HTR PLUS MODERN TURBINE TECHNOLOGY FOR HIGHER EFFICIENCIES

H. BARNERT, K. KUGELER
Research Centre Jülich,
Institute for Safety Research and
Reactor Technology,
Jülich, Germany

Abstract

The recent efficiency race for natural gas fired power plants with gas-plus steam-turbine-cycle is shortly reviewed. The question 'can the HTR compete with high efficiencies?' is answered: Yes, it can - in principle. The gas-plus steam-turbine cycle, also called combi-cycle, is proposed to be taken into consideration here. A comparative study on the efficiency potential is made; it yields 54.5. % at 1 050 °C gas turbine-inlet temperature. The mechanisms of release versus temperature in the HTR are summarized from the safety report of the HTR MODUL. A short reference is made to the experiences from the HTR-Helium Turbine Project HHT, which was performed in the Federal Republic of Germany in 1968 to 1981.

Keywords:
High Temperature Reactor HTR, modern turbine technology, gas-plus steam-turbine cycle, combi-cycle, efficiency natural gas fired power stations with gas-plus steam-turbine cycle, 3-pressure-steam-turbine cycle, release versus temperature, experiences from HTR-Helium-Turbine Project HHT.

HTR plus Modern Turbine Technology for Higher Efficiencies

1. Efficiency Race Triggered by Natural Gas

1.1. In summary: The decline of the price of fossil energy carriers after the end of the oil price crisis, in particular the low price of natural gas, have triggered an impetuous development in gas turbine cycle technology. An efficiency race has been opened up to achieve higher values of efficiencies for fossil fired power plants, and in particular for natural gas fired power plants. The preferred solution of modern turbine technology is the gas-plus steam-turbine cycle technoloy, also called combi-cycle. A high efficiency value of existing plants is e.g. 52 %; a typical value for the future perspective is 58 %.

1.2. As an appetizer for this chapter two references:

1.2.1. Siemens AG, Bereich Energieerzeugung (KWU): "The development of gas turbines did achieve a new culmination at December 1994. During normal operation at our test site in Berlin the model V84.3A demonstrated performances which are number one in the world:

- An efficiency (of a gas turbine) of 38 %, which leads to an efficiency of a GUD-plant of 58 % (GUD = Gas- und Dampf-Turbine, Trademark) and
- a power (of a gas turbine) of 170 MW, the largest in the class of the 60-Hz-turbines." Lit. SIEMENS-1995.

1.2.2. From a scientific report: "The efficiency can be increased from yesterday's promising 54 % in two steps to values around 60 % at the end of the decade. In each step three parameters are important, these are: higher effiencies by optimalization of the design of the blades, increased gas turbine-inlet temperature and improvements in the steam-turbine process, e.g. with a sub-critical 3-pressure-process including re-heat steps", lit. RIEDLE-1994, S. 39.

1.3. In detail on efficiencies on gas turbines combi-cycles and future prospects of natural gas fired power plants:

1.3.1. In 1994 natural gas-fired power plants with gas turbines with the total power of about 240 GWe were in operation with a total efficiency of 32 %, and natural gas fired power plants with combi-cycles, that is gas-turbine plus steam-turbine cycles,GST, with the total capacity of about 130 GWe were in operation with an efficiency of 49 %, RIEDLE-1994, fig. 1. The bigger number of capacity for gas turbines - in contrary to combi-cycles - is an indication that smaller unit capacities and smaller capital costs are also decisive in the decision for an investment. But there is a trend to make use of the potential for higher efficiencies with the combi-cycles, fig. 1.

1.3.2. Natural gas fired power stations with steam cycles achieve efficiencies between 42 and 47 %, fig. 1. But obviously the gas turbine technology offers, in particular for natural gas based systems, a number of advantages, e.g. low capital cost, short construction time, and last not least high potential for efficiency.

1.3.3. Official measurements at the power station AMBARLI, Turkey, with a gas plus steam-turbine-cycle, GST, called GUD, and constructed by Siemens resulted in an efficiency of 52,5 % at nominal power, fig. 1, and 53,2 % at peak power, lit. SIEMENS-1993. This applies for the first block with the total power of 450 MWe. The second and third block showed efficiencies at nominal power of 52.0 % and 51.9 %. These measured values, fig. 1, fit with the theoretical evaluations, lit. RUKES-1993 and REUTER-1993, and they apply for a gas turbine-inlet temperature of 1050 °C. The recently finished construction of the 205 MWe GUD power station TROMBAY, India, has a measured value of the efficiency at nominal operation of 50,48 %, lit. NAUEN-1995, table 1, at the air temperature of 35 °C, which adjusted to 24 °C means about 51,5 % at a gas turbine-inlet temperature (ISO 2314) of 1037 °C, lit. NAUEN-1995, table 2.

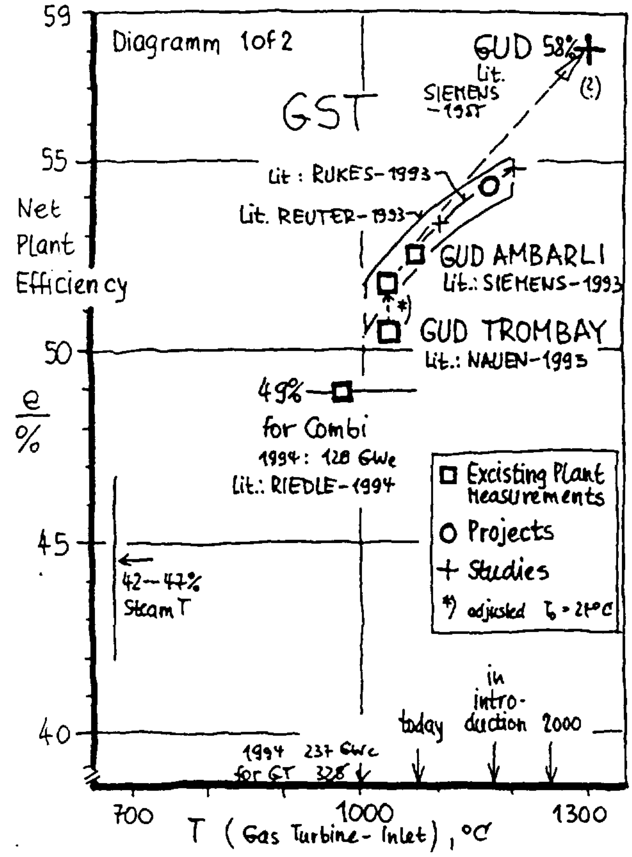


Fig. 1: Efficiency race natural gas, status and trend for the steam turbine cycle, the gas turbine cycle and the gas-plus-steam-turbine cycle: Net plant efficiency versus gas turbine inlet temperature, diagram 1 of 2.

1.3.4. With increasing gas turbine inlet temperature the efficiency increases at about 2 %-points/100 K gas turbine-inlet temperature, so that at around 1200 °C about 55 % can be achieved, fig. 1. Gas turbines with gas turbine-inlet temperatures in the range of 1 100 to 1 200 °C are now in introduction into the market. The perspectives is that at about the year 2000 the gas turbine-inlet temperature could achieve 1 250 °C, lit. RIEDLE-1994.

1.3.5. It should be remarked here that the information about the promising value of efficiency of 58 % in the advertisement of the vendor industry - as usually - does not contain any precise information about the gas turbine-inlet temperature; therefore the respective value in fig. 1 is labled with a question mark. The reason is simple: The gas turbine inlet temperature is the simplest indicator for progress in the gas turbine technology.

1.3.6. Another factor to be considered is - of course - the capital investment.

Table 1: HTR with Gas-plus Steam-Turbine Cycle, 2 Designs

1. Primary circuit		Design A	Design B
Cooling fluid		Helium	Helium
Thermal power	MW	200	200
Reactor inlet temperature	°C	350	364
Reactor outlet temperature	°C	950	1050
Reactor outlet pressure	bar	60	60
Relative pressure losses	%	3,3	0,8
Helium mass flow	kg/s	64,2	58,7
Electric blower power	MW	3,3	0
2. Gas turbine circuit			
Working fluid		Helium	same
Log. temperature difference in IHX	°C	50	-
Relative pressure losses	%	6	3
Turbine inlet temperature	°C	900	1050
Turbine outlet temperature	°C	580	548
Relative cooling massflow	%	3	3
Turbine mass flow	kg/s	64,2	58,7
Turbine pressure ratio		2,42	3,71
Polytrope turbine efficiency	%	90	92
Compressor inlet temperature	°C	97	97
Compressor outlet temperature	°C	291	396
Compressor mass flow	kg/s	66,2	60,4
Compressor pressure ratio		2,58	3,91
Polytrope compressor efficiency	%	90	91
Generator power	MW	39	59,2
3. Steam turbine circuit			
Helium inlet temperature in waste heat boiler	°C	580	548
Helium outlet temperature in waste heat boiler	°C	97	97
HP - High pressure steam\HP	°C/bar	550/60	515/140
LP -Low pressure steam\MD	°C/bar	200/8	300/29,4
HD -Steam mass flow\LP	kg/s	43,8	230/5,6
LP - Steam mass flow	kg/s	6,9	-
Polytrope efficiency of steam turbine	%	85	85
Generator power	MW	57,9	52,3
4. Total plant			
Internal thermal efficiency of combined cycle	%	48,9	55,7
Total power (sum minus mech. losses)	MW	96,8	110
Total efficiency	%	48,4	55,0
Self demand (with blower)	MW	4,2	1,0
Net power	MW	92,7	109
Net efficiency	%	46,3	54,5

Remark:
Design A: Lit.: HAVERMANN-1993, BARNERT-SINGH-1994
Design B: This study

2. HTR with Gas-plus Steam-Turbine, GST

2.1. In summary: The efficiency potential of the gas turbine technology for the conversion of high temperature heat from the HTR into electricity is - in principle - as high as that based on natural gas. Therefore it is proposed here to take the gas-plus-steam-turbine-cycle, GST, into consideration, in particular with a "3-pressure-steam-turbine-cycle". With further improvements, in particular in the gas turbine cycle, and with the assumption that the gas turbine-inlet temperature is 1 050 °C (100 K more than AVR in 1974) the calculated net efficiency is 54.5 %. A particular advantage of the GST versus the gas turbine cycle with recuperation is that the core-inlet temperature is smaller at comparable efficiency conditions.

2.2. In detail on efficiencies from various projects and on the efficiency potential, in comparison to the conventional natural gas based technology:

2.2.1. The measured efficiency of electricity production in the THTR-300 as the ratio of the measured generator power vs. the thermal power is 39,7 % (303 MWe/763 MWt, not the net-

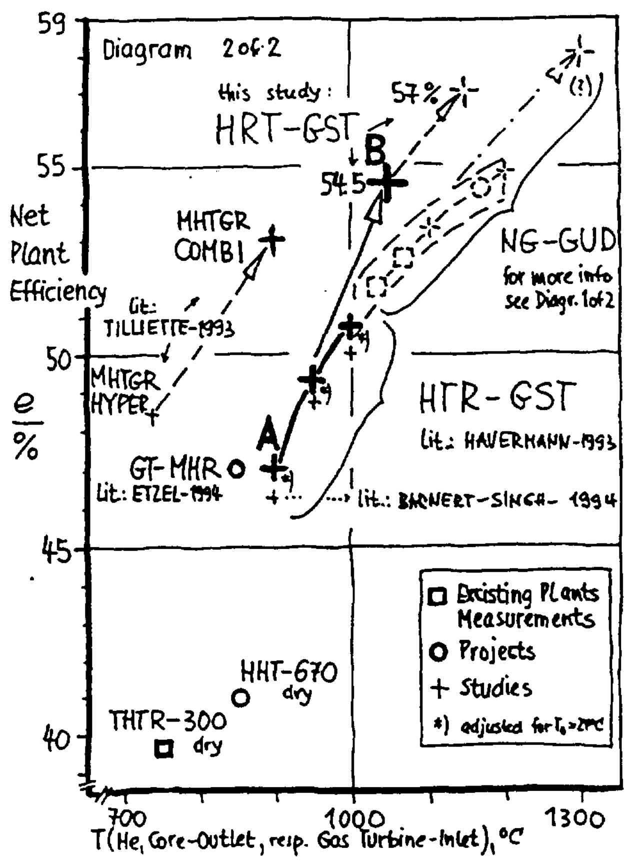


Fig. 2: HTR with gas-plus steam-turbine-cycle, GST, trends in efficiency and comparison to natural gas: Net plant efficiency versus helium temperature at core-outlet, respectively gas turbine-inlet, diagram 2 of 2: The HTR-GST has the same efficiency potential as the natural gas based system.

efficiency), lit. SCHWARZ-1987, p. 8, table 2, measurement made 100 % power. These measured values were close to the calculated values. The THTR-300 had a steam turbine cycle and a dry cooling tower, it was operated at a core-outlet temperature of 750 °C, fig. 2. The operation of the THTR-300 was terminated in 1989, due to financial and political difficulties; rigth now (October 1995) the unloading of the fuel pebbles is finished since more than half a year.

2.2.2. The HHT-670 (HHT = HTR plus Helium Turbine, 670 MWe, projected demonstration plant) had an efficiency of 41 % at a gas turbine-inlet temperature of 850 °C, lit. ARNDT-1979. It should be remarked, that this efficiency value applies for dry cooling. The project HHT was performed from 1968 to 1981 in the Federal Republic of Germany; it was terminated in 1981 because of the decision that the THTR-300 follow up-plant should be an HTR with a steam cycle. More details are given in lit. WEISBRODT-1995, respectively in this workshop.

2.2.3. The efficiency of the GT-MHR (GT-MHR = Gas Turbine-Modular High Temperature Reactor) is 47 % at the gas turbine-inlet temperature of 850 °C, lit. ETZEL-1994, table 1. The gas turbine cycle includes a compact plate fin recuperator. An important design feature in that project is that all part of the gas turbine and the heat exchangers, as well as the generator, are located in the power conversion vessel.

2.2.4. The MHTGR-Combi (MHTGR = Modular High Temperature Gas-Cooled Reactor with Combined Gas Turbine - Hypercritical Steam Turbine Cycle, 238.5 MWe) has an efficiency of 53 % at the gas turbine-inlet temperature of 900 °C, fig. 2, lit. TILLIETTE-1993, fig. 11 on page 14, with an MHTGR of 450 MWt. It is foreseen to be operated with an intermediate heat exchanger, the core outlet temperture is 950 °C and the core inlet temperature 512 °C. The base for this proposal is an MHTGR-HYPER utilising an advanced, hypercritical steam cycle alone with an efficiency of 48.4 % at the steam generator-inlet temperature of 730 °C, fig. 2. The interesting thermodynamical feature of this proposal is that the hypercritical steam turbine cycle allows a strong reduction in exergy losses in the steam generator: It fits very well to the heat cascading between the gas turbine and the steam turbine cycles.

2.2.5. Another possibility for the reduction of exergy losses in the heat cascading between the gas turbine cylce and the steam turbine cycle is the "2 or 3 pressure steam cycle" as used in modern conventional GST-cycles based on natural gas, chapter 1. Therefore it is proposed here to take the gas-plus steam-turbine cycle, GST, into consideration, in particular with a "3-pressure-steam-turbine-cycle".

2.2.6. The HTR-GST, design A, has an efficiency of about 47 % at the gas turbine-inlet temperature of 900 °C, fig. 2, being adjusted for T_0 = 24 °C in this figure, from 46,3 %, table 1, lit. BARNERT-SINGH-1994 and lit. HAVERMANN-1993. The HTR-GST, design A has the following main data: modular HTR-200 MWt, 950 -350 °C (core-outlet,-inlet temperature), intermediate heat exchanger 900-291 °C, gas turbine with 2,42 turbine pressure ratio, steam turbine cycle with 2 pressures and internal thermal efficiency of 48,9 %, table 1, column design A, lit. BARNERT-SINGH-1994 and lit. HAVERMANN-1993. An important design detail of design A (not given in table 1) is the pintch point temperature difference of 8 K. The higher values of efficiencies in fig. 2, about 49 % at 950 °C and about 50,5 % at 1 000 °C, were achieved by the omittance of the intermediate heat exchanger and the increase of the gas turbine inlet temperature to 1 000 °C, lit. HAVERMANN-1993. Here it can be remarked that the tendency of these efficiency values does well fit with the tendency of measured efficiency values of assisting plants based on natural gas, called NG-GUD in fig. 2.

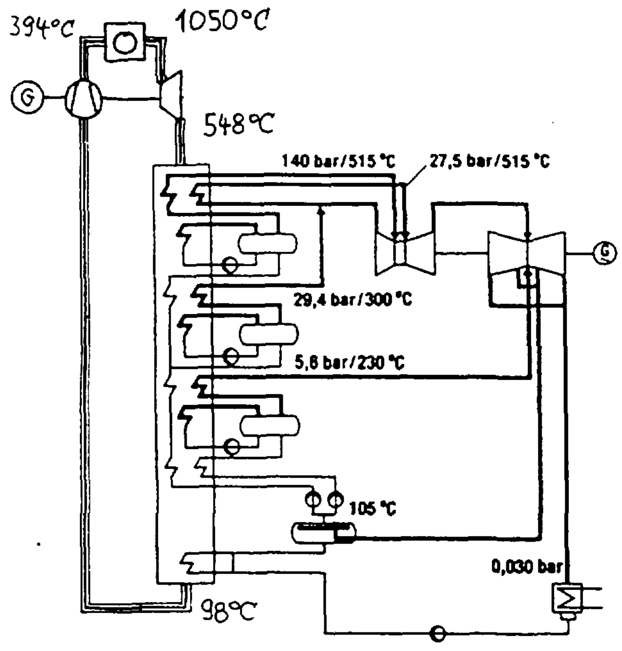
2.3. In detail on HTR with gas-plus steam turbine cycle, GST, in particular with a "3-pressure steam turbine cycle", design B, this study:

2.3.1. The HTR-GST-design B has an efficiency of 54,5 % at the gas turbine-inlet temperature of 1 050 °C, fig. 2, this study. The design B consists of an HTR with 200 MWt, a gas turbine cycle, comparable to the conventional ones and a 3-pressure-steam turbine cycle, taken from conventional design proposals, fig. 3 and fig. 4, lit. RUKESS-1993, p. 28, fig. 6. The calculated design data, table 1, column design B, are made for a gas turbine-inlet temperature of 1 050 °C, and include some improvements of the gas turbine technology as compared to design A. These are: polytrope turbine efficiency: 92 % (instead 90), polytrope compressor efficiency: 91 % (instead 90), relative pressure losses: 3 % (instead 6, because steam generator instead of compact recuperator) and relative cooling mass flow: 3 % (unchanged, in spite of increased gas turbine inlet temperature).

2.3.2. The gas-turbine-cycle of design B is similar to conventional ones, fig. 3. It has the following temperature data: gas turbine-inlet temperature 1 050 °C, and core-inlet temperature 396 °C. It can be remarked, that the low core-inlet temperature is an advantage of the GST-cycle compared to the gas turbine cycle with recuperation.

2.3.3. The 3-pressure-steam-turbine-cycle of design B, fig. 3, has been taken unchanged from a conventional design, because it can be considered to be an optimum design already. The steam generator-inlet temperature is 548 °C, the steam generator outlet temperature is 98 °C. The process also includes some re-heat. A possible disadvantage of the 3-pressure steam turbine cycle in comarison to the 2-pressure steam turbine cycle is the increased value of the 3rd pressure of 140 bar, which is higher than the primary helium pressure and therefore needs to be particularly considered in design base accidents.

2.3.4. An impression on the reduction of exergy losses can be derived from the temperature-heat-diagram, fig. 4. The bundles in the steam generator are arranged in such a way, that the temperature-heat-lines of the steam cycle fit best to that of the helium cycle. The pintch point temperature difference in design B has also not been changed and therefore is 12 K (not



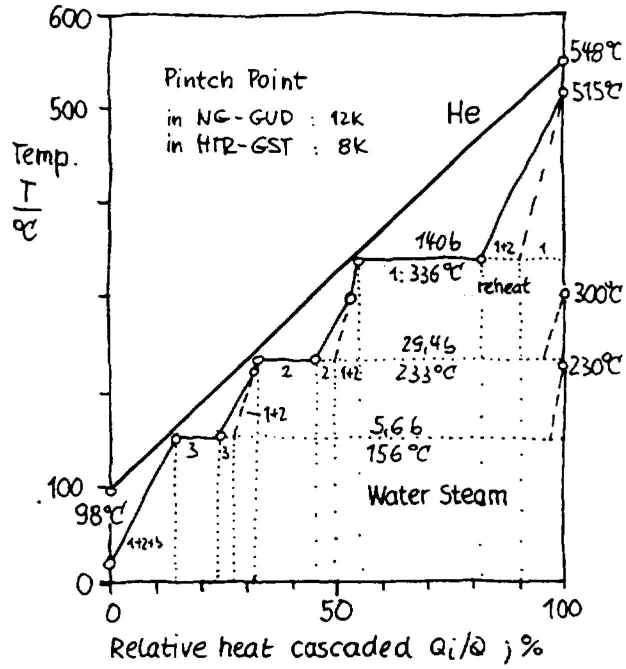


Fig. 3: Potential HTR-GST with an efficiency of 54.5 %, flow sheet with gas-plus 3-pressure -steam-turbine-cycle, taken from conventional designs, gas turbine cycle adjusted for reactor outlet temperature of 1 050 °C.

Fig. 4: Potential HTR-GST with an efficiency of 54.5 %, temperature-heat-diagram for the 3-pressure-steam-turbine for the flow sheet of fig. 3: the exergy losses of heat transfer are reduced.

mentioned in table 1). For future evaluations this value may be reduced to 8 K, resulting in a further improvement of the efficiency.

2.3.5. An even higher efficiency of HTR-GST could be 57 % at a gas turbine-inlet temperature of 1 150 °C, fig. 2, dashed arrow and cross; the conditions is - of course - that a future HTR can produce high temperature heat of 1 150C °C.

2.3.6. An important advantage of the "gas-plus steam-turbine cycle" in comparison to the "gas turbine cycle with recuperation" is that the core-inlet temperature is smaller at comparable efficiency conditions. The following comparison can be taken as an example: The GT-MHR with 47 % at 850 °C, fig. 2, has an core inlet temperature of 493 °C (919 °F), lit. ETZEL-1994, fig. 7, upper part; the HTR-GST with 54.5 % at 1 050 °C, fig. 2, has an core inlet temperature of 396 °C, fig. 3.

2.3.7. In addition to these evaluations on efficiencies and other design data, it is of course decisive to take capital investments into consideration.

2.3.8. The gas turbine-inlet temperature of 1 050 °C used in design B of this study is just 100 K higher than the mean core-outlet temperature of the AVR, which was achieved already in 1974.

3. HTRs with Increased Gas Outlet Temperature, e.g. 1 050 °C

3.1. In summary: The biggest challenge to increase the temperature of the produced heat is put on the HTR by the improving gas turbine technology. Therefore future designs of HTR fuel on the basis of the TRISO-coated particle and of new HTR cores may realize increased gas outlet temperatures, e.g. 1 050 °C. Reasons are good experiences of the operation of the AVR, other experimental results and proposals to increase the retention capability of the HTR fuel. Another reason may be that contamination of the turbine may not be an important issue as before.

3.2. In detail on the retention capability of HTR-fuel in dependence from the temperature:

3.2.1. In the THTR-300 the maximum fuel temperature of the fuel pebbles is 1 250 °C as the required design value and - at the same time - as a value for the commercial guarantee, fig. 5, lit. HKG-1969, Bd. 1, S. 4.16, tab. 4.2.2-1 (THTR-300 Safety Report). For the release it is stated there: "For these fuel elements the fraction of release for Xe-133 shall not exceed the value of 3 x 10^{-5} as the mean over the lifetime and as the mean over the core". The coated particles of the fuel elements of the THTR-300 had a BISO-coating.

3.2.2. A good overview on the retention capability of modern fuel pebbles with TRISO coated particles has been prepared for the HTR-MODULE describing the mechanisms of release of fission products, lit. SIEMENS-INTERATOM-1988 (HTR-MODUL Safety Report), Bd. 1:

3.2.2.1. In the lower range of temperature below about 1 200 °C the fraction of brakes of coated particles (expectation value) is alone fabrication induced; it is less than 3 x 10^{-5}, fig. 5. The hereby produced release is rather low and not very much dependent from temperature, lit.: S. 3.2.2.1.-8 and 9.

3.2.2.2. At temperatures up to 1 300 °C no brakes of coated particles in material test reactors have been observed, lit. S. 3.2.1.-7.

3.2.2.3. With increasing temperatures above 1 200 to 1 300 ° C some diffusion starts from intact particles. An additional fraction of brakes of coated particles in the range of 1 200 to 1600 °C does not need to be considered according to the experiments, lit. S. 3.2.2.1-9.

3.2.2.4. The temperature-induced fraction of brakes of coated particles - as the maximum value - is 5 x 10^{-5} at 1 600 °C, lit.: S. 3.2.2.1-8.

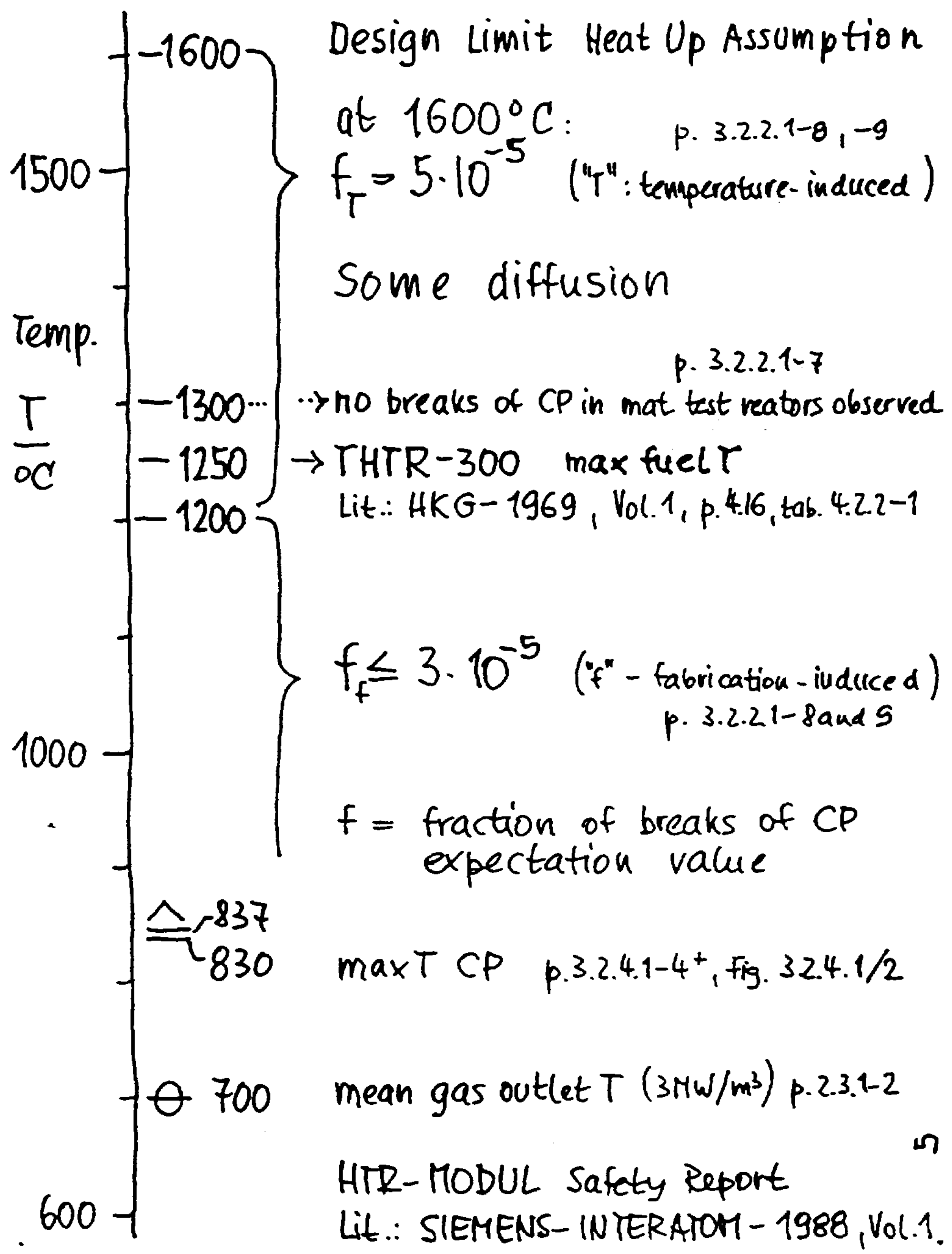


Fig. 5: HTR-MODUL fuel design data, release versus temperature, mechanisms of the release, and THTR-300 fuel data: From these data it is concluded, that the core-outlet temperature can be increased to 1 050 °C for future HTRs with modern gas turbine technology.

3.2.2.5. The design limit for the heat up assumption is 1 600 °C.

3.2.2.6. The various ranges and limits of temperatures are illustrated in fig. 5 in linear scale.

3.2.4. The temperature load conditions for the HTR Modul are: Mean gas-outlet temperature: 700 °C, mean power density 3 MWt/m^3, lit. : S. 2.3.1-2, producing a maximum value of temperature of the coated particles of 830, respectively 837 °C, lit.: S. 3.2.4.1-4$^+$ and fig.

3.2.4.-1/2. These values are also illustrated in fig. 5. As a conclusion: the maximum value for heat transfer in the fuel pebbles, as the difference between the maximum fuel temperature and the mean gas outlet temperature is at a power density of 3 MWt/m^3 about 130 K, respectively 137 K.

3.3. In conclusion for a future core outlet temperature of 1 050 °C:

3.3.1. The perspective for an increased value of the mean core-outlet temperature of the HTR with pebble bed core is the value of 1 050 °C. This follows from the information given in the above chapter 3.2. For this reason the evaluation of the HTR-GST-cycle in chapter 2 has been done with the gas turbine-inlet temperature (being equal to the core-outlet temperature) of 1050 °C.

3.3.2. Among the various applications of the HTR, (as e.g. steam cycle, steam cycle plus district heat or process steam, process heat applications for methane reforming and coal refinement, and others) the biggest challenge to improve the temperature of the produced heat is put on the HTR by the improving gas turbine technology. The reasons is the relatively strong influence on the efficiency, mainly because of its reducing influence on capital costs.

3.3.3. A possible contamination of the blades and other structures of the gas turbine due to the long term release of fission products, e.g. Cs-137, may in future not be an important issue as before, e.g. in the HHT-project, because the technologies for remote handling and inspection as well as other maintenance conditions have improved.

4. Experiences from the Project "HTR with Helium-Turbine, HHT"

4.1. In summary: The project "HTR with Helium-Turbine, HHT" was carried out in the Federal Republic of Germany in 1968 to 1981. It has produced a large number of valuable experiences. The project had been terminated because of the industrial decision to project an HTR with steam turbine plant as the THTR-300-follow-up-plant.

4.2. In some detail on the HHT-project and the high temperature helium test plant HHV:

4.2.1. The project "HTR with Helium-Turbine, HHT", being carried out in the Federal Republic of Germany in 1968 to 1981 in cooperation with the United States and Switzerland" and with the support from Swiss and German utilities had the objective to convert high temperature nuclear heat into electricity, using helium as the working fluid. Within that project to bigger test facilities were design and operated: The "helium turbine co-generation power plant, EVO" (EVO = Energie-Versorgung Oberhausen, Energy Supply at the City of Oberhausen in Germany) and the "High Temperature Helium Test Plant, HHV" (HHV = *Hochtemperatur-Helium-Versuchsanlage, High Temperature Helium Experimental Plant*, at KFA Jülich). A recently produced summary on the technical experiences is given in lit.: WEISBRODT-1995, which is reported also in this workshop.

4.2.2. Within the HHT-project a project study has been performed for a demonstration plant HHT-670 with a net output of 670 MWe, a net plant efficiency of 41 % and with dry cooling. The gas turbine-inlet temperature was 850 °C at a pressure ratio of 2.84 and with a reactor pressure of 70 bar, lit.: ARNDT-1976. Details on the design are given in fig. 6 and on the cycle and turbo-machinery in fig. 7.

4.2.3. An additional look, compared to lit. WEISBRODT-1995, on the High Temperature Helium Test Plant HHV with respect to the turbo-machine, the test loop and the temperature-entropy-diagram is given in fig. 8, lit. WEISKOPF-1970. An interesting feature of the HHV-plant was that heat was brought into the test loop only via the compessor of the turbo-machinery (and not via a heat exchanger). That is illustrated in the temperature entropy-diagram in fig. 8.

5. Summary and Results

5.1. Main result: Nuclear energy, as a source for high temperature heat, e.g. from the High Temperature Reactor, HTR, has - in principle - the same high efficiency potential as the natural gas-based conversion process, both using modern turbine technology. The most modern gas turbine technology is the "gas-plus steam-turbine-cycle, GST", which also can be used in a closed form. A comparative study shows: At 1 050 °C gas turbine-inlet temperature the net efficiency is about 54 %.

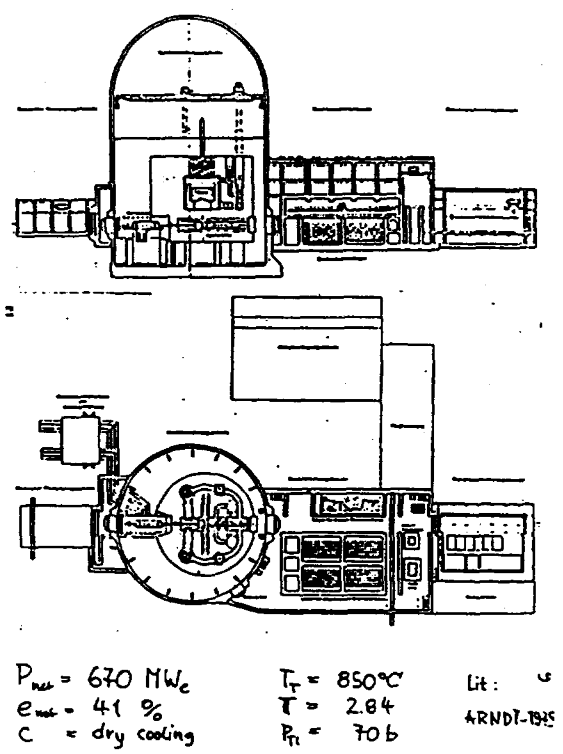


Fig. 6. HTR Heliumturbine Proj. HHT 1968-1981
Project-Studie Demo-Plant HHT 670 1979

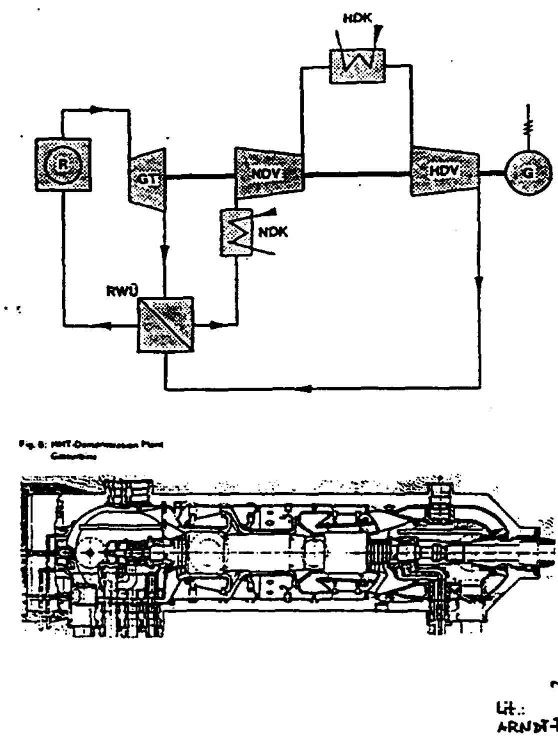


Fig. 7. HTR Heliumturbine Proj. HHT 1968-1981
Flowsheet and Turbomachine

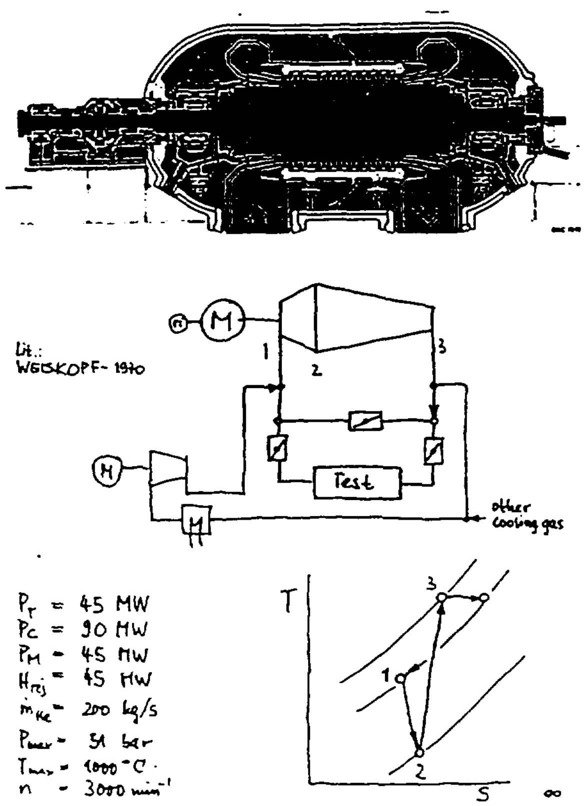


Fig. 8. High Temp. Helium Test Plant HHV

5.2. In detail: As a summary of previous chapters:

5.2.1. The decline of the price of fossil energy carriers after the end of the oil price crisis, in particular the low pric of natural gas, have triggered an impetuous development in gas turbine cycle technolgy. An efficiency race has been opened up to achieve higher effiencies for fossil fired power plants, and in particular for natural gas fired power plants. The preferred solution of modern turbine technology is the "gas-plus steam-turbine cycle, GST" also called combi-cycle. A high efficiency value of an existing plant is e.g. 52 %; a typical value for a future perspective is 58 %.

5.2.2. The efficiency potential of the gas turbine technology for the conversion of high temperature heat from the HTR into electricity is - in principle - as high as that based on natural gas. Therefore it is proposed here to take the "gas-plus-steam-turbine-cycle, GST", into consideration, in particular with a "3-pressure steam turbine cycle". With further improvements, in particular in the gas turbine cycle, and with the assumption that the gas turbine-inlet temperature is 1 050 °C (100 K more than AVR in 1974) the calculated net efficiency is 54.5 %. A particular advantage of the GST-cycle in comparison to the "gas turbine cycle with recuperation" is that the core-inlet temperature is smaller, at comparable efficiency conditions.

5.2.3. The biggest challenge to increase the temperature of the produced heat is put on the HTR by the improving gas turbine technology. Therefore future designs of HTR fuel on the basis of the TRISO-coated particle and of new HTR-cores may realize increased gas outlet temperatures, e.g. 1 050 °C. Reasons are the good experiences of the operation of the AVR, other experimental results and proposals to increase the retention capability of the HTR fuel. Another reason may be that the contamination of the turbine may not be an important issue as before.

5.2.4. The project "HTR with Helium-Turbine, HHT" was carried out in the Federal Republic of Germany in 1968 to 1981. It has produced a large number of valuable experiences. The project had been terminated because of the industrial decision to project an HTR with steam turbine plant as the THTR-300-follow-up-plant.

BIBLIOGRAPHY

ARNDT-1979
Arndt, E., Biele, B., Kirch, N., Sarlos, G., Schlösser, J.:
HHT-Demonstration Plant, European Nuclear Conference ENC '79, Hamburg, 6-11 May, 1979.

BARNERT-SINGH-1994
Barnert, H., Singh, J.: Future Applications of HTR: Electricity Production and Process Heat Applications, IAEA Technical Committee Meeting "Development Status of Modular HTRs and their Future Role", November 28.+29. 1994 and ENC Workshop on the Role of Modular High Temperature Reactors in the Netherlands, November 30 and December 1, 1994, ENC, Energy Innovation, Petten, The Netherlands.

ETZEL-1994
Etzel, K., Baccaglini, G., Schwartz, A., Hillman, S., Mathis, D.: GT-MHR Power Conversion System: Design Status and Technical Issues, General Atomics, Allied Signal Aerospace GA-A21827, Dezember 1994, IAEA Technical Committee Meeting "Development Status of Modular High Temperature Reactors and their Future Role", November 28-30, 1994 ECN, Petten, The Netherlands.

HAVERMANN-1993
Havermann, M., Barnert, H., Singh, J.: Thermodynamische Optimierung einer HTR-Kombi-Anlage, Forschungszentrum Jülich GmbH, KFA, Institut für Sicherheitsforschung und Reaktortechnik, Interner Bericht, KFA-ISR-IB-5/93, März 1993.
in English: Thermodynamical optimization of an HTR-Combi-Plant, Research Centre Jülich GmbH, KFA, Institute for Safety Research and Reactor Technology, Internal Report, KFA-ISR-IB-5/93, March 1993.

HKG-1969
Hochtemperatur Kernkraftwerk GmbH: 300 MW_e THTR Prototyp-Kernkraftwerk, Sicherheitsbericht, Konsortium THTR, Brown, boveri & Cie AG, Brown Boveri/Krupp Reaktorbau GmbH, Bände 1 und 2, Aug. 1969;
In English: 300 MW_e THTR Prototype-Power Plant, Safety Report, Consortia THTR, Volumes 1 and 2.

NAUEN-1995
Nauen, A.: 205 MW GUD Kraftwerk Trombay: deutsch-indische Kooperation, Brennstoff/Wärme-Kraft, BWK, Band 47, Nr. 7/8, S. 289-294, July/August 1995.
in English: 205 MW GUD Power Plant Trombay: German-Indian Cooperation.

REUTER-1993
Reuter, F.D.: Dampferzeuger für Kraftwerkskonzepte mit hohem Wirkungsgrad in VDI-1993, S. 125-140;
in English: Steam generator for concepts of power plants with high efficiency.

RIEDLE-1994
Riedle, K., Voigtländer, P., Wittochow, E.: Fragen zur Nutzung fossiler Energieträger und der Klimarelevanz, in: VDI-1995, S. 35-54;
in English: Question to the application of fossil energy carriers and the relevance of the climate.

RUKES-1993
Rukes, B.: Kraftwerkskonzepte für fossile Brennstoffe, in: VDI-1993, S. 3-40;
in English: Concepts for power stations for fossil fuels.

SCHWARZ-1987
Schwarz, D., Bäumer, R.: THTR Operating Experience , 1st International Seminar on "Small and Medium-Sized Nuclear Reactors, Lausanne, August 24-26, 1987.

SIEMENS-1995
Siemens AG, Bereich Energieerzeugung (KWU): Die 3A-Gasturbinen-Familie von Siemens, Firmenschrift, 1995;
in English: The Familiy of the 3A-Gas Turbines from Siemens, Booklet from the Company.

SIEMENS-1993
Siemens AG, Bereich Energieerzeugung (KWU): Das GUD-Kraftwerk Ambari, ein Kraftwerk setzt Maßstäbe, Firmenschrift 1993;
in English: The GUD-Power Plant Ambari marks the Future. Booklet from the Company.

SIEMENS-INTERATOM-1988
Siemens/Interatom: Hochtemperaturreaktor-Modul-Kraftwerksanlage, Sicherheitsbericht, Bände 1-3, November 1988;
in English: High Temperature Reactor-Modul Power Plant, Safety Report, Volumes 1-3, November 1988.

TILLIETTE-1993
Tilliette, Z.P.: Modern Energy Conversion System and Nuclear Energy, Utilization - of a European, Commercial, Supercritical Steam Cycle, - of an Advanced Hypercritical Steam Cycle, - of Combined Gas-Steam Cycles, American Nuclear Society 1993 Winter Meeting, San Francisco, California, U.S.A., Nov. 14-19, 1993.

VDI-1995
Verein Deutscher Ingenieure, VDI, VDI-Gesellschaft Energietechnik: Kernenergie nach 2000, Tagung Aachen, 15.-16. März 1995,
in English: Society of German Engineers, Society of Energy Technology: Nuclear Energy after the Year 2000.

VDI-1993
Verein Deutscher Ingenieure, VDI, VDI-Gesellschaft Energietechnik: Fortschrittliche Energiewandlung und -anwendung, Tagung Bochum, 24. und 25. März 1993;
in English: Society of German Engineers, Society of Energy Technology: Advanced Energy Conversion and Application.

WEISBRODT-1995
Weisbrodt. I.A.: Summary Report on Technical Experiences from High Temperature Helium Turbo Machinery Testing in Germany, Prepared for IAEA under Contract 622 I 3-94-CT 1941, 94-CL9085, Reproduced by the IAEA, Vienna, Austria, 1995.

WEISKOPF-1970
Weiskopf: Hochtemperatur-Helium-Versuchsanlage, HHV, Firmendruckschrift Hochtemperaturreaktorbau GmbH, HRB, Mannheim, 1979;
in English: High Temperature Helium-Test Plant HHV, Booklet of the Company.