operation of back pressure turbine, change in splitting of reactor power for steam reforming and steam generation, changes in needed gas specifications ( $T, p, H_2O/CH_4$ )).

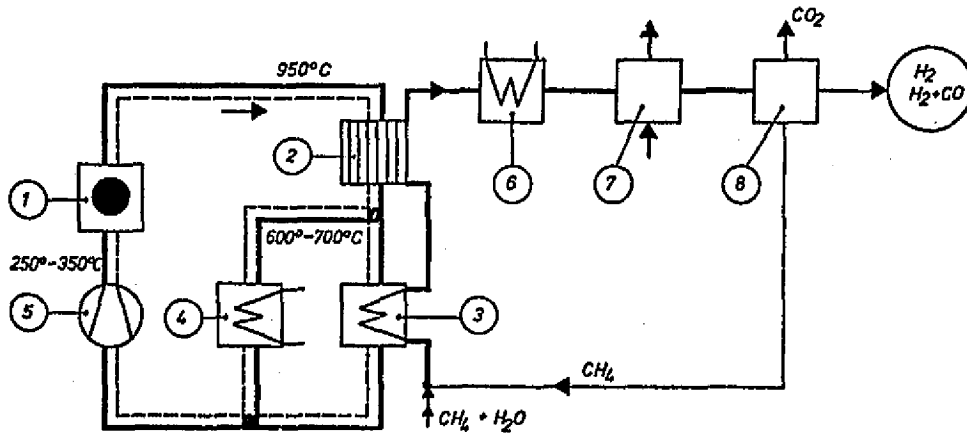


Fig. 1.2-3 Steam Reforming of Methane

- 1) Nuclear Reactor
- 2) Steam Reformer
- 3) Preheater for Feed
- 4) Steam Generator
- 5) Circulator
- 6) Waste Heat Utilization
- 7) Shift Converter
- 8) CO<sub>2</sub>-Purification + CH<sub>4</sub>-Separation

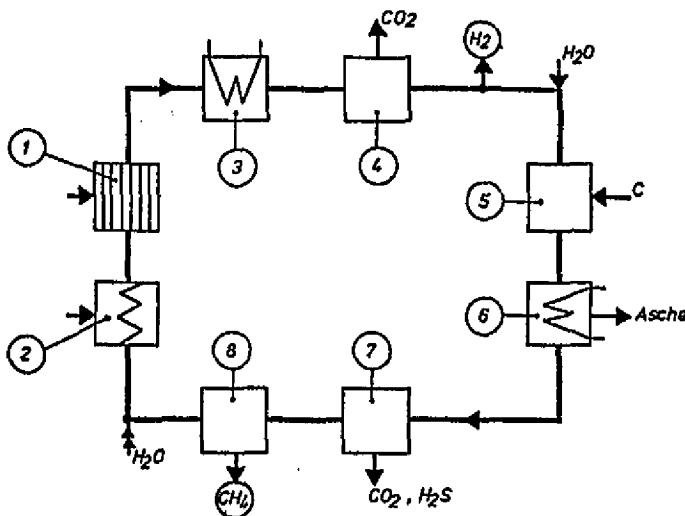


Fig. 1.2-4: Hydrogasification

- 1) Steam Reformer
- 2) Preheater for Feed
- 3) Waste Utilization
- 4) CO<sub>2</sub>-Purification
- 5) Hydrogasification
- 6) Ash Separation + Waste Heat Utilization
- 7) CO<sub>2</sub>/H<sub>2</sub>S-Purification
- 8) CH<sub>4</sub>-Separation

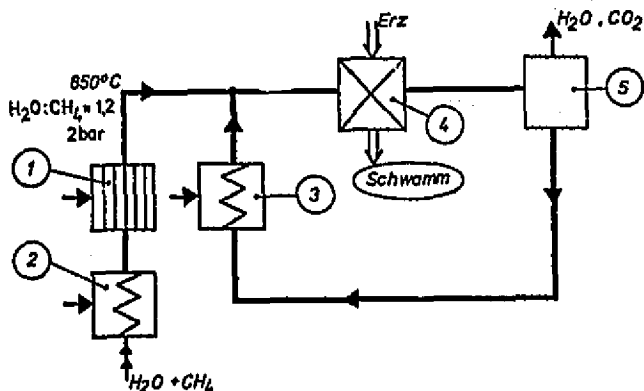


Fig. 1.2-5: Direct Reduction

- 1) Steam Reformer
- 2) Preheater for Feed
- 3) Heater for Reducing Gas
- 4) Reducing Furnace

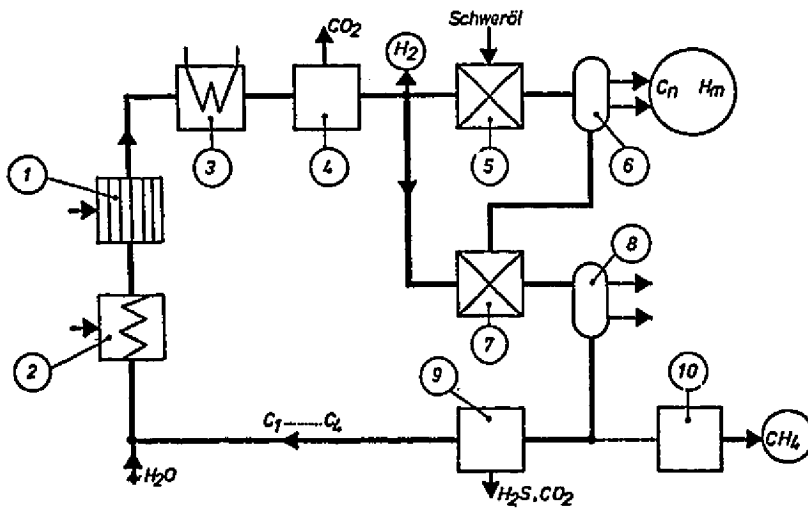


Fig.1.2-6: Hydrocracking

- 1) Steam Reformer
- 2) Preheater for Feed
- 3) Waste Heat Utilization
- 4) CO<sub>2</sub>-Purification
- 5) 1. Hydrocracking Unit
- 6) 1. Distillation
- 7) 2. Hydrocracking Unit
- 8) 2. Distillation
- 9) H<sub>2</sub>S/CO<sub>2</sub>-Removal
- 10) Enriched Gas Stage

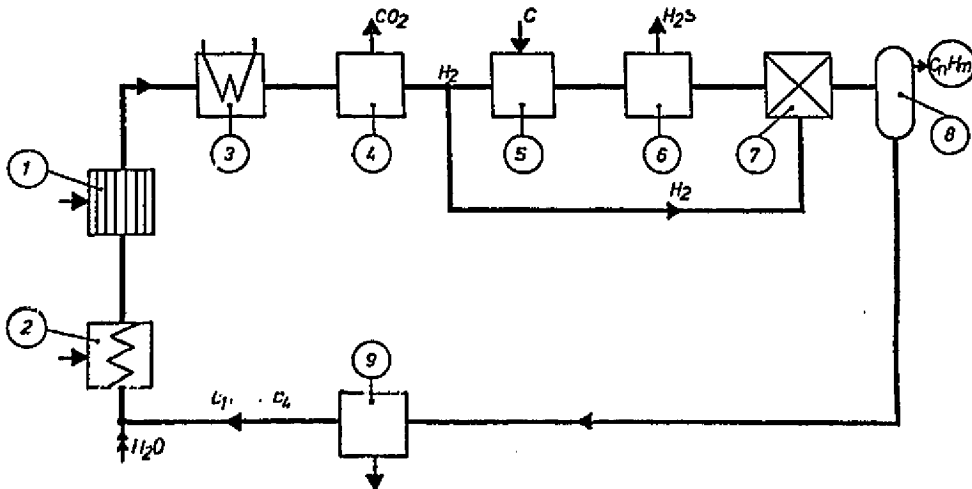


Fig.1.2-7: Coal Hydrogenation

- 1) Steam Reformer
- 2) Preheating of Feed
- 3) Waste Heat Utilization
- 4) CO<sub>2</sub>-Purification
- 5) Hydrogenation Unit
- 6) H<sub>2</sub>S-Purification
- 7) Hydrocracking
- 8) Distillation
- 9) Gas Purification

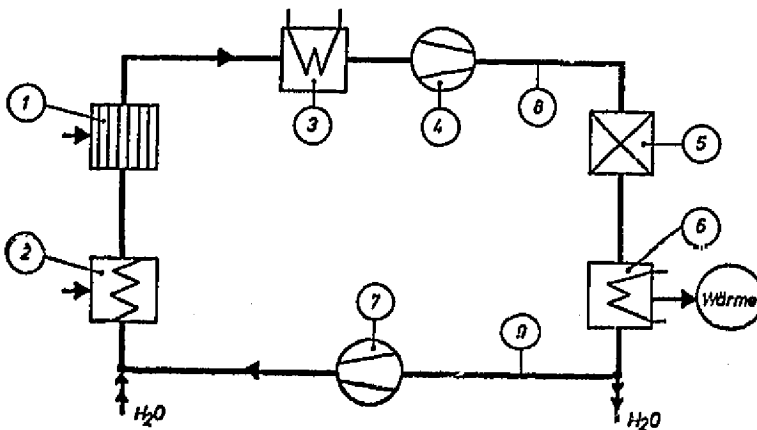
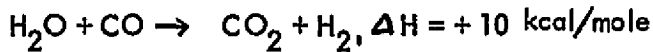
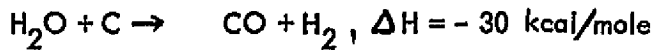


Fig.1.2-8: Chemical Heat Pipe

- 1) Steam Reformer
- 2) Preheating of Feed
- 3) Waste Heat Utilization
- 4) Gas Compressor
- 5) Methanation
- 6) Steam Generator
- 7) CH<sub>4</sub>-Compressor
- 8) Pipe for Reformer Gas
- 9) Pipe for Methane

### 1.2.3 Coal Gasification with Steam

The direct gasification of coal with steam is done in gasification units following the reactions:



with high temperatures and high pressures. Dependent on the type of coal, the temperature on the heating site of the process must be 900 °C (for lignite with reaction temperature of 700 °C to 800 °C for hard coal). Higher reactor outlet temperatures help to get smaller reaction volumes and higher throughput of coal. The gasification process itself should work at a pressure of 40 b.

For these processes an intermediate heat exchanger is necessary. The reasons are as follows:

- 1) The handling of ash and coal in the reactor containment building is very difficult and probably not allowed, due to technical safety reasons.
- 2) Coal gasifiers are more susceptible and have a shorter lifetime than steam reformers. Therefore these installations should be set up outside the nuclear part, to allow turning off and repairs.

Fig. 1.2-9 shows the results of laboratory experiments on coal gasification by steam obtained by Bergbau-Forschung, Essen/Germany.

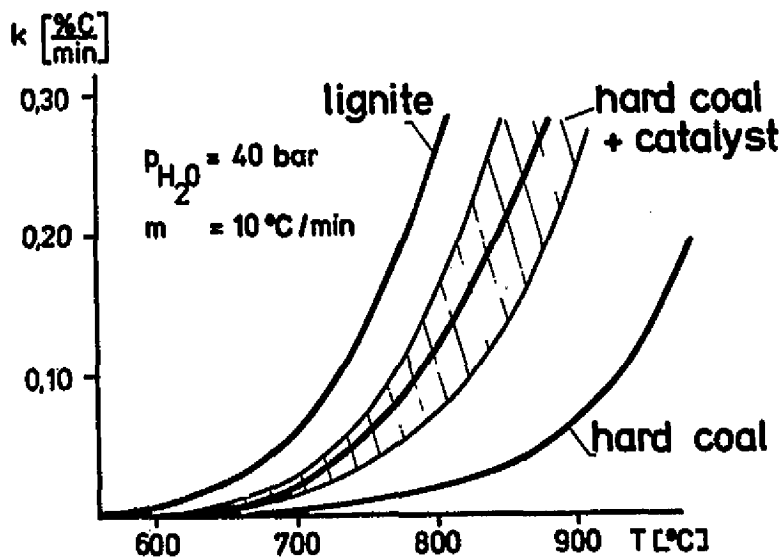


Fig.1.2-9: Velocity of Gasification of Coal (ref.6)

Using helium as IHX-medium which seems to be best from the thermodynamical point of view and the same pressure in the IHX-circuit as in the reactor primary circuit, very high stresses in the walls of the tubes in normal operation are avoided. The material of the IHX, however, must be operated at 900 °C in the first stage of development. For higher temperatures new materials must be tested and developed.

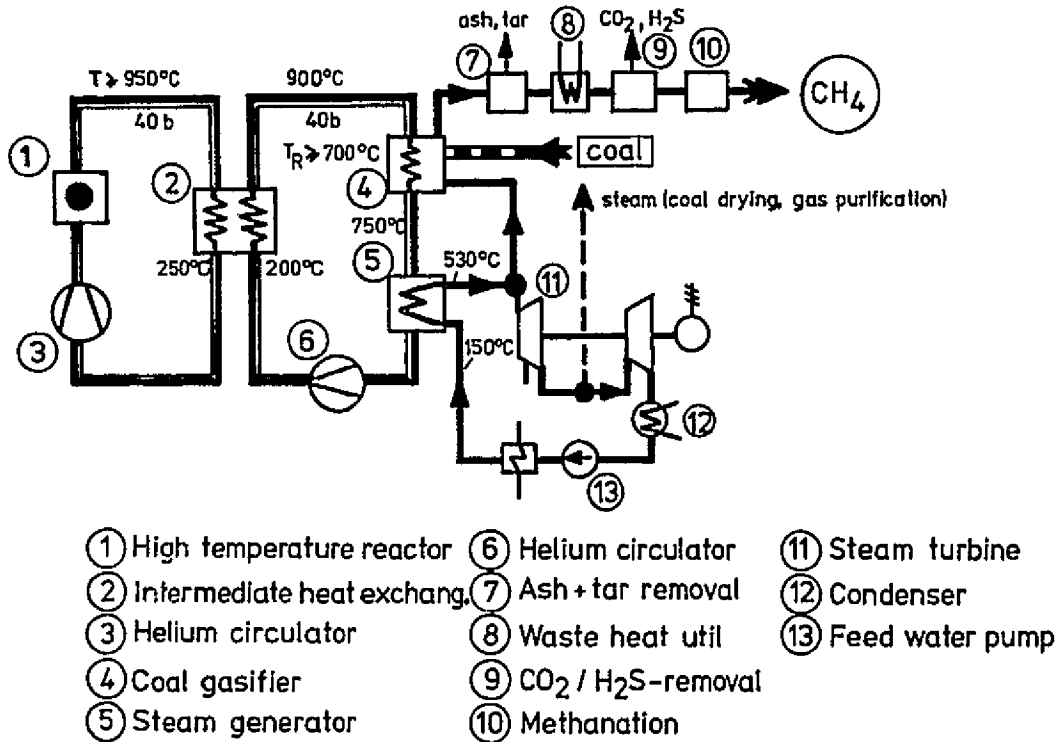


Fig. 1.2-10

Coal Gasification with Steam

KFA / IRE

The outlet temperature of the nuclear reactor should be in the order of 950 °C (for lignite) to 1100 °C (for hard coal) to allow heat fluxes, which are consistent with economical considerations and to get high throughputs of coal.

### 1.3 Conceptual Design of Pebble-Bed Reactors for High Temperature Process Heat Application

#### 1.3.1 Flow Sheet, Mass and Energy Balances

The reactor plant is designed for the production of process heat for steam reforming of methane and for electricity generation with steam turbines.

The flow diagram (Fig. 1.3.1-1) shows that in the process heat exchanger, the heat of the helium in the temperature range  $950 - 700^{\circ}\text{C}$  is utilized for steam reforming of methane and for superheating the process gas. In the lower temperature range of helium  $700 - 250^{\circ}\text{C}$ , the production of turbine steam is carried out.

The turbine steam ( $540^{\circ}\text{C}/195\text{ b}$ ) is led to a high pressure turbine, in which the enthalpy drop to  $320^{\circ}\text{C}/47\text{ b}$  is utilized for electricity production. The steam taken off from the high pressure turbine is mixed with preheated methane. By utilizing a part of the waste heat of the product gas the mixture is superheated to  $450^{\circ}\text{C}$  and led to the steam reforming furnace. The remaining steam leaving the high pressure turbine is led to an intermediate pressure turbine, and after that partly condensed and partly used for the  $\text{CO}_2$  scrubber. The waste heat of the product gas is utilized partly for preheating feed water and partly for steam generation, and preheating of methane. The steam reforming process itself takes place at an end temperature of  $825^{\circ}\text{C}$ , an end pressure of 40 b and a steam/hydrocarbon ratio of 3/1.

By using inner return ducts for the product gas in the reformer tubes, the temperature difference of the product gas between  $825^{\circ}\text{C}$  and  $600^{\circ}\text{C}$  is utilized for heat transfer to the process itself.

Table 1.3.1-2 shows the most important thermal data for the various designs shown here. Such a plant is assumed to be a typical plant for hydrogen production from natural gas or refinery gas. Basically all the considerations made here are also assignable to all other processes which use a steam reformer.

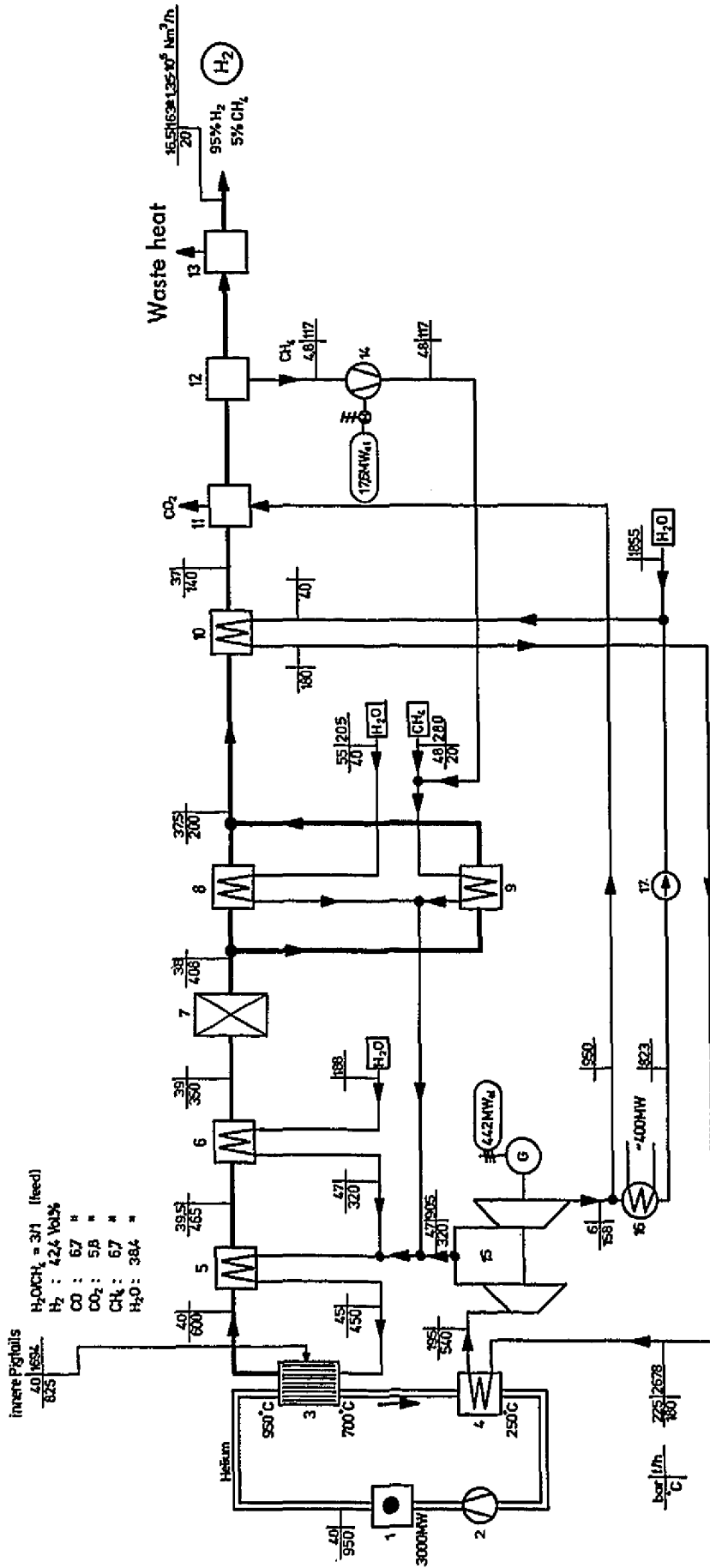


Fig. 1.3.1-i: Flow Sheet of a typical Nuclear Steam Reforming Process for Hydrogen Production

- 1 Nuclear Reactor
- 2 Circulator
- 3 Steam reformer
- 4 Steam generator
- 5 Waste heat vessel
- 6 Waste heat vessel
- 7 Conversion
- 8 Steam generator
- 9 Methane preheater
- 10 Feed water preheater
- 11 CO<sub>2</sub>-scrubbing
- 12 Methane separation
- 13 Methanation
- 14 Methane compressor
- 15 Back pressure turbine
- 16 Condenser
- 17 Feed water pump

Table 1.3.1-2: Data for Heat Flow Diagram

Thermal reactor power	3000 MW
Temperature range for high temperature process heat	700 - 950 °C $\cong$ 1071 MW
Temperature range for low temperature process heat	700 - 250 °C $\cong$ 1929 MW
Number of steam reforming furnaces	8
Number of steam generators	4
Number of circulators	4
Hydrogen production (95 %)	$1.35 \cdot 10^6 \text{ Nm}^3/\text{h}$
Net electrical power	370 MW
Methane consumption	$3.5 \cdot 10^5 \text{ Nm}^3/\text{h}$
Feed water consumption	2060 t/h
Steam reforming temperature	825 °C
Steam reforming pressure	40 b
Steam/methane ratio in steam reformer	3/1
Methane conversion in steam reformer	64.6 %

---

With the chosen reaction data for the reforming process:  $T = 825 \text{ }^\circ\text{C}$ ,  $p = 40 \text{ b}$ ,  $\text{H}_2\text{O}/\text{CH}_4 = 3/1$  the gas analysis is as follows:

Table 1.3.1-3: Gas Analysis

	<u>Vol %</u>	<u>Vol % (dry)</u>
H <sub>2</sub>	42.4	68.9
CH <sub>4</sub>	6.7	10.8
CO	6.7	10.8
CO <sub>2</sub>	5.8	9.5
H <sub>2</sub> O	<u>38.4</u>	<u>---</u>
	100 %	100 %

The conversion of methane is 64.4 %. The steam/methane mixture enters the steam reformer tubes with a temperature of 450 °C. Inside the reformer tube the gas is heated up to 825 °C. At the same time the reaction starts above a temperature of 600 °C and the heat for the reaction is transferred from the helium circuit.

The product gas is taken off by an inner pipe, there is a heat transfer from the gas in this tube to the catalyst bed and the processed gas. The product gas is cooled by this heat transfer to 600 °C. Related to 1 kmol of CH<sub>4</sub> ( $\hat{=} 16 \text{ kg CH}_4 \hat{=} 22.4 \text{ Nm}^3 \text{ CH}_4$ ) the heat balance is as follows:

Heat for reaction	$3.127 \times 10^4 \text{ kcal}$
Heat for preheating (450 → 825 °C)	$1.619 \times 10^4 \text{ kcal}$
Heat coming from inner tube (825 → 600 °C)	$- 1.058 \times 10^4 \text{ kcal}$
Total heat for steam reformer (in high temperature level)	$3.688 \times 10^4 \text{ kcal}$

This amount of heat in the steam reformer allows a throughput of methane of  $2.498 \times 10^4$  kmol CH<sub>4</sub>/hr. ( $\hat{=} 3.966 \times 10^5 \text{ kg CH}_4/\text{hr.} \hat{=} 5.595 \times 10^5 \text{ Nm}^3/\text{hr.}$ )

Table 1.3.1-4 shows the mass-balance for the process including all stages of the gas purification, which consists of shift conversion, CO<sub>2</sub>-removal, CH<sub>4</sub>/H<sub>2</sub>-separation and methanation.

Table.1.3.1-4: Mass Balance for Hydrogen Production

	Input Steam Reformer (kg/h)	Output Steam Reformer (kg/h)	Output Shift Converter (kg/h)	CO <sub>2</sub> from CO <sub>2</sub> -stripper (kg/h)	Hydrogen Fraction coming from low Temp. Separation (kg/h)	Recycle Methane (kg/h)	Hydrogen from Methanation
H <sub>2</sub>	406	108474	122446	624	121416	406	114744
CH <sub>4</sub>	384528	135968	135968	704	303528	104736	48320
CO	11620	238588	42980	224	31136	11620	--
CO <sub>2</sub>	--	326876	634260	634260	--	--	--
H <sub>2</sub> O	1297782	884430	758682	--	--	--	(20016)
Σ	1694336	1694336	1694336	635812	183080	116762	163064 (183080)

### 1.3.2 Design Criteria

As measured by today's HTR technology, the production and utilization of helium temperatures of 950 °C and higher bring a series of new and difficult problems. The present status is as follows: The AVR is presently operated at a mean helium outlet temperature of 950 °C; but hot gas streams reach a temperature of 1050 °C as a result of the radial temperature profile in the reactor. This reactor serves as a permanent test for the fuel elements which can be used for process heat applications. The behaviour of the fuel elements in the AVR until now is excellent. The fission product release is very low (20 Ci gaseous fission products, solid fission products Cs-137  $2,5 \times 10^{-10}$  Ci/Nm<sup>3</sup>). Ball type fuel elements for 950 °C gas outlet temperature can therefore be presently developed. The THTR-300 and the Fort St. Vrain Reactor are both designed for a mean coolant gas outlet temperature of 750 °C. A higher value is not necessary because of the application of these reactors for turbine steam generation (530 °C/180 at).

Basically, for the present designs, as many already known components as possible are used, and experience is made use of from the operation of the AVR, from the THTR development program or from results of the development programs of other types of gas cooled reactors. The essentially new components are the hot gas ducts between core and heat exchanger as well as the process heat exchangers itself. The core design makes use of presently developed and tested technology. Related to the present HTR scientific status, there are many technical possibilities and design criteria. They are listed in table 1.3.2-1.

Two different vessel designs are shown. The pod-boiler design is similar to current practice. In high temperature reactors the prestressed cast steel vessel seems to be a promising alternative from the standpoint of fabrication, ease of repair, reliability, construction time, and cost.

Intermediate heat exchangers are not necessary for steam reformer processes, if the temperature of the helium does not exceed 950 °C. If there are reasons in the future to have an IHX, the reformer can be substituted by an IHX without changing the design of reactor vessel internals, blowers, etc. Possibilities for flow sheets with IHX are shown in Fig. 1.3.2-2.

The power density used in the design is 5 MW/m<sup>3</sup>. There seem to be no economic advantages for higher power densities, because the blower power increases with power density. This compensates for the saving in capital cost with higher power densities resulting from smaller vessel size. The fuel cycle cost is nearly independent of power density. As far as material behaviour in core, fission product release, and conversion are concerned, a small

design choice	Technical possibilities	Remarks	Choice for designs
reactor vessel	a) podboiler concrete b) loop concrete (with burst protection) c) prestressed steel vessel (podboiler) d) prestressed steel vessel (loop) e) prestressed steel vessel (THTR)	podboiler design is standard prestressed steel vessels should have advantage in cost, construction time, flexibility, repair, fabrication	a) podboiler concrete b) integrated loop prestressed steel vessel
intermediate heat exchanger	no yes apart of reactor heat transfer	safety (H <sub>2</sub> , T, explosion) technical difficulties with hot pipes, penetrations, valves, costs dependent on process for CH <sub>4</sub> -reforming not needed for coal gasification with steam needed safety, aftercooling materials (reflector) no cost advantage with higher power density	no for steam reforming. Fall back position is needed
core power density	5...10 MW/m <sup>3</sup>	Design must be removable, depressurization of system must be limited to ~1 b/sec	5 MW/m <sup>3</sup> coaxial pipe metallic with insulation
hot gas ducting	a) single tubes b) coaxial pipes (metallic without insula.) c) coaxial pipes (metallic with insulation) d) coaxial pipes (ceramic)	carbon stone for worst accident, that all circulators fails aftercooling of core by liner fiber today standard HITGR	carbon stone for core cavity fiber for hot gas ducts
insulation materials	a) fiber b) metallic grid c) carbon stone d) other ceramics	tubes improved by conventional plants and EVA pilot plant	tubes
steam reformer	b) steam generator (H <sub>2</sub> O/CH <sub>4</sub> ) <sub>2</sub> > 8 in process c) gas heater, external beds	more redundancy with 6...12 production loops	normal production loops for auxiliary cooling. Additional liner cooling for afterheat-removal
auxiliary cooling systems	a) separate loops (4 x 50 % or 3 x 100 %) b) normal production loops (4...12 loops)	safety for external accidents (aircrash, fire pressure waves by explosions) costs, fusion product retention by earth Thorium is more interesting in future from point of reserves	for design 1: above earth and air for design 2: below earth and N <sub>2</sub>
containment	a) above earth, below earth b) air or N <sub>2</sub> -filling		Thorium - normal converter
fuel cycle	a) Thorium normal converter b) low enrichment thermal breeder (with BeO balls)		
circulators	a) electrical motors b) steam turbine drive	electrical motors are used in AVR, Dragon, THTR, Improved technology (bearings with oil)	electrical motors

Table 1.3.2-1: Design Criteria

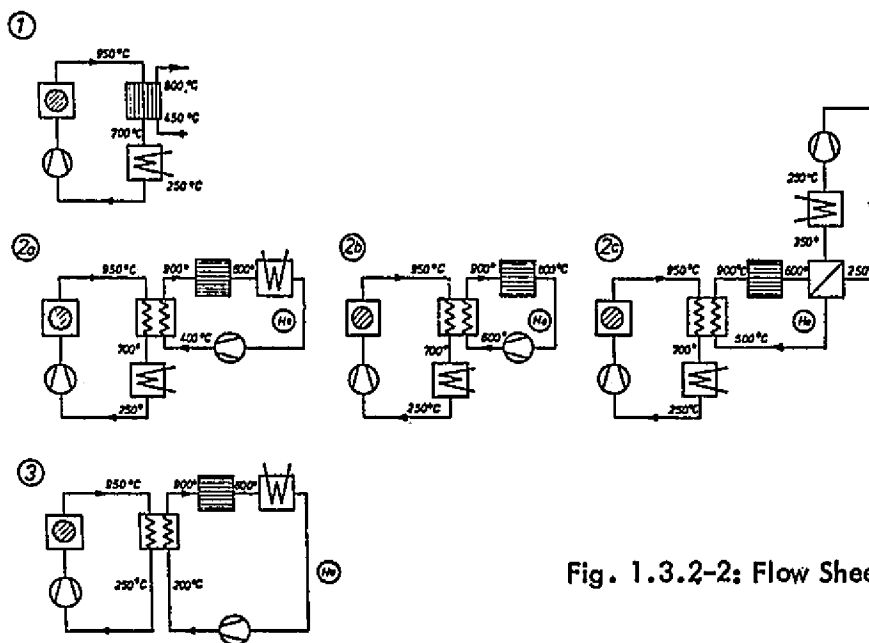


Fig. 1.3.2-2: Flow Sheets for IHX

power density is better. With a power density of  $5 \text{ MW/m}^3$ , the heat capacity of the core is large enough to restrict the fuel temperature to allowable values, even if all emergency cooling should be lost. In this case the liner cooling acts as a sufficient heat sink.

Hot gas ducting in these designs occurs by coaxial pipes with inner insulation. In this case, vibration and compensation for expansion are minimized because of the low temperature of the inner thick-walled insulated hot gas pipe. A removable design must be chosen because the behaviour of the gas ducting metallic liner tube for  $950^\circ\text{C}$  and a 30 year lifetime is not known at present.

For the steam reformer, the tubes are similar to those used in conventional steam reforming plants. These tubes have also been tested in a full-scale helium-heated single tube model (EVA-plant in Jülich). Other possibilities can be considered, but they must first be tested.

Auxiliary cooling should be done by the normal production loops, to save money and space in the reactor vessel. For the necessary redundancy, four or more loops must be used. Reactor designs with 12 loops which are identical (steam reformer and steam generator tubes in one vessel) and contain a blower each are better from this point of view. The AVR, THTR and Fort St. Vrain normal production loops are used to remove the after-heat.

The containment should be below the earth and filled with nitrogen for safety reasons. External accidents, such as aircraft crash, fire, pressure waves by explosion, can be better tolerated. Nitrogen is needed to avoid core burnup by air and explosive mixtures in the containment.

In the fuel cycle, thorium should be chosen because for HTR the thorium cycle is much more interesting from the point of view of reserves. Furthermore there is the possibility to change over to high converter operations or even to a Breeder by use of BeO-dummy balls.

The blowers should be driven by electric motors because there is a lot of experience from AVR, Dragon and Peach Bottom with these components. The THTR will also have electrically driven blowers.

The reactor system described here has the following main features:

- OTTO cycle (Once Through Then Out) fuel element flow.
- Primary system in the containment.
- Carbon stone insulation of the core liner.
- Coaxial pipes for the hot gas ducts.
- Podboiler design of the prestressed reactor vessel, or alternatively.
- A prestressed cast steel vessel for the primary system.

For the following reactor design, this data has been used:

Thermal reactor power	3000 MW
Core power density	5 MW/m <sup>3</sup>
Reactor inlet temperature	250 °C
Reactor outlet temperature	900 °C
Helium pressure	40 b
Helium mass flow	820 kg/sec
Core height	6 m
Core diameter	11.28 m

Table 1.3.2-3: Main Data of Reactor

### 1.3.3 Podboiler Design (Concrete Reactor Vessel)

The total primary system is integrated in a prestressed concrete reactor vessel. For the chosen splitting up of reactor power into a part for steam reforming ( $950\dots700^{\circ}\text{C}$ ) and for steam generation ( $700\dots250^{\circ}\text{C}$ ), 8 cavities are required for the steam reformer tubes and 4 cavities for the support of the steam generators.

Fig. 1.3.3-2 shows a design of this reactor system.

The helium flow is as follows (see Fig. 1.3.3-1): Cold helium ( $280^{\circ}\text{C}$ ) flows from the upper cold gas chamber through the top reflector to the core and is heated up in the pebble bed to  $980^{\circ}\text{C}$ . It passes through the bottom reflector, which contains a lot of small holes and arrives in the hot gas chamber at the bottom of the reactor, which is made of graphite blocks and graphite columns. From here the hot helium ( $950^{\circ}\text{C}$  includ. bypass) is ducted by a coaxial pipe to the 8 steam reformers. In the heat exchangers the helium is cooled down to  $700^{\circ}\text{C}$ . The heat is used for the steam reforming process and for super-heating of the feed.

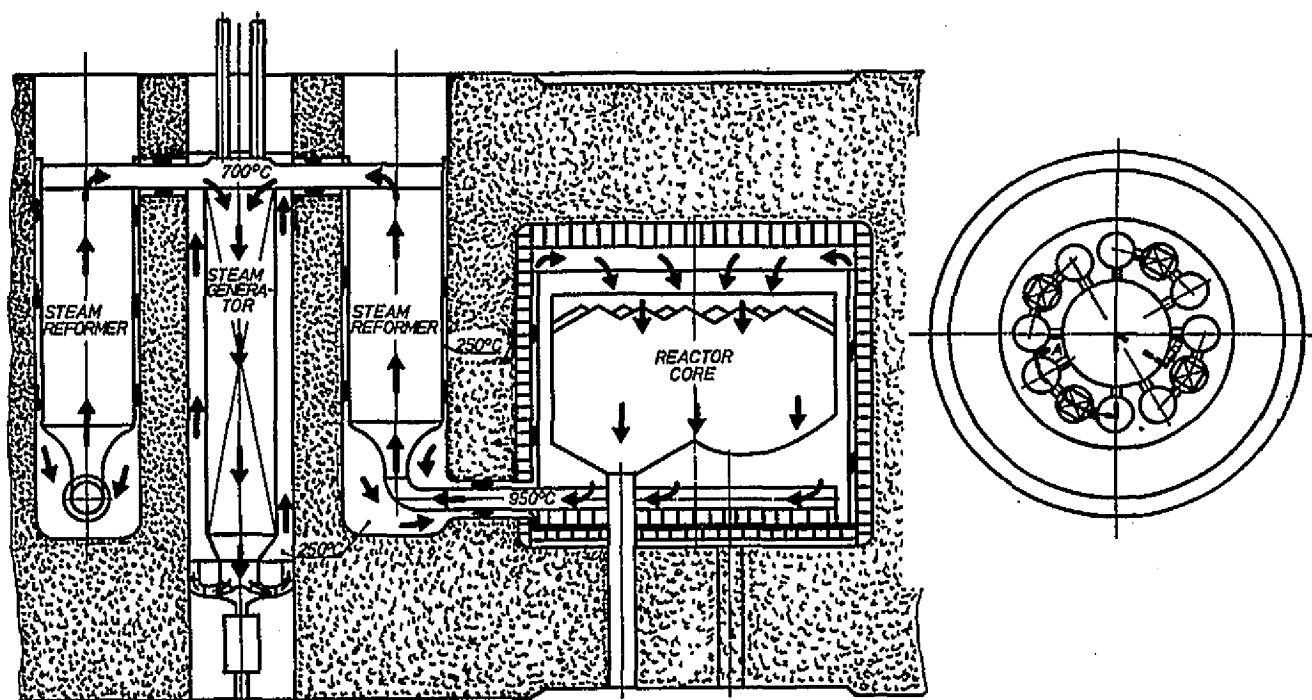
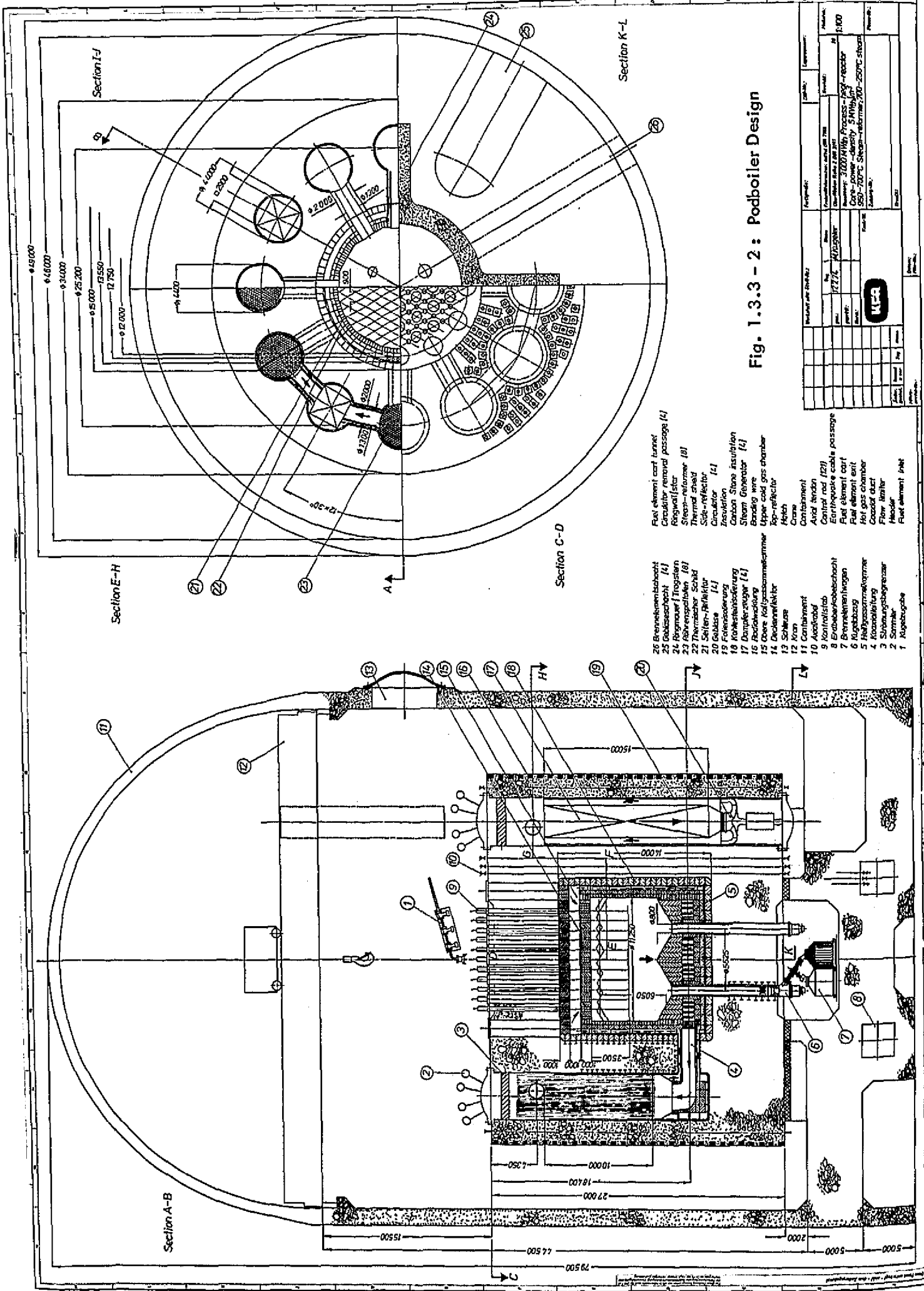


Fig. 1.3.3-1: Gas Flow in Primary Circuit

From here, helium flows through hot gas pipes to the steam generator. In a downward stream, the enthalpy of helium between  $700$  and  $250^{\circ}\text{C}$  is used to produce steam. Two steam reformers are each connected to one steam generator. Circulators are located at the end of the steam generator gas ducting system. They compress the helium to the normal operation pressure (40 b).



Now this cold helium in counterflow cools all hot gas ducting systems as it flows back to the reactor, i.e. the gas ducting system for the steam generator, the hot gas ducting between steam generator and steam reformer (coaxial pipes), the gas ducting system in the steam reformer and the hot gas duct between steam generator and core (coaxial pipe). The cold gas is sampled in the bottom of the reactor in a cold gas chamber, which is part of the thermal shield. From here the cold gas is led to the upper cold gas chamber inside the thermal shield by holes. By using this flow arrangement all liner and penetration areas in the reactor vessel only must be insulated against 280 °C helium. An additional advantage is that the pressure difference for all gas ducting systems is small and in all cases leakage will be of cold gas into hot gas rather than vice versa.

The handling of fuel elements is very simple in this reactor design. The balls are fed continuously into the top of the reactor by systems of three valves connected with a fuel element distributor. Each day dependent on the fuel cycle, 3,000 to 4,000 balls must be fed into the reactor. The valves act as a lock to change over from air at 1 b to helium at 40 b. The fuel balls move through the core (duration: 3 years) and are taken off at the bottom of the core by 3 discharge tubes. These discharge machines consist a rotating disk with a hole, which takes off the fuel elements continuously. By a system of 3 valves, the fuel elements fall into a pressure vessel (40b) for spent fuel elements without operation of the valves. This vessel is removed when it is filled. The spent fuel then will be brought to a reprocessing plant or to fuel storage. Irradiated fuel elements are not recycled as in THTR. All components of this fuel handling system have good performance and qualified by seven years of operation of AVR.

The reactor is shut down by rods which are inserted directly into the pebble bed. For load control, it is not required to penetrate the core, because the upper reflector is very important to the reactivity of the system. Therefore it is sufficient to remove the rods at the top reflector and the space above the core. Scram is made by inserting the rods 0.5 m into the core. Cold subcritical shutdown must be made by insertion of the rods to 2.5 m depth into the pebble bed. There are no problems with these shut down systems following the experience with the THTR-development.

The core structure is made as follows: The pebble bed is surrounded only by graphite (top reflector, bottom reflector, side reflector). The graphite structure is enclosed in a thermal shield of cast iron, which is cooled by helium at 280 °C. Between this thermal shield and

the liner of the core cavity in the vessel there is a layer of carbon stone as an insulating material. This layer is needed, if the liner cooling system is to be used as an emergency cooling system for the very unlikely accident, that all circulators fail. The top reflector and the upper part of the side reflector, which get relatively high neutron irradiation dose, are removable by using the penetrations of the control rods in the top of the reactor. By the use of the OTTO fuel cycle (see 1.3.5.1), no prohibitively high fast flux will exist in the upper side reflector or in the top reflector if the mean power density in the core is limited to  $5 \text{ MW/m}^3$ . The hot parts of the side reflector and the hot core bottom will, on the contrary, receive a very low radiation dose in the OTTO cycle, so that in this area many of the usual problems of core design are avoided.

For this process heat reactor design, a podboiler vessel was used, because this today is the standard design for HTGRs. The dimensions of the reactor vessel and especially the diameter of the core cavity are obtained from the size and the number of pods. At the design pressure of 40 b, at least half a pod diameter must be left as spacing between the pods - diameter 4.4 m - so the core cavity has a diameter of 15 m. This leads necessarily to a mean core power density of  $5 \text{ MW/m}^3$ , since space and material in the container should not be wasted by superfluous concrete. In this design, the blowers are arranged underneath the container. Other arrangements are also possible. The pod liners and penetration areas are insulated by fiber and a covering metallic plate against helium at  $280^\circ\text{C}$ . To avoid failures in these insulation systems by rapid depressurization of cooling gas, a flow limitation is needed in all big penetrations of the vessel. This can be made by double closures. The core cavity liner is insulated by a layer of carbon stone. Bypass flow in this layer can be avoided by metallic sealing systems. The reactor vessel is prestressed by circumferential tendons on the outside of the cylindrical wall and by vertical tendons. The vessel is supported by a ring-wall on the foundation.

The reactor containment building contains all parts of the primary system together with the auxiliary system e.g. gas purification, helium circuits, helium storage, and reactor safety systems. It is made of concrete with an inner metallic liner. It contains the usual cranes, locks, penetrations for feed water, steam, reformer gas, energy supply and cooling water.

The height of this containment is large enough to allow the heat exchanger to be withdrawn in the upward direction for replacement.

All main components of the system like vessel, fuel elements, internal structures, process heat exchangers, fuel handling systems, control rods, circulators, and containment are discussed in more detail in 1.3.5. There is a short discussion of possible accidents and the safety behaviour of this system in 1.3.6.

#### 1.3.4 Loop Design (Prestressed Cast Steel Variant)

A big advantage in HTR-technology would be to use prestressed cast steel vessels instead of concrete vessels. There is hope to reduce cost and construction time, to get the possibility to repair and demount the vessel and to be more flexible in design than with concrete vessels.

By using prestressed cast steel blocks instead of prestressed concrete as vessel material, the difference between the loop and pod boiler system are small, as will be shown in detail in Vol. 3, Sect. 8. Because of the greater flexibility in adaptation of the heat exchangers, an integrated loop system is first investigated here. The reactor vessel itself consists of steel blocks, which are prestressed against pressure by axial and radial cables. This system has no inner liner and no armoured liner for the flow ducts. Sealing welds on the outer surface between the separate blocks make this container gas-tight. This is because the construction material, cast steel, is inherently gas-tight for helium and because it is easy to weld. The separate blocks are additionally prevented by shearing wedges, keys and bolts from being dislocated. The separate heat exchangers as well as the various coaxial ducts are constructed according to the same principle and prestressed. They are additionally fastened onto the main vessel to be safe against earthquakes. The foundation of the whole vessel and its loop is, similar to the prestressed concrete vessel, on a concrete ring wall with neoprene bearings. The separate blocks of the vessel each represent a unit in itself, and each is separately cooled with water.

A disadvantage in this vessel is that the drive for the control rods is not automatically integrated into the container wall, as is the case in the prestressed concrete vessels. Additional burst and splinter protection measures for this component are therefore required.

Here also the whole primary system is placed in a reactor containment building. The components are identical to those which were mentioned in the previous designs. All details which have been mentioned about gas flow, fuel handling, core internals, and control are the same as before.

Contrary to the podboiler design each loop contains steam reformer and steam generator heat transfer surfaces. Furthermore each loop is connected with a circulator. Therefore the developed circulators of THTR can be used with a small power rise.



### 1.3.5 Components

#### 1.3.5.1 Fuel Elements

If high temperature reactors are operated at gas temperatures which are interesting for nuclear process heat applications (i.e. 950 °C and more), the fission product release from the coated particles and the corrosion of the fuel element surface must be limited. Therefore, all fuel element temperatures during continuous operation should be held as low as possible. According to all considerations of fuel element cycles and fissile material distributions which have been employed up to now, the following method should achieve the lowest fuel element temperatures at defined outlet gas temperatures:

Fresh ball type fuel elements are introduced at the top of the core, and flow once through the core due to gravity. After reaching their specified burn up (about 3 years) they are removed from the bottom of the reactor: OTTO cycle (Once Through Then Out) . The helium coolant gas flows in the same direction as the flow of the fuel elements, and is heated to the desired temperatures.

Using this flow system, the following results are achieved:

In the axial direction, the fissile material content of the fuel elements in the core decreases from the top to bottom. The heat flux and power density have the corresponding distribution, decreasing from the top to the bottom. In this manner, the highest power density is achieved at the top of the core, where the coolant gas enters at a relatively low temperature. The power density of the fuel elements is very low at the bottom of the core, only an after-burning occurs, which results in an equalization of burn up. With such a power distribution, the coolant is very rapidly heated in the upper part of the core, where large temperature differences between the gas and the fuel elements occur, while in the lower part of the core the differences become very small.

The following review shows the conditions in a reactor with the OTTO-fuel loading explained above. A detailed consideration of a single element shows that for a power density of 1 MW/m<sup>3</sup>, a temperature difference of about 30 °C exists between the gas and the coated particle. In order to obtain high coolant outlet temperatures, the above OTTO cycle has the best prerequisites, in which a low power density automatically occurs at the coolant outlet and not through control of various levels of enrichment in the axial direction.

For the design of the fuel elements the following numbers can be applied (see Tab. 1.3.5.1-2). With a specified coolant outlet temperature of 980 °C, and a mean power density in the core of 5 MW/m<sup>3</sup>, the surface temperature of the fuel element reaches a maximum value of

about  $1000^{\circ}\text{C}$ , and the coated particle reaches a maximum temperature of about  $1010^{\circ}\text{C}$ . In general, a 2-zone loading of the core will be suitable, so that for the radial temperature profile, a maximum temperature difference of  $50^{\circ}\text{C}$  is to be expected.

According to today's technology, the design is such that the ball fuel elements of the THTR have the following specifications: surface temperature:  $1050^{\circ}\text{C}$ , coated particle temperature:  $1250^{\circ}\text{C}$ . While the fuel temperature includes a high safety factor, the surface temperature limit is reached. Fig. 1.3.5.1-1 shows typical power and temperature distribution curves for a HTR operating on the OTTO cycle.

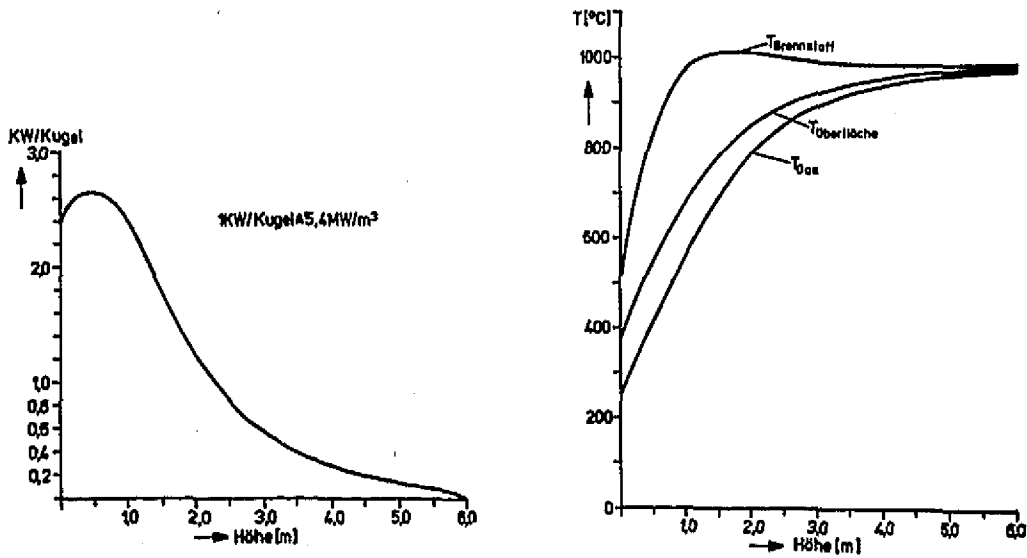


Fig. 1.3.5.1-1 a): Typical Power and Temperature Distribution in a HTR-pebble bed reactor using OTTO cycle (ref.7)

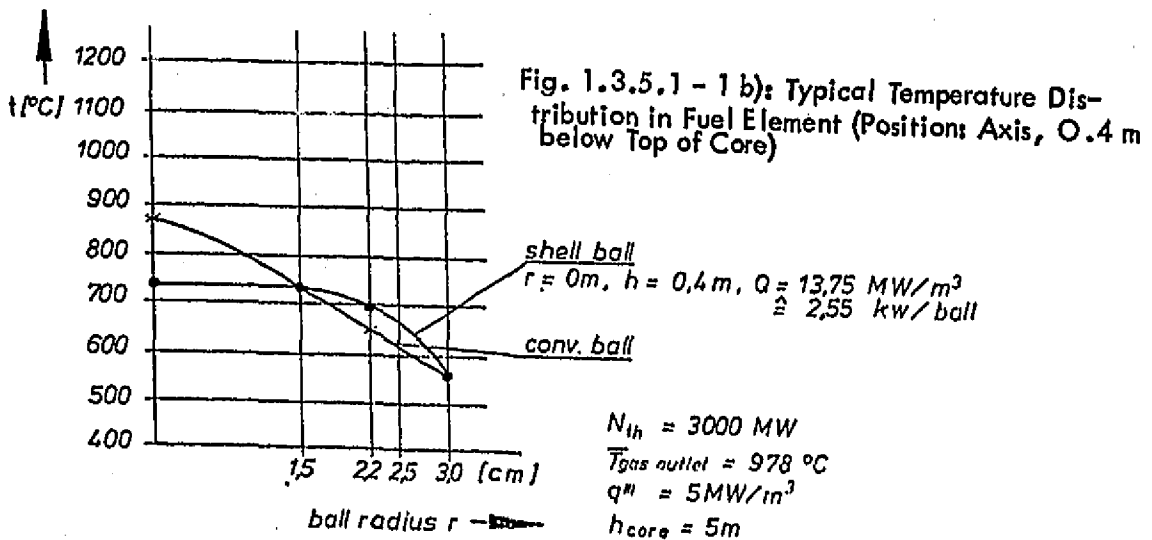


Fig. 1.3.5.1-1 b): Typical Temperature Distribution in Fuel Element (Position: Axis, 0.4 m below Top of Core)

Now irradiation tests have been started to prove the assumption that predictions regarding the typical, new type of behaviour of the fuel elements (low temperatures at high dose during the first half of reactor operation, high temperature at low dose and low temperature gradients in the second part) can be made from the results of the fuel element irradiation program undertaken up to now.

Outer fuel element diameter	6 cm	
Diameter of fuel zone	5 cm	
Thorium cycle		
	zone 1	zone 2
Initial enrichment	6.7	8.9 %
Burnup	99200	112180 MWd/tHM
Lifetime of fuel in core	1547	2030 days
Conversion rate	0,625	
Max. power of balls	2.37	2.65 kW/ball
Max. burnup	102116	118317 MWd/t
Fast dose in fuel element	$5.77 \times 10^{21}$	$6.04 \times 10^{21}$ n/cm <sup>2</sup> (E>100 KeV)
Fissile material in core	1514 kg U-235/ U-233	
Max. gas outlet temperature	997	971 °C
Max. fuel element surface temperature	1002	975 °C
Max. fuel temperature	1010	1010 °C
Pressure drop in Core	~ 0.4 b	

Table 1.3.5.1-2: Data of Fuel Elements (ref.7)

A big advantage of the pebble bed reactor system should be shown by the following table 1.3.5.1-3 which demonstrates how versatile the fuel cycle can be handled. Starting from the normal balls of AVR and THTR type the layout for a normal process heat reactor system can be made. If required by high uranium ore prices and if possible by high throughput of fuel elements through the reprocessing and refabrication plant, the burnup can be lowered and the conversion ratio made higher. The heavy metal content of the ball must be higher, but this is a well known step which can be made without difficulty in a qualification program. If necessary a thermal breeder can be realized by using BeO-balls without fuel. The mixture fuel element - BeO-balls should be 1/1. That means that the heavy metal content of the fuel elements must be higher than in a converter fuel element. If a lower power density and a smaller burnup are used, this seems to be feasible.

Data	Dimension	AVR	THTR	PR 3000		
				normal Converter	high Converter	thermal Breeder (BeO/C <sub>1</sub> /1)
Power	MWth	50	750	3000	3000	3000
Power density	MW/m <sup>3</sup>	2.5	6	5	5	3.5
Gas outlet temperature	°C	950	750	950	950	950
Heavy metal content of balls	g/ball	7	12	12	20	30...40
Burnup	MWd/tHM	140 000	100 000	100 000	40 000	25 000
Conversion	-	0.7	0.6	0.6	0.95	1.0-1.02
Fuel cycle cost	Dpf/kWhel	1.5	0.9	0.6	~ 0.9 <sup>+</sup>	~ 0.9 <sup>+</sup>

Table 1.3.5.1-3: Versatile Fuel (+ assumption of the same Uranium price)

### 1.3.5.2 Reactor Vessels

#### 1.3.5.2.1 Concrete Reactor Vessel

The reactor vessel is a standing cylinder constructed of prestressed and reinforced concrete. The vessel contains one large cavity for the core and twelve smaller cavities for the steam reformers and steam generators. The eight steam reformers are each directly connected by a duct to the core cavity. Eight additional ducts connect the steam reformers to the steam generators, two reformers being connected to each steam generator. At the top of the vessel there are 109 small penetrations for the control rods and 12 larger penetrations which are needed for removal of the top and side reflector<sup>+)</sup> . The reactor vessel is located inside the reactor containment building on a ring-wall of concrete. Neoprene bearings compensate for variations in temperature and pressure. The reactor is prestressed by circumferential cables on the cylindrical wall and by tendons for the vertical prestressing. If the reactor is operated with an inner pressure of 40 b, the concrete loses the prestressing. Tensile stresses which can occur in the walls are prevented by reinforcement of the concrete structure.

<sup>+)</sup>  there are other technical solutions, too, which need only 3 big penetrations to remove the reflector

The bursting of this type of vessel is impossible because of the redundancy in the prestressing system. A rapid loss of cooling gas however must be avoided to prevent damage to the insulation system. Therefore flow limitations in all large penetrations are needed, for instance, double closures for the blowers and heat exchanger penetrations. The inside of all cavities is covered by a layer of steel (liner, penetrations, pods). This steel is cooled from the outside by cold water which flows in small pipes welded onto the outer surface. The inner surface of the core cavity liner is protected against temperature by a layer of carbon stone, a material with low thermal conductivity ( $\approx 5 \text{ kcal/mh}^\circ\text{C}$ ). This layer allows a heat transfer of the afterheat from the core to the liner cooling system even if all circulators fail. The carbon stone insulation is made of blocks, which need a sealing system to avoid bypass flow and hot spots on the liner. The liner surfaces in the regions of the penetrations and pods are insulated against  $280^\circ\text{C}$  helium by a layer of fiber (Kaowool) which is covered and held in position by metallic plates, screwed onto the liner surfaces. All liner areas are anchored in the concrete by bolts..

The main data of the podboiler concrete vessel are summarized in table 1.3.5.2.1-1.

Inner diameter of core cavity	15 m
Inner height of core cavity	14 m
Number of pods	12
Diameter of pods	4.4 m
Outer diameter of vessel	34 m
Outer height of vessel	27 m
Operation pressure	40 b
Accident pressure	48 b
Velocity of depressurization	1 b/sec
Liner wall thickness	2 cm
Liner temperature	max. $50^\circ\text{C}$
Heat flux liner	max. $3\text{kW/m}^2$
Integrated heat flux for core cavity liner	max. 3 MW (normal operation)
Cooling system	water ( $\Delta T \sim 10^\circ\text{C}$ )
Material of vessel	reinforced concrete prestressed from the outside by cables and vertical tendons.
Material of liner, pods, penetrations	mild steel
Insulation of core cavity	carbon stone
Insulation of pods penetrations (against $280^\circ\text{C}$ helium)	fiber + metallic covering plate

Table 1.3.5.2.1-1: Data of Concrete Reactor Vessel

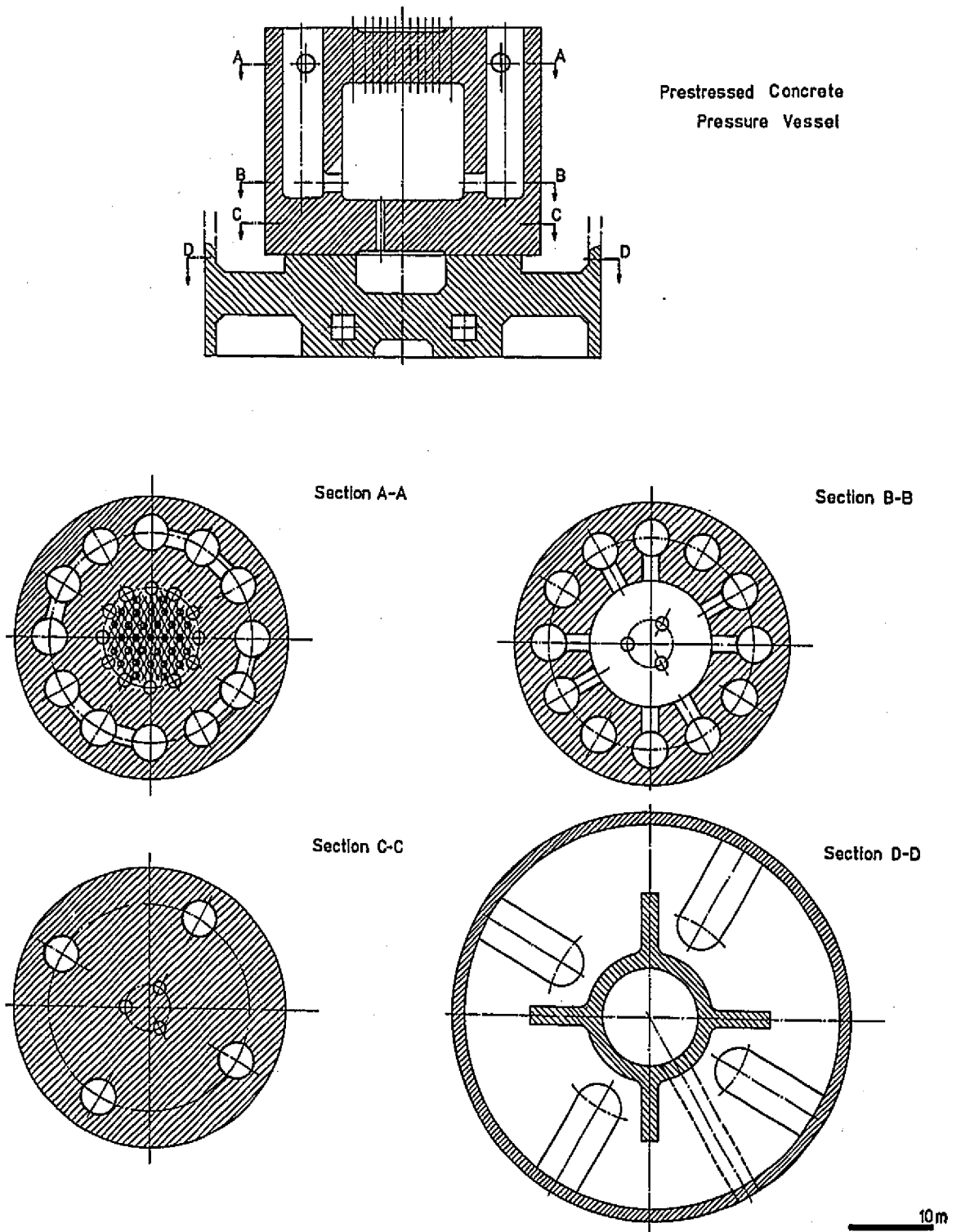


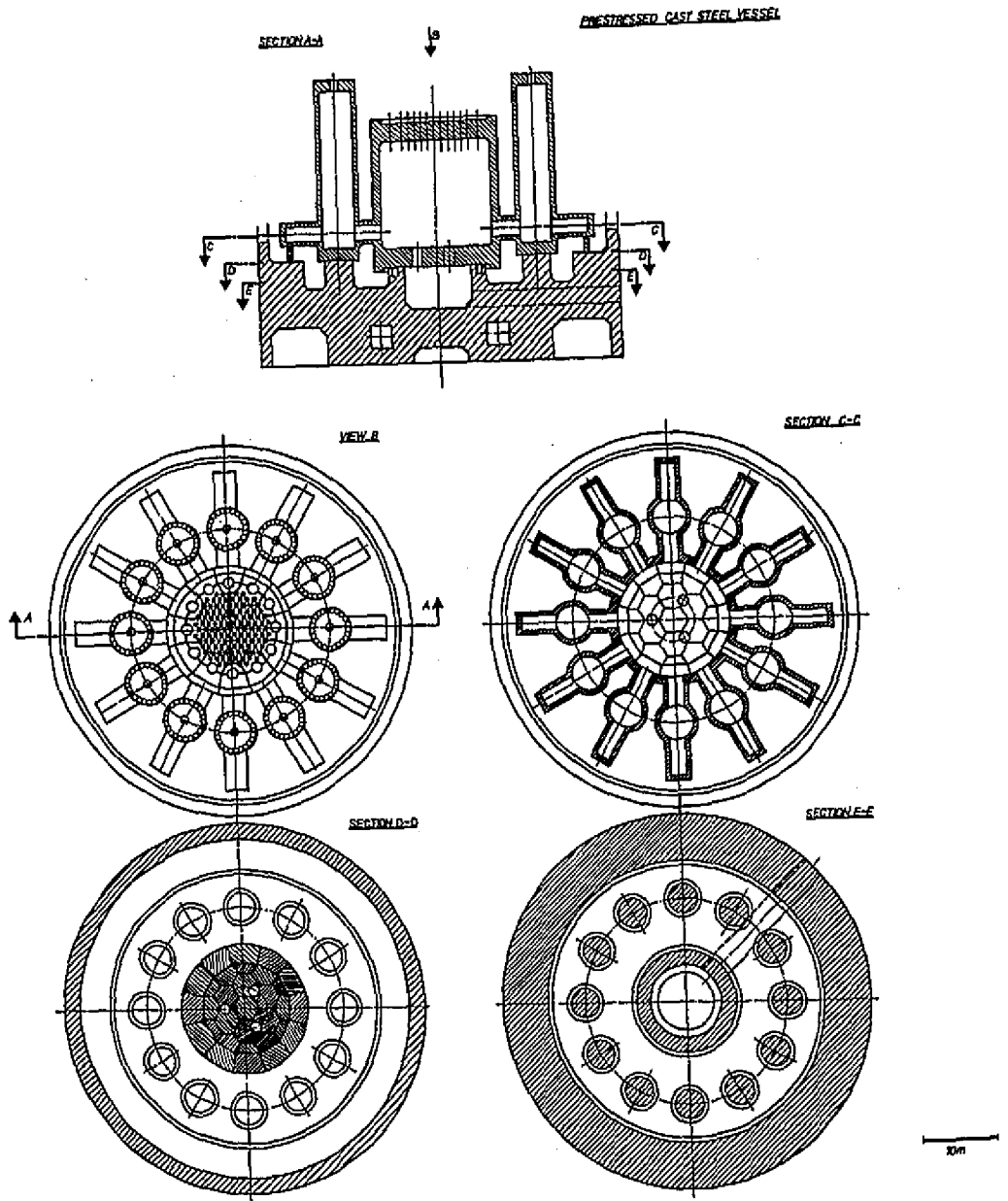
Fig. 1.3.5.2.1-2: Schematic Representation of the Podboiler Reactor Vessel

### 1.3.5.2.2 Prestressed Cast Steel Vessel

As an alternative to the prestressed concrete vessel, the development of a prestressed cast steel vessel is of great interest. In this case the liner and penetration tubes would not be necessary and the individual blocks could be connected by gastight membrane welding on the outside. The blocks themselves are helium-tight and hollow inside and serve as cooling chambers. They are prestressed in the radial direction by winding steel cables, which are put on clamp fittings and in the axial direction by vertical tendons, which penetrate the blocks. The loop vessel is fastened on to the main vessel in such a way as to be safe against earthquakes. The circulators are also spanned against the loop vessels. The blocks are held in position by heavy wedges and bolts. The plurality of the radial cables ensures safety against a sudden loss of gas by the formation of ruptures or openings in the cylindrical ring wall. On the lid and the bottom of the vessel additional constructive measures are necessary to ensure this redundancy as cable spanning here is not possible in the same measure as for the girth of the vessel. There are possibilities in the use of suitably interconnecting blocks or in the application of many successive heavy wedges, somewhat represented by a large screw, which is put into the corners of the block and so ensures their mutual safety.

Data:

Inner height of core cavity	15 m
Inner diameter of core cavity	15 m
Outer height of reactor vessel	20 m
Outer diameter of reactor vessel	17 m
Inner height of loop vessel	22 m
Inner diameter of loop vessel	4.5 m
Outer diameter of loop vessel	5.5 m
Outer height of loop vessel	24 m
Pressure	40 b
Accident pressure	48 b
Temperature of cooling water	50 °C
Temperature rise of cooling water	10 °C
Insulation of core cavity	carbon stone
Insulation of loop vessel	fibre (280 °C)
Number of loops	12



**Fig. 1.3.5.2-2: Schematic Representation of a Prestressed Steel Vessel (integrated Loop System)**

### 1.3.5.3 Core Internals

The core structure consists in the radial direction of a 70 cm thick graphite layer, a metallic thermal shield (thickness 0.3 m) with cooling gas holes, and a 70 cm thick layer of carbon stone insulation to protect the liner of the reactor vessel. The top reflector is constructed of graphite blocks, hung from the upper thermal shield by steel rods. The top reflector and the upper part of the side reflector can be removed by remote handling if necessary by using the penetrations of the control rods and additional openings in the top of the vessel.

Between the ceiling liner and the thermal top shield there is a carbon stone layer of 70 cm thickness for insulation of the top liner.

The reactor bottom has, corresponding to the size of the core, three cone-shaped exits or outlets designed to facilitate the removal of the fuel element balls. The support, as is usual with pebble bed reactors, is made up of hexagonal blocks of graphite columns, which form the hot gas collecting chamber or plenum (height of 1.1m). The bottom of this hot gas plenum also consists of graphite. Between this graphite and the liner, there is also a layer of carbon stone, separated from the graphite by a layer of gas-tight steel foil. The entire reactor construction is supported on a steel plate, which compared to the bottom liner possesses a certain flexibility.

Coolant gas in the primary system flows in the following way:

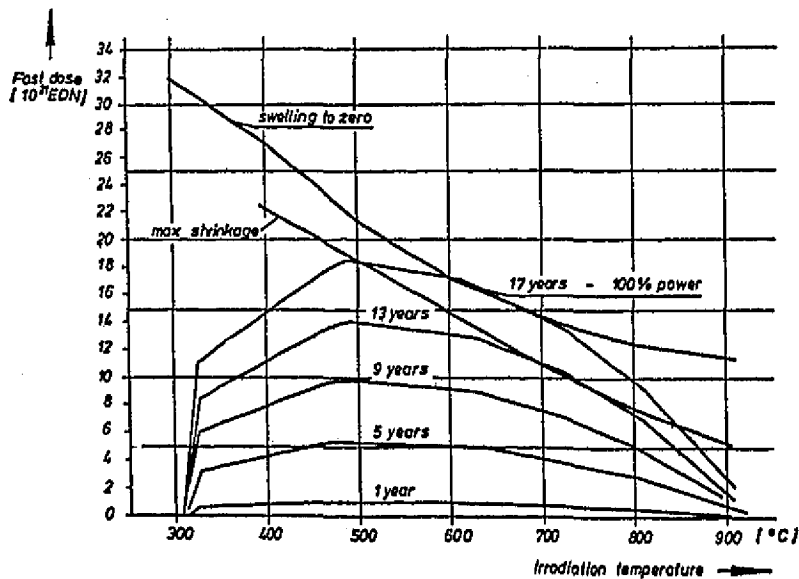
After passing through the core bulk and being heated from 280 °C to 980 °C, it passes into the hot gas plenum made up of graphite columns, and then through eight coaxial ducts to the heat exchangers. After compression to the reactor nominal pressure, the helium is led back through the outer annulus of the coaxial ducts to the cold gas plenum, also at the bottom of the reactor. The cold gas plenum is circular and surrounds the hot gas plenum. It is part of the thermal shield. Applying the principle of counter flow cooling with the total cold helium flow, the walls of the hot gas duct are held at low temperature.

From the metallic cold gas plenum at the reactor bottom, the helium passes through vertical holes in the thermal shield to the upper cold gas plenum. The helium then flows through holes in the upper reflector to enter the reactor core.

Table 1.3.5.3-1 shows the main data of the internal structure.

Thermal power	3000 MWth
Mean core power density	5 MW/m <sup>3</sup>
Core height	6 m
Core diameter	11.3 m
Side reflector thickness	0.7 m
Top reflector thickness	1 m
Number of discharge tubes	3
Mean thickness of bottom reflector	2 m
Thickness of carbon insulation	0.75 m
Thickness of cast iron thermal shield	0.3 m
Height of hot gas chamber	1.1 m
Temperature of top reflector	300 °C
Fast dose on core side in top reflector (30 a)	$\sim 2.5 \times 10^{22}$ n/cm <sup>2</sup> (E > 0.1 MeV)
Critical temperature in side reflector	600 °C
Critical fast dose on core side of side reflector (30 a)	$\sim 3 \times 10^{22}$ n/cm <sup>2</sup> (E > 0.1 MeV)
Temperature of bottom reflector	$\sim 1000$ °C
Fast dose on core side of bottom reflectors (30 a)	$\sim 5 \times 10^{21}$ n/cm <sup>2</sup> (E > 0.1 MeV)
Temperature of cast iron thermal shield	$\sim 300$ °C
Max. dose to thermal shield	$\sim 3 \times 10^{19}$ n/cm <sup>2</sup> (E > 0.1 MeV)
Temperature of carbon stone	< 300 °C

Table 1.3.5.3-1: Data of Core Internals (ref.8)







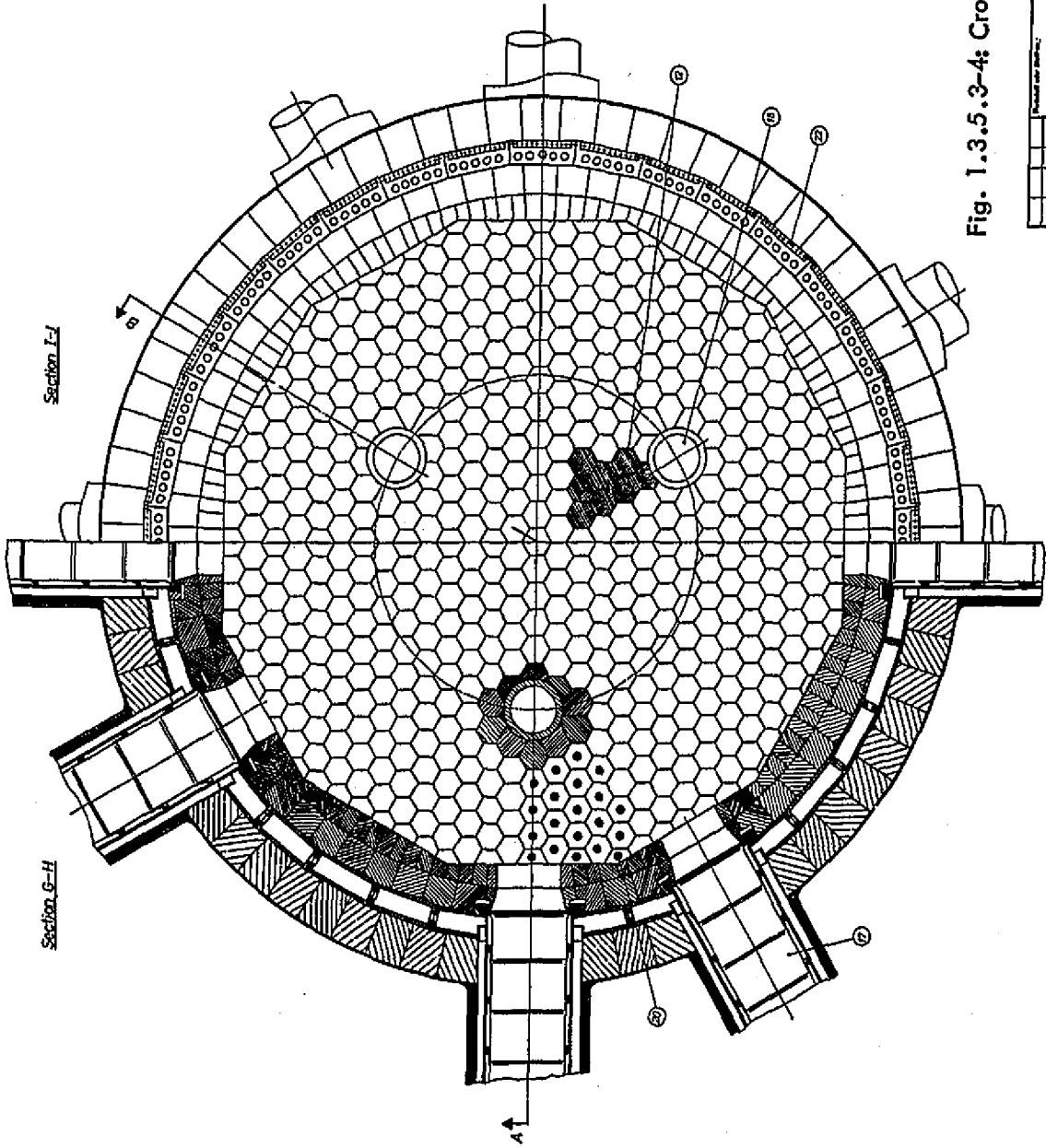


Fig. 1.3.5.3-4: Cross-Sections 3000 MWth

Project	Task	Sub-Task	Phase	Start	End	Responsible
KCS	3000 MWth	CROSS-SECTIONS	CROSS-SECTIONS	1	1	1
				2	2	2
Project: 3000 MWth						
Task: CROSS-SECTIONS						
Sub-Task: CROSS-SECTIONS						
Phase: CROSS-SECTIONS						
Start: 1.1.1970						
End: 1.1.1970						
Responsible: 1						

#### 1.3.5.4 Hot Gas Ducting

The transport of the hot helium between reactor core and the steam reformer occurs via coaxial pipes. The hot cooling gas flows out of the hot gas chamber at the bottom of the reactor through the hot gas pipe, which is concentric inside a cold gas pipe. The hot gas pipe is insulated on the inside and cooled by counter flow on the outside (see fig. 1.3.5.4-1).

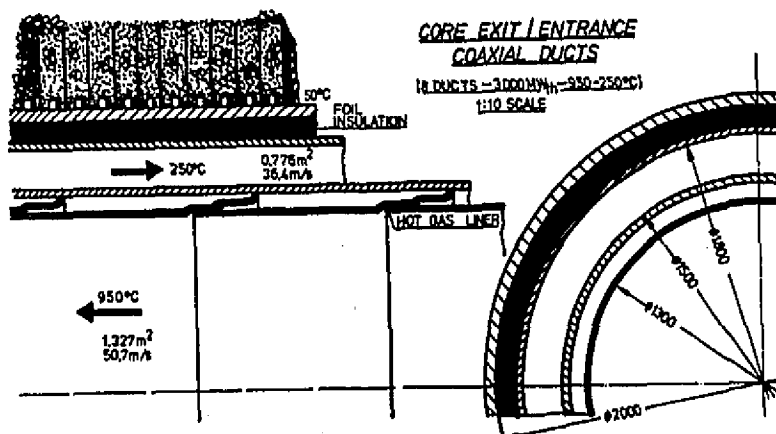


Fig. 1.3.5.4-1: Hot Gas Ducts between Core and Steam Reformer

The hot gas pipe is operated at a temperature of less than  $300^{\circ}\text{C}$  because of the insulation and cooling. The ducting material in the hot gas pipe however, reaches temperatures of  $950^{\circ}\text{C}$ . Because there is no knowledge presently about the long time behaviour of these materials at very high temperatures, (corrosion by impurities  $\text{H}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{CH}_4$  in helium, fatigue by thermal cycling, vibrations) the design must be made such that these components are removable.

The insulation can be made by fiber with a covering metallic plate or by layers of metallic foils. In the last case, questions of fretting in helium must be considered. Failure in the insulation systems caused by rapid depressurization are avoided in both designs because the depressurization rate is limited to  $\approx 1$  b/sec by flow limitations in the big openings of the reactor vessel.

The cold gas duct is insulated in the same way, eventually there are bearing systems for the hot gas duct in the concentric gas room. The heat flux to the cooling system of the penetrations is in the order of  $10\text{kW}/\text{m}^2$  which can easily be removed by water in cooling chambers around the penetrations.

The following table shows typical data for the duct between core and steam reformer, the data for the connections between steam reformer and steam generators are similar. However the temperatures on the hot gas side (700 °C) are lower.

Number	8
<u>Hot gas pipe (950 °C)</u>	
Helium temperature	950 °C
Helium pressure	39.3 b
Mass flow	205 kg/sec
Velocity	50.7 m/sec
Inner diameter	1300 mm
Insulation layer	100 mm
Temperature of bearing pipe	300 °C
Temperature of metallic duct	950 °C
<u>Cold gas pipe</u>	
Helium temperature	250 °C
Helium pressure	39.9 b
Velocity	36.4 m/sec
Mass Flow	205 kg/sec
Inner Diameter	1800 mm
Insulation layer	100 mm

Table 1.3.5.4-2: Data of Hot Gas Duct

These types of coaxial ducts have already been realized in some reactors, for instance the first AGR-System or in Dragon and Peach Bottom, however, partly without insulation because the temperature was lower and with smaller diameters.

### 1.3.5.5 Process Heat Exchangers (Steam Reformer and Steam Generator)

Hot helium leaves the hot gas plenum of the reactor core with an average temperature of  $950^{\circ}\text{C}$  (the mean gas outlet temperature of the core of  $980^{\circ}\text{C}$  is assumed to be reduced to  $950^{\circ}\text{C}$  by 4 % bypass) through the hot gas tube of the coaxial duct. In the lower part of the heat exchanger, the helium is guided to flow past and then enters the region of the steam reformer tubes. Here the helium flows into the space between the tubes and the region of the upper sheet. The temperature level up to  $700^{\circ}\text{C}$  is utilized to superheat the reactant gas from  $450$  to  $825^{\circ}\text{C}$  and for the chemical reaction heat.

From here the gas is led through a coaxial pipe to the steam generators. It is cooled to  $250^{\circ}\text{C}$  and the heat is used to produce steam for the turbine. The gas then flows to the circulators, where it is compressed and then cools all hot gas ducting systems. In this system of gas flow, all the walls of the heat exchangers come into contact with helium at  $250^{\circ}\text{C}$  and so require insulation only for  $250^{\circ}\text{C}$ .

The design of this steam reformer variant is held as near as possible to the conventional steam reforming techniques and to the experiments of the single steam reforming tube pilot plant (EVA) in using centrifugally cast steel steam reformer tubes. The "active" length is conservatively chosen at 10 m, the inner diameter of 100 mm as well as the wall thickness of 15 mm are in accordance with the data presently in use. The steam reformer tubes are hung from a cooled carrier plate (see fig. 1.3.5.5-2).

The process gas (preheated methane and steam) is led to the steam reformer through small tubes, which pass outside through the vessel closure. Demounting of these terminal connections to change the catalyst is not necessary, as the upper man hole has a large enough opening. The catalysts are removed with the help of vacuum cleaners after detaching the respective steam reformer lid. After regeneration, they are replaced. The product gas is led upwards by the inner pigtails arranged in the reformer tubes. These small tubes are led through the vessel closures, too. Through the plurality of the steam reformer terminal-connections it is ensured that in the case of rupture of tubes, tube cross-sections set free are very small from the point of view of technical safety. The steam reformer tubes are of one of the usual materials (25 % Cr, 20 % Ni) produced by centrifugal casting. The heat exchanger surface for the production of turbine steam, is made of meander-formed parallelly arranged tubes. Feed water and superheated steam are led separately through tubes, which pass through the vessel closure. In this way, in case of rupture of steam generating tubes, the amount of water which can penetrate into the primary circuit is limited. Following

this accident the separate tubes can be plugged off and the plant can continue operation. The external collecting systems for feed water, fresh steam and reformer gas have a sufficiently large redundancy, to limit the amounts of gas coming to the containment in case of accidents, as is normal in the case of the nuclear steam generation technology. Vibration of the tube bundle is prevented by welding it onto the feed water ducts (see Fig. 1.3.5.5-4).

Table 1.3.5.5-1: Main Data of Heat Exchangers

1. General Data

Nuclear reactor thermal power	3000 MW
Temperature range in nuclear reactor core	280 → 980 °C
Temperature range in the heat exchanger system	950 → 250 °C
Mass flow of helium	820 kg /s
Max. heat available for high temperature range 950 °C → 700 °C	9.211 × 10 <sup>8</sup> kcal/h ≅ 1071 MWth
Specific heat consumed in the process	655 kcal/(Nm <sup>3</sup> CO+H <sub>2</sub> )
Gas production	1.406 × 10 <sup>6</sup> (Nm <sup>3</sup> CO+H <sub>2</sub> )/h
Number of steam reformers	8
Max. heat available for low temperature range 700 °C → 250 °C	16.59 × 10 <sup>8</sup> kcal/h ≅ 1929 MWth
Steam produced (540 °C/195 b)	2,678 t/h
Amount of steam used in process	905 t/h
Number of steam generators	4

2. Data of a Steam Reformer

Number of units	8
Total thermal power produced/unit	134 MWth
Mass flow of helium/unit	102.5 kg/s
Number of reforming tubes/unit	559
Gas production/unit	176,000 (Nm <sup>3</sup> CO+H <sub>2</sub> )/h

3. Data of a Steam Generator

Number of units	4
Total thermal power produced/unit	482 MWth
Mass flow of helium/unit	205 kg/s
Amount of steam/unit	670 t/h

Thermodynamic Data for a Single Reformer Tube

Helium Side

Inlet temperature	950 °C
Outlet temperature	700 °C
Inlet pressure	39.4 b
Outlet pressure	39.2 b
Mass flow rate	0.1846 kg/s
Heat available	$2.059 \times 10^5$ kcal/h

Process Side

Inlet temperature	450 °C
Reforming temperature	825 °C
Outlet temperature (pigtail)	600 °C
Inlet pressure	46 b
Outlet pressure	40 b
Methane mass flow rate	$125.1 \text{ Nm}^3 \text{CH}_4/\text{h}$
Steam mass flow rate	290 kg H <sub>2</sub> O/h
Total amount product gas	$640 \text{ Nm}^3/\text{h}$
Gas production	$314 (\text{Nm}^3 \text{CO} + \text{H}_2)/\text{h}$
Amount of heat required	$2.058 \times 10^5$ kcal/h

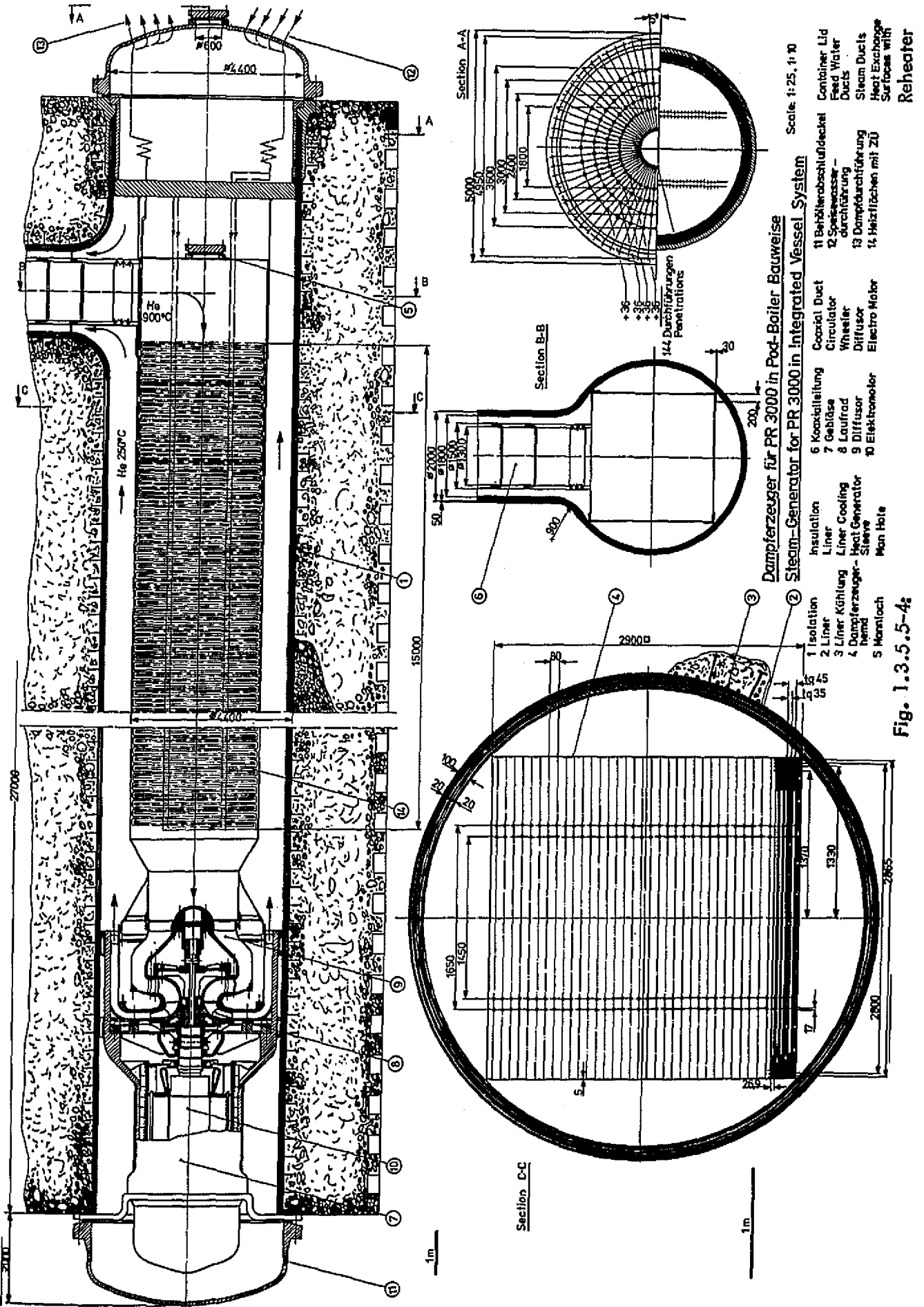
Reformer Tube Data

Inner diameter fo the tube	100 mm
Outer diameter of the tube	130 mm
Length of the chemically "active" reformer tube	10 m
Length of the chemically "inactive" reformer tube	1 m
Helium velocity in tube bundle	13,5 m/s
Film coefficient of heat transfer on the helim side (with baffles)	$810 \text{ kcal}/\text{m}^2 \text{h} \text{ } ^\circ\text{C}$
Film coefficient on product side	$1000 \text{ kcal}/\text{m}^2 \text{h} \text{ } ^\circ\text{C}$
Thermal conductivity of the tube wall	$23 \text{ kcal}/\text{m h} \text{ } ^\circ\text{C}$
Overall heat transfer coefficient	$304 \text{ kcal}/\text{m}^2 \text{h} \text{ } ^\circ\text{C}$
Average log. temperature difference ( $\Delta T$ )	180 °C
Heat flux	$54,720 \text{ kcal}/\text{m}^2 \text{h}$
Effective heat transfer area	$4.08 \text{ m}^2$
Transferable heat/tube	$2.235 \times 10^5 \text{ kcal}/\text{h tube}$
Max. wall temperature of the tube	900 °C
Pressure drop at the max.wall temp of the tube	1 b



Nth	MW	1928			
Number of Steam Generator(SG)		4			
Nth/SG	MW	482			
$Q \times 10^{-8}$	Kcal/h	4,1452			
$\dot{m}_{He}/Loop$	kg/s	203,1			
$T_{He\ in}$	$^{\circ}C$	700			
$T_{He\ out}$	$^{\circ}C$	250			
$P_{He\ in}$	bar	39,1			
$P_{He\ out}$	bar	38,67			
		U 2	U 1	Verdampfer	Economiser
Helium Velocity	m/s	31,1	28,4	24,5	19,9
Heat-transfer Coefficient Helium	Kcal/m <sup>2</sup> h $^{\circ}C$	2018	1970	1890	1781
$P_{W\ in}$	bar	197,7	206,3	208,8	222,8
$T_{W\ in}$	$^{\circ}C$	490	365,1	366	180
$\dot{m}_{Water}$	t/h	668,083	668,083	668,083	668,083
$P_{W\ out}$	bar	195	197,7	206,3	208,8
$T_{W\ out}$	$^{\circ}C$	540	490	365,1	366
$v_{Water}$	m/s	34,6	22,8	7,03	3,52
Heat-transfer Coefficient Water	Kcal/m <sup>2</sup> h $^{\circ}C$	6535,8	6747,4	$2,17 \times 10^4$	$1,75 \times 10^4$
over-all Coefficient	Kcal/m <sup>2</sup> h $^{\circ}C$	1087,7	1132,3	1426,6	1339,3
$\Delta T\ log.$	$^{\circ}C$	167,6	173,2	101,7	54
Heat Transfer per Unit Surface	Kcal/m <sup>2</sup> $\times 10^{-5}$	2,489	2,68	1,98	0,9879
Heating Surface	m <sup>2</sup>	139	637,7	656,8	2148,9
Number of Tubes	--	275	275	275	275
Length of Tube	m	5,98	27,44	28,27	92,48
Thermal Capacity	MW	29,46	154,45	110,82	196,27
Tube-Material	--	X15CrNiSi 2520	X15CrNiSi 2012	13CrMo44	17Mn4
Outer Diameter of Tubes	mm	26,9	26,9	26,9	26,9
Wall-Thickness of Tubes	mm	3,6	3,6	3,6	3,6
Measurement of SG	m	2,8 x 2,8			
Bundle Height	m	0,84	2,39	2,45	7,08

Fig. 1.3.5.5-3: Data of Steam Generator



**Dampferzeuger für PR 3000 in Pod-Boiler Bauweise**  
**Steam-Generator for PR 3000 in Integrated Vessel System**

Scale: 1:25, 1:30

- |                                  |  |
|----------------------------------|--|
| 11 Behälterabschlußdeckel        | Container Lid                              |
| 12 Speisewasser-<br>durchführung | Feed Water<br>Ducts                        |
| 13 Dampfdurchführung             | Steam Ducts                                |
| 14 Heizflächen mit ZU            | Heat Exchange<br>Surfaces with<br>Reheater |
| 6 Koaxialleitung                 | Coaxial Duct                               |
| 7 Gehäuse                        | Circulator                                 |
| 8 Laufrad                        | Wheel                                      |
| 9 Diffusor                       | Diffuser                                   |
| 10 Elektromotor                  | Electro Motor                              |
| Insulation                       |  |
| Liner                            |  |
| Liner Kühlung                    |  |
| Heat Generator                   |  |
| Sleeve                           |  |
| Man Hole                         |  |

Fig. 1.3.5.5-4:

### 1.3.5.6 Circulators

The pressure drop in the primary system is compensated by 4 circulators. The circulators are connected to the steam generators and are hanging from the bottom of the vessel. They are driven by electrical induction motors and regulated by the speed i.e. the frequency of the energy supply. The design is of radial compression type. On the gas inlet there is a shutoff- and bypass-system. The bearings are lubricated with oil, oil-feed system is integrated on to the blower itself. Sealings are made by special gas circuits. The circulators are used for after heat removal and therefore their emergency supply must be redundant, i.e. there must be sufficient diesel engine power. The operation region of the circulators is 20...100 % achieved by regulators; a throughput of helium of 15 %, which is used for afterheat removal, is made by bypassing of helium.

The electrical motor itself is an induction motor, which is cooled by water. Experience with this kind of circulators exists until now through the THTR development program for a power of 2.5 MWe for each circulator. In CO<sub>2</sub>-cooled reactors, however, circulators with more than 11 MWe have been used.

Number	4
Inlet temperature	250 °C
Inlet pressure	38.6 b
Outlet pressure	40 b
Mass flow	205 kg He/sec
Power	11 MWe
Speed	6000 r.p.m.
Pressure drops in system	
Core	0.4 b
Steam reformer	0.2 b
Steam generator	0.45 b
Gas ducts & internal structure (top reflector, bottom reflector, thermal shield)	0.35 b

Table 1.3.5.6-1: Data of Circulators

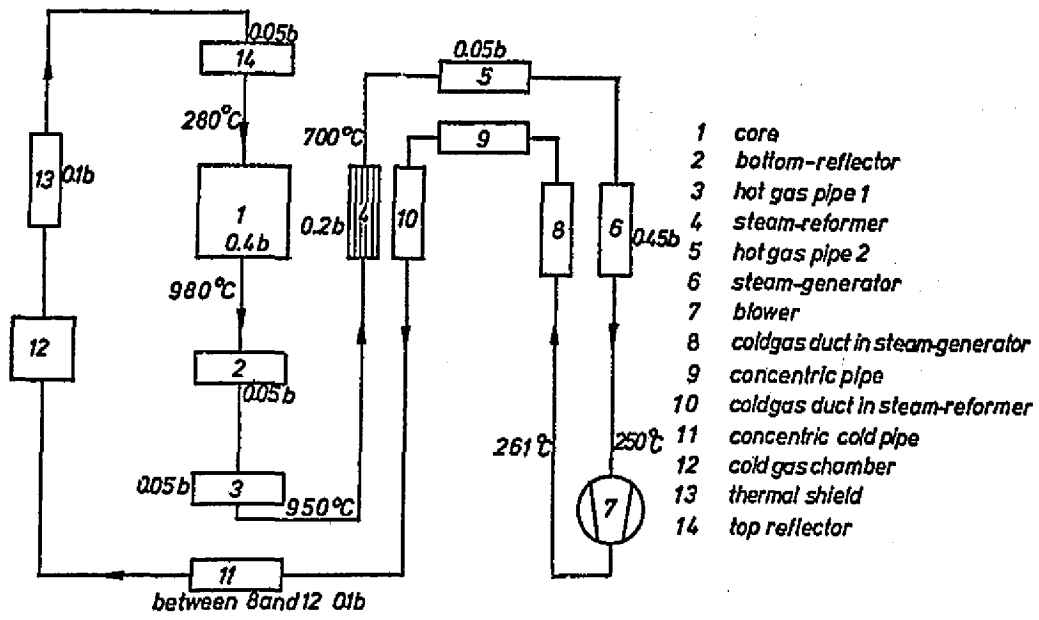


Fig. 1.3.5.6-2: Schema for Pressure Drops in the Circuit

### 1.3.5.7 Fuel Handling System

The loading and unloading of this reactor with fuel elements is relatively simple because of the handling of small ball type fuel elements (6cm diameter) and because of the once-through system (see fig. 1.3.5.7-1). Fresh elements are introduced at the top of the reactor through a lock system with three valves. In this way, fuel elements from an air environment at normal pressure are introduced into an atmosphere of helium at a pressure of 40 b. A mechanical fuel element distributor, which consists chiefly of an adjustable turntable, ensures the introduction of the fuel elements at the correct position (2-core zone). The fuel elements pass downwards through the core by gravity and reach the bottom in 3 years. The fuel elements are removed from the bottom of the reactor at one of the three exit tubes by means of a revolving plate device, and pass into a transport car, which is at the same (reactor) pressure and is flanged onto the exit tube. When the transport car becomes full, it is disconnected and removed for reprocessing or end-storage of the fuel elements. It is replaced by an empty container.

Continuous loading of the reactor is very important for applications of nuclear power to process heating. It basically permits a higher availability of the entire system, which is indispensable for the operation of the peripheral equipment.

The fuel handling system which uses the OTTO cycle is very simple because of the following reasons:

- no burnup measurement
- no recycle of fuel elements
- no handling of spent fuel except for transportation to reprocessing plant
- fuel elements have low residual activity when leaving the reactor ( $\sim 100$  Ci/ball)
- no operation of locks for spent fuel
- no separation of scrap fuel elements needed.

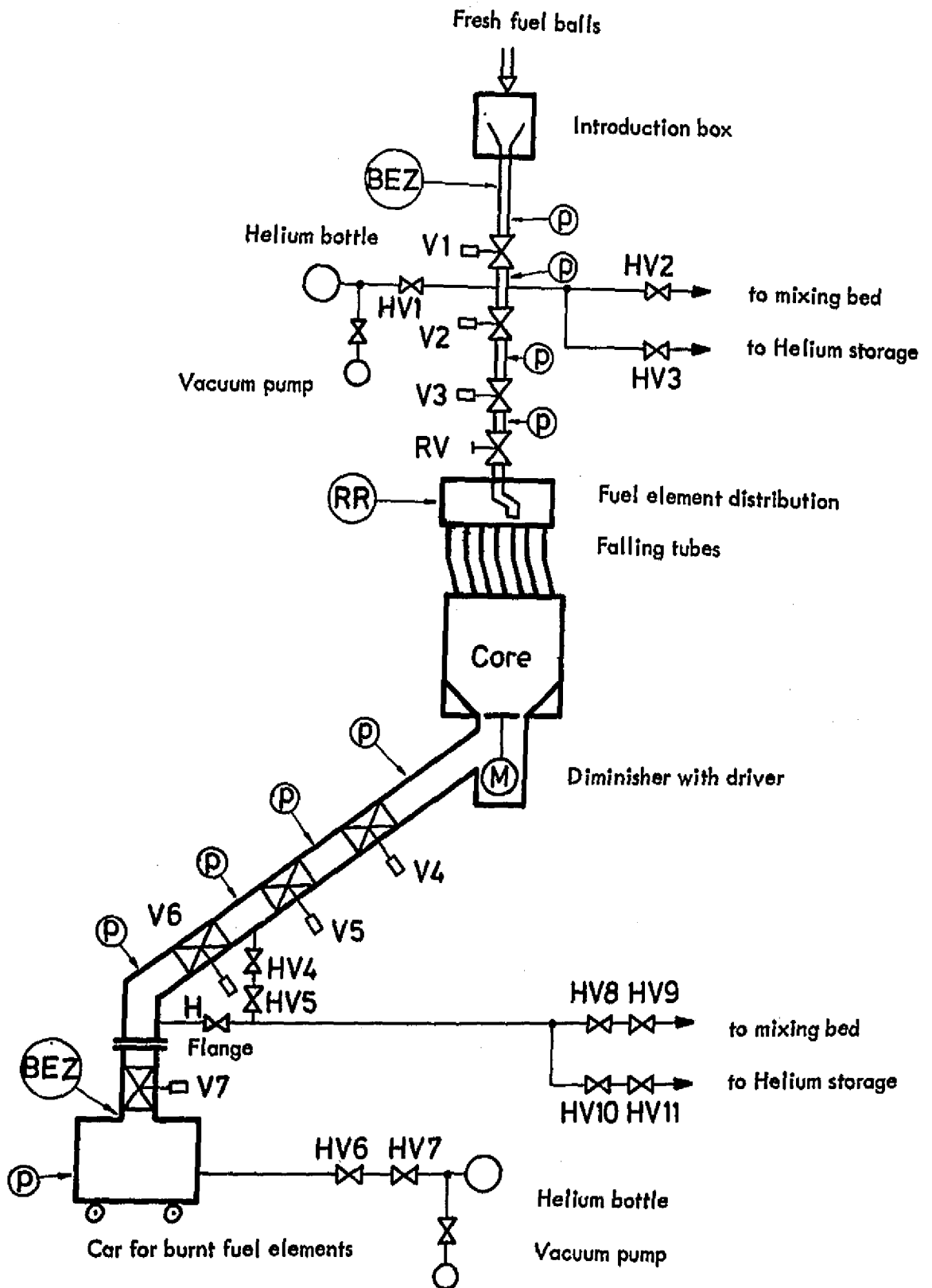


Fig. 1.3.5.7-1: Flow Diagram of the Loading Scheme

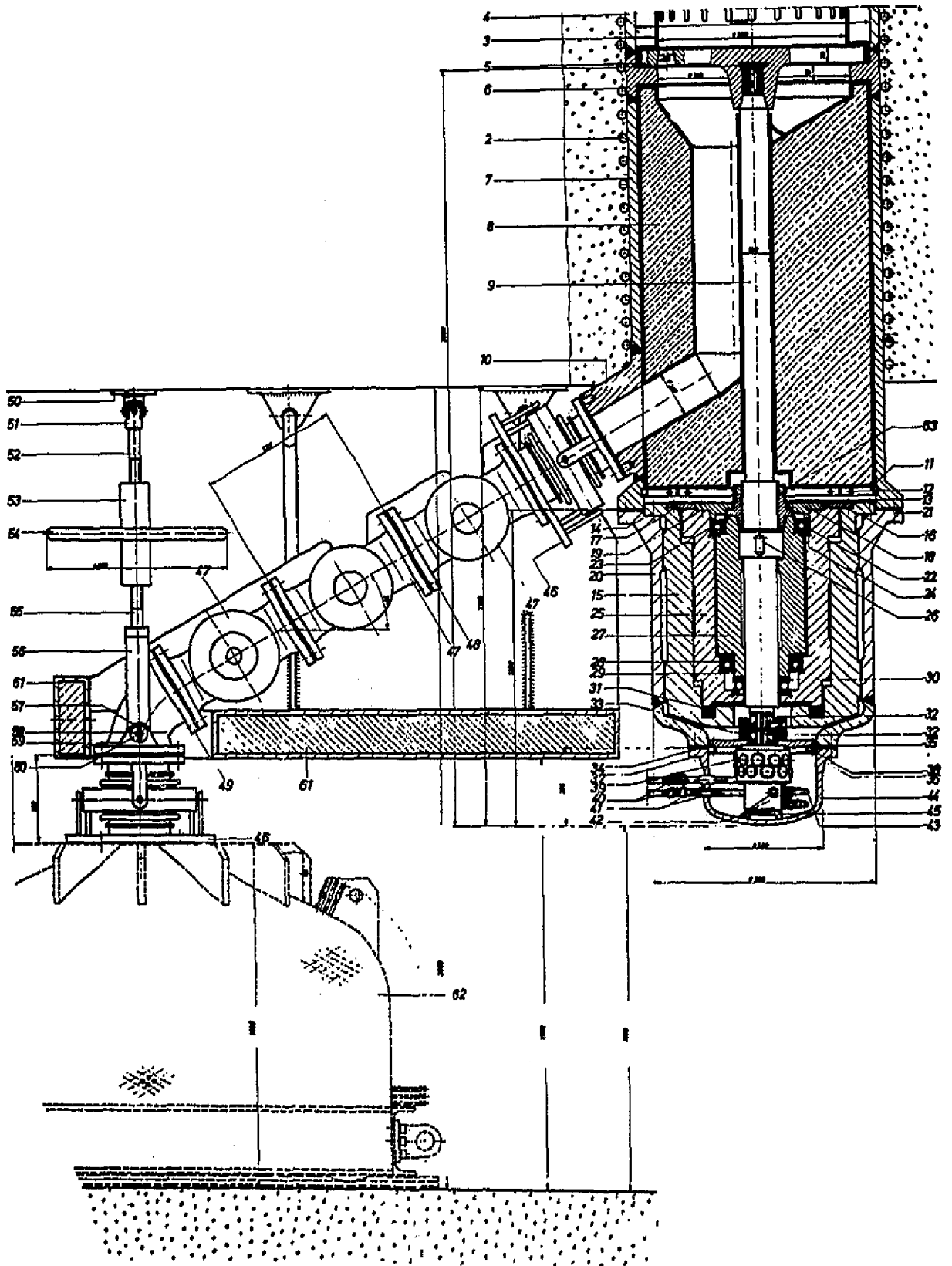


Fig. 1.3.5.7 - 2: Discharge Maschine

Fig. 1.3.5.7-2: Fuel Handling System

Diameter of fuel elements	6 cm
Number of fuel element in core	$3.25 \times 10^6$
Number of loading positions	42
Number of discharge tubes	3
Input of fresh fuel elements	$\sim 4000$ balls /day
Output of spent fuel elements	$\sim 4000$ balls /day
Lifetime of fuel elements in core	$\sim 3$ years
Pressure in all parts of the fuel handling system	40 b
Temperature in all parts of fuel handling system	50 °C
Operation	continuously
Activity of spent fuel	$\sim 100$ Ci/ball
Capacity of a transportation car	5400 balls $\approx 1 \text{ m}^3$

#### 1.3.5.8 Control and Shutdown System

The reactor is controlled and shutdown by rods, which are inserted from the top of the reflector directly into the pebble bed. The rods are driven by a spindle drive and electrical motor. The tube of the rod itself is filled with absorber rings of boroncarbide. The penetration depth in the pebble bed depends on the needed operation.

- Control of load (40...100 %) is made by movement of the rods in the upper reflector and in the void room above the pebble bed without penetration into the pebble bed. This can be done because of the OTTO cycle, which means a very high flux at the top of the reactor connected with a high efficiency of the rods.
- Scram is made by insertion of a small part of the rods into the pebble bed with a depth of nearly 0.5 m.
- The reactor can be shut down (cold subcritical) if the rods are inserted to a depth of nearly 2.5 m into the pebble bed. This can be done without difficulties if the flow lines of the pebble bed are relatively parallel to each other, i.e. if the core height is big enough. The probability of destroying a ball during insertion is very small because the load which can be taken by the balls (2100 kg) is large in comparison to the loads produced by insertion of rods. The probability of breaking a ball by the cold subcritical shutdown operation is less than 1 ball per 3 million balls per insertion of all rods. The overall reactivity demand for this operation is 16.9 % as the following table 1.3.5.8-2 shows. The efficiency of the rods can be taken from the fig. 1.3.5.8-2. With insertion of the rods to a depth of 2.5 m into the core, a reactivity value of -16.9 % is gained which is sufficient to hold the core cold subcritical.

The shown reactivity values are pessimistic because all requirements of longtime and shorttime reactivity demands are put together. By development of a more realistic shutdown philosophy the value of 16.9 % can be reduced.

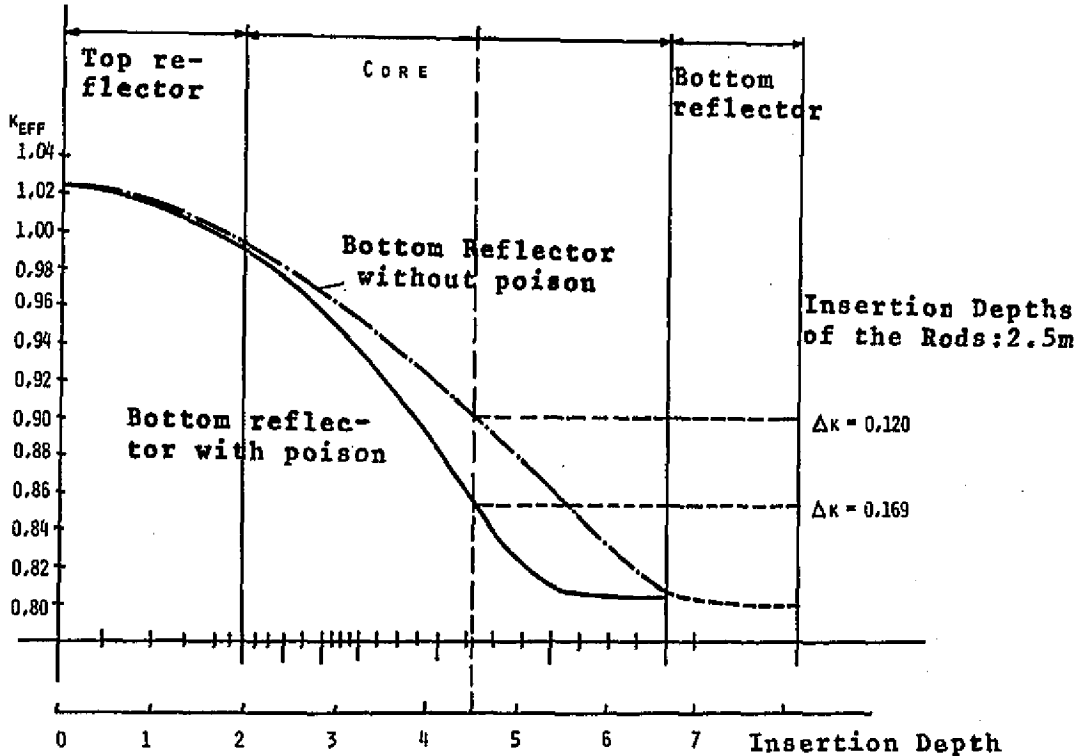


Fig. 1.3.5.8-1: Efficiency of Rods Dependent on Depth in Pebble Bed (ref.9)

For safety reasons there must be a second shutdown system. Usually for pebble bed high temperature reactors, boron trifluoride is discussed as a useful second system. There are further possibilities to put small pebbles of absorbing material into the reactor core and to remove them partly by discharging some  $m^3$  of pebbles. This system now is in development.

1) Longtime shutdown (contains Xe 135 decay, Pu-build up, temperature drop of core to 20 °C)	- 10 %
2) Xe-Override 100/40/100 %	- 2.3 %
3) Loss of most effective rod	- 3 %
4) Failures in loading	- 0,5 %
5) Frequence regulation	- 0,5 %
6) Reserve	- 0,5 %
7) Running-in period	- 1,5 %
8) 10 % addition to pos. 1...5	- 1,6 %
	- 19.9 %
9) Reactivity gain due to influence of top reflector and upper empty space)	+ 3 %
	- 16,9 %

Table 1.3.5.8-2: Reactivity Demands

### 1.3.5.9 Reactor Containment Building

The primary circuit together with the auxiliary system, such as gas purification plant, helium circuits, safety system, mixed cooler and safety reliefs are located in a reactor containment building. This building is divided in three parts: 1) an upper room for the loading system and for the control rods, 2) a room at the bottom of the reactor for the discharge machine and, 3) a large one which contains all other components. The first two small rooms are filled with air. The third is filled partly (podboiler design) or fully (steel vessel design) during operation with inert gas (nitrogen). The nitrogen filling is used for safety reasons against explosives in the containment, and to prevent O<sub>2</sub> from burning the core structure. The containment should be designed for a short time pressure of 3 b, which occurs if there is a loss of coolant accident. This can be achieved by a prestressed concrete structure.

Furthermore, the containment should, if possible, be underground because of safety reasons in case of accidents from outside. Aircraft, fire by gasoline and pressure wave by explosion of gas mixture can be handled better if the containment is underground. Additional future safety requirements can be better fulfilled. Even in case of failures of containment, the earth acts as a filter for nearly all fission products. However, connection with ground water should be avoided.

The additional costs for underground location for these types of containments are relatively small, if the height of the containment is not too big, as it can be realized with all loop designs and with the small height of the loading machine of the pebble bed reactor.

Inner height	65 m
Inner diameter	46 m
Wall thickness	1.5 m
Foundation thickness	5 m
Free volume	~ 70,000 m <sup>3</sup>
Pressure normal	1 b
Pressure accident (cooling gas loss from primary circuit)	3 b
Material	Concrete with inner steel liner

Table 1.3.5.9-1 Data of Containment Building

### 1.3.5.10 Helium Purification

The purification of the reactor cooling gas helium from impurities ( $H_2$ ,  $H_2O$ ,  $CO$ ,  $CO_2$ ) is made by a purification plant consisting of  $CuO$ -beds, molecular sieves and additional filters for such fission products as iodine.

The bypass ( $20000 \text{ Nm}^3/\text{hr}$ ) for the purification plant is taken from the carbon stone region in order to have a very effective gas cleaning system. The clean gas leaving the purification plant is recycled to the reactor primary circuit at the inlet of the blower.

There are 3 parallel gas cleaning systems for a  $3,000 \text{ MW}_{th}$  plant. The limits for the tolerable impurities in the helium are fixed by corrosion limits on the reflector graphite, fuel elements combined with a specification for the resulting carbon deposition on heat exchanger surfaces. Normally the following impurities can be tolerated:  $H_2$ : 5 vpm,  $H_2O$ : 0.1 vpm,  $CO$ : 15 vpm,  $CO_2$ : 1,0 vpm.

A fission product separation is not needed, because the experience of the HTR system shows that the fission product content of the helium is very small and therefore all gas cleaning systems are very ineffective. For instance, in AVR, there are only 20 Ci gas activity in the cooling gas, which is a value below tolerable limits for breathing. More or less, this value is caused by Xenon and Krypton activity. Normally, all HTR systems lose one inventory of helium per year, which means that nearly all activities are given off by normal leakage to the containment which acts as a further intermediate storage for the activity. The activity which is given to the surrounding is far below tolerable limits.

Each parallel circuit of the gas cleanup system consists of a  $CuO$ -catalyst bed (to convert  $H_2 \rightarrow H_2O$ ,  $CO \rightarrow CO_2$  at temperatures of  $250^\circ\text{C}$ ), a cooler, an active charcoal filter (for iodine) and a molecular sieve (to absorb  $H_2O$ ,  $CO_2$  at temperatures of  $50^\circ\text{C}$ ).

The regeneration of the  $CuO$ -bed is made by additions of oxygen intermittently. The regeneration of the molecular sieve can be made by exchange with dry nitrogen.

All components of the gas cleaning system are inside the reactor containment building.

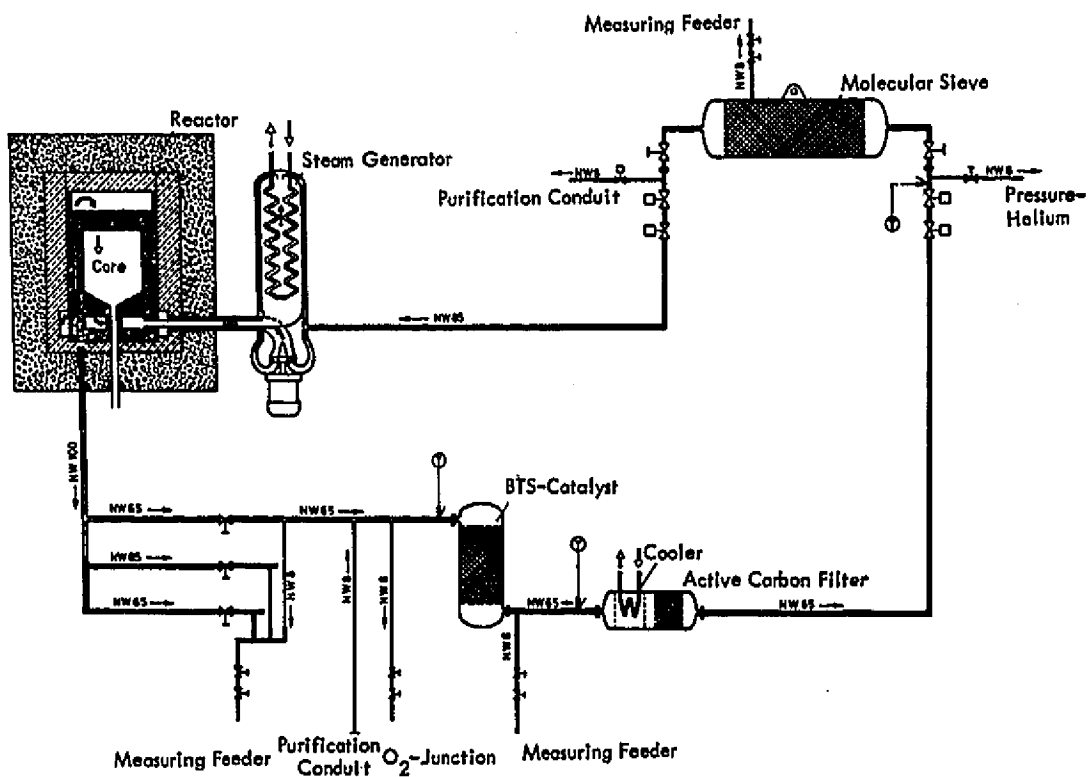


Fig. 1.3.5.10-1: Principle of Gas Purification

### 1.3.6 Accidents and Safety

#### 1.3.6.1 Shutdown of Reactor

The normal control rods are used for scram. The rods are inserted in max. 6 sec to a depth of 0.5 m into the pebble bed. There is only a small temperature rise in fuel temperature in case of the accident of water inleakage into the core (failure of steam generator or steam reformer tubes). Redundancy of the system is made by dividing the number of control rods (109) in different groups with independent emergency supply.

A second shutdown system (emergency) uses Boron trifluoride, which is brought to the core in big amounts if all control rods have failed.

A third shutdown system can eventually be made by small high-absorbing balls, which are fed to the core. These small balls can be removed by taking off normal balls from the core. The high negative temperature coefficient of all high temperature reactors acts as a further shutdown system.

Cold subcriticality is made by insertion of all control rods to a depth of 2.5 m into the core.

An additional possibility for cold subcritical shutdown would be to add big amounts of boron balls with normal shape to the core. Later on a part of the core must be removed.

#### 1.3.6.2 Aftercooling of Core

The normal condition for aftercooling is a helium pressure of 40 b in the primary system. One of the four loops is sufficient to remove the decay heat and to cool down the core. One steam generator represents the heat sink. There must be emergency energy supply to the circulator by diesel engines. The feedwater pumps for the steam generator must be separate always, that means there must be redundancy.

In the accident of cooling gas loss from the primary system there is a mixed pressure in the containment of 3 b. In this case one loop is sufficient to remove the afterheat also and to cool down the core. Because the vessel cannot burst (redundancy of cables) and because the velocity depressurization is limited to  $dp/dt \sim 1 \text{ b/sec}$  by flow limitations, there will not be failures of insulation systems or internal structures in this accident.

If the containment also fails in the accident, there will be a pressure of 1 b in the containment. This case is not considered to be credible. In this accident two loops would be needed to remove the afterheat and cool the core.

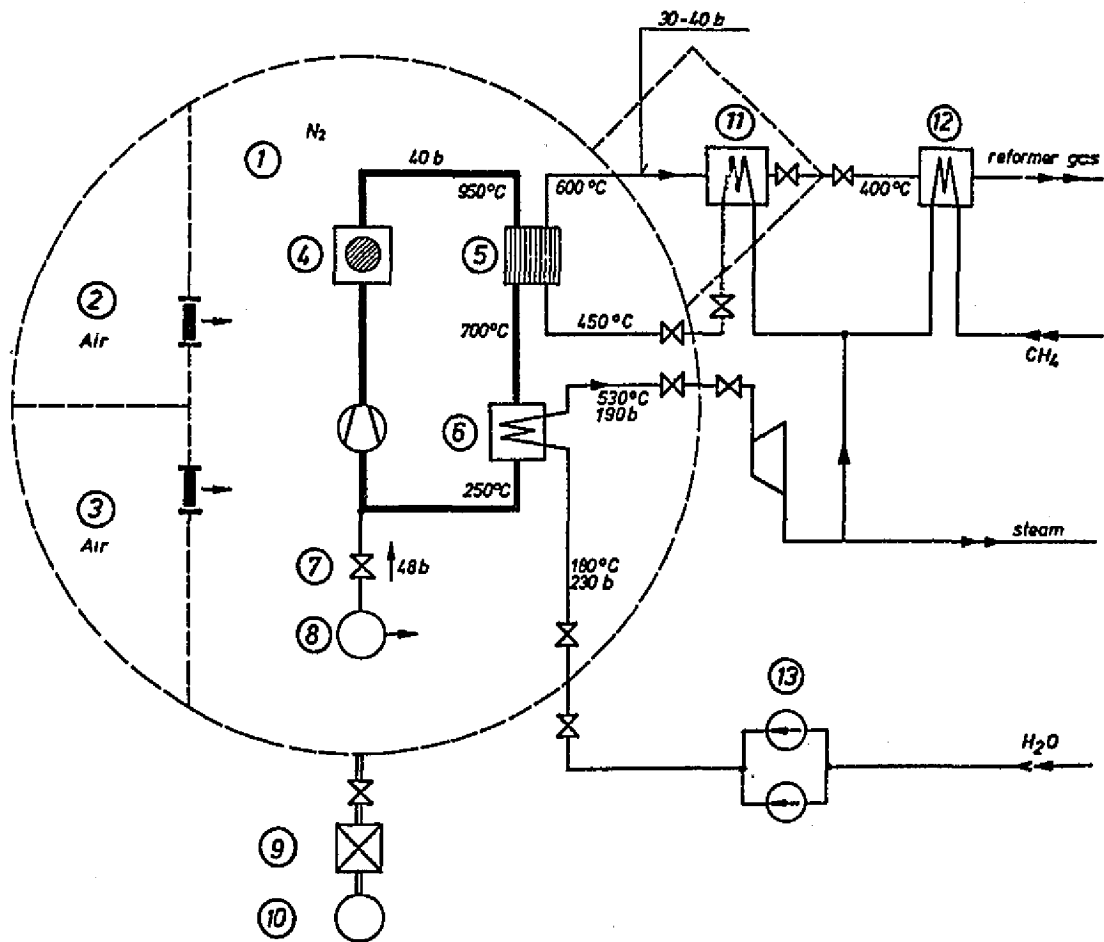
In an even much more improbable accident additionally all circulators fail and cannot be operated. In this case the big heat capacity of the reactor core acts as a storage for heat. In the first 6 hours if there is no aftercooling at all, the temperature rise in fuel temperature is  $140\text{ }^{\circ}\text{C/h}$ , that means that the maximum fuel temperature rises from  $1100\text{ }^{\circ}\text{C}$  in normal operation to nearly  $2000\text{ }^{\circ}\text{C}$  after 6 hours. If the temperature rises in the core, more and more heat is transferred through the layers of graphite, thermal shield and carbon stone to the liner cooling. This liner cooling now is operated with a higher temperature difference than in normal operation (heating up of water  $\Delta T = 80\text{ }^{\circ}\text{C}$  instead of  $\Delta T = 5\text{ }^{\circ}\text{C}$  as in normal operation). In this case more than 1 % of the normal reactor power can be removed by the liner cooling (afterheat after 5 h is 1 % of normal reactor power). The liner cooling consists of three independent parallel systems which are made redundant by parallel pumps and cooling systems. Melting down of the core cannot occur, because the materials are ceramic and the maximum temperatures are limited.

In all these accidents there is a lot of time to do something. This is caused by the small power density of the core ( $5\text{ MW/m}^3$ ), the big heat capacity (60 % of room filled with graphite) and the low fuel temperatures (max  $T = 1100\text{ }^{\circ}\text{C}$  for process heat applications  $950\text{ }^{\circ}\text{C}$ ). The fission product release in all cases stays in limits, which are not critical for the surroundings.

### 1.3.6.3 Internal Accidents

**Loss of coolant to containment:** As already described there are no problems with this accident, because the velocity of depressurization of the system is limited and aftercooling can be made in all cases.

**Failure of steam generator tubes:** There is a rise of pressure in the primary system, a rise in reactivity of core, higher corrosion rates on fuel elements and on graphite structures. If this accident occurs the following operation must be done: Shutdown of the system by scram, stop the water supply for the loop, safety reliefs open at 48 b, the mixture helium and steam blows down to a mixed cooler (water filled) to condense the steam, Helium fills the containment with a pressure of 3 b. Aftercooling starts and cools down the core very rapidly, therefore corrosion is limited. However, there should be a limitation of water throughput through the parallel tubes in the steam generator such that the amount of water coming to the core is of the order of 2 t.



- 1 Containment (N<sub>2</sub>)
- 2 Room for control rods and loading systems
- 3 Fuel element discharge room
- 4 HTR
- 5 Steam reformer
- 6 Steam generator
- 7 Safety relief valve
- 8 Mixed cooler
- 9 Filter
- 10 Stack
- 11 Cooler
- 12 Cooler
- 13 Feedwater pumps

Fig. 1.3.6.3-1: Schematic Diagram for Technical Safety Considerations

#### Failure of steam reformer tubes:

- 1) If the pressure on the reformer side always is the same but higher than the helium pressure, in case of broken tubes the process gas (mixture of  $H_2$ ,  $CO$ ,  $CO_2$ ,  $CH_4$ ,  $H_2O$ ) flows to the reactor system. This case is handled in the same way as a failure in the steam generator. There is only one difference. The throughput through one reformer tube ( $\sim 400 \text{ Nm}^3 \text{ H}_2/\text{h}$ ) is much smaller than that of a steam generator tube. Therefore for an accident only 2-3  $\text{Nm}^3 \text{ H}_2$  come to the core. These amounts can easily be removed by the gas purification plant. Even the safety relief systems must not be opened.
- 2) If the pressure on the process side is smaller than the reactor pressure and if there is a failure in one reformer tube, helium comes to the process itself. The flow is limited by the flow area of the pigtails. However, there must be a possibility to stop the feed and to shut valves behind the first waste heat utilization heat exchanger ( $T \sim 400 \text{ }^\circ\text{C}$ ) and to recycle the helium to the containment. A catalytic burner should be used to convert the hydrogen and carbon monoxide to  $H_2O$  and  $CO_2$  before entering the containment. After this procedure, the accident is the normal case of cooling gas loss.

Failures of steam pipes in containment: In this accident pressure in the containment rises. To avoid that pressure rises even higher than 3 bar, the throughput of the pipes must be limited.

Failures of pipes for methane or steam reformer gas: Mass throughput must be limited to avoid too high pressure in containment. Pipes should be surrounded by inert gas ( $N_2$ ) to avoid explosive mixtures with air (if containment is filled with air).

#### 1.3.6.4 External Accidents

Earthquake: Both designs are inherently safe because vessel and heat exchanger form a unit. Core construction is fixed at thermal shield, which itself is connected to the bearing plate at the bottom of the reactor core. This plate is fixed in the middle point of the vessel bottom. Vessels are held by cables to the foundation of the containment. The movement of the control rods is not influenced during or following an earthquake because the pebble bed has no definite structure. The aftercooling of the core in both cases is guaranteed by the integrated loops consisting of steam generator and circulator.

Pressure waves by explosion of gas mixtures: The wall thickness of the containment is sufficiently large to withstand this accident. A location of the containment below the earth is better to fulfill further additional requirements.

*Aircrash: Here are the same conditions and remarks, as in the accident above, hold good.*

*Fire (burning large amounts of gasoline after an air crash): Redundant arrangement of emergency energy (diesel engines) and cooling systems is needed. In this case an underground location of the containment has advantages, too.*

#### 1.3.6.5 Release of Radioactivity from Plant

*Normal activity release: The content of fission product of the cooling gas in normal operation will be following the AVR experience (20 Ci for 50 MWth-plant) in the order of 10,000 Ci noble gases. Per day there is a helium loss of 3 % into the containment, i.e., 30 Ci/d to the containment. The containment acts as an intermediate storage for the fission products. The estimation is that 1 Ci/d is released by stack, which is far below the allowed values. Further possibilities to reduce the release by additional filters can be considered.*

*In a coolant gas loss accident to the containment, 10,000 Ci can be given off by stack after a short intermediate storage to reduce the activity by decay in the containment. No allowed limits are violated.*

*In the very improbable accident of coolant loss with failure of containment, the location of the containment below earth would be an additional safety barrier to retain the fission product by the earth. However, the problem of transport of iodine by water must be considered, i.e., the connection of containment and water should be avoided.*

*Even in the worst case, which really never should happen, that all circulators cannot be operated and that emergency cooling must be made by liner cooling, the fission product release from the fuel elements is limited because the fuel temperatures stay in the order of 2000 °C and because even with these high temperatures the fission product retention of the fuel elements is relatively good. The solid fission products are more or less plated out in the reactor vessel or in the containment. An underground situation of the containment would be of big advantage in this accident.*

## 1.4 State of Development, Development Work

### 1.4.1 Steam Reformer

The steam reformer process is very well known since more than 20 years. It is developed worldwide in a big number of conventional ammonia-, methanol- and hydrocracking-plants for production of hydrogen. The main difference by adaptation of this process to nuclear heat sources with the HTR is to change over from heating the reformer tubes with flue gases at normal pressure to helium at 40 b pressure. However, the heating temperatures are much smaller in case of helium (950 °C) than in case of flue gases (1500 °C). The following table shows the main data of a conventional and of a nuclear process

Data	Conventional Plants	Nuclear Plants
Tube length	8...12 m	10 m
Inner diameter	100...150 mm	100 mm
Wall-thickness	15...20 mm	15 mm
Pigtails	outside tube	inside tube
Reforming pressure	1...25 b	30...40 b
End-temperature of reforming process	800...850 °C	800...850 °C
Pressure on heating side	1 b	40 b
Max. heating temperature	1400...1500°C	950 °C
Max. temperature of tube wall	900...950 °C	900 °C
Max. pressure difference in the tube wall	0...25 b	0...10 b
H <sub>2</sub> O/CH <sub>4</sub> -ratio	2/1...5/1	2/1...5/1
Mean heat flux	60 000 kcal/m <sup>2</sup> h	60000...70000 kcal/m <sup>2</sup> h
Mean heat flux max/min ratio	10/1	1.5/1
Throughput of gas	~ 50 000 Nm <sup>3</sup> H <sub>2</sub> + CO/m <sup>2</sup> h	~ 50 000 Nm <sup>3</sup> H <sub>2</sub> + CO/m <sup>2</sup> h
Heating	radiation	convection
Tubes per volume	< 1 tube/m <sup>2</sup>	< 45 tubes/m <sup>2</sup>
Lifetime of tubes	100 000 h (today reached 60 000 h)	100 000 h
Materials reformer tubes	G-X40CrNiNb 2524 (W.-Nr.1.4855; 1N 519) 'G-X45 NiCrCoWNB 4625 (1N643) 'G-X45 NiCrCoWNB 3626 (1N638)	(same as for conventional plants)
Material: pigtails	Incoloy 800 Incoloy 807	

Table 1.4.1-1: Comparison of Data of Conventional Reformer Tubes and Helium heated Reformer Tubes

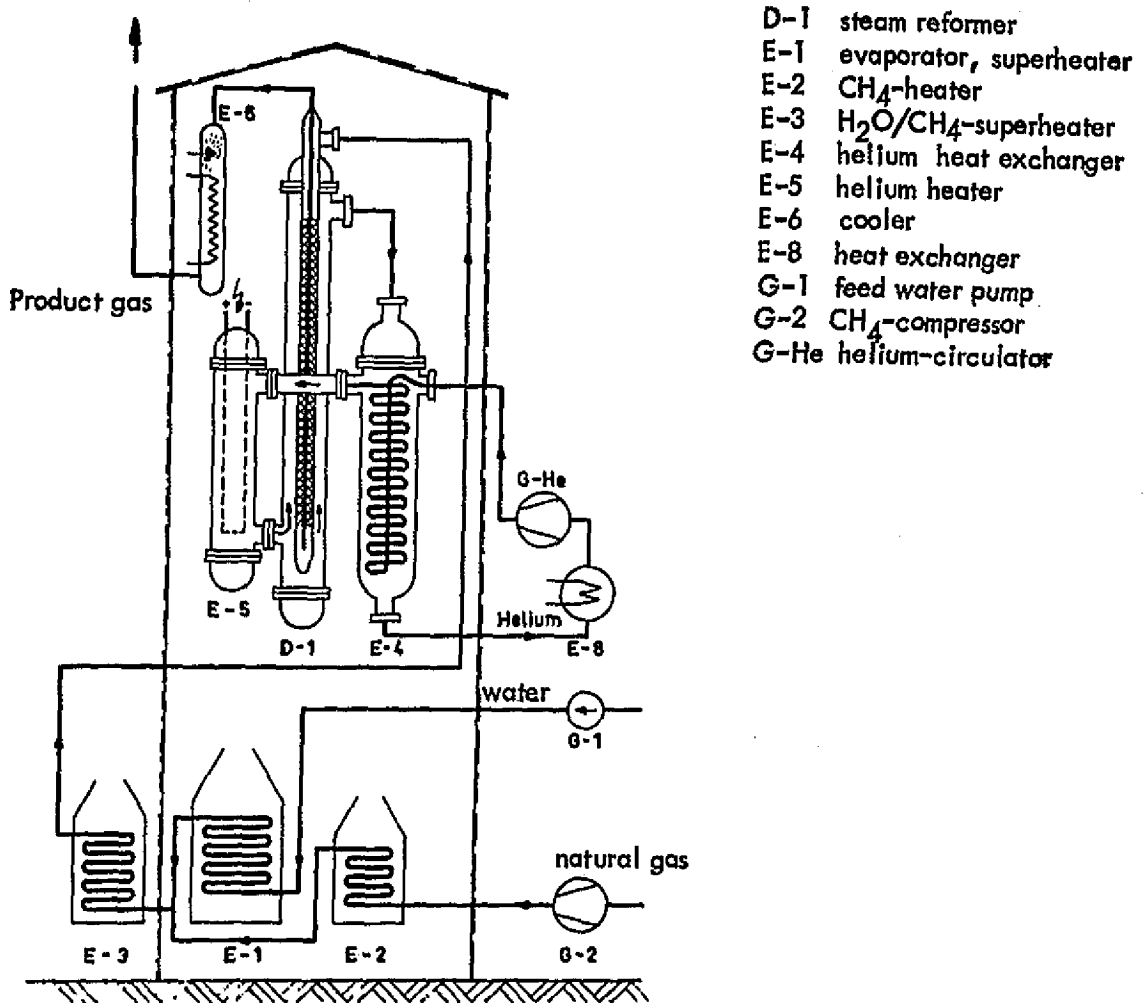


Fig. 1.4.1-2: EVA-plant (ref.10)

Main data:

Max. helium temperature	1000 °C
Max. helium pressure	50 b
Max. helium throughput	0.4 kg/sec
Inlet-temperature process gas	450...550 °C
Outlet-temperature process gas	750...850 °C
Reforming pressure	30...40 b
Throughput CH <sub>4</sub> max.	200 Nm <sup>3</sup> /h
Throughput steam max.	500 kg/sec

The data for the nuclear plant have been tested in a full scale tube experiment with helium heating (EVA-plant in KFA Jülich).

The following fig. 1.4.1-3 shows the flowsheet and the main data. The most interesting result of this experiment is that helium at 950 °C and 40 b is sufficient to heat the process and to obtain gas analysis and the methane conversion as in a conventional process. The heat flux through the tube walls is the same or even higher as in conventional tubes.

In a next bigger pilot plant (30 tubes heated by helium) the typical engineering aspects of a tube bundle must be tested and demonstrated.

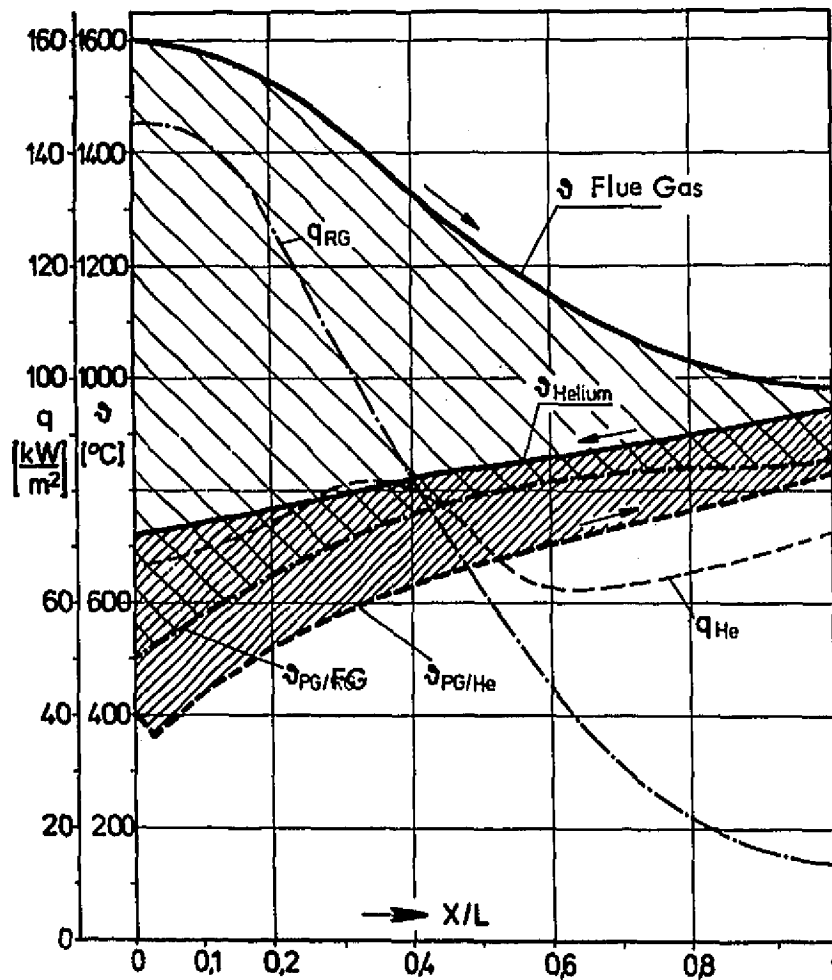


Fig. 1.4.1-3: Results of Steam Reforming in EVA-plant (for comparison also curves for conventional plants) (ref.10)

FG = Flue Gas  
He = Helium  
PG = Process Gas

Hydrogen diffusion from the process gas into the helium circuit of the nuclear reactor as well as tritium diffusion from the helium circuit into the process gas present considerably new problems for nuclear steam reforming plants. The first measurements regarding hydrogen diffusion on a laboratory scale show the following results: Pure hydrogen diffuses at high rates through the centrifugally cast materials of the reformer tubes at high temperatures (950 °C). For a mixture of hydrogen/steam in the ratio 1/1, this value is drastically reduced to about 60 ml H<sub>2</sub>/m<sup>2</sup> h due to the formation of inner oxide layers. A value of this magnitude was also determined in H<sub>2</sub>-measurements on the EVA plant. Starting from these experimental results, about 1 Nm<sup>3</sup> H<sub>2</sub> per hour can be expected to enter the helium circuit of the nuclear reactor (3000 MWth). This amount does not present any problem for the gas purification plant.

According to present knowledge, the tritium problem can be represented as follows:

The graphite of the core construction as well as the fuel elements form an excellent storage for tritium, so that only a fraction of the tritium formed by fission, He<sup>3</sup>- and Li<sup>6</sup>-transformation are actually released to the helium circuit. Even if it is assumed that the whole amount of this released tritium enters the process gas, the tritium content remains below the allowed limit. However, methods to remove the tritium by gas purification as completely as possible from the coolant circuit of the reactor would be advantageous.

### 1.4.2 Fuel Elements

Ball type fuel elements with the specifications for process heat reactors (burnup  $\sim 100\,000$  MWd/t HM, fast dose  $\sim 6 \times 10^{21}$  n/cm<sup>2</sup> ( $E > 0.1$  MeV),  $T_{\max}$ , fuel = 1250 °C,  $T_{\max}$ , surface = 1050 °C, normal conversion rate 0.6, Thorium cycle) are tested and proved by a lot of irradiation experiments. Series tests with more than 100 000 balls in AVR have been made even with higher burnups. Although the fast doses in the irradiation tests were even higher than the specification, the influence of higher fast dose is now being demonstrated in AVR, too, with more than 20 000 balls. Fig. 1.4.2-1 shows the irradiation experiments in the THTR 300 MWe development program and the results of AVR-operation.

Following these results the fuel elements of process heat reactors seems to be developed and tested.

Further qualification tests to find the limits of the fuel elements and the behaviour with typical other cycles must be made and have been started now.

To change over to high converter reactors ( $C \sim 0.95$ ), fuel elements with higher heavy metal contents (20...30 g/ball instead of 12 g/ball) must be tested. The burnup in this case must be lowered to 40 000 MWd/t HM. The shell ball as a fuel element for very high temperatures or as a method to lower all fuel temperatures must be tested, too.

As a very futuristic fuel cycle one can think of thermal breeders, too. In this case BeO-balls must be added to the core as dummy balls ( $C/\text{BeO} \sim 1/1$ ). Furthermore the burnup should be changed to 25 000 MWd/t HM. If the fuel cycle contains no U-236 (either U-233 cycle or separation of U-236 in low enriched cycle) a breeding factor of  $\sim 1.00$  seems to be realistic. There has been a lot of experimental work on the material behaviour of BeO as a reactor material, for instance: irradiation damage, He-buildup, Li<sup>6</sup>-removal by reprocessing, thermal stresses by  $\gamma$ -heating, allowed mechanical loads. Series tests to develop and demonstrate the behaviour during reactor operation have to be made in the future.

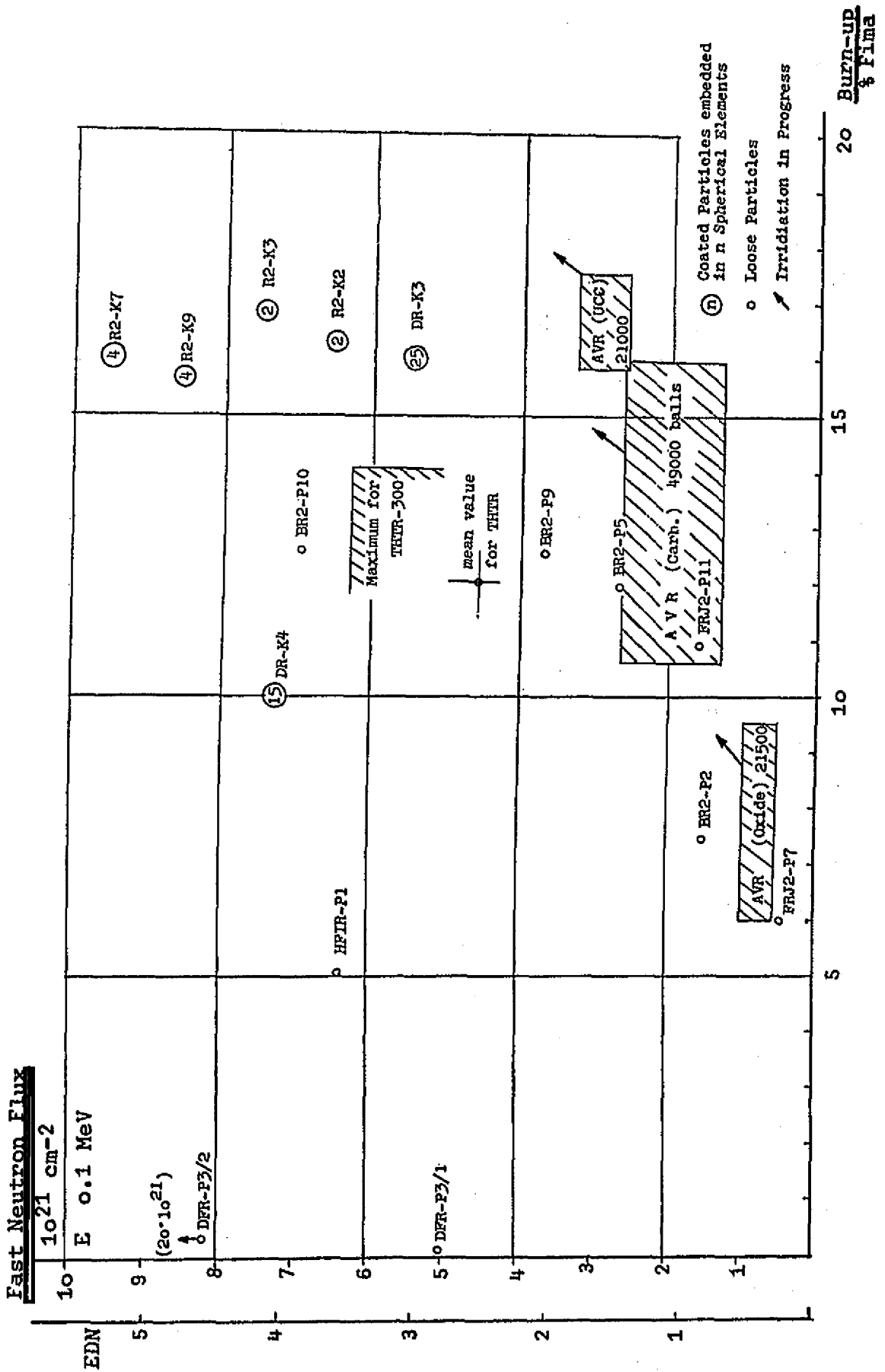


Fig. 1.4.2-1: Irradiation Experiments on coated particle fuel for THTR 300 (Status 1974) (ref.11)

### 1.4.3 Components

Most of the components of pebble bed high temperature nuclear reactors for process heat applications are developed by the AVR-reactor, the THTR-development program and the experience with other high temperature reactor systems (DRAGON, Peach Bottom, Fort St.Vrain).

There are some components which require further investigations:

- the hot gas duct between reactor core and heat exchanger.
- the prestressed steel vessel.
- the top reflector and upper side reflector of the core.

All other components (control rods, loading- and disloading systems, blowers, podboiler vessel, gas purification, instrumentation, containment, gas circuits, steam generators) require qualification tests.

In the hot gas ducting system there are some possibilities which must be investigated experimentally and which are already in investigation:

- single pipes with inner insulation.
- coaxial pipes without insulation of the hot gas pipe, the principle of cooling by counter-flow is used.
- coaxial pipes with inner insulations.
- gas ducts consisting of carbon stone with holes for hot gas surrounded by holes for cold gas.
- gas ducts consisting of cast iron with inner insulation and holes for hot and cold gas.

As insulation material fibres, metallic foils, carbon stone and other ceramics now are in qualification tests for high temperatures.

The development of prestressed steel vessels requires a qualification and verification program to solve the questions of fabrication, welding, prestressing and licensing. Now this program has started.

For the solution of the question of graphite reflector there are some independent ways which are as follows:

- development of graphites with irradiation doses higher than  $2 \times 10^{22} \text{ n/cm}^2 \text{ EDN}$  for  $600^\circ \text{C}$ .
- development of removable reflector designs ;for details, see Vol. 4.
- cooling of the reflector by a small bypass.
- development of special geometries for the reflector blocks to avoid too high stresses and swelling.

#### 1.4.4 AVR-Experience (ref. 12)

The AVR-reactor has been operated since 1968. Starting with a mean gas outlet temperature of 850 °C, the reactor now is operated (since nearly one year) with a mean gas outlet temperature of 950 °C, which is sufficient for application of nuclear process heat.

The reliability of the system was very good as the following fig. 1.4.4-1 shows.

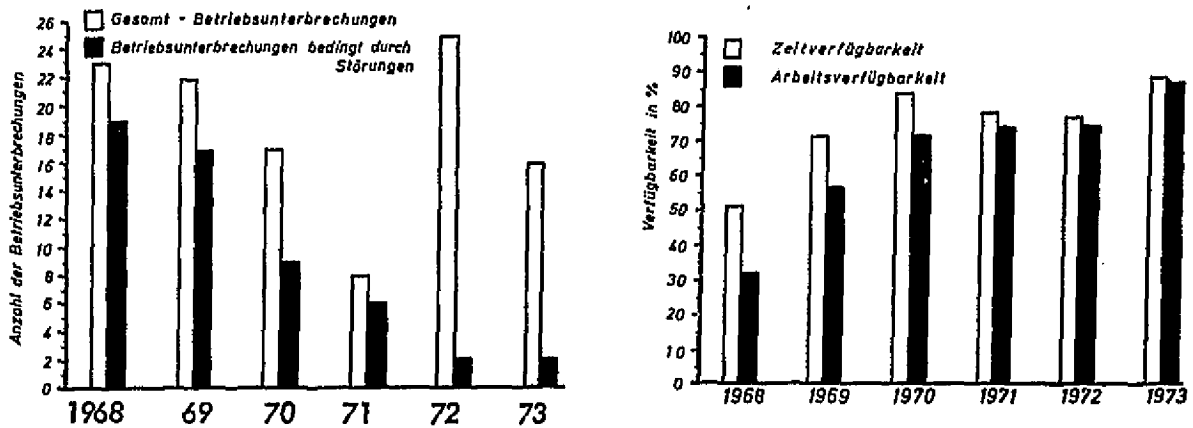


Fig. 1.4.4-1: Reliability of AVR power station

If some time had not been lost for installation and operation of the VAMPYR-loop (to measure the solid fission products) in the years 1972 and 1973, the reactor would have reached an availability of more than 90 %.

This demonstrates the excellent behaviour of the reactor components which is necessary for continuous nuclear process heat plant operation.

A second main result of AVR is that the activity of cooling gas is very low. Now there is a stationary cooling gas activity of 30 Ci (noble gases), which is generated by the uranium contamination in the coating of the coated particles.

The specific activities caused by solid fission products are very small, too, as is shown by the VAMPYR-experiments of AVR.

The following table shows the specific values which are so small that components of the reactor system can be handled and repaired.

Nuclide	Spec. Activity in Hot Gas		Spec. Activity in Cold Gas		Concentration in Air according to "1.SSVO <sup>†)</sup> " $10^{-9} \text{Ci/m}^3$
	$10^{-9} \text{Ci/Nm}^3$ $t_G = 770^\circ\text{C}$	$10^{-9} \text{Ci/Nm}^3$ $t_G = 850^\circ\text{C}$	$10^{-9} \text{Ci/Nm}^3$ $t_G = 770^\circ\text{C}$	$10^{-9} \text{Ci/Nm}^3$ $t_G = 850^\circ\text{C}$	
Sr-90	0.027	0.021			0.1
J-131	2.9	7.6	0.015	0.12	2
Cs-134	0.20	0.22	0.22	0.018	4
Cs-137	0.15	0.21	0.10	0.025	5
Ag-110 m	0.76	2.8	0.71	0.28	3
Ag-111	0.08	51.7	0.00	8.1	80
Fe-59	0.56	0.35	0.50	0.20	20
Cr-51	0.77	0.35	0.47	0.10	800
Zn-65	17.2	78.0	0.95	4.0	20

Table 1.4.4-2: Specific Activity of solid fission products in hot and cold cooling gas with different reactor outlet temperatures

The main interesting isotope is Cs-137, because it has a long halflife (30 a).

A way to get even lower radioactivity in the system is to improve the fabrication process for coated particles and to lower the value of outer uranium contamination (today  $10^{-4}$ , future  $10^{-5}$ ). The following fig. 1.4.4-3 gives an extrapolation of the results to higher gas outlet temperatures and for a larger reactor system of 3000 MWth. In the next months, experimental results will be obtained for  $950^\circ\text{C}$  from the VAMPYR-experiments of AVR.

A further main result of AVR operation is to show the safety of the system. The inherent safety for shutdown and after-cooling has been demonstrated by stopping the circulators, i.e. by demonstrating the worst accident (loss of coolant) and by taking out of operation of all the shut down rods. Nothing happened, the nuclear chain reaction was stopped by the negative temperature coefficient of the reactor, the afterheat was removed by natural convection in the core. The system stayed subcritical and the temperatures were limited by the large heat capacity of the system ( $\approx 1 \text{ t graphite/m}^3$  core volume) and the small power density of the core ( $2.5 \text{ MWth/m}^3$ ).

This behaviour of the core should be used for large reactors, too. Furthermore all core designs should be made to use the liner cooling as three parallel heat sinks for the afterheat of the core which is independent of the usual afterheat removal system.

Table †) Persons in the control areas are allowed under certain preconditions to remain in an atmosphere, which contains upto ten times this activity concentration.

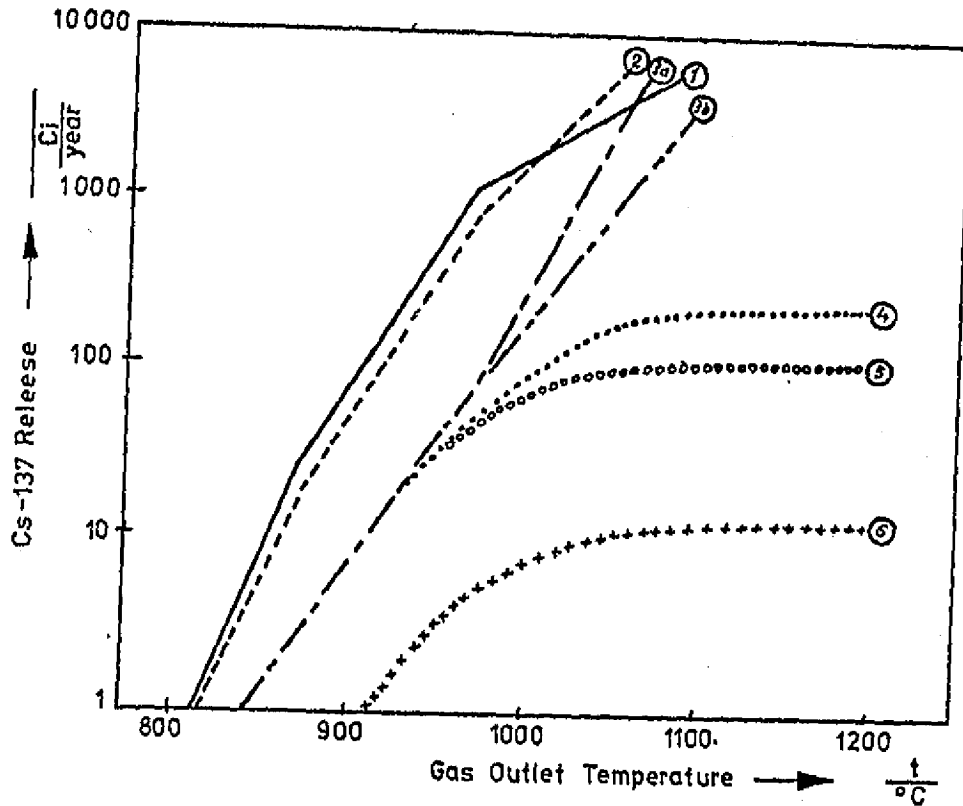


Fig. 1.4.4-3: Cs-137-release to Primary Circuit dependent on Gas outlet Temperature and Coated Particle Type (ref 13).

Release of Cs-137 as a function of gas outlet temperature (7)

Cycle: OTTO  
 Power: 3000 MWth  
 Burn up: 100,000 MWd/t  
 Gas inlet temp.: 250 °C  
 Fuel residence time: 800 days  
 Power density: 9 MW/m<sup>3</sup>

Curve No.	Symbol	Fuel	Matrix Contamination	Fraction of Failed Particles	Fuel Element
1	—————	Feed-TRISO Breed-BISO	$2.5 \times 10^{-4}$	$10^{-3}$	Conventional
2	- - - - -	Mixed-BISO	$2.5 \times 10^{-4}$	none	Conventional
3a	- · - · - ·	Mixed-BISO	$2.5 \times 10^{-5}$	none	Conventional
3b	- - - - -	Mixed-BISO	$2.5 \times 10^{-5}$	none	Zoned
4	· · · · ·	Feed-TRISO Breed-TRISO	$2.5 \times 10^{-5}$	$10^{-4}$	Conventional
5	o o o o o	Mixed-TRISO	$2.5 \times 10^{-5}$	none	Conventional
6	x x x x x	Mixed-TRISO	$2.5 \times 10^{-6}$	none	Conventional

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