Chapter 2

HTGR HEAT SOURCE AND UTILIZATION

The HTGR is the only nuclear energy source, which can produce temperatures higher than 950°C for different process heat applications, such as coal refinement and steam reforming of natural gas. Through refining the fossil energy carriers and thereby producing benign secondary energy carriers, e.g. hydrogen and methanol, with high process efficiency, it is possible to make a contribution for the atmospheric reduction of CO_2-emission and thereby to help address this global environmental issue. Moreover, the modular HTGR concepts under development offer the prospect of cost effective energy production at smaller unit size due to the simplifications arising from an emphasis on passive safety features. This supports a better match to local industrial process heat loads, and simplification of operational safety requirements makes the concept better suited to a process industry environment.

2.1 DIFFERENCES IN THE USE OF CONVENTIONAL AND HTGR HEAT SOURCES

The conventional heat sources for the chemical process applications are based on the use of furnaces, which burn the products of these processes or some other fossil energy carrier e.g. natural gas or oil. An example is the reformer of the ammonia technology of the UHDE-company in Germany (Figure 2.1), whereby the burners are arranged at the ceiling of the furnace and the flue gas heats the reformer tube along it's entire length primarily through thermal radiation. The temperature of the flue gas at the top of the furnace is ~ 1800°C and > 1,000°C at the bottom. Figure 2.2 shows the temperature profiles of the reformer tube as well as that of the process fluid along the heated length of the tube. The maximum heat flux in the range of about 65 kW/m^2 prevails near the inlet of the reformer tube. This is located in the upper part of the furnace and results in the production of the maximum temperature gradient in the reformer tube. However, during the part load conditions intensive cooling of the reformer tube via cold process fluid takes place in this area and a similar temperature profile also prevails. In the lower part of the reformer tube, where equilibrium of reaction is approached, the heat flux has been reduced to the value of about 15 kW/m^2. Some furnaces are designed with the arrangement of wall fired burners, instead of top fired, so that an average heat flux prevails along the heated reformer tube length.

Utilising the HTGR as the heat source provides hot helium from the core outlet, which flows through the reformer tube bundle in counter flow to the process gas flow. This allows for the transfer of its heat via endothermic chemical process through heat convection between the two fluids and through heat conduction in the reformer tube wall, as shown in Figure 2.3 of the test reformer bundle of Steinmüller-company in Germany [2]. However the average heat flux is generally lower in this case because of the higher flue gas temperatures available with the conventional steam reformer. With the HTGR as the heat source, an average value of heat flux between 40 and 60 kW/m^2 can be realized in the steam reformer [3] as well as in other relevant heat transfer components.

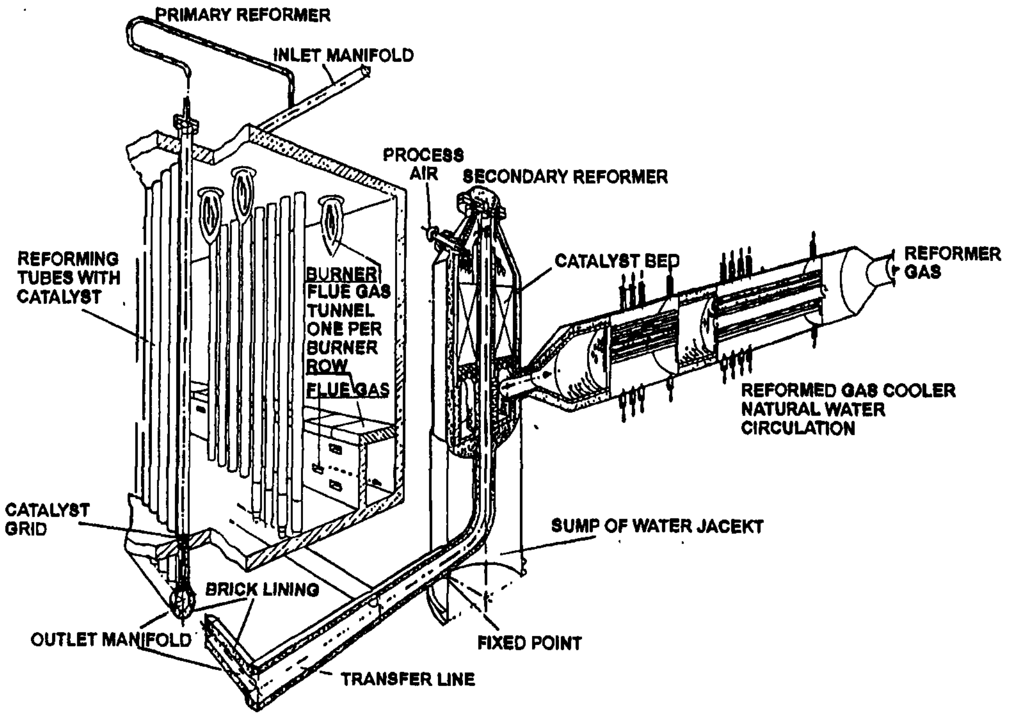
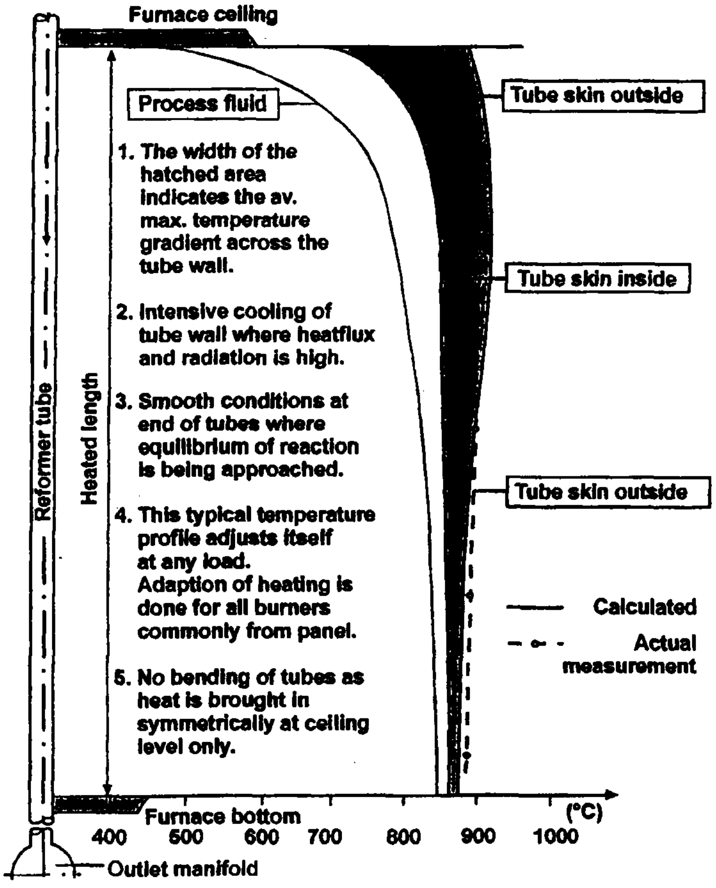


FIG. 2.1: UHDE Ammonia Technology, Reformer Section & Gas cooling



1. The width of the hatched area indicates the av. max. temperature gradient across the tube wall.
2. Intensive cooling of tube wall where heatflux and radiation is high.
3. Smooth conditions at end of tubes where equilibrium of reaction is being approached.
4. This typical temperature profile adjusts itself at any load. Adaption of heating is done for all burners commonly from panel.
5. No bending of tubes as heat is brought in symmetrically at ceiling level only.

FIG. 2.2: Temperature Profiles for Top Fired Reformer, UHDE Ammonia Technology

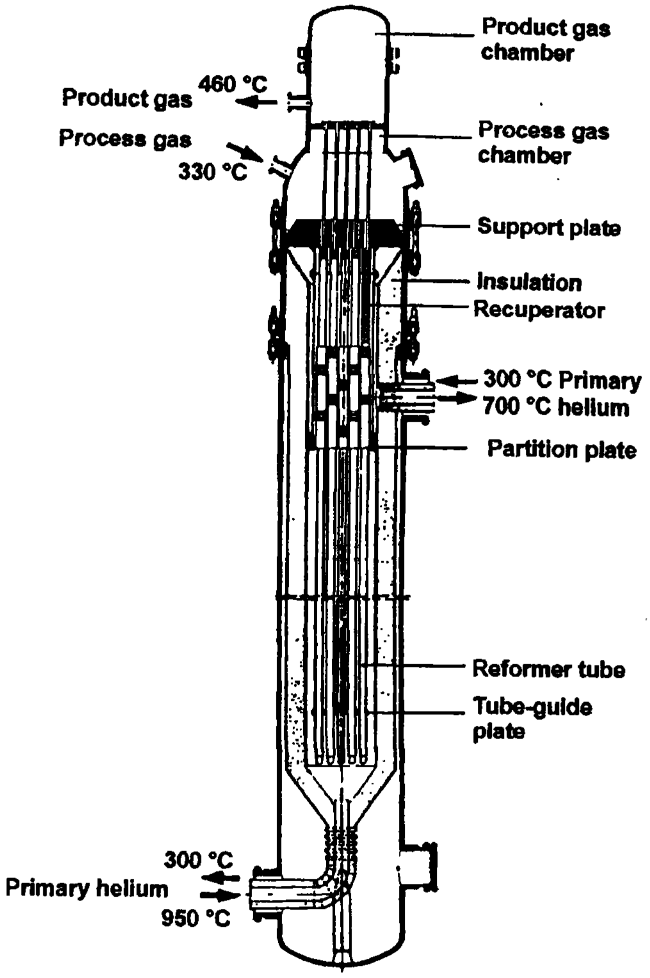


FIG. 2.3: Test Steam Reformer (5 MW)

2.1.1 Advantages and Disadvantages of HTGR heat source

Operation of the German AVR experimental HTGR over a span of twenty years resulted in consistently achieving a helium temperature of 950°C at the core outlet, thereby generating electricity with a steam turbine under conventional live-steam conditions. Good experiences were also obtained from the operation of HTGR plants in different countries of the world, however up till now the heat of HTGR has only been used for electricity production with the steam turbine cycle.

The potential exists for the HTGR heat source to support a multitude of applications including different chemical processes in the high temperature range, electricity generation in the high and middle temperature range and district heat in the low temperature range. This multiple utilisation of the HTGR can result in the attainment of very high system efficiency. The process for the production of methanol and hydrogen with steam reformer is shown in Figure 2.4, whereby an efficiency of ~ 74% has been achieved. At the same time with this process, the fossil energy carrier has been converted to a benign secondary energy carrier with a conversion rate of about 110 % [4].

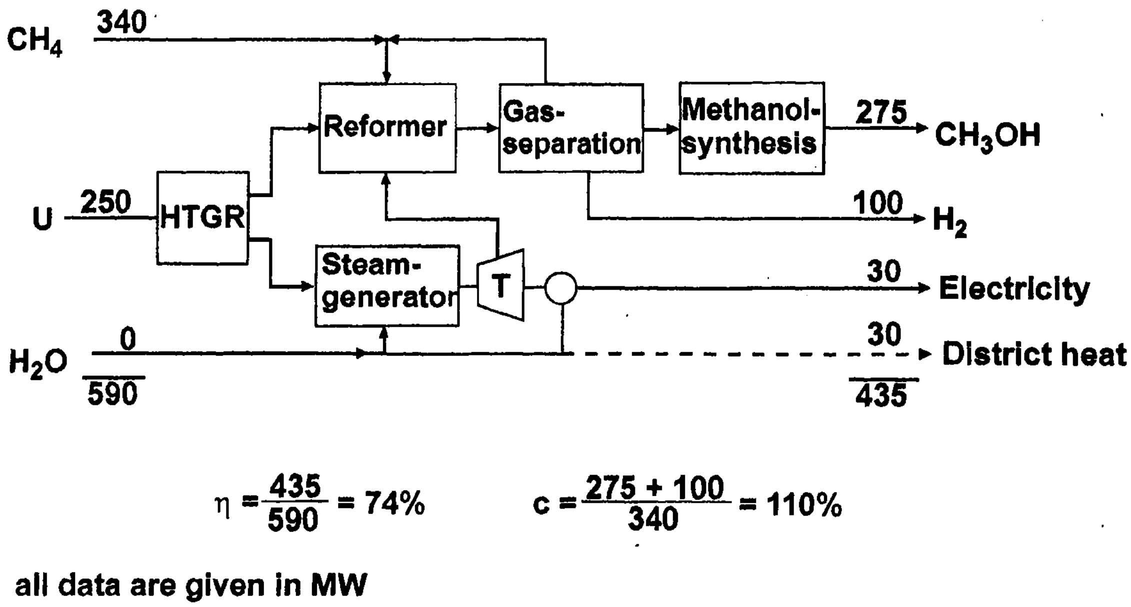


FIG. 2.4: Process of the Production of Methanol and Hydrogen [4]

The surplus hydrogen from this process can be used with the addition of CO_2 to increase the productivity of methanol. The required CO_2 can be provided from the burning of the fossil energy carrier or CO_2-rich natural gas e.g. from the Natuna-gas field of Indonesia. This gas can be used directly in the steam reforming of methane to optimize the composition of synthesis gas produced from this process, and for its further synthesis to methanol, as described in detail in the following chapters. A further advantage for the use of this CO_2 is to also improve the global environmental issue.

Under the consideration of the aspects of high heat utilization, optimal design-concept of the steam reformer and economic competitiveness of it's products, analyses were performed of different design parameters resulting in changes to the system pressure of the process gas and the equilibrium reforming temperature. The following conditions of the primary helium side have been adopted for further analyses:

Reformer power	70 MW
Mass flow	50,3 kg/s
Inlet Temperature	950°C
Outlet Temperature	680°C
System pressure	40 bar.

Moreover the feedgas with a temperature of 560°C enters the catalyst region of the reformer with the following composition:

CH_4: 19,77 %

C_2H_6: 0,17 %

CO: 0,02 %

H_2O: 80,05 %

These conditions remain unchanged for further studies.

Compositions of the product gas for an equilibrium reforming temperature of 800°C with different process gas exit pressures are provided in Table 2-1. Compositions and mass flow of the product gas for a process gas exit pressure of 41.9 bar and with different equilibrium reforming temperatures are provided in Table 2-2 [5]. By these analyses, the equilibrium reforming temperature is ~ 10°K lower than the exit temperature of the product gas out of the catalysts region.

Table 2-1: Composition and volumetric flow of the product gas with different process gas pressures [5]

Composition		**Exit pressure of product gas**	
		41,9 bar	20 bar
CH_4	Vol %	5,38	2,83
H_2	Vol. %	37,35	43,06
CO	Vol. %	4,53	6,10
CO_2	Vol. %	5,98	6,23
H_2O	Vol. %	46,76	41,77
Reaction enthalpy	kJ/kg	1554	1933
Mass flow	kg/s	37,2	31,1
Volume flow (process gas)	m^3(STP)/s	47,3	39,5
Volume flow (product gas)	m^3(STP)/s	59,8	52,4
Conversion (CH_4+C_2H_6)	%	66,1	81,3

By reducing the system pressure of the process gas, the methane conversion rate can be increased, whereby the cost of the refinement of the synthesis gas can be reduced to achieve the required product, hydrogen or methanol. However, in this case, the volume flow of the H_2 and CO is not considerably increased, because of higher reaction enthalpy. The total volume flow has to be decreased with the same heat source capacity. Moreover, the investment costs of the steam reformer has to be increased with the required thicker walls of the reformer tubes in order to compensate for the stresses caused due to the higher pressure difference between the primary helium and secondary process gas. Therefore, the pressure decrease of the process gas has no economical advantage.

Table 2-2: Composition and Mass flow of the product gas with different equilibrium reforming temperatures [5]

Reforming Temp. (°C)		800	825	850	860
Composition of product gas					
CH_4	Vol. %	5,38	4,36	3,42	3,08
H_2	Vol. %	37,35	39,45	41,31	41,97
CO	Vol. %	4,53	5,36	6,17	6,48
CO_2	Vol.. %	5,98	5,89	5,74	5,68
H_2O	Vol. %	46,76	44,95	43,36	42,79
Conversion (CH_4+C_2H_6)	%	66,1	72,0	77,6	79,8
Reaction enthalpy	kJ/kg	1554	1710	1859	1915
Mass flow	kg/s	37,2	34,4	32,1	31,3

With a constant helium inlet temperature of 950°C, the equilibrium reforming temperature can be increased only through the increase of heat transfer area of the reformer tubes. Also in this case, with the increase of the equilibrium reforming temperature the product gas mass flow has to be decreased with the same capacity of the heat source, because of the higher reaction enthalpy. Therefore, the economical advantages can not be realized by these analyses. Only with the use of better materials or through enhancement of the heat transfer characteristics or through the increase of helium inlet temperature, can the economic advantage of an increase of methane conversion rate be achieved.

To achieve the goal for higher efficiencies by the chemical conversion processes, higher process temperatures are required. Moreover, the heat utilization components, which are the barrier between the primary and secondary circuits such as steam reformer, must fulfill the safety requirements during normal operation and also in accident conditions. Any leakage of the primary helium outside the reactor building must be avoided. Therefore, the walls of the heat transfer components should be built from very good high temperature resistant materials. These should have good properties in regard of creep behaviour, fatigue properties, structural stability and corrosion resistant. Further, through design criteria, the primary and secondary stresses by these components should be kept low.

Commercially available alloys, INCONEL 617, HASTELLOY X and INCOLOY 800H, have been tested in different experimental facilities under operational conditions with good results. However, for long term use of the steam reformer for ~ 100,000 hours, the best results have been achieved by INCONEL 617, which has a higher investment material cost. To realize a higher helium temperature than 950°C, new materials such as ceramics will have to be developed for future heat utilisation components.

Different studies have shown that the economic competitiveness of the nuclear process heat plant has improved through different potentials already applied in the refinement of coal, and it is comparable to non-nuclear alternatives [5]. However the economic competitiveness of the coal refinement in total in comparison to the present market conditions has not existed since the end of the oil price crisis. Similar investigations have also been performed for the conversion of natural gas to methanol e.g. with the gas of the Natuna gas field in Indonesia [6]. The highest potential for economic competitiveness of this gas field is realised with the main product being methanol as a substitute for gasoline and diesel. However, the capital costs of the HTGR heat source plays a dominant role in this economic evaluation. The cost of this process needs to be improved for future deployment in order to justify the introduction of the HTGR in the heat market parallel to electricity generation. However, it is the only nuclear heat source which can supply heat in the higher temperature range of 900° to 1100°C.

Also, this nuclear heat source has significant safety characteristics which would allow its construction directly near the heat market. Under all possible cases of accident, there is no appreciable radiological consequences which can occur outside the plant i.e. no immediate or delayed fatalities, no evacuation, no relocation and no changes in eating and drinking habits. Therefore, in the future, 'catastrophe-free' nuclear energy is expected to be realized with the design of HTGR [7]. This NPP should also provide the benefit of not causing risk to the surrounding investments associated with the heat utilization plant. The HTGR plant size can be realized compatible with the consumer demand, so that customers and consumers with smaller financial resources are in position to use such plants.

The HTGR heat source also has advantages in comparison with fossil energy carriers with respect to the global environmental issue, particularly because of it's potential to reduce CO_2-emission. Moreover, if the HTGR can be utilized for co-generation applications including process heat for industry in parallel to electricity generation, it can further provide for the environmental attribute of a reduction in CO_2-emission. At present, the energy demand in the total world is increasing, although it is stagnant in some of the industrialized countries.

The industrialized countries, with a population of only 25 % of the world, produce almost 75 % of the total CO_2-emission in the world. The average CO_2-emission of these countries is ~ 3,6 tC/y per inhabitant in comparison with only 0,4 tC/y per inhabitant for the remaining 75% of the world population [8]. Therefore, according to the goal of the world energy conference, the CO_2-emission in these countries has to be reduced dramatically by the factor of ~ 4 in the coming 20 to 50 years. This can be achieved only if these countries produce and consume their energy through the use of non-fossil energy carriers. The HTGR can play a dominant role for the world energy supply system in the future because of its positive safety and high temperature operational characteristics. This energy source will also be enhanced economically if future additional taxes are assessed on the emission of CO_2.

Positive experiences gained through past operation of HTGR plants has encouraged utilities, particularly in South Africa, to establish new related nuclear technology. Cost savings are achievable due to the excellent safety of these plants as well as through their series fabrication, and the economic competitiveness of their associated products is expected to be realized with future development [9].

2.2 REFERENCES TO CHAPTER 2

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