4.1 Design and Evaluation of Heat Utilization Systems for the HTTR through International Cooperation

by Dr. Irene Lewkowicz

Abstract

The International Atomic Energy Agency (IAEA) has the statutory function to "foster the exchange of scientific and technical information", and "encourage and assist research on, and development and practical application of, atomic energy for peaceful uses throughout the world". The IAEA Co-ordinated Research Programmes (CRPs) are effective vehicles for implementing the above.

The CRP on Design and Evaluation of Heat Utilization Systems for HTTR has started in September 1994 and is aimed at promoting international co-operation to identify the most promising heat utilization system(s) to be demonstrated at the HTTR, for the benefit of current operators and future designers and constructors of HTGRs. Participating Member States are collaborating by exchanging existing technical information on the technology of heat utilization systems, by developing design concepts and by performing evaluations of candidate systems for potential demonstration with the HTTR.

The systems being assessed in the CRP for potential demonstration have been selected by the participants according to their own national interests and,n depending on the status of the technology chosen, its economic potential, and other factors such as safety and environmental considerations. The systems and/or processes are:

- steam reforming of methane for production of hydrogen and methanol
- CO_2 reforming of methane for production of hydrogen and methanol
- combined coal conversion and steam generation
- thermochemical water splitting for hydrogen production
- high temperature electrolysis of steam for hydrogen production
- gas turbine for generation of electricity

The key tasks of the CRP are to:

a. define the R&D requirements prior to coupling to the HTTR
b. define the goal of the demonstration at the HTTR
c. prepare design concepts for coupling selected systems to the HTTR and perform preliminary safety evaluations
d. check licensability of selected systems under Japanese conditions.

At the First Research Co-ordination Meeting (RCM) of the CRP held in October 1994 at Oarai (Japan), it was determined that based on evaluations of technology status until then, the first priority candidate systems that will very likely be selected for connection to the HTTR are: the steam (and/or CO_2) methane reforming and the gas turbine. R&D will continue on the other processes and/or systems until their development reaches a status where they can be considered feasible for demonstration at the HTTR.

CRP activities during the first two years have focussed on steps a and b, and with some progress in c and d. At the Second RCM to be held in February 1996, also at Oarai, the progress attained by the participants will be assessed in detail. The timing of initiating specific design of the Heat Utilization Plant (HUP) will be discussed.

It is believed that timely completion and successful operation of the HTTR and these heat utilization systems will be the major milestones in gas-cooled reactor development and in development of nuclear process heat applications.

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1. Introduction

The International Atomic Energy Agency (IAEA) has the statutory function to "foster the exchange of scientific and technical information", and "encourage and assist research on, and development and practical application of, atomic energy for peaceful uses throughout the world".

Many IAEA Member States are concerned about global environmental problems which result from burning fossil fuels. Nuclear power provides a means to produce energy in all forms, i.e. as electricity, district heat, process steam and high temperature process heat, under environmentally acceptable conditions. Currently, nuclear energy produces approximately 17% of the world's total electricity generation at competitive costs. At present, about 30% of the world's primary energy consumption is used for electricity generation, about 15% is used for transportation and the remaining 55% is converted into hot water, steam and heat. This shows that the potential for applications of nuclear energy in the non-electric sector may be quite large, although currently only a few nuclear plants are used for non-electric applications.

The ultimate potential offered by HTGRs derives from their unique ability to provide heat at high-temperatures (e.g., in the range from about 550°C to 1000°C) for endothermic chemical processes and, at 850°C and above, for highly efficient generation of electricity with gas turbine technology. Heat from HTGRs could be used for production of synthesis gas and/or hydrogen and methanol by steam-methane reforming, production of hydrogen by high temperature electrolysis of steam and by thermochemical splitting of water, production of methanol by steam or hydrogasification of coal, and for processes requiring lower temperatures, such as petroleum refining, seawater desalination, district heating and generation of steam for heavy oil recovery. If the heat demand is not in the immediate vicinity of the reactor, a chemical heat pipe could be developed as a high temperature heat transporter. It is important to establish nuclear heat process application technology through research, development and demonstration.

In Japan an important milestone was reached in March 1991 with the start of construction of the High Temperature Engineering Test Reactor (HTTR) at the Oarai Research Establishment of the Japan Atomic Energy Research Institute (JAERI). This 30 MW(t) reactor will produce core outlet temperatures of up to 950°C. It is anticipated that the HTTR will be the first nuclear reactor in the world to be connected to a high temperature process heat utilization system. Criticality is expected in 1997. The timely completion and successful operation of the HTTR and its heat utilization system will be major milestones in gas-cooled reactor development and in development of nuclear process heat applications.

2. Coordinated Research Programme framework and goals

The early development of nuclear power was conducted to a large extent on a national basis. However, for advanced reactors, international co-operation is playing an increasingly greater role. The IAEA promotes international co-operation in advanced reactor development and application. Especially for designs incorporating innovative features, international co-operation allows a pooling of resources and expertise in areas of common interest to help to meet the high costs of developing the technology. Agency sponsored Co-ordinated Research Programmes (CRP's) are one method, of promoting international cooperation. These are typically 3 to 6 years in duration, and often involve experimental activities in selected technology areas of mutual interest to the participating countries. Such CRPs allow a sharing of efforts on an international basis and benefit from the experience and expertise of researchers from the participating institutes.

To foster international cooperation in HTGR applications, the IAEA has established a Coordinated Research Programme on Design and Evaluation of Heat Utilization Systems for the High Temperature Engineering Test Reactor (HTTR). This is a joint activity of the IAEA's Division of Nuclear Power and the Division of Physics and Chemistry. The CRP began in January 1994 and will last 5 years.

The most promising nuclear heat application systems in terms of feasibility, safety, size of market, the associated economics, and environmental considerations will be selected for demonstration at the HTTR. In order to establish and upgrade the HTGR technology basis, JAERI is willing to provide the HTTR for international use to promote R&D on HTGRs and their applications more efficiently.

The objective of this CRP is to identify the most promising heat utilization system(s) to be demonstrated at the HTTR. Participating Member States are collaborating by exchanging existing technical information on the technology of heat utilization systems, by developing design concepts and by performing evaluations of candidate systems for potential demonstration with the HTTR. The participating institutes are:

* JAERI, Oarai (Japan)
* Kurchatov Institute, Moscow (Russia)
* Institute of Nuclear Energy Technology, Beijing (China)
* KFA Jülich (Germany)
* National Atomic Energy Agency, Jakarta (Indonesia)
* Weizmann Institute of Science, Rehovot (Israel)
* General Atomics, San Diego (USA)

The systems being assessed for potential demonstration have been selected by CRP participants, during the 1st RCM in November 1994, [1] according to their own national interests depending on status of the technology, economic potential, safety and environmental considerations, and other factors.

The following systems are being examined:

- steam reforming of methane for production of hydrogen and methanol
- CO_2 reforming of methane for production of hydrogen and methanol
- combined coal conversion and steam generation
- thermochemical water splitting for hydrogen production
- high temperature electrolysis of steam for hydrogen production
- gas turbine for electricity generation

In addition, testing of advanced intermediate heat exchangers will be examined.

For the systems being examined key tasks of the CRP are to

a) define the R&D needs remaining prior to coupling to the HTTR
b) define the goal of the demonstration with the HTTR
c) prepare design concepts for coupling selected systems to the HTTR and perform preliminary safety evaluations
d) check licensability of selected systems under Japanese conditions

3. The HTTR and its heat utilization system

The HTTR is a high temperature gas cooled test reactor with thermal output of 30 MW and an outlet coolant temperature of 850°C at rated operation and 950°C at high temperature test operation. The HTTR consists of a reactor pressure vessel with a prismatic, graphite moderated core, a main cooling system with a helium-to-helium intermediate heat exchanger and a pressurized water cooler in parallel, an auxiliary cooling system, reactor vessel cooling system and related components (see Figure 1). The major technical parameters of the HTTR are given in Table 1. The construction schedule for the HTTR is shown in Table 2.

JAERI is proposing to construct the high temperature nuclear process heat utilization system close to the HTTR a few years after completion of the HTTR (Figure 2) and then to connect it to the helium-to-helium intermediate heat exchanger (IHX) at the first refuelling. The secondary helium from the IHX will transfer 10 MW to the heat utilization plant. The IHX is a counter-current and helically wound tube type shell-and-tube heat exchanger (Figure 3). Under high temperature test operation the IHX will provide a supply of compressed helium gas at a temperature of about 900°C with practically no contamination risk to the heat utilization plant.

As is shown in the schedule and test plan (Table 3) it is proposed to start the heat utilization system test at the end of fiscal year (FY) 2002, or 2001. To do this, construction of the heat utilization plant should be started in FY 2000.

4. Incentives, technical status and development needs of heat utilization systems being examined

As an energy source, nuclear energy provides a means to produce not only electricity but also other clean energy carriers. Hydrogen is a convenient medium for storing and transporting energy in chemical form and has a high energy density. Methanol is attractive as automobile fuel, is easy to transport and store, and is less CO_2 emissive than gasoline. Hydrogen and/or methanol production with nuclear energy could play a key role in resolving global warming and conserving fossil fuels. At the same time, it is important to bear in mind that the large scale use of hydrogen as an energy carrier would require changes in the energy infrastructure.

Hydrogen can be produced by several methods. The most important process used on an industrial scale is steam reforming of methane. Produced in this way it serves as feedstock for the ammonia and the fertilizer industries, for oil refining and for the synthesis of methanol. Another small scale industrial process is the electrolysis of water, which produces much purer but more expensive product. Integration of coal hydrogasification to produce methane together with steam reforming of methane leads to production of methanol from coal.

A number of other processes may also provide the link between the nuclear heat source and hydrogen. These are high temperature steam electrolysis and the various thermochemical cycles for splitting water. Presently at the R&D stage, these processes require extensive development and demonstration to establish their technical feasibility and their economic viability as candidate processes for thermal energy conversion.

4.1 Hydrogen and Methanol Production by Steam Reforming

Steam reforming of methane is a well known industrial process, often combined with hydrogasification of coal. The basic reactions involved in these processes are shown in Figure 4. The coal to methanol reaction requires substantial quantities of heat. For efficient reaction rates, the reformer requires heat at temperatures of 790°C and above. If the heat were supplied by coal about 80% more coal feedstock would be required along with oxygen for combustion and would produce 1 to 1.4 moles of CO_2 per mole of methanol produced.

In order to produce methanol from coal without CO_2, two process inputs in addition to coal and steam are required: a supplemental hydrocarbon feed with a H/C ratio higher than two, and a non-combustion source of high temperature heat. The ideal supplemental feed would be H_2. Although small quantities of inexpensive H_2 are available as process by-products, a large scale methanol economy would require enormous quantities of H_2. In lieu of a cheap H_2 source, CH_4 from natural gas can be an interim feedstock.

If a HTGR is the heat source, the principal challenge is the method of transporting heat to the process. Conventional coal conversion technologies introduce oxygen into the steam coal gasifier to provide the reaction heat via direct combustion. Nuclear heat must be generated separately and supplied indirectly to the process steam through a heat exchanger.

Although the full scheme presented in Figure 4 is sound on the economical basis for countries having large fossil energy reserves, principally in the form of coal and natural gas, it was decided to test individual parts of the scheme to establish the HTGR as a process heat source. Steam reforming of methane to produce hydrogen and methanol (or syngas) has been chosen as a first priority candidate nuclear process heat application to be demonstrated using the HTTR. The following reasons led to this decision:

- steam reforming for production of hydrogen and methanol is an endothermic reaction
- it is a well-experienced production process in non-nuclear industrial applications
- at present and in the near future, the most economical process to produce hydrogen is considered to be steam reforming of natural gas
- hydrogen and methanol are co-produced from the syngas. Hydrogen, as shown in Figure 4, can be used further for coal hydrogasification or liquefication.

When heat is supplied from an HTGR to the steam reforming process, the nuclear plant dictates the main design and operation parameters of the process. To attain similar heat fluxes and high conversion rates with helium heating despite the 50 to 100°C lower temperature than with flame heating, a different steam reformer design is required compared with existing commercial steam reformer plants.

Test module helium heated steam reformers have been successfully tested at the 10 MW(t) level in Germany in the 1980s, using 40 bar helium heated by electric heaters to 950°C and steam reforming temperature of ~820°C. Total operation included 13,000 hrs, of which 7,750 hr were above 900°C verifying the operation of reformers with convective helium heating [2].

The goal of testing at the HTTR is to demonstrate reliability, and the ability to operate and control the process effectively utilizing nuclear heat (10 MW). The flow diagram is shown in Figure 5. The reformer tubes are packed with catalyst (e.g. Ni on alumina) and are heated by helium gas flow outside the tubes (Figure 6). The reformer design developed by JAERI will produce 1390 Nm^3/h of hydrogen and 1930 Kg/h of methanol from 950 kg/h of methane [3].

4.2 CO_2 reforming of methane for production of hydrogen and methanol

While CO_2 reforming of methane is not commercially performed, it is currently experimentally investigated at the solar energy research facilities of the Weizmann Institute of Science, Rehovot, Israel. The system investigated involves a "solar chemical heat pipe". The CO_2 reformer could potentially be adapted for demonstration at the HTTR to produce syngas as feed for a methanol synthesis plant.

Figure 7 shows a solar heat pipe system which is based on the chemical heat pipe concept originally developed in connection with the HTGR at the KFA Research Center, Juelich, Germany, and adapted and modified to solar energy at the Weizmann Institute. The method, which involves conversion of solar energy to a chemical form that can be stored and then transported at the time and to the place that energy is needed is based on the following reaction:

$$CH_4 + CO_2 \rightleftarrows 2\,(CO + H_2)$$

The reforming reaction is conducted in a solar furnace by passing methane and CO_2 through a catalyst (1% Ru on alumina) at 800 to 1000°C. In the chemical heat pipe process the stored solar energy is released in a methanator plant that reacts hydrogen and carbon monoxide to recover methane and release high temperature heat to generate steam, electric power or both. The methane is returned to the solar site, completing the cycle. CO_2 reforming is preferred to steam reforming for solar application because its gaseous phase simplifies the start up - shutdown cycle which occurs daily.

The cycle has been proven at a laboratory-scale facility using 5 to 10 KW of heat. The process has been scaled up to 480 KW and testing has started in 1994. The temperatures achieved in the solar heated reformer are similar to those produced by HTTR heat.

4.3 Combined coal conversion and steam generation

Hot water or steam injection to enhance oil recovery is commercially performed. However, if the hot water or steam is produced by burning oil, about 40% of the recovered oil is used. An alternative is to use HTGR heat to produce the steam.

The steam temperature and pressure conditions required for oil recovery are highly dependent on the geological conditions of the oil field and range up to about 550°C. Coal liquefaction processes need temperatures from 400-550°C, and, for the pyrolysis process, up to 870°C. Combined coal conversion and steam generation for oil recovery may be reasonable in special locations where there are dual needs such as in the Sumatra and Kalimatan Islands of Indonesia.

The feasibility of coupling a combined system to the HTTR will be examined.

4.4 Thermochemical water splitting for hydrogen production

The most extensively studied and promising thermochemical water splitting cycles are the ones based on the high temperature decomposition of sulfuric acid:

(i) $2H_2O + I_2 + SO_2 \rightarrow H_2SO_4 + 2HI$ Bunsen reaction ~100°C

(ii) $H_2SO_4 \rightarrow SO_2 + H_2O + \frac{1}{2}O_2$ 950°C and above (endothermic)

(iii) $2HI \rightarrow H_2 + I_2$ ~ 300°C - 370°C

Preliminary analytical studies showed the process thermal efficiency of ~ 40-50% can be expected under optimum operating conditions. Carlo Rubia CERN [4] predicts a thermal efficiency of 64%.

Experimental results reported by JRC Ispra in 1983 [5] point out that thermochemical production of hydrogen is feasible on a pilot plant scale (10Nm^3/h) using the above mentioned technology. The overall efficiency of the process has been assessed to be around 36-40%. However many difficulties remain in establishing the gaps in optimal engineering design including materials corrosion resistivity, coupling of the chemical plant to the nuclear heat source and safety problems. As a result JAERI has developed an improved process on the laboratory scale of 1-10 liter H_2/h in glass, quarz and teflon apparatus. Since the process utilizes corrosive chemicals the structural materials impose a serious problem and their proper selection constitutes an important part of the R&D. The main achievements are the demonstration of thermal efficiency higher than 40% and selection of better structural materials.

Further R&D will focus on optimization of the hydrogen iodide decomposition step with respect to structural materials and efficiency, and on the sulphuric acid decomposition step. The optimal engineering design is in progress including coupling to the helium loop. Mechanical properties of the selected structural materials will be investigated. The planned demonstrations are:

(i) laboratory scale to show continuous production of hydrogen in more efficient operation mode
(ii) process demonstration using metallic reactors to produce 1Nm^3 H_2/h
(iii) scale-up process 100Nm^3 H_2/h coupled to the 10 MW non nuclear HENDEL facility of JAERI.

Some critical items which must be addressed with the further development of thermochemical water splitting are:

a) materials appropriate for large industrial plants
b) engineering design to improve efficiency and decrease investment costs
c) coupling of the chemical plant to the nuclear heat source, and establishment of safety design criteria and procedures for the combined nuclear and chemical plant complex

4.5 High temperature electrolysis of steam for hydrogen production

Hydrogen production by high-temperature electrolysis of steam is also one of candidates of nuclear heat application. The process is the reverse of that used for solid oxide fuel cells (Figure 8). The process requires temperatures ranging from 900 to 1000°C. The high temperature electrolysis of steam, although very promising, is still at an early stage of technology. The main technology challenges are in development and low cost production of efficient, reliable and durable electrolysis cells. The cells technology is known from the ceramic fuel cells. This technology, however, is currently too expensive and not suitable for mass production. A fundamental study on material selection of solid electrolytes and ceramics electrodes for application to electrolysis of steam has been carried out by measurements of electrical conductivity and phase stability in the JAERI. A hydrogen production rate of 7 liters/hr has been attained at 950°C by the laboratory scale tests. For further development, the following tasks are planned by JAERI in cooperation with Fuji Electric Co.

(i) Improvement of electrolysis cell in order to reduce ohmic loss, and increase the working life of the cell. New construction materials such as Yterbia stabilized zirconia will be tried, together with new geometrics of the cell. The mechanical strength of the cell and its durability during heat cycles impose a problem especially when scale-up is planned.

(ii) Optimization of the full system will include auxiliary equipment such as steam generators, steam super heaters and heat exchangers.

The working plan includes demonstration of a system with hydrogen production rate 10 Nm^3/h. Based on the results obtained, a prototype system with a production capacity of 100 Nm^3/h will be tested to provide data for safety review for the possible coupling to HTTR.

4.6 Gas turbine for electricity generation

A promising approach for making good use of the high temperature capability of HTGRs is to use the primary helium coolant to drive a gas turbine in a direct closed cycle arrangement. In the seventies, this was extensively studied in the USA, in Germany, in Great Britain and in France. At that time, the concept was based on enclosing a large (2000 to 3000 MWt) reactor core and the gas turbine power conversion system within a prestressed concrete reactor vessel (PCRV). After nearly a decade of work, this concept was abandoned primarily because the system achieved only about 39% efficiency and would have required substantial development to resolve design and safety issues. It was concluded that the HTGR with a gas turbine offered little advantage over a steam cycle HTGR, which could be deployed with much less development.

However, recent advances in turbomachinery and heat exchanger technology, and the development of smaller modular reactor concepts, have resulted in renewed design and development activities in the USA and Russia for a gas turbine HTGR. Key technology developments have been achieved the last decade associated with large gas turbines, magnetic bearings and compact plate-fin heat exchangers. Turbine and compressor efficiencies have increased, and more compact recuperators with a higher effectiveness have been developed. Direct, indirect and combined cycles can be considered.

In the USA, activities have focused on design and development of a direct cycle modular HTGR gas turbine system of 600 MW(t) with a predicted 47% cycle efficiency at a turbine inlet helium temperature of 850°C. Natural gas combustion turbines are now commercially available in sizes up to 200 MW(e) and operate reliably at temperatures well above this 850°C level. Use of magnetic bearings would provide efficiency gains and eliminate the possibility of ingress of lubricating fluids into the reactor environment; performance of magnetic and thrust bearings of adequate capacity to support large-size turbo generators must be shown. In extending the open-cycle gas turbine recuperator experience to meet the requirements of a high pressure system, development is necessary to demonstrate that the compact surface geometries have structural integrity for long service life.

The helium turbine technology base includes a comprehensive programme conducted in Germany for a Brayton (closed) cycle power conversion system. The programme, which was initiated in 1968, was for electric power application with a high temperature gas cooled reactor heat source (the HHT project) using helium as the working fluid. The R&D program involved two experimental facilities. The first was an experimental cogeneration power plant (district heating and electricity generation) constructed and operated by the municiple utility, Energieversorgung Oberhausen (EVO), at Oberhausen, Germany. It consisted of a fossil fired heater, helium turbines, compressors and related equipment. The second facility was the High Temperature Helium Test Plant (HHV) for developing helium turbomachinery and components at the Research Center Jülich (KFA). The heat source for the HHV derived from an electric motor-driven helium compressor.

In both facilities negative and positive experiences were gained. At initial commissioning, operation difficulties were encountered with the EVO facility, including failure to meet fully the design power output of 50 MW. The reasons for these difficulties were identified and to a large extent were corrected. The EVO facility achieved an operation period of 24,000 hrs of which 11,500 were at 750°C [5].

Start-up problems also occurred, at the HHV, but these were subsequently corrected. The HHV achieved 1100 hrs of operation, of which 325 hrs were at 850°C [6].

The results of the research and development programmes at both facilities support the feasibility of the use of high temperature helium as a Brayton cycle working fluid for direct power conversion from a helium cooled nuclear reactor. Ultimately, the HHT project was terminated in Germany and both test facilities have been shut down. Except for information on life testing the facilities accomplished their missions.

Within the CRP activities, in the USA [7], two theoretical heat balances were developed for a Brayton cycle, coupled to HTTR, based on the interface conditions. The potential goals and benefits of a demonstration involving the coupling of a small helium turbine to the HTTR can be summarized as follows:

(I) Basic proof of concept
(II) System interactions and operational characteristics for power conversion system coupled to nuclear heat source
(III) Evaluation of integrated operation and control strategies including startup and shutdown
(IV) Power conversion system integration data on system interfaces, operation, reliability,and maintainability
(V) Additional confirmation of component technology in high temperature helium environment

In China [8] the thermodynamic calculations, preliminary design of the system configuration, and the accident analysis have been carried out for the indirect GT cycle of the 200 MW Modular HTGR, also Japan has evaluated conceptual designs of the direct cycle helium gas turbine for both a 450 MWt and 1200 MWt MHTGR [9].

4.7 Advanced intermediate heat exchangers

High temperature process heat utilization systems for HTGRs would operate in a circuit to which the nuclear heat is transferred through an intermediate heat exchanger. This serves the purpose of isolating the reactor from possibly explosive gases produced in the heat utilization plant, as well as, of providing a barrier to radioactivity circulating in the primary helium.

Major considerations for IHXs include fabricability, repair capability, flow induced vibration, thermal stress, cost and lifetime. Very significant IHX development and testing in the 1.5 to 10 MW range in Japan and Germany for primary helium gas temperatures of 950°C has been conducted.

The feasibility of testing advanced IHXs with the HTTR will also be considered in the CRP.

5. Status and plans for CRP

The steps in examining each of the processes/systems/components described in section 4 are:

a. Collect existing information (6 months)
b. Define boundary conditions for tests (6-12 months)
c. Define research and development work, testing requirements and demonstration goals (12-24 months)
d. Prepare design concept (parallel to step 3)
e. Perform preliminary safety evaluation (12 months)
f. Check licensability under Japanese conditions (12 months)

CRP activities during the first year have focused on steps a and b, also with progress in c and to a lesser extent, in d.

Based on evaluations up to now on technology status, the first priority candidate systems to be connected to the HTTR are (1) steam (and/or CO_2) methane reforming system and (2) gas-turbine system. For the other candidate systems the R&D shall be continued to bring them to the stage in their technology development when they will be considered feasible to be demonstrated at the HTTR.

6. Summary

IAEA Coordinated Research Programmes are an effective way of promoting international cooperation in gas-cooled reactor development and in development of high temperature applications.

The HTTR is a unique research facility from a viewpoint of supplying high temperature heat of about 900°C at the exit of the IHX, and could serve as an international joint research facility for nuclear heat utilization systems.

The timely completion and successful operation of the HTTR and its heat utilization system will be major milestones in gas-cooled reactor development and in development of nuclear process heat applications.

First priority candidate systems for demonstration with the HTTR have been determined to be the steam (and/or CO_2) reforming of methane and gas turbine systems. R&D is continuing for the other candidate systems towards the stage when they can be considered feasible for demonstration at the HTTR.

References

[1] First Research Coordination Meeting (RCM), Tokai, Japan, 9-11 November 1994

[2] R. Harth, et. al, Experience Gained from the EVA II and KVK Operation, *Nuclear Engineering and Design*, 121 (1990) 173-182.

[3] High Temperature Application of Nuclear Energy, Proceedings of a Technical Committee Meeting held in Oarai, Japan, 19-20 October 1992 (IAEA-TECDOC-761).

[4] C. Rubia, CERN/AT/95-12 (ET), June 1995

[5] Nuclear Heat Application, Proceedings of a Technical Committee Meeting and Workshop, Cracow, 5-9 December 1983 (IAEA, Vienna).

[6] Summary Report on Technical Experiences from High Temperature Helium Turbomachinery Testing in Germany (IAEA report, in publication).

[7] A. Shenoy, private information, November 1995

[8] Xu Yuanhui, Progress Report, September 1995

[9] Technical Committee Meeting on "Design and Development of Gas Cooled Reactors with Closed Cycle Gas Turbines, Beijing, People's Republic of China, 30 October - 2 November 1995 (IAEA TECDOC in preparation).

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Table 1 Major technical parameters of HTTR

Thermal power	30 MW
Core outlet coolant temperature	850°C / 950°C [a]
Core inlet coolant temperature	395°C
Primary coolant pressure	4 MPa
Fuel	Low enriched UO_2
Fuel element type	Prismatic block
Pressure vessel	Steel
Number of main cooling system	1
Heat removal	Pressurized water cooler and IHX, parallel loaded
Hot helium temperature (secondary side of IHX)	905°C [a]
Intermediate loop helium flow rate	9.07 t/h
Intermediate loop pressure	4.1 MPa
Targeted temperature at inlet/outlet of heat utilization plant	880 [a] / 144°C
Plant lifetime	20 years (load factor = 60%)

[a] at high temperature test operation

Table 2 Construction Schedule of HTTR

ITEM / FY*1	1990	1991	1992	1993	1994	1995	1996	1997	1998
MILESTONE	Construction start ▼		C/V Installation ▼		RPV installation ▼			Fueling ▽	Criticality ▽
Safety review									
Approval of design and construction method									
Site renovation									
Excavation of reactor building									
Reactor building									
Containment vessel									
Cooling system									
Reactor pressure vessel and core internals									
Fuel fabrication									

*1 Fiscal year of Japan starts in April and ends in March

Table 3 Operation schedule and test plan of the HTTR

Development objective	FY'98	'99	'00	'01	'02	'03	'04~
(1) To establish HTGR basic technologies though operating the HTTR	Reactor performance tests at ascent to power		Rated power operation (30MW) at T_{out}= 850~950°C *		Re-fueling	Rated power T_{out}=950°C	
(2) To upgrade HTGR basic technologies though the following test							
1) Irradiation test			at T_{out}=850°C				
2) Safety demonstration tests							
3) Nuclear heat utilization demonstration test				Construction of a heat utilization system		Demonstration test	
(3) To serve as an irradiation facility for innovative and basic researches							

(*) T_{out} : Reactor outlet coolant temperature

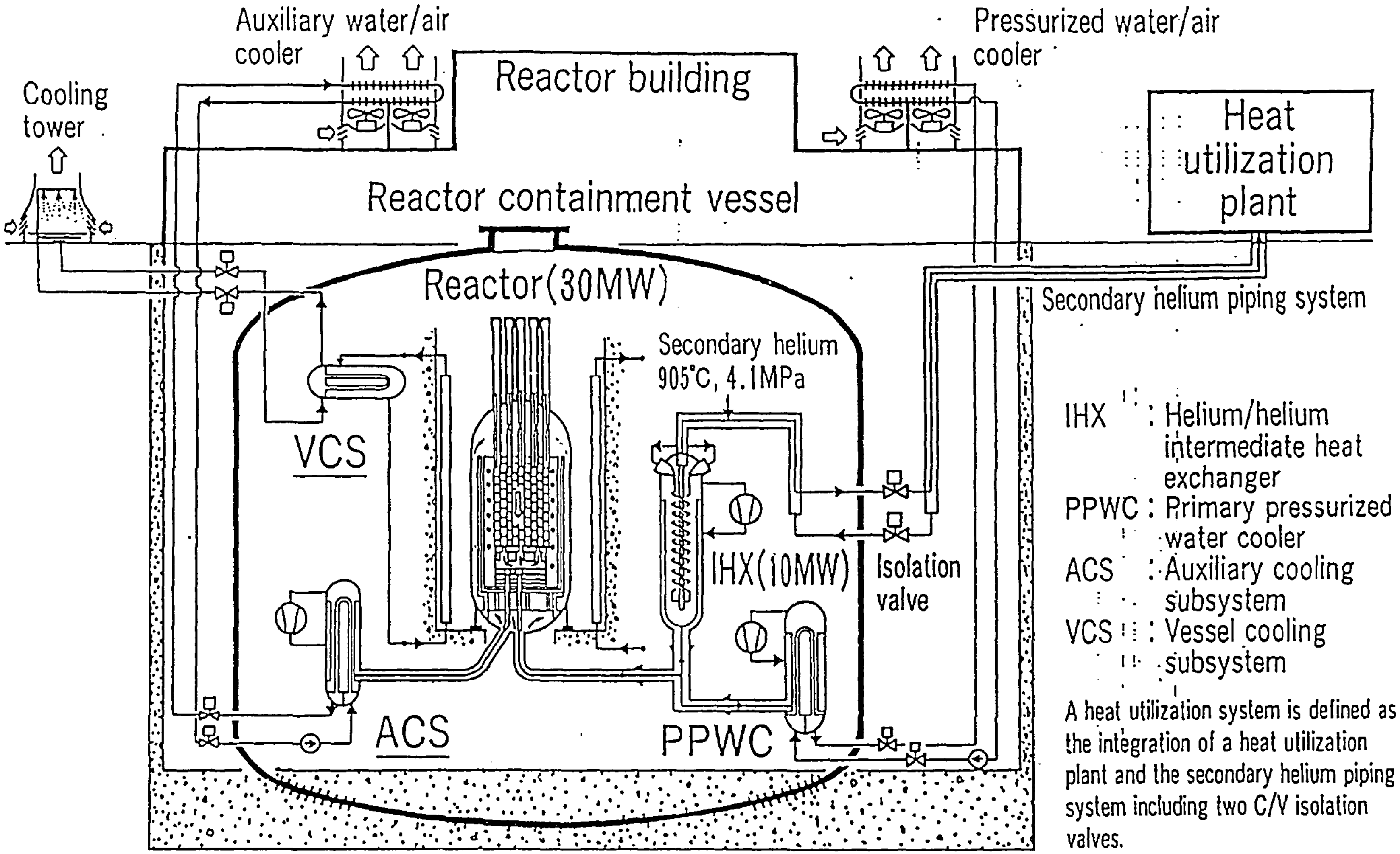


Fig. 1 Simplified diagram of the HTTR plant with a heat utilization system

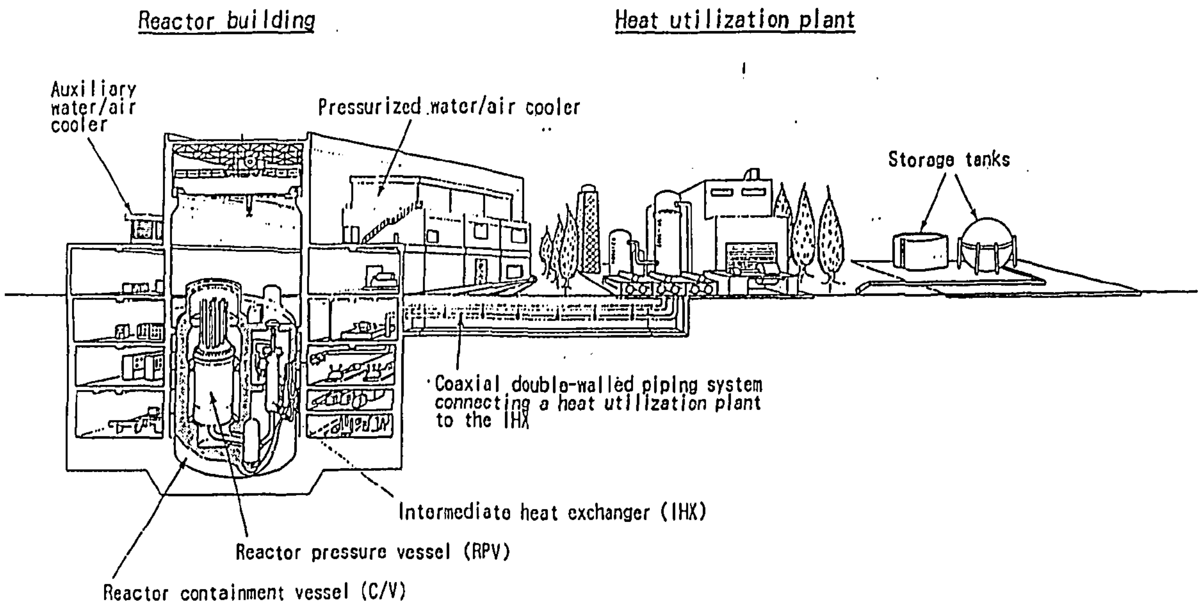


Fig. 2 Cutaway drawing of the HTTR plant with a heat utilization system

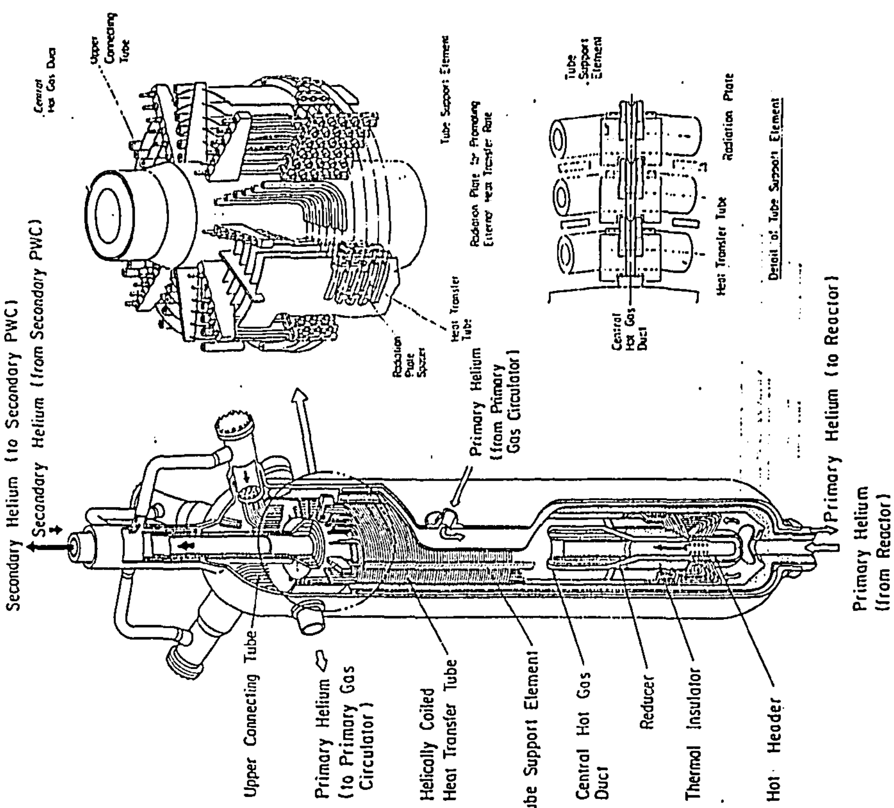


Fig. 3 View of the He/He intermediate heat exchanger of HTTR

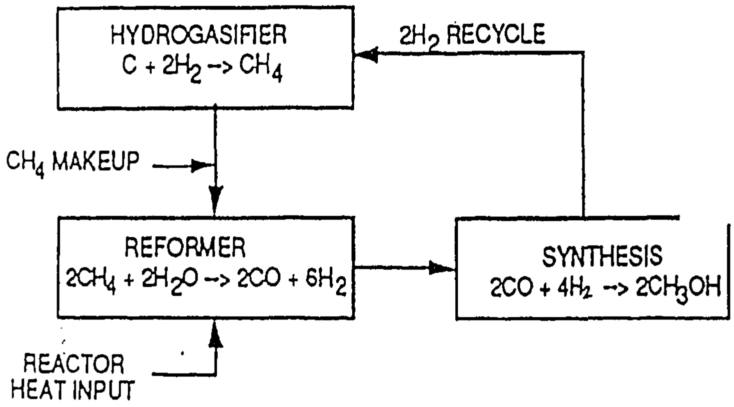


Fig. 4 Reactions for coal to methanol by hydrogasification

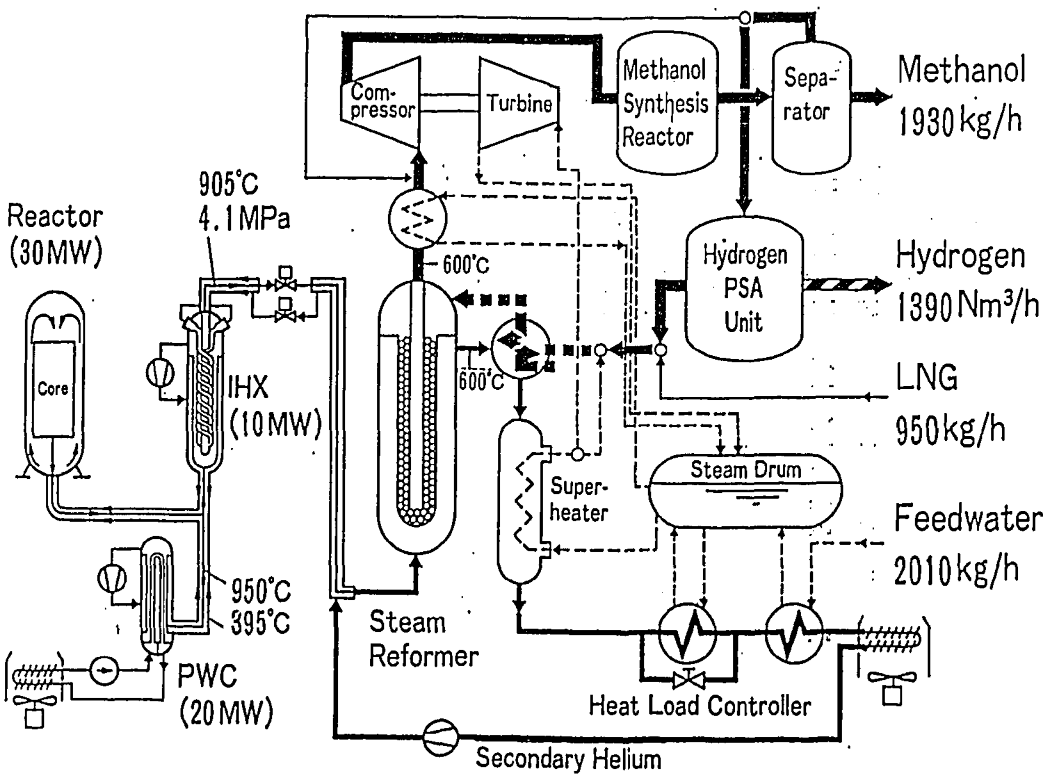


Fig. 5 Schematic Illustration of HTTR steam reforming hydrogen/methanol co-production system

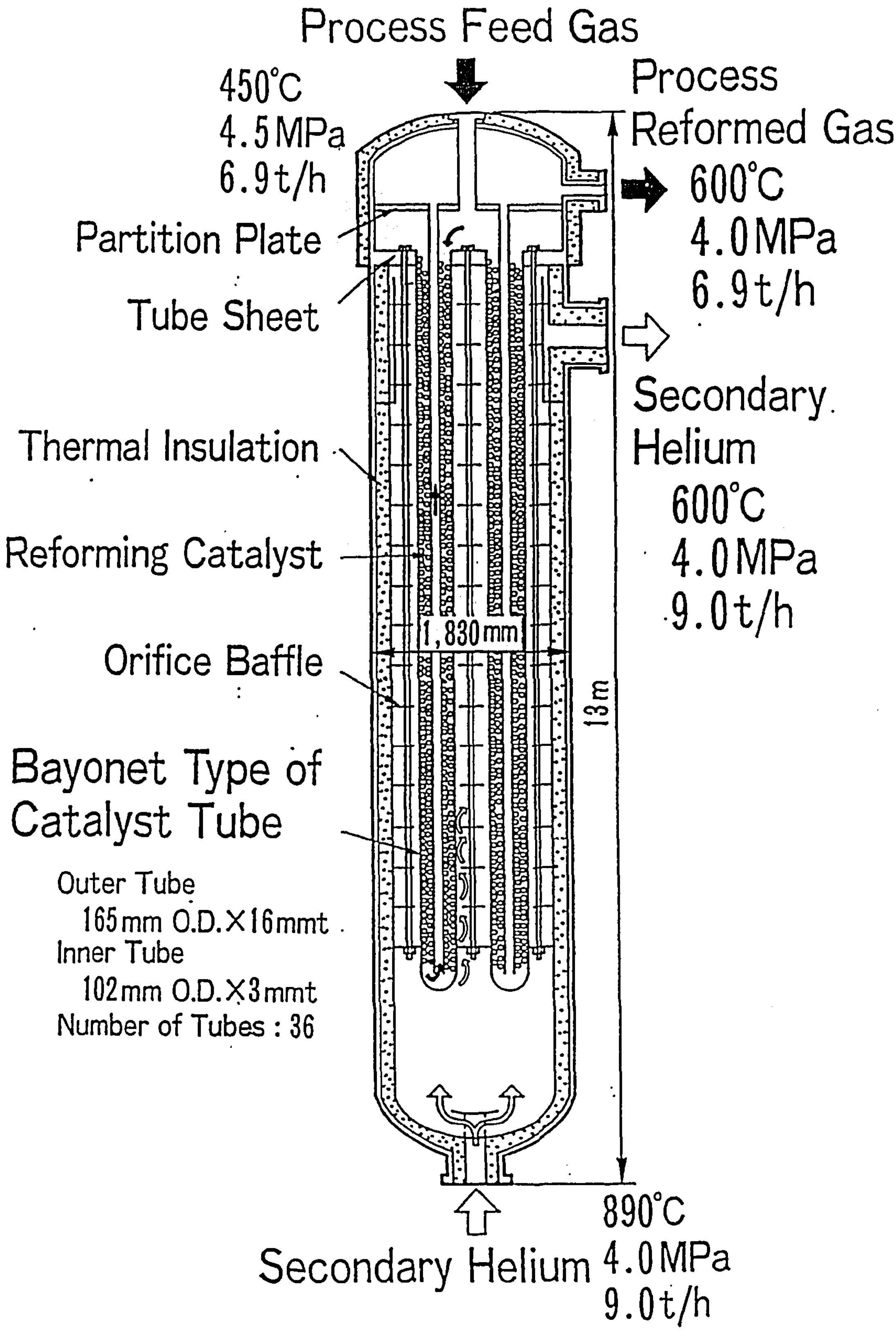


Fig. 6 Sectional view of steam reformer

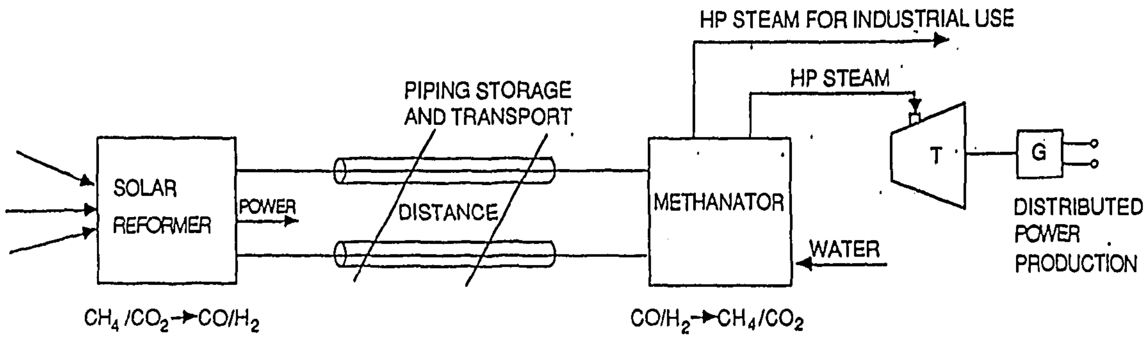
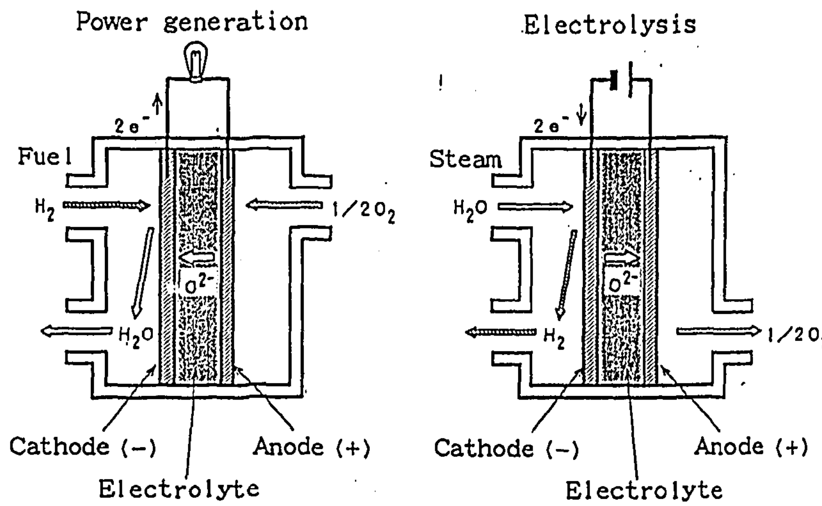


Fig. 7 **Solar thermochemical concept reference system**



	Power generation	Electrolysis
Cathodic reaction	$H_2+O^{2-} \rightarrow H_2O+2e^-$	$H_2O+2e^- \rightarrow H_2+O^{2-}$
Anodic reaction	$1/2O_2+2e^- \rightarrow O^{2-}$	$O^{2-} \rightarrow 2e^-+1/2O_2$
Total reaction	$H_2+1/2O_2 \rightarrow H_2O$	$H_2O \rightarrow H_2+1/2O_2$

Fig. 8 **Principle of high-temperature electrolysis of steam (Reverse reaction of solid oxide fuel cell)**