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Proceedings of the 1st JAEA/KAERI Information Exchange Meeting on HTGR and Nuclear Hydrogen Technology

August 28-30, 2006, Oarai Research and Development Center, Japan Atomic Energy Agency, Japan

Nuclear Applied Heat Technology Division

Nuclear Science and Engineering Directorate

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Japan Atomic Energy Agency 日本原子力研究開発機構

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Oarai-machi, Higashiibaraki-gun, Ibaraki-ken

(Received January 31, 2007)

Japan Atomic Energy Agency (JAEA) has completed an implementation with Korea Atomic Energy Research Institute (KAERI) on HTGR and nuclear hydrogen technology, "The Implementation of Cooperative Program in the Field of Peaceful Uses of Nuclear Energy between KAERI and JAEA." To facilitate efficient technology development on HTGR and nuclear hydrogen by the IS process, an information exchange meeting was held at the Oarai Research and Development Center of JAEA on August 28-30, 2006 under Program 13th of the JAEA/KAERI Implementation, "Development of HTGR and Nuclear Hydrogen Technology". JAEA and KAERI mutually showed the status and future plan of the HTTR (High-Temperature Engineering Test Reactor) project in Japan and of the NHDD (Nuclear Hydrogen Development and Demonstration) project in Korea, respectively, and disused collaboration items. This proceedings summarizes all materials of presented technical discussions on HTGR and hydrogen production technology as well as the meeting briefing including collaboration items.

Keywords: Information Exchange Meeting, JAEA/KAERI Implementation, High-Temperature Gas-Cooled Reactor (HTGR), Nuclear Hydrogen Technology, HTTR Project, NHDD Project

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(Eds.) Hiroyuki SATO, Nariaki SAKABA, Tetsuo NISHIHARA, Xing L. YAN, and Ryutaro HINO

高温ガス炉及び核熱利用水素製造に関する第1回情報交換会議論文集
2006年8月28～30日，日本原子力研究開発機構大洗研究開発センター，大洗町

日本原子力研究開発機構
原子力基礎工学研究部門
核熱応用工学ユニット

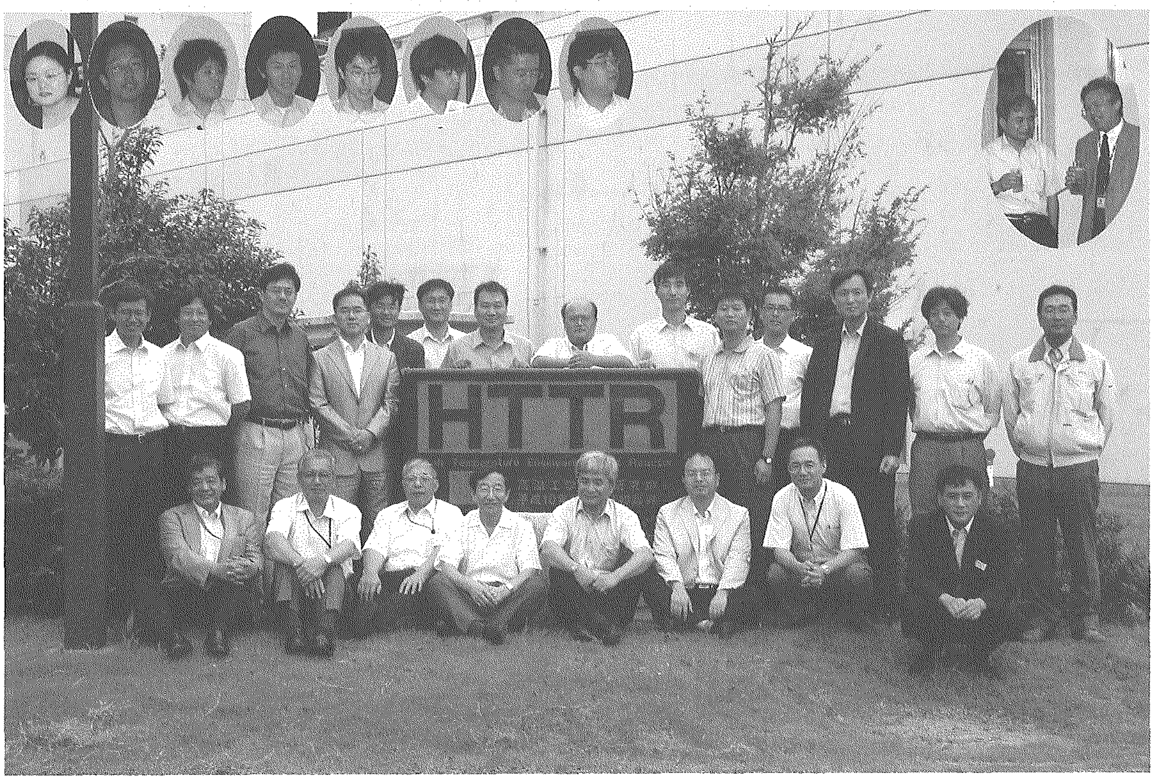
(2007年1月31日 受理)

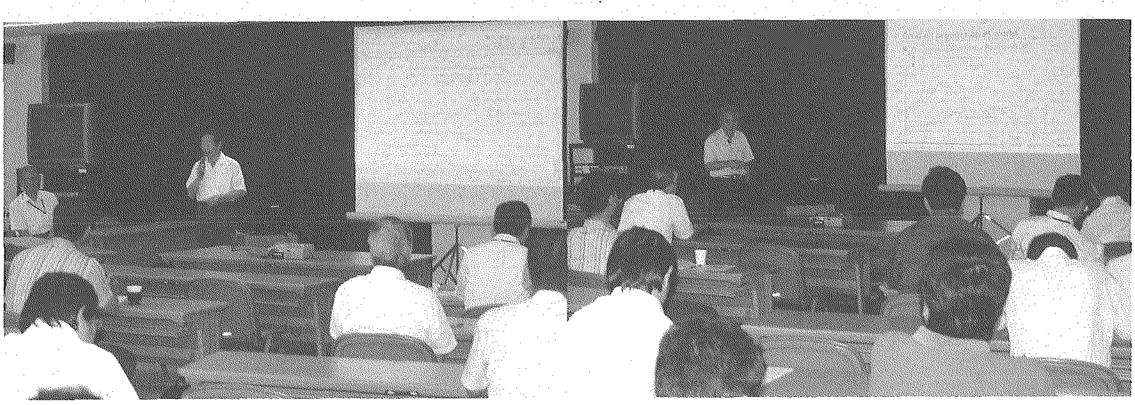
日本原子力研究開発機構（JAEA）は韓国原子力研究所（KAERI）と、「韓国原子力研究所と日本原子力研究開発機構の間の原子力の平和利用分野における研究協力実施取決め」を締結し、高温ガス炉と原子力水素技術の開発に関わる研究協力計画の下で、高温ガス炉と熱化学法 IS プロセス水素製造法の技術開発を効率的に進めるために、情報交換会議を 2006年8月28日～30日に大洗研究開発センターにおいて開催した。会議では、JAEA 及び KAERI 両機関の研究者により、我が国の高温工学試験研究計画（HTTR 計画）及び韓国の原子力水素開発実証計画（NHDD プロジェクト）の現状と将来計画が示され、今後の共同研究について討議した。本論文集は、会議で発表された資料とともに共同研究項目を含む会議サマリー等を収録したものである。

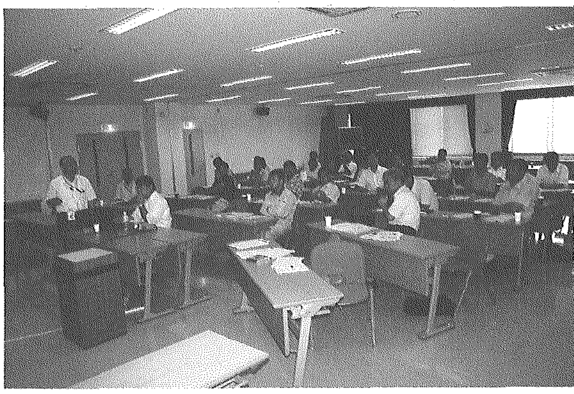
原子力基礎工学研究部門 核熱応用工学ユニット：〒311-1393 茨城県東茨城郡大洗町成田町 4002
（編）佐藤博之，坂場成昭，西原哲夫，Xing L. YAN，日野竜太郎

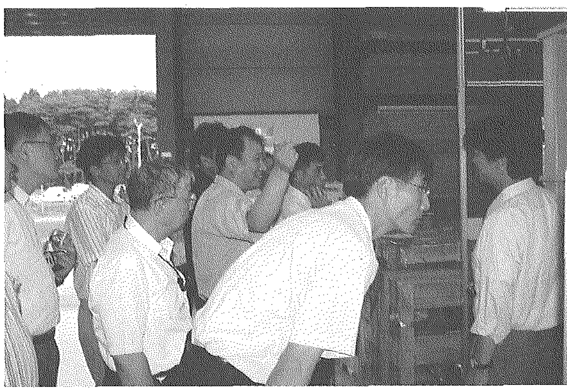
1st JAEA/KAERI Information Exchange Meeting on HTGR and Nuclear Hydrogen Technology

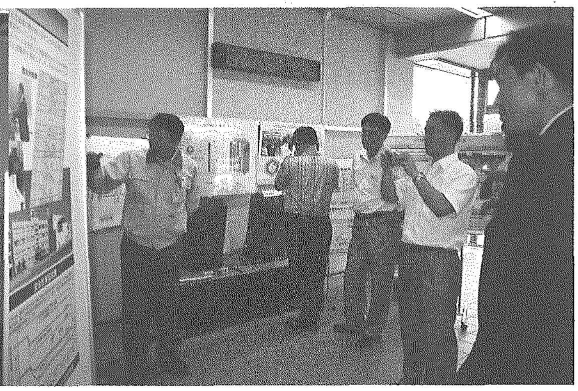
August 28-30, 2006, Oarai Research and Development Center, Japan Atomic Energy Agency, Japan

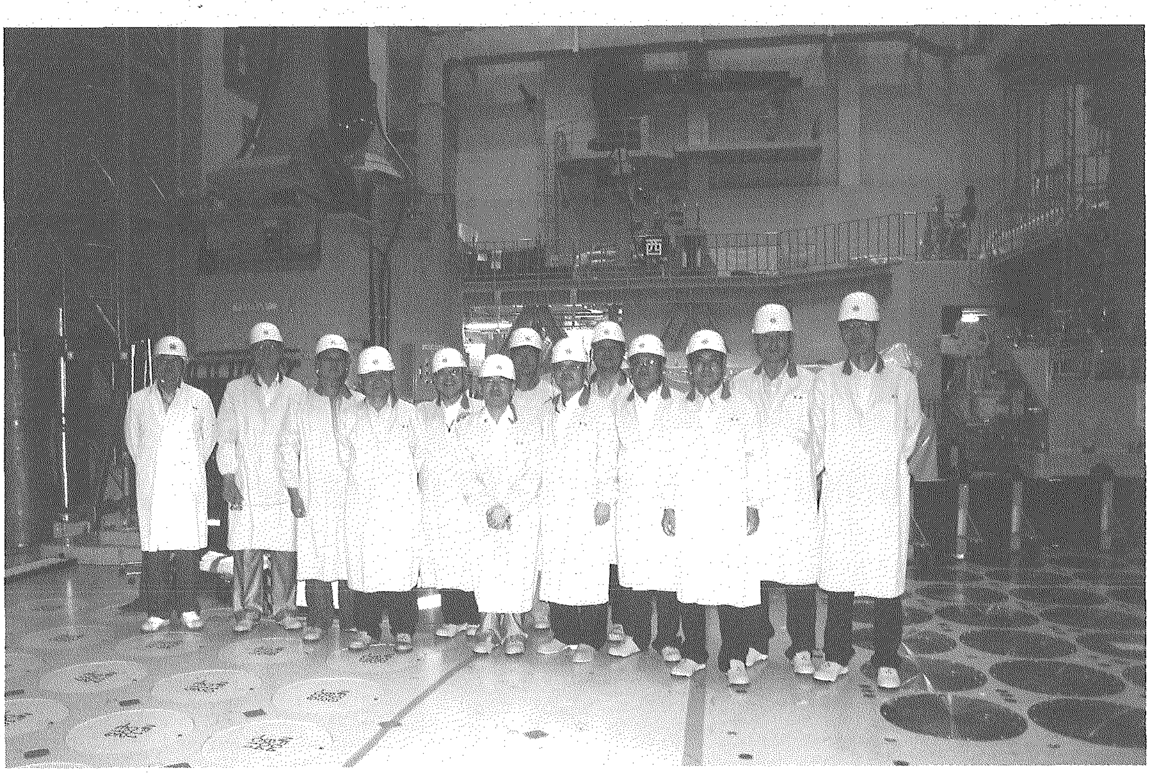








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Introduction

At the present time, we are alarmed by depletion of fossil energy and adverse effect of rapid increase in fossil fuel burning on environment such as climate changes and acid rain, because our lives depend still heavily on fossil energy. It is thus widely recognized that hydrogen is one of the important future energy carriers in that it is used without emission of carbon dioxide (CO_2) greenhouse gas and atmospheric pollutants and that the demand to it is expected to increase greatly as the fuel cells are developed and applied widely in the near future.

Hydrogen hardly exists naturally, however. Hydrogen production by direct thermal decomposition of water molecule would require heat at extreme temperature of several thousands Kelvin. For practical purpose, technology shall be developed for hydrogen production from water but at temperatures below 1000°C, for which industrial materials can be applicable for production process construction. And to be a practical answer to protecting global environment, hydrogen shall be produced economically and from energy sources without CO_2 emission and air pollution. In these regards HTGR hydrogen production with water splitting methods such as the thermochemical iodine-sulfur (IS) process offers one of the most attractive solutions.

The interests in HTGR as an advanced nuclear power source for the next generation reactor, therefore, continue to rise. To enhance nuclear energy application to heat process industries, the Japan Atomic Energy Agency (JAEA) has continued extensive efforts for development of hydrogen production system using nuclear heat from HTGR in the framework of the HTTR (High Temperature Engineering Test Reactor) Project. The HTTR Project has the objectives of establishing both HTGR technology and heat utilization technology. The HTTR is the only Japanese high-temperature gas-cooled reactor, built and operated on the site of the Oarai Research & Development Center of JAEA, and technologically comes nearest to the next generation high-temperature gas-cooled reactor (VHTR). The HTTR reactor outlet temperature of 950°C was successfully achieved in April 2004, which opened the door to the VHTR. Using the HTTR reactor performance and safety demonstration tests have been conducted as planned.

For hydrogen production as heat utilization technology, JAEA has been conducting R&D on thermochemical water-splitting by the "Iodine-Sulfur process" (IS process) in incremental steps. Proof of the basic IS process was made in 1997 on a lab-scale of hydrogen production of 1 L/h. In 2004, one-week continuous operation of the IS process was successfully demonstrated using a glass-made bench-scale apparatus with hydrogen production rate of 31 L/h. A pilot test program with hydrogen production rate of up to 30 Nm^3/h has been initiated following the successful bench-scale test of the IS process. Through the pilot test program, essential engineering data will be acquired to prepare for constructing and operating a nuclear demonstration plant connected with the HTTR (HTTR-IS test program).

A similar project to the HTTR has been started in Korea as the Nuclear Hydrogen

Development and Demonstration (NHDD) Project, in which hydrogen is to be produced by the thermochemical water-splitting by the Iodine-Sulfur process coupling with the VHTR. The Korea Atomic Energy Research Institute (KAERI) as the central organization of the NHDD project is carrying out VHTR system design and R&D on the IS process aiming to construct the VHTR hydrogen system around after 2015.

JAEA has completed an implementation with KAERI on HTGR and nuclear hydrogen technology, "The Implementation of Cooperative Program in the Field of Peaceful Uses of Nuclear Energy between KAERI and JAEA." An information exchange meeting was held at the Oarai Research & Development Center of JAEA on 28-30 August 2006 under the Program 13th of the JAEA/KAERI Implementation, "Development of HTGR and Nuclear Hydrogen Technology." Attended in the meeting are more than 30 researchers including Dr. Jonghwa Chang, the Vice President of KAERI, and 10 other Korean participants, Dr. Osamu Oyamada, the Director General of Nuclear Science and Engineering Directorate of JAEA, Dr. Shusaku Shiozawa, the scientific consultant of JAEA, and other Japanese participants. JAEA and KAERI mutually showed the status and future plan of the HTTR Project in Japan and the NHDD Project in Korea as well as latest design and R&D results, respectively, through about 30 presentations.

The meeting was successfully completed with the recognition and reaffirmation of the necessity of the in-depth cooperation between the two organizations, and with the agreement that the cooperation between two projects shall be strengthened by launching cooperative R&D in the framework of the existing JAEA/KAERI Implementation in addition to the general information exchange, etc. Also, the general philosophy and technical feasibility of the Japanese approach were well understood by the Korean delegation.

This report summarizes all presentations on the status and future plan of the HTTR Project in Japan and the NHDD Project in Korea, on the latest design and R&D results obtained in JAEA and KAERI, including discussions on technologies and cooperation, etc.

Chairman of the 1st JAEA-KAERI information Exchanging Meeting
Dr. Eng. Masuro Ogawa
Director of Nuclear Applied Heat Technology Division

1 Presentations in the Information Exchanging Meeting

1.1 Session 1 Overview of the projects

1.1.1 Overview of the HTTR Project

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Summary

A High Temperature Gas-cooled Reactor (HTGR), which is a graphite moderated, helium cooled reactor, is particularly attractive due to capability of producing high temperature helium gas and its inherent safety characteristics. Especially hydrogen production using HTGR heat is expected to be one of the most promising applications to solve the current environmental issues of CO_2 emission.

An interest in HTGR as an advanced nuclear power source for the next generation reactor, therefore, has been increasing more and more. This is represented by the Japanese HTTR Project and the Chinese HTR-10 Project, followed by the international Generation IV development program, US nuclear hydrogen initiative program, EU innovative HTR technology development program, etc…

To enhance the nuclear energy application to heat process industries, JAEA has continued extensive efforts for development of hydrogen production system using the nuclear heat from HTGR in the framework of the HTTR Project.

For nuclear reactor technology to supply heat, the HTTR was constructed and reactor performance test is underway as well as safety demonstration test. The reactor outlet temperature of 950 C was successfully achieved in April 2004. For hydrogen production technology, R&D on the "Iodine-Sulfur-process" (IS process) by thermo-chemical water splitting is underway at JAEA. The continuous loop operation for the IS process was successfully conducted using bench-scale apparatus with hydrogen production rate of ca. 30 L/h. Further larger scale test using pilot scale equipment with hydrogen production rate of up to 30 m^3/h is planned in the next step, then hopefully connection to the HTTR is taken into consideration. In the future JAEA has a plan to couple the IS Process to the HTTR and demonstrate the feasibility of the hydrogen production using heat from HTGR, aiming at deployment of a commercial HTGR plant for hydrogen production expected in around 2020.

In the presentation, the necessity of the new energy source of hydrogen and its production using HTGR is briefly explained and the overview of the HTTR project is given with emphasis on the hydrogen production system development as well as design work of HTGR cogeneration system.

1st JAEA/KAERI Information Exchange Meeting
on HTGR and Nuclear Hydrogen Technology
Oarai, 28-30 August, 2006.

Overview of HTTR Project

Shusaku SHIOZAWA
Japan Atomic Energy Agency (JAEA)

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1. HTGR Demands for Hydrogen Production - Japanese Policy -

1. Long-term Program for Research, Development and Utilization of Nuclear Energy by the Atomic Energy Commission of Japan recommended that the development study of high temperature heat application using HTGR shall be continued to enhance the application fields of the nuclear energy.
2. In response to the recommendation, ex-JAERI (now JAEA) proceeds with the HTTR Project to provide useful database for the commercialization.
3. The development of HTTR hydrogen production is the next big target for the heat application development.

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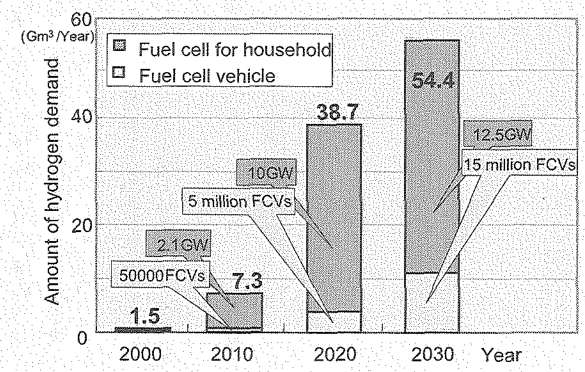
1. HTGR Demands for Hydrogen Production - Future Demands of Hydrogen -

- Target for introduction of fuel cell vehicles to market



(Source: WE-NET Report & MEXT home page)

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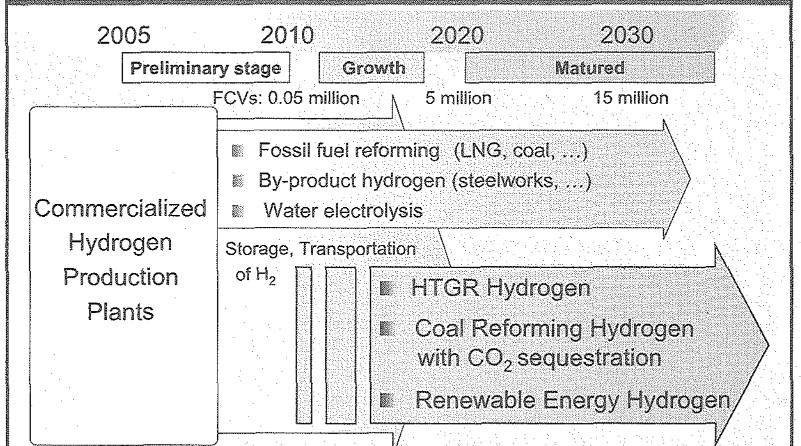
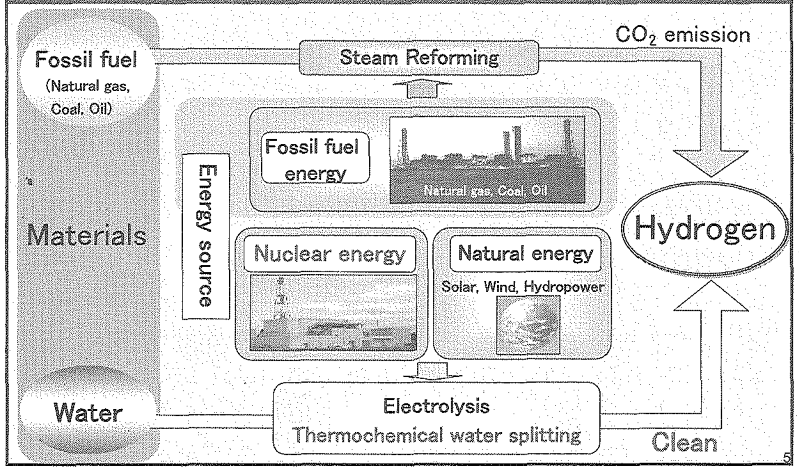
1. HTGR Demands for Hydrogen Production
- Future Plants for Hydrogen Production -



NEDO: Research on Scenario towards Hydrogen Society (FY2003-FY2004) Final Report, March, 2005. 4

1. HTGR Demands for Hydrogen Production
- Methods of Hydrogen Production -



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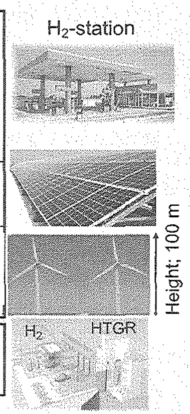
1. HTGR Demands for Hydrogen Production
- Site Area Necessary for Supplying Hydrogen to One H_2-Station -

Facility for energy conversion (1300kWe)	Site area necessary for producing hydrogen of 300m³/h at one small H_2-station of 0.1ha (=40m x 25m)
Photovoltaic cells	6-10 ha 60-100 times area of H_2-station
Windmills Two large windmills (75-88 m blade-diameter)	30 ha 300 times area of H_2-station
HTGR Thermal output of 600MW	6 ha for about ***270*** H_2-stations



(M. Ogawa and S. Shiozawa, GENES4/ANP2003, Sep. 15-19, 2003, Kyoto, JAPAN, Paper 1055) 6

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1. Introduction
   - HTGR Demands for Hydrogen Production
2. HTTR Project
   - Establishment of HTGR and Heat Utilization Technology
3. Concluding Remarks

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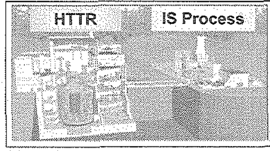
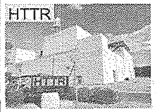
2. HTTR Project
- Research and Development at JAEA -



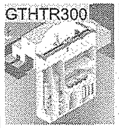
Hydrogen Production Technology

System Integration
- Safety evaluation, Isolation valve test; → On going

IS Process
- Bench-scale ; June 2004
- Pilot-scale ; planning
- HTTR IS ; planning



Reactor Technology
- Achievement of 950°C (30MW) ; Apr. 2004
- Safety Demonstration Test ; on going
- High Performance Test of Fuel and Materials ; on going



Design and Gas Turbine Technology
- Design of GTHTR300 (Electricity, 850°C) and GTHTR300-Cogeneration (Electricity and hydrogen, 950°C) ; on going
- Tests of Compressor, Magnetic Bearing and Control ; on going

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Organization of HTTR Project

Nuclear Science and Technology Directorate
Director General : O. Oyamada

Oarai Research & Development Center
Director General : T. Nagata

HTTR Project — **Scientific Consultant : S. Shiozawa**

Nuclear Applied Heat Technology Division
Unit Manager : M. Ogawa, Deputy Unit Manager : R.Hino

- HTGR Cogeneration Design & Assessment Group (GL : K. Kunitomi)
- High Temperature Fuel & Material Group (GL : K. Sawa)
- HTGR Performance & Safety Demonstration Group (GL : T. Takeda)
- IS Process Technology Group (GL : K. Onuki)
- HTGR-IS Coupling Technology Group (GL : Y. Inagaki)

Dept. of HTTR
Director : Y.Komori

Operation and Maintenance

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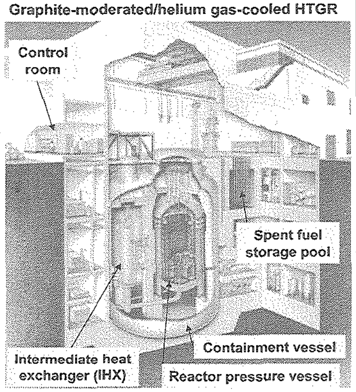
High Temperature Engineering Test Reactor (HTTR)

HTTR
Graphite-moderated/helium gas-cooled HTGR



Major specification

Thermal power	30 MW
Fuel	Coated fuel particle / Prismatic block type
Core material	Graphite
Coolant	Helium
Inlet temperature	395 °C
Outlet temperature	950 °C (Max.)
Pressure	4 MPa

History
- First criticality : 1998
- Full power operation : 2001
- Safety demonstration test : 2002
- High temperature operation (950°C) : 2004

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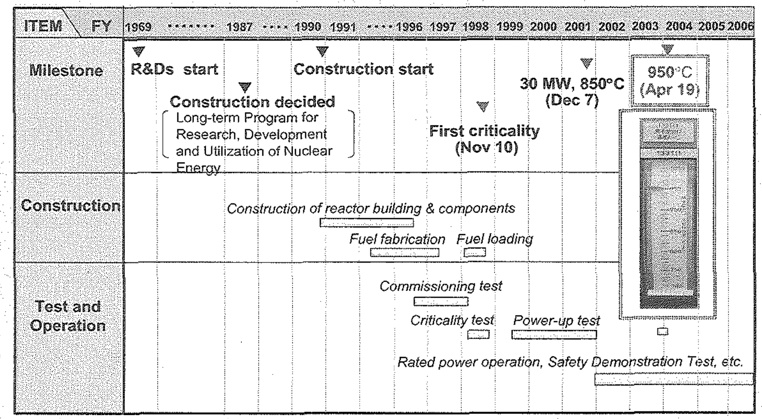
Construction, Test and Operation Schedule of the HTTR



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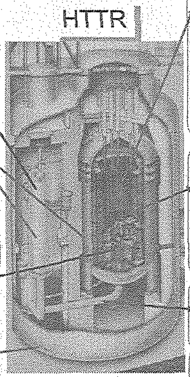
Major Technical Achievements for the HTTR Construction



Metallic Materials
- *Development of heat and corrosion resistant super alloy Hastelloy XR*

Design Guideline for High Temperature Components
- *Establishment of high temperature structural design guideline*

Reactor Physics
- *R&D using VHTRC*

Seismic Design

Fuel
- *Development of fabrication technology*
- *Irradiation tests at OGL-1*
- *Design Guideline for fuel*

Graphite
- *Development of high grade graphite*
- *Design Guideline for graphite components*

Thermal Hydraulics
- *R&D using HENDEL*

Safety Evaluation

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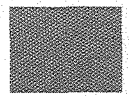
Fuel fabrication process

Uranyl nitrate solution

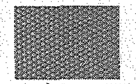
↓

UO_2 particle



↓ **Buffer coating (C_2H_2+Ar)**
IPyC coating (C_3H_6+Ar)
SiC coating (CH_3SiCl_3+H_2:MTS)
OPyC coating (C_3H_6+Ar)

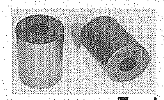
TRISO coated particle



↓ **Graphite powder**
Binder

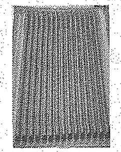
Overcoat particle

Overcoat particle



↓ **Hot pressing**
Preheating
Heating

Fuel compact



↓ Graphite sleeve

Fuel rod

↓ Graphite block
Burnable poison

Fuel assembly

Optimize fluidization &
Continuous coating
Optimize hot pressing

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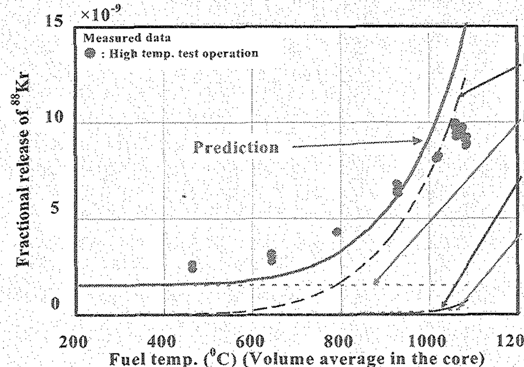
Fuel performance in HTTR - Normal operating condition -

Uranyl nitrate solution **Overcoat particle**



J. Am. Ceram. Soc., 75 (1992) 2985.

- In the HTTR, dominant source of fission gas generation is not failed particle but contamination. Fission gas release mechanism changes from recoil to diffusion from contaminated uranium as fuel temperature rising.

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Major Items of Rise-to-Power Test

Test item		10MW	20MW	30MW
Commissioning test	Control rod reactivity worth measurement (at thermal power of the about 30kw)	○ (30kW)		
	Loss of off site power test	○	○	○
	Coolant pressure/temp. measurement	○	○	○
	Radiation shielding performance	○	○	○
	Radioactive material concentration in reactor building	○	○	○
Reactor & plant performance test	Reactor control system performance	○	○	○
	Calibration of NIS to thermal power	○	○	○
	Thermal hydraulics in the core	○	○	○
	Performance of heat exchangers in MCS	○	○	○
	Performance of vessel cooling system	○	○	○
	Behavior of fuel and fission product	○	○	○
	Measurement of impurity in MCS	○	○	○
	Thermal expansion of high temp. components	○	○	○

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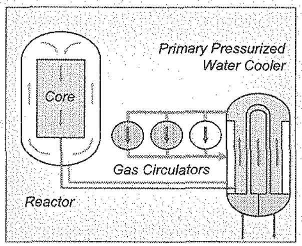
Safety Demonstration Test

Objective

*To demonstrate **Inherent Safety Features** of HTGRs under conditions simulated:*

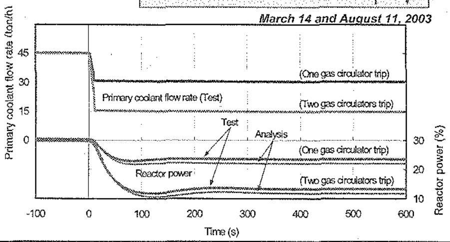
- ***Malfunction of Cooling System and***
- ***Malfunction of Reactivity Control System***

- ***Improve safety evaluation technologies of HTGRs***
- ***Contribute to VHTR System (Gen IV)***



An Example of Test Result
(Coolant Flow Reduction Test)

- *Test result;*
  Reactor power decreased to a stable level only by negative reactivity feedback.



[This study is entrusted from MEXT of Japan.]

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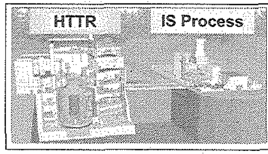
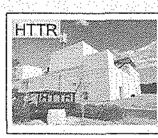
2. HTTR Project - Research and Development at JAEA -



Hydrogen Production Technology

System Integration	IS Process
Safety evaluation, Isolation valve test; → On going	Bench-scale ; June 2004 Pilot-scale ; planning HTTR IS ; planning



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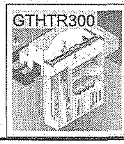

Design and Gas Turbine Technology

- Design of GTHTR300 (Electricity, 850℃) and GTHTR300-Cogeneration (Electricity and hydrogen, 950℃) ; on going
- Tests of Compressor, Magnetic Bearing and Control ; on going

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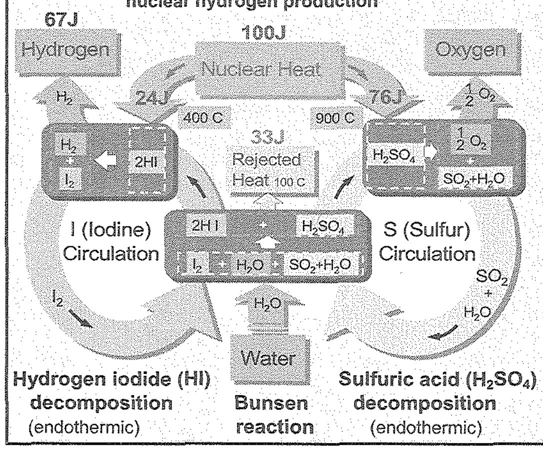
Thermochemical Iodine-Sulfur (IS) Process

developing IS process aiming to realize nuclear hydrogen production



IS Process

- ***H_2 is produced by thermal decomposition of HI at ca. 400℃, and O_2 is produced by thermal decomposition of H_2SO_4 below 900℃. (Pyrolysis of water; Heat more than 4000℃)***
- ***Iodine and sulfur compounds are used as recycling materials under thermochemical close cycle***

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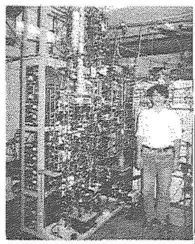
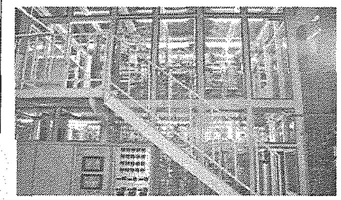
R&D Stage for IS Process Operation

0.001	0.03	30	1000 H_2 (m^3/h)
Electric heater Glass	Electric heater Glass	He gas Industrial materials	
Lab-scale test (~1997) ⇨	Bench-scale test (~2004) ⇨	Pilot test ⇨	HTTR-IS test



How to recycle chemicals?
⇩
Verification of Theory



How to control process?
⇩
Completion of one-week continuous hydrogen production with automatic control system

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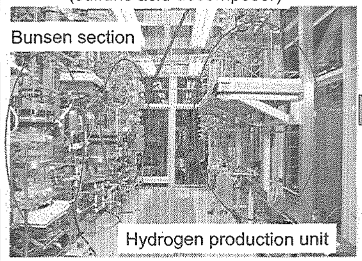
Continuous Hydrogen Production Tests

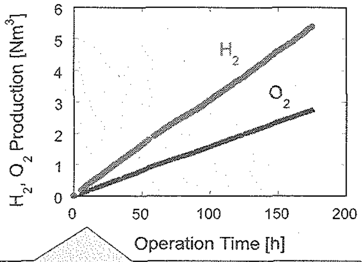
Bench-scale test (1999-2004)

aims to develop the control method under modified conditions using an glass apparatus.



Completion of Hydrogen Production (Jun. 2004)

Continuous hydrogen production was successfully achieved with the hydrogen production rate of ca. 31NL/h for 1week.



Automatic control system with ultra-sonic detectors etc. were developed for the control of the Bunsen reaction.

Ref) S. Kubo et al., Proc. GLOBAL 2005, Tsukuba, Japan, Oct. 9-13, 2005, Paper No.474

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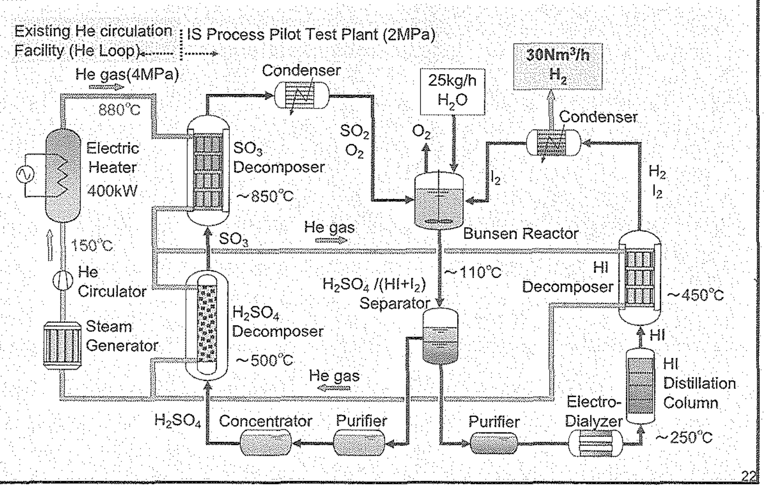
Next Step : Pilot Test (JAEA's Plan)

	Bench-scale Test	Pilot Test	HTTR Test nuclear demonstration
Hydrogen production rate	~ 0.03 m^3/h	~30 m^3/h	~1000 m^3/h
Heat supply	Electrical heater	Heat exchanger with helium gas (Electrical heater 0.4MW)	Heat exchanger with helium gas (Nuclear heat 10MW)
Material of chemical reactors	Glass	Industrial material (SiC, coated)	Industrial material
Pressure of chemical process	Atmospheric pressure	High pressure (up to 2MPa)	High pressure (up to 2MPa)
Time	FY 1999 - 2004	(under planning)	(under planning)

21

Flow Diagram of IS Process Pilot Plant (tentative)



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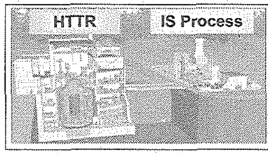
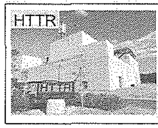
2. HTTR Project
- Research and Development at JAEA -



Hydrogen Production Technology

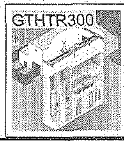
System Integration
- Safety evaluation, Isolation valve test; → On going

IS Process
- Bench-scale ; June 2004
- Pilot-scale ; planning
- HTTR IS ; planning



Reactor Technology

- Achievement of 950℃ (30MW) ; Apr. 2004
- Safety Demonstration Test ; on going
- High Performance Test of Fuel and Materials ; on going



Design and Gas Turbine Technology

- **Design of GTHTR300 (Electricity, 850℃) and GTHTR300-Cogeneration (Electricity and hydrogen, 950℃) ; on going**
- Tests of Compressor, Magnetic Bearing and Control ; on going

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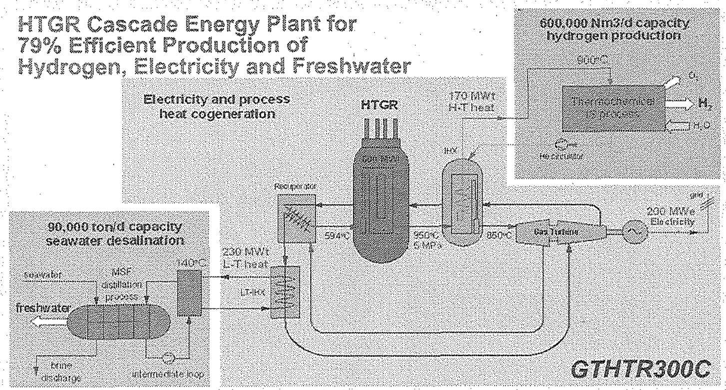
GTHTR300C for Electricity, Hydrogen and Desalination



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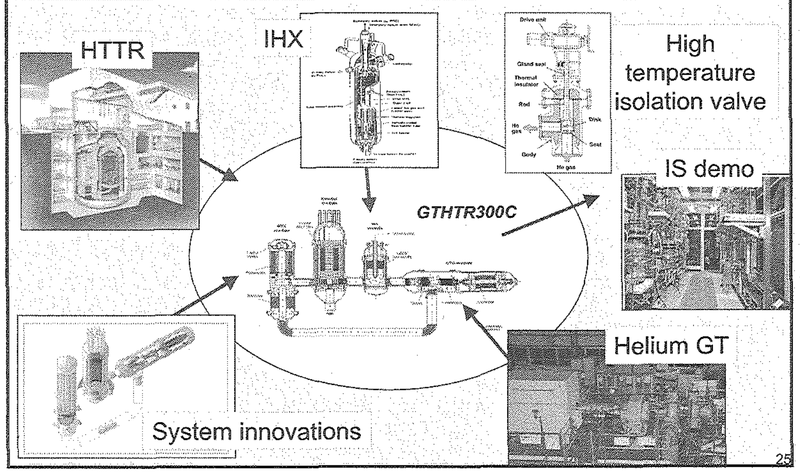
Developing Technologies for GTHTR300C in JAEA



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Contents

1. Introduction
   - HTGR Demands for Hydrogen Production
2. HTTR Project
   - Establishment of HTGR and Heat Utilization Technology
3. Concluding Remarks

26

Future Plan of HTTR Project

2005 | 2010 | 2020-30

Reactor Technology (HTTR)
- Attainment of reactor-outlet coolant temperature of 950°C (April, 2004)
- Safety demonstration test
- Improvement of fuel and materials

Hydrogen Production Technology
IS Process
- Completion of 1 week continuous hydrogen production (Jun, 2004)
- Improvement of system efficiency
- Pilot test (under planning)

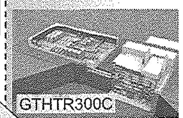
System Integration
- Safety evaluation
- Isolation valve tests

HTGR Plant Design and Gas Turbine Technology
- Design of GTHTR300 and GTHTR300-Cogeneration
- Tests of compressor, magnetic bearing etc.

Hydrogen Production with HTTR-IS System ($1000m^3/h$)

Commercial HTGR System

Hydrogen production for commercial use in 2020s



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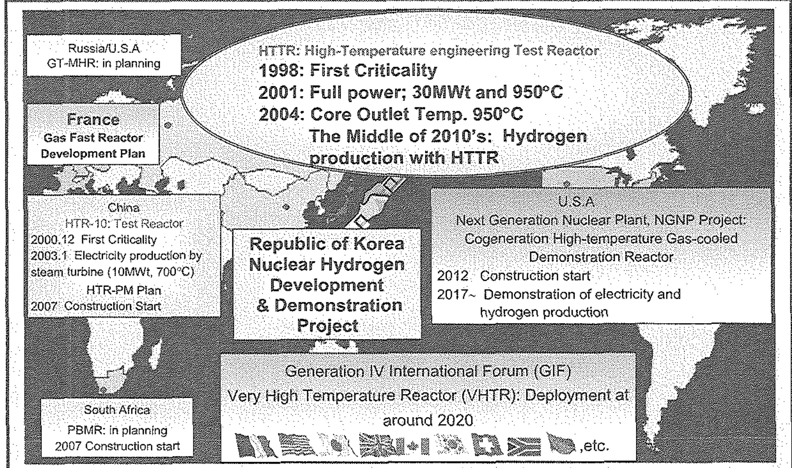
HTGR Projects in the World



3. Concluding Remarks

- Nuclear production of hydrogen, which is one of the most promising systems in near future around 2020 or later could meet massive demand in the future hydrogen economy.
- The HTTR project ongoing at JAEA will play an important role of facilitating the transition to the hydrogen economy and contributing to protect the environment from the carbon emission.
- JAEA welcomes your participation in the HTTR Project to globally commercialize the HTGR hydrogen production systems.

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1.1.2 Nuclear Hydrogen Development in Korea

Jonghwa CHANG

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jhchang@kaeri.re.kr

Summary

Global warming and resulting climate change is a driving force for hydrogen economy. Use of hydrogen as a fuel will greatly reduce the carbon emission to atmosphere. Current fuel such has crud oil and natural gas has resource limitation of less than 40 years of cheap supply. The rise of price is obvious from the fact that the discovery rate becomes less than the production rate since early 1990's. Development of fuel cell vehicle is another drive for efficient use of fuel.

In korea, domestic energy supply is practically absent. Nuclear power is regarded as semi-indulgent energy source due to its low cost fraction of nuclear fuel and localization of the technology. Nuclear power has contributed about 40% of electricity during 30 years of safe operation. In terms of import price of energy fuel, nuclear is about 10 dollar per T.O.E. while crud oil is reaching 400 dollars per T.O.E. recently.

Demand of hydrogen in future was predicted from government study as much as 8 million tons of hydrogen at 2040. Hydrogen production using nuclear heat is promising in view of its cheapest production cost and limitation of land for natural energy deployment.

KAERI has setup a plan to develop and to demonstrate the production of hydrogen using nuclear energy in 2003. From 2004 the government funded study was carried. KAERI is in the phase of key technology development for nuclear hydrogen during next 12 years. Areas of study in the project is the development and validation of core analysis tools, the development of fuel manufacturing and qualification methods, the development of iodine-sulfur thermo-chemical cycle at high pressure environment, and the development and experimental verification of the reactor and the chemical plant coupling technology.

Nuclear Hydrogen Development in Korea

First JAEA/KAERI Information Exchange Meeting on VHTR System

2006. 8. 28

Jonghwa Chang

Korea Atomic Energy Research Institute

KAERI- Nuclear Hydrogen Development and Demonstration Project

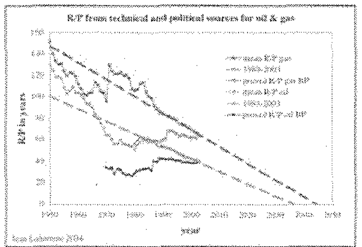
Contents

- Why hydrogen
- Energy situation in Korea
- Nuclear hydrogen
- Status of Nuclear hydrogen project

JAEA-KAERI Information Exchange Meeting, 28-30 Aug. 2006, Oarai. - 1 - KAERI - NHDD Project

Background of Hydrogen Economy

- Global warming and Climate change
  - Fossil fuel emits CO_2
- Crud oil and natural gas Resource Limit
  - within 2 generation
  - demand growth in developing country



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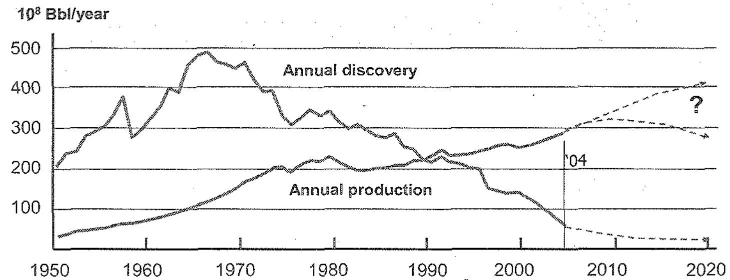
Crud oil production in world

- Production rate overruns Discovery rate
  - Price raise is seen and occuring !
  - End of cheap oil. Too expensive to burn.



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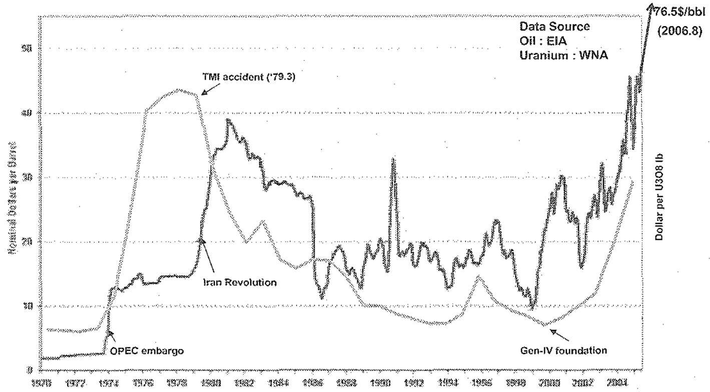
Primary energy price



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Fuel Efficiency of Hydrogen Vehicle

- Fuel efficiency is twice by using Fuel Cell.
- No air pollution and GHG emission.

Ref : Hyundai Motor (2003)

Santa-Fe	Well-to-Tank(%)	Tank-to-Wheel(%)	Overall Eff.(%)
Gasoline Car	88	18	16
Diesel Car	89	22	20
Electric Car	26	80	21
Fuel Cell Vehicle	75 (H2 from Natural Gas)	48	36 (Target: 43)

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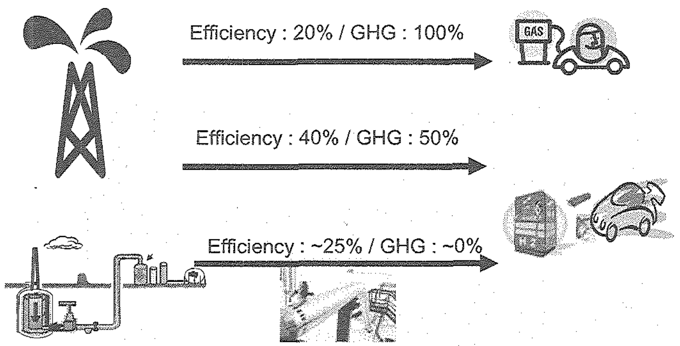
Hydrogen Fuel

Well – Wheel efficiency / GHG emission



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Energy situation in Korea

- Korea do not have domestic energy resources.
  - domestic energy supply is less than 2.5%. (hydro, waste and biomass)
- Energy consumption is expanded with development in Economy.
  - 3.4% growth for 4.7% GDP growth (during '00-'05)
- Nuclear electricty was proved as a stabilizer during the economic crisis in 1997.

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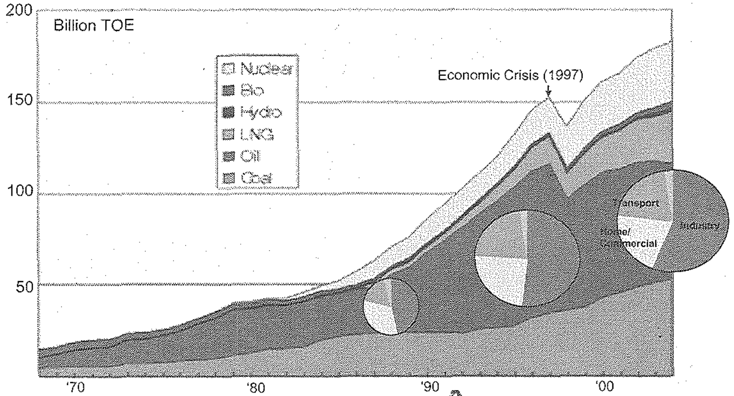
Energy Usage and Consumption in Korea



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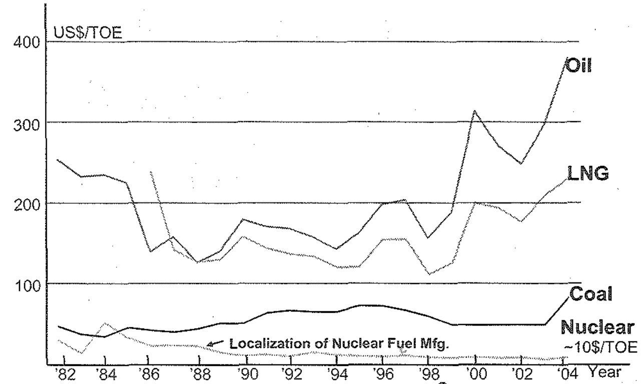
Energy Import Price in Korea



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Nuclear Energy in Korea

- **Produce 40 % of Electricity**
- **Pay less than 5% of Fuel import for electricity**
- **Nuclear energy is technology leading energy.**
  - Enriched uranium cost is less than 5 % in generation cost.
  - Uranium ore cost is less than 1.5%.
- **Price volatibilty is very small**
  - Long term storage is easy (1 kg of uranium produces energy of 10,000 barrel oil.)
  - Uranium mine is found in every continent on earth.

❖ World uranium reserve is sufficient for next 200 ~ 300 years of PWR need. Fast reactor can recycle the spent fuel for next 10,000 years. Ref: OECD/NEA News, 2002, 2006.

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Nuclear Energy in Korea

- **Nuclear Energy is regarded as indigeous.**
- **Good infrastructure for development.**
- **Less land for "renewables" (or high population density)**

▶▶ **Hydrogen production using Nuclear energy is necessary in future.**

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Limit of Renewable Energy

Ref) Energy in Japan, METI, 2003.

■ Solar
- on Roof of every building
  770 km², 700 B$ investment
  equiv. 11 plants (1000MWe)

■ Wind
- on No-plant land
  1,500 km², 60 B$ investment (except land price)
  equiv. 6 plants (1000 MWe)

✓ Korea can have 17 plants after 760B$ investment !

	Nuclear power generation	Solar power generation: For business use	Solar power generation: For household use	Wind power generation
Capacity per power plant	1 million kW	300kW	3.3kW	1,000kW
Load factor	80%	12%	12%	20%
Annual power generation per plant	7 billion kWh	320,000 kWh	3,700 kWh	1.75 million kWh
Investment per plant	300 billion yen	300 million yen	3 million yen	250 million yen
Number of power generating units required to generate equivalent electricity to one block of a 1 million kW nuclear power plant	1 unit	21,875 units	1.9 million units	4,000 units
(For reference) Necessary investment	300 billion yen	7 trillion yen	6 trillion yen	1 trillion yen
Required site area (・Solar power generation: 10 m²/kW ・Wind power generation: 0.062 km²/generating unit)		Approx. 67 km² (Almost equivalent to 1,500 Tokyo Domes)		Approx. 248 km² (Almost equivalent to 5,350 Tokyo Domes)
Generating cost	5.9 yen/kWh	Mean price (Household use): 66 yen/kWh Lowest price (Household use): 46 yen/kWh		Large-scale: 9-14 yen/kWh
(For reference) Comparison with the costs of the competing energies listed below		Approx. 2-3 times		Approx. 1.2-2 times
Assumed costs of competing energies		Unit price of household power: 23.3 yen/kWh		Unit cost of thermal power generation: 7.3yen/kWh

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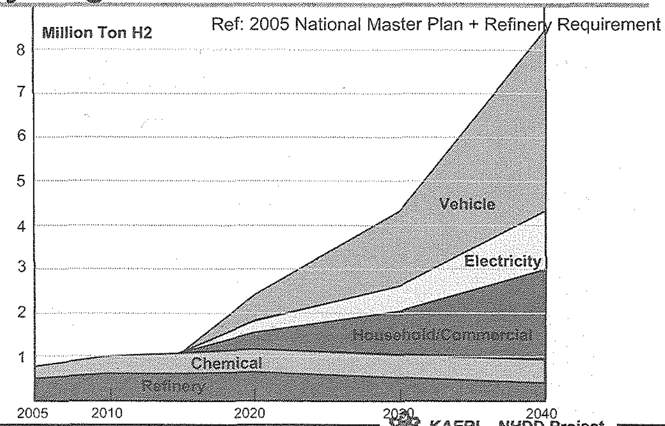
Hydrogen Demand in Korea



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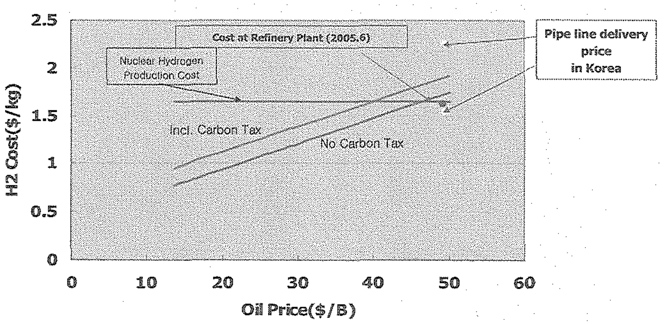
Hydrogen Production Cost



✓ Nuclear Hydrogen is cheap when crud oil price is more than 40~45$/bbl.

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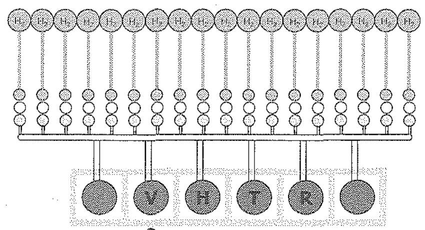
Vision of Nuclear Hydrogen

Profile	2040		Modules (600MW)	Const/yr
	Share	H2-ton/yr		
Low	15%	1,130,000	19	1.1
Medium	20%	1,500,000	25	1.7
High	50%	3,800,000	63	5.5

- Construction : 2020 ~ 2040
- Dedicated H-2 producer



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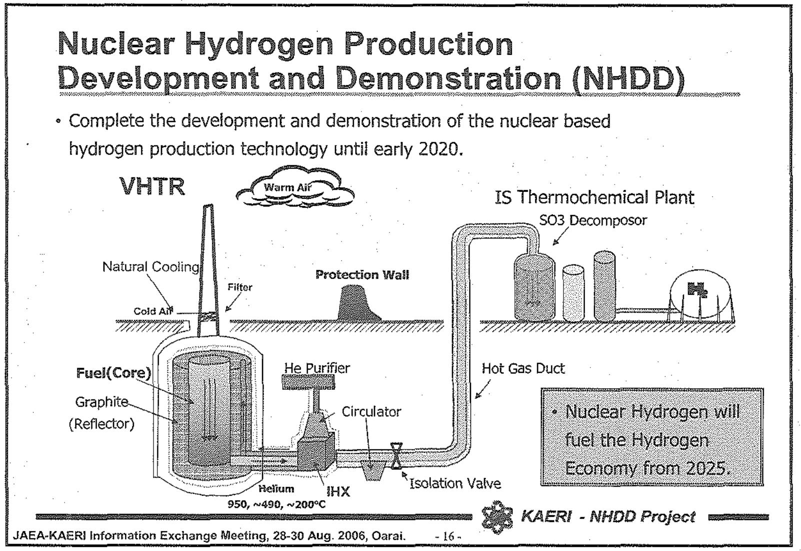
Nuclear Hydrogen Production Development and Demonstration (NHDD)
• Complete the development and demonstration of the nuclear based hydrogen production technology until early 2020.
VHTR
Warm Air
IS Thermochemical Plant
SO3 Decomposor
Natural Cooling
Filter
Cold Air
Protection Wall
Fuel(Core)
Graphite (Reflector)
He Purifier
Circulator
Hot Gas Duct
Helium
950, ~490, ~200°C
IHX
Isolation Valve
• Nuclear Hydrogen will fuel the Hydrogen Economy from 2025.
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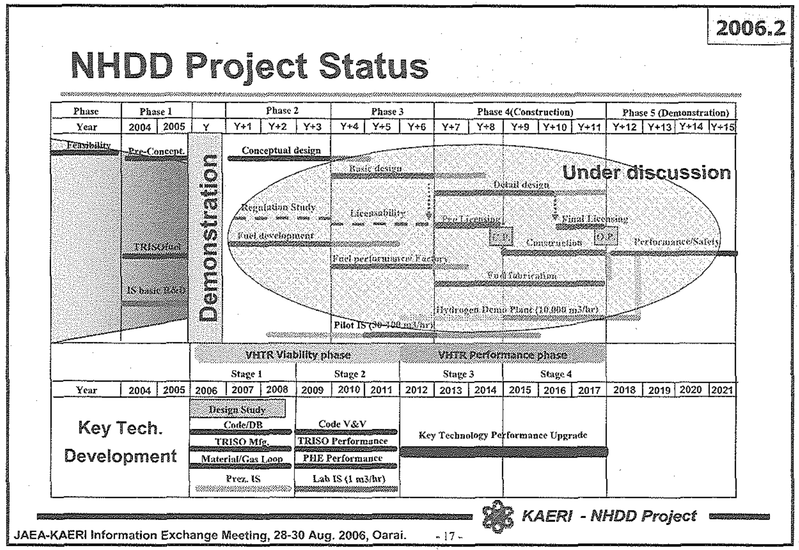
2006.2
NHDD Project Status
Phase 1
Phase 2
Phase 3
Phase 4(Construction)
Phase 5 (Demonstration)
Year 2004 2005 Y Y+1 Y+2 Y+3 Y+4 Y+5 Y+6 Y+7 Y+8 Y+9 Y+10 Y+11 Y+12 Y+13 Y+14 Y+15
Feasibility
Pre-Concept.
TRISOfuel
IS basic R&D
Demonstration
Conceptual design
Basic design
Detail design
Regulation Study
Licensability
Pre Licensing
Final Licensing
Fuel development
Fuel performance
Construction
Performance/Safety
Fuel fabrication
Hydrogen Demo Plant (10,000 m3/hr)
Pilot IS
Under discussion
VHTR Viability phase
VHTR Performance phase
Stage 1
Stage 2
Stage 3
Stage 4
Year 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021
Key Tech. Development
Design Study
Code/DB
TRISO Mfg.
Material/Gas Loop
Prez. IS
Code V&V
TRISO Performance
PHE Performance
Lab IS (1 m3/hr)
Key Technology Performance Upgrade
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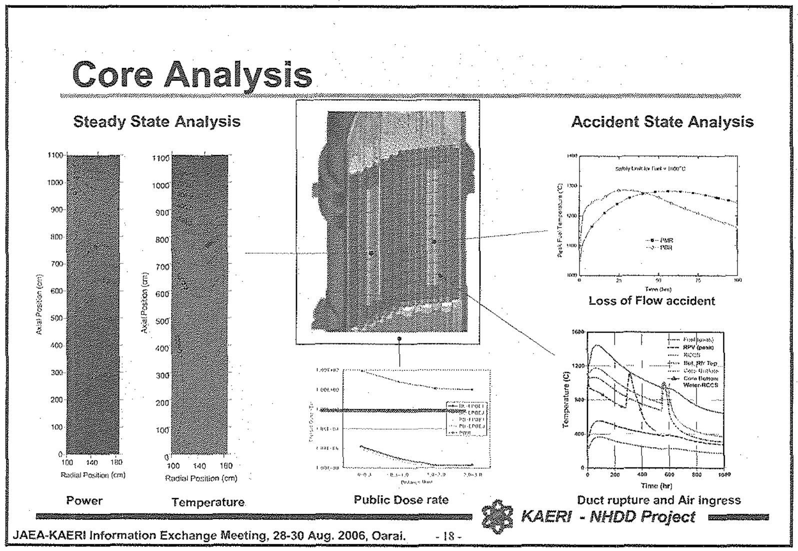
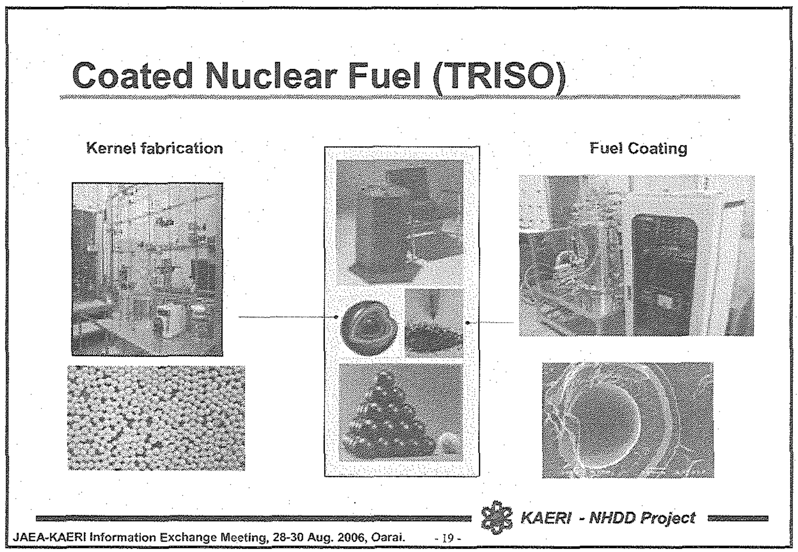
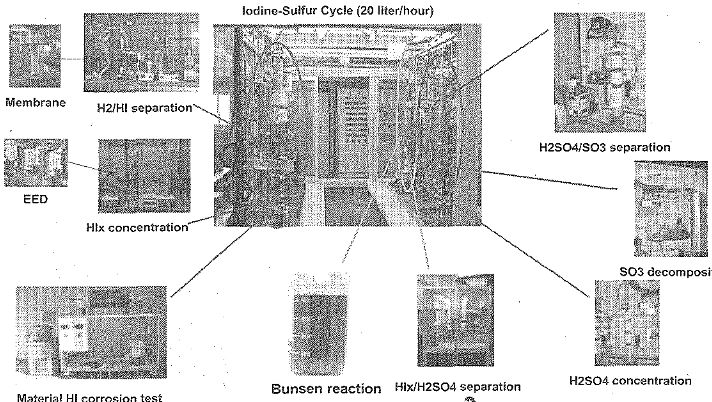

Core Analysis
Steady State Analysis
Accident State Analysis
Loss of Flow accident
Power
Temperature
Public Dose rate
Duct rupture and Air ingress
KAERI - NHDD Project
JAEA-KAERI Information Exchange Meeting, 28-30 Aug. 2006, Oarai. - 18 -


Coated Nuclear Fuel (TRISO)
Kernel fabrication
Fuel Coating
KAERI - NHDD Project
JAEA-KAERI Information Exchange Meeting, 28-30 Aug. 2006, Oarai. - 19 -

Thermochemical Hydrogen Production



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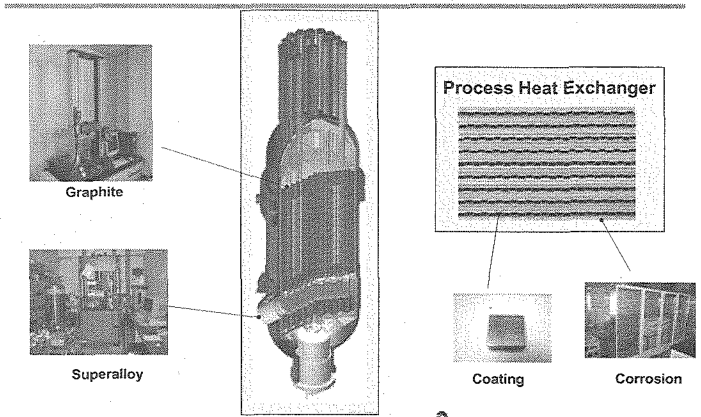
Material Assessment and Improvement



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1.2 Session 2 VHTR system design and related evaluations

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1.2.1 VHTR Cogeneration System: Reactor Concept, Turbomachine, High-temperature Valve and GTHTR300C

Kazuhiko KUNITOMI, Takakazu TAKIZUKA, Shoji TAKADA, Nariaki SAKABA, Hiroyuki SATO, Xinglong YAN and Tetsuo NISHIHARA

Nuclear Science and Engineering Directorate
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kunitomi.kazuhiko@jaea.go.jp

Summary

The technical approaches undertaken by JAEA for design and development of VHTR cogeneration system are given by three sections of a presentation entitled 1) VHTR cogeneration system for production of electricity and hydrogen, 2) VHTR helium turbomachine and 3) Development of high temperature valve.

The first section of the presentation begins with a description of the VHTR design philosophy of system simplicity, economical competitiveness, and originality, namely SECO. The key elements of such philosophy are sharing of common system technologies, incorporating original design simplification, and focused research and development in quest for a strong and practical plant economy. The SECO philosophy has enabled the evolution of a family of plant design variants with production ranging from electricity to hydrogen or co-production of both via a particular design variant GTHTR300C. Common to all design variants is a prismatic core reactor of top rated power 600MWt with passive safety and highest coolant outlet temperature 950°C by existing fuel and material. Major technical and economical advantages of selecting prismatic other than pebble-bed core are shown. The reactor is combined, when appropriate, with an iodine-sulfur thermo-chemical process for hydrogen production and with a mechanically and aerodynamically similar line of direct cycle helium turbomachine for electricity generation. The generated electricity supplies reactor and hydrogen plant operations in addition to grid output.

The second section presents JAEA's comprehensive R&D for helium turbomachine, a key VHTR technology. Placed in primary system, helium turbomachine enables most effective circulation of reactor coolant in addition to generating electricity. Efficient aerodynamics, reliability and maintainability are key requirements of qualification for nuclear service. Because of little prior practical experience, R&D to meet these performance goals is challenging, the extent of which has been minimized by our basic design approach of taking full advantage of successful experience in gas turbine industry, while incorporating new design elements only when must. As a result, the baseline design employs single shaft with minimum number of turbine and compressor stages, horizontal installation and synchronous speed operation, the features used typically in industrial gas turbines. The new elements of narrow helium compressor flowpath and magnetic bearing require further development. The status and results of development and related tests by JAEA are presented.

The last section of the presentation is about development and testing of the high temperature valve, an important component to ensure functional performance of

reactor confinement and structural integrity of the IHX heat transfer tubes. Major results are shown of JAEA's design study and mock-up tests, which have verified the technical basis with promising performance potential of the high temperature valve for helium gas service.

日本原子力研究開発機構 Japan Atomic Energy Agency — 超高温ガス炉 GTHTR300 series

#2-1 VHTR Cogeneration System
for Production of Electricity and Hydrogen

K.Kunitomi, T. Takizuka, S. Takada, T. Nishihara,
N. Sakaba, H. Sato and X. Yan

Presentation at 1st JAEA/KAERI Information Exchange Meeting

August 28, 2006

Slide 1

日本原子力研究開発機構 Japan Atomic Energy Agency — 超高温ガス炉 GTHTR300 series

Japan's HTGR and VHTR Design

- **GTHTR300** for electricity generation (850°C, 600MWth)
  - *Highly efficient electricity generation system*
  - *To be deployed in 2010s*
- **GTHTR300+** for electricity generation (950°C, 600MWth)
  - *Highly efficient electricity generation system*
  - *To be deployed in 2020s*
- **GTHTR300C** for Cogeneration of electricity and hydrogen(950°C, 600MWth)
  - *Highly efficient cogeneration system*
  - *To be deployed in 2030s*
- **GTHTR300H** for Hydrogen production(950°C,600MWth)
  - *System for hydrogen era*

Slide 2

日本原子力研究開発機構 Japan Atomic Energy Agency — 超高温ガス炉 GTHTR300 series

Design Philosophy

Simplicity, Economical Competitiveness and Originality (SECO)

1. Sharing of common technologies by all design variants
   - — a unified reactor primary circuit
   - — an aerodynamically and mechanically similar line of gas turbines
   - — the selected hydrogen production process, the IS process
2. Focused development that limits cost and risk
   HTTR-type high burnup fuel, a baseline gas turbine, and IS process ation
3. Original design attributes
   - — Conventional material RPV, high burnup fuel cycle
   - — Horizontal gas turbine, non-intercooled power conversion cycle
   - — New IS process technologies

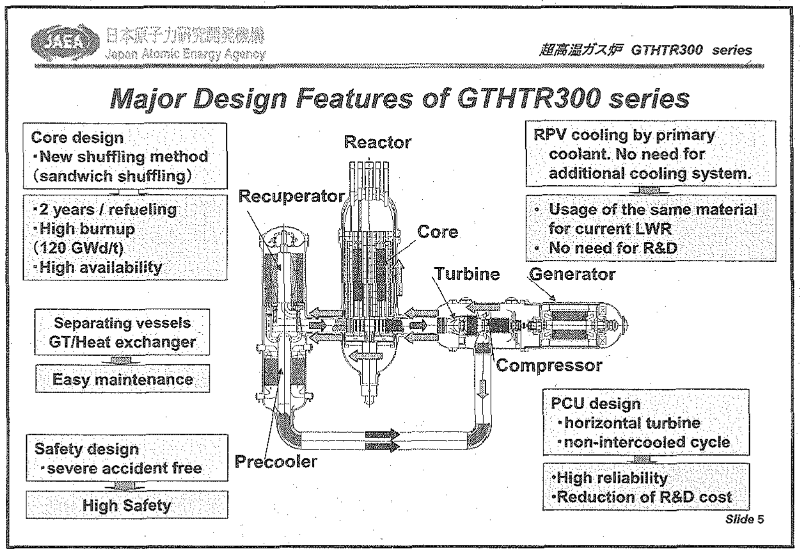
Slide 3

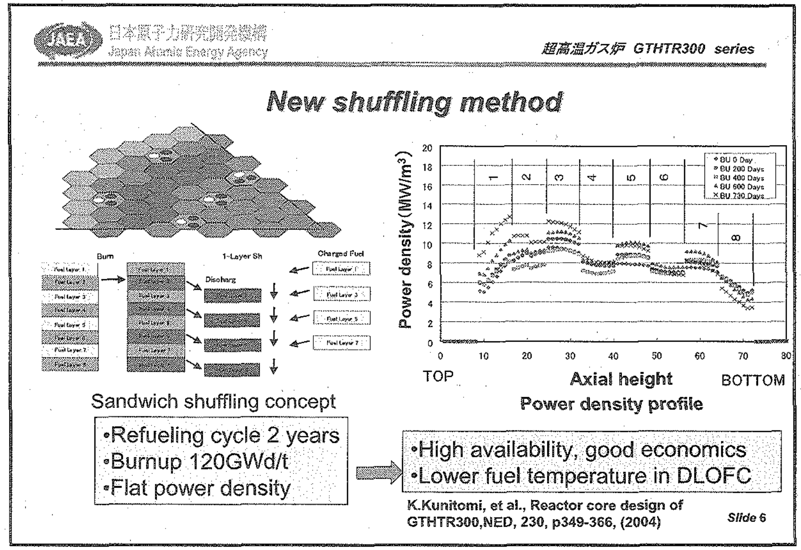
日本原子力研究開発機構 Japan Atomic Energy Agency — 超高温ガス炉 GTHTR300 series

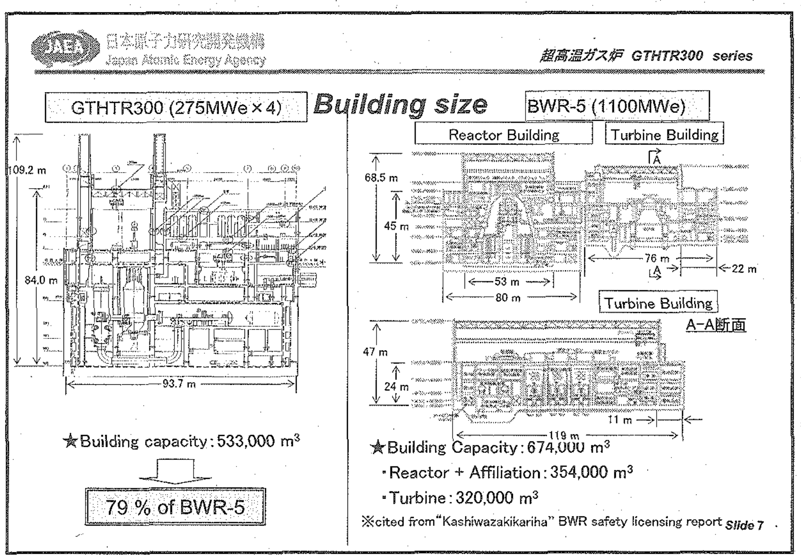
Major specification of GTHTR300C and GTHTR300

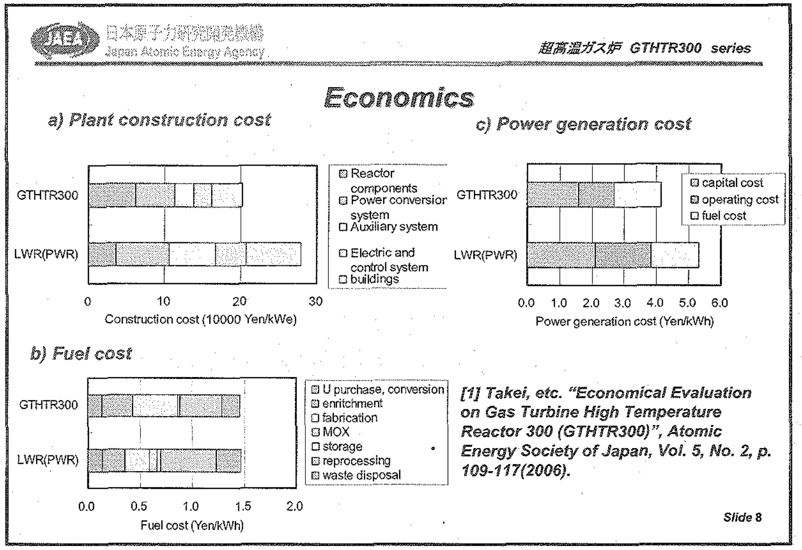
Items	GTHTR300C	GTHTR300
Reactor power	600MW	600MW
(Hydrogen／Electricity)	170/430MW	600MW
Outlet gas temperature	950°C	850°C
Inlet gas temperature	594°C	587°C
Primary flow rate	324kg/s	439kg/s
Primary pressure	5.1MPa	6.9 MPa
Operational cycle	1.5 year	2 year
Burnup rate	120GWd/t	120GWd/t
Electricity generation	202MWe	274MWe
Hydrogen production	1.9～2.4t/h	-
Efficiency of electric generation	45.7%	45%
Efficiency of hydrogen production	45～55%	

Slide 4


日本原子力研究開発機構
Japan Atomic Energy Agency
超高温ガス炉 GTHTR300 series
Major Design Features of GTHTR300 series
Core design
·New shuffling method (sandwich shuffling)
·2 years / refueling
·High burnup (120 GWd/t)
·High availability
Separating vessels GT/Heat exchanger
Easy maintenance
Safety design
·severe accident free
High Safety
Reactor
Recuperator
Core
Turbine
Generator
Compressor
Precooler
RPV cooling by primary coolant. No need for additional cooling system.
· Usage of the same material for current LWR
· No need for R&D
PCU design
·horizontal turbine
·non-intercooled cycle
·High reliability
·Reduction of R&D cost
Slide 5

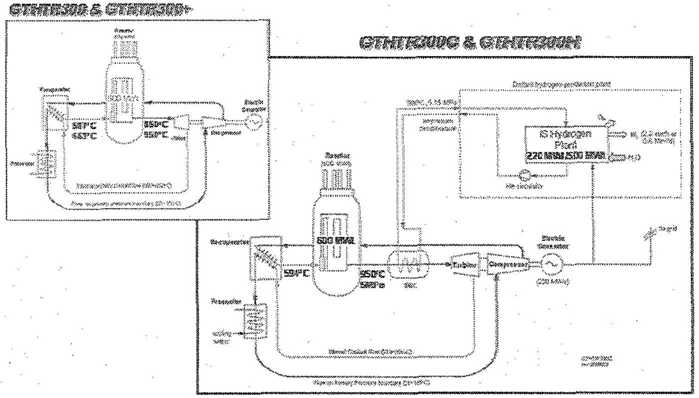

日本原子力研究開発機構
Japan Atomic Energy Agency
超高温ガス炉 GTHTR300 series
New shuffling method
Sandwich shuffling concept
·Refueling cycle 2 years
·Burnup 120GWd/t
·Flat power density
Power density (MW/m3)
TOP
Axial height
BOTTOM
Power density profile
·High availability, good economics
·Lower fuel temperature in DLOFC
K.Kunitomi, et al., Reactor core design of GTHTR300,NED, 230, p349-366, (2004)
Slide 6


日本原子力研究開発機構
Japan Atomic Energy Agency
超高温ガス炉 GTHTR300 series
Building size
GTHTR300 (275MWe×4)
109.2 m
84.0 m
93.7 m
★Building capacity: 533,000 m3
79 % of BWR-5
BWR-5 (1100MWe)
Reactor Building
Turbine Building
68.5 m
45 m
53 m
80 m
76 m
22 m
Turbine Building
A-A断面
47 m
24 m
119 m
11 m
★Building Capacity: 674,000 m3
·Reactor + Affiliation: 354,000 m3
·Turbine: 320,000 m3
※cited from "Kashiwazakikariha" BWR safety licensing report
Slide 7


日本原子力研究開発機構
Japan Atomic Energy Agency
超高温ガス炉 GTHTR300 series
Economics
a) Plant construction cost
GTHTR300
LWR(PWR)
Construction cost (10000 Yen/kWe)
Reactor components
Power conversion system
Auxiliary system
Electric and control system
buildings
b) Fuel cost
Fuel cost (Yen/kWh)
U purchase, conversion
enrichment
fabrication
MOX
storage
reprocessing
waste disposal
c) Power generation cost
Power generation cost (Yen/kWh)
capital cost
operating cost
fuel cost
[1] Takei, etc. "Economical Evaluation on Gas Turbine High Temperature Reactor 300 (GTHTR300)", Atomic Energy Society of Japan, Vol. 5, No. 2, p. 109-117(2006).
Slide 8

日本原子力研究開発機構
Japan Atomic Energy Agency
超高温ガス炉 GTHTR300 series

Cogeneration Production Cycles



Slide 9

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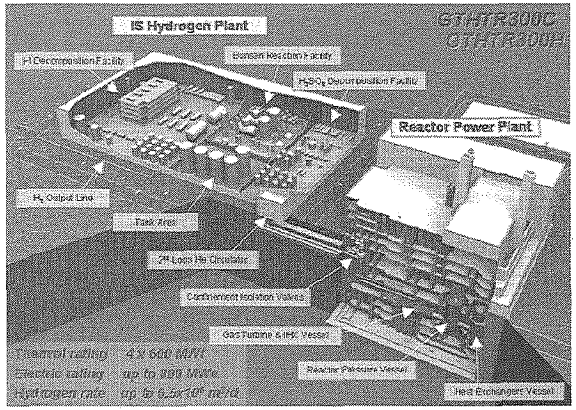
Japan Atomic Energy Agency
超高温ガス炉 GTHTR300 series

Plant layout of GTHTR300C



Slide 10

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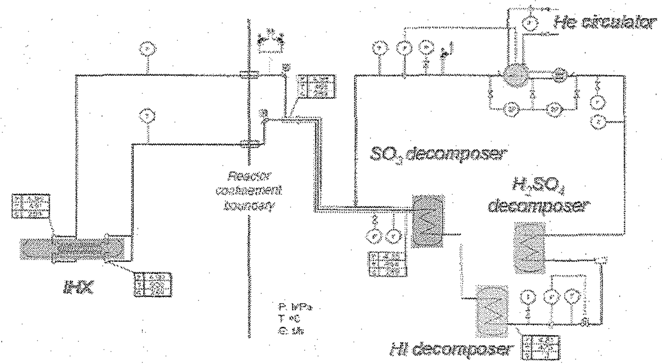
Japan Atomic Energy Agency
超高温ガス炉 GTHTR300 series

2nd He Loop Coupling Hydrogen Plant to Reactor



Slide 11

日本原子力研究開発機構
Japan Atomic Energy Agency
超高温ガス炉 GTHTR300 series

Flowsheet Calculated Performance (Target)

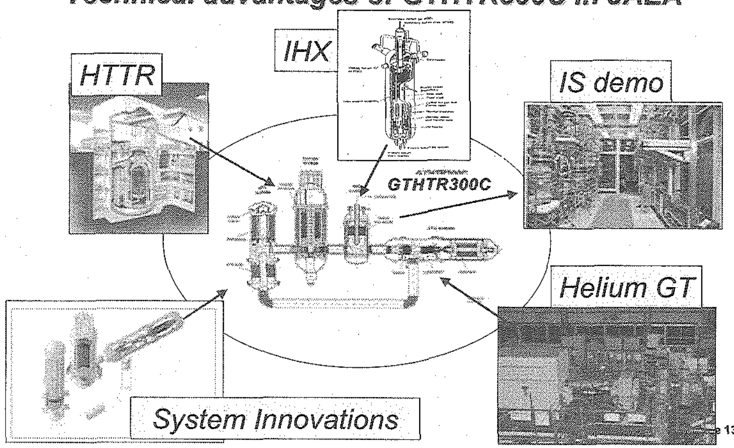
(1) He supply temperature : 824°C
He return temperature : 475°C
He pressure : 5 MPa abs
(2) EED HI concentrate : 13mol/kg H2O(62.5 wt%)
EED cell voltage : 0.2V
EED current density : 2.0 A/cm²
(3) Membrane H2O removal : 2,221kmol/hr
(4) H2SO4 process pressure : 1.2MPa abs
(5) SO3 decomposer temperature : 850°C
(6) H2SO4 conversion rate : 50.0%
(7) HI process pressure : 1.2MPa abs
HI conversion rate : 80%
HI decomposition temperature : 400°C
(8) I2 scrubber rate : 100%
Co to I2 reaction ratio : 1 by mol
Co reaction temperature : 400°C
Co recycle temperature : 800°C

Thermal Heat (MWt)	Electricity consumed (MWe)	Electric generating efficiency	IS plant net Efficiency (HHV)
170.8	21.7	40%	42.4%
		45%	43.8%
		50%	44.8%

Slide 12

日本原子力研究開発機構 Japan Atomic Energy Agency　超高温ガス炉 GTHTR300 series

Technical advantages of GTHTR300C in JAEA



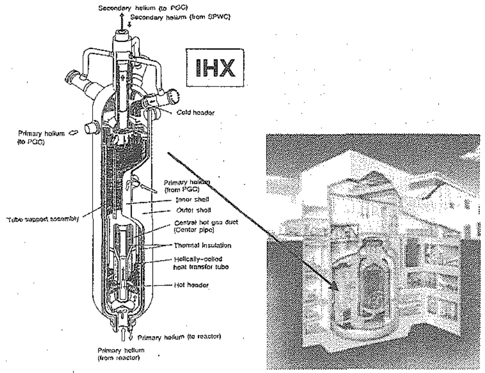
Slide 13

日本原子力研究開発機構 Japan Atomic Energy Agency　超高温ガス炉 GTHTR300 series

950°C capable helical He/He IHX in HTTR

IHX developed technologies and experience:

- Heat and corrosion resistant super alloy Hastelloy-XR (helium ~950°C)
- High temperature structural design guideline
- Licensing experience
- Operations experience



Slide 14

日本原子力研究開発機構 Japan Atomic Energy Agency　超高温ガス炉 GTHTR300 series

IHX for GTHTR300C and HTTR

Items	GTHTR300C	HTTR
Heat capacity	168MW	10MW
Primary He temp.(in/out)	950/850 ℃	950 ℃/389 ℃
Secondary He temp. (in/out)	500/900 ℃	237/869 ℃
Primary coolant flowrate	324kg/s	3.4kg/s
Primary coolant pressure	5.02MPa	4.06MPa
Secondary coolant flowrate	81/kg/s	3.0kg/s
Secondary coolant pressure	5.15MPa	4.21MPa
Legalistic average temp.	154 ℃	113 ℃
Heat transfer tube		
Material	Hastelloy XR	
Dimension	31.75mm × 3.5t	
Manifold		
Material	Hastelloy XR	
Dimension	1.056m(O.D.)	0.827m(O.D.)

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日本原子力研究開発機構 Japan Atomic Energy Agency　超高温ガス炉 GTHTR300 series

Economics of IS process

a) Plant construction cost

Plant specifications

- Amount of hydrogen production 25,000 Nm³/h
- Plant design life: 40 years

Items of construction cost

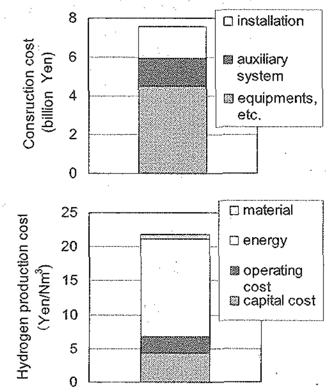
- Main equipments, etc: ¥ 4.5 billion
- Auxiliary system: ¥1.4 billion
- Installation: ¥1.6 billion

Estimation condition

- NOAK plant
- Replacement of chemical equipments every 10 years

b) Hydrogen production cost

Hydrogen production cost: ~22 yen/Nm³



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日本原子力研究開発機構 Japan Atomic Energy Agency — 超高温ガス炉 GTHTR300 series

Comparison between pebble bed and block(1/2)

	Block	Pebble
• Maximum Power	600MWth	400MWth
• Core design		
➢ Pressure loss	Lower	Higher
➢ Fuel temp.	Higher in normal operation Lower in DLOFC	Lower in normal operation Higher in DLOFC
➢ Refueling	butch (2years)	on-line

NO clear difference. Pebble reactor changes central reflector blocks around the core. Maintenance shall be done at least every two years.(current 13 months in Japan) .

	Block	Pebble
➢ Seismic	Many experiences	No experiences*

* Especially, annular core arrangement.

	Block	Pebble
➢ Burnup	120 GWd/ton	120GWd/ton
➢ Discharged ^{235}U	Higher	Lower*

* But it is still too high to dispose directly.

- Fuel design — No clear difference
- Safety design — No clear difference

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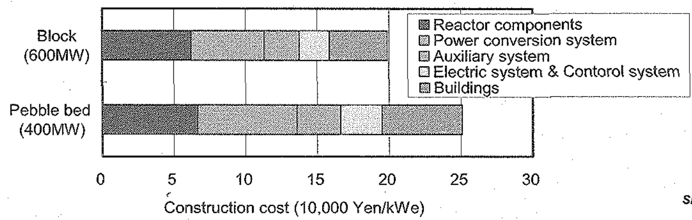
日本原子力研究開発機構 Japan Atomic Energy Agency — 超高温ガス炉 GTHTR300 series

Comparison between pebble bed and block(2/2)

	Block	Pebble
• PCU design		
➢ Turbine speed	3600 rpm	High speed turbine
➢ Shaft	single	Multi or high speed gear
• R&D needs	Not many	Many
• Economics	Clearly better (84-88% of pebble)	

➢ Cost(B)= Cost (P) × (PowerB/PowerP)^n N=0.4-0.7



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Summary of VHTR Design

- ❑ The GTHTR300 design provides a family of electricity, hydrogen or cogeneration plants, strongly adaptable to changing market needs.
- ❑ By sharing common technologies, the design limits development scope and risk and enables flexible demonstration and deployment.
- ❑ The design, through GTHTR300C and GTHTR300H, can play a significant role in supplying both emerging and matured hydrogen economy in Japan.

... and the Future Plan

- ❑ Design and safety analysis code development using the HTTR
- ❑ Basic design of GTHTR300C & GTHTR300H
- ❑ IS process improvement and demonstration
- ❑ R&D for fuel and alternative fuel cycles

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日本原子力研究開発機構 Japan Atomic Energy Agency — GTHTR300

#2-2 VHTR
Helium turbomachine

Xing L. Yan
JAEA

1st JAEA/KAERI Information Exchange Meeting on HTGR and Nuclear Hydrogen Technology

August 28-30, 2006

August 28-30, 2006 — Slide 1

日本原子力研究開発機構 Japan Atomic Energy Agency — GTHTR300

Three pillars of the VHTR system technologies:

✓ ***The** 950°C-capable **HTR reactor*** *(JAEA's HTTR demo)*

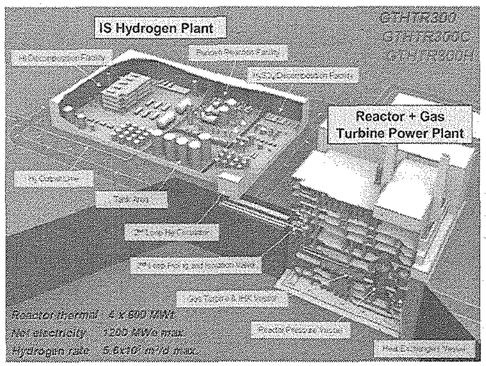
✓ ***The helium turbomachine*** *(under development at JAEA)*

✓ ***The IS process*** *(under development at JAEA)*

August 28-30, 2006 — Slide 2

日本原子力研究開発機構 Japan Atomic Energy Agency — GTHTR300

VHTR System Arrangement (GTHTR300)



3

August 28-30, 2006
Slide 3

日本原子力研究開発機構 Japan Atomic Energy Agency — GTHTR300

Why is helium turbomachine needed for VHTR?

Helium turbomachine *enables any one or combination of the followings:*

✓ ***600MWt VHTR-capacity compatible primary helium circulation***
450 kg/s helium circulating capacity by one turbomachine unit
(vs. 4 kg/s helium circulator used in HTTR)

✓ ***Most efficient and economical power generation possible by VHTR***
Direct Brayton cycle helium turbine for 50% efficiency at least count of components

✓ ***Cogeneration of electricity to supply hydrogen plant***
VHTR hydrogen plant energy requirement:
I-S: *75% heat + 25% electricity*
HTE: *25% heat + 75% electricity*

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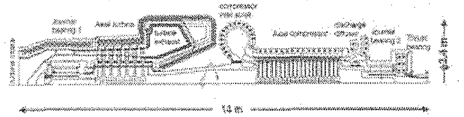
日本原子力研究開発機構 Japan Atomic Energy Agency — GTHTR300

JAEA's Helium Turbomachine Design Philosophy:

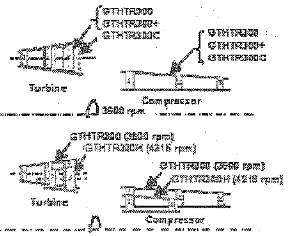
An aerodynamically and mechanically similar line of turbomachines to serve all GTHTR300 design variants

Baseline Design for GTHTR300: 6 turbine stages, 20 compressor stages, non-intercooled, horizontal shaft, 3600 rpm synchronous, magnetic bearing, and 300 MWe class



Aerodynamic Scaling from baseline design for all other units: GTHTR300+, GTHTR300C and GTHTR300H:

- Scaled from baseline gas turbine by changing inlet pressure or rotational speed while holding wheel speed constant
- Similar aerodynamics
- Similar disc stresses
- Needed to develop the baseline gas turbine only



August 28-30, 2006
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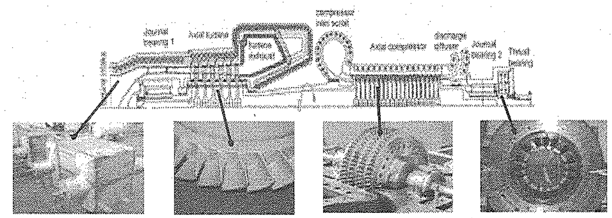
Source: X. Yan, et al., Nuclear Production of Hydrogen, Proc. Of OECD/NEA 3rd Information Exchange Meeting, pp. 121-139, Oct.5-7,2005

日本原子力研究開発機構 Japan Atomic Energy Agency — GTHTR300

JAEA's Helium Turbomachine R&D:

✓ *Only R&D on the baseline design is necessary (see design philosophy)*

✓ *JAEA's R&D activities:*



1. Brayton cycle helium gas loop: Designed and partially constructed
2. Helium turbine aerodynamics R&D: Designed and partially built
3. Helium compressor aerodynamics R&D: Program nearly completed
4. Magnetic bearing design and control: Test rig under commissioning

August 28-30, 2006
Slide 6 — 6

日本原子力研究開発機構 Japan Atomic Energy Agency — GTHTR300

Compressor Aerodynamics R&D

The Background

Neither successful helium compressor nor proven design existed, prior to the present program !

The R&D Goal

Development of high performance helium compressor for VHTR

The Results

1. Proposal of original design techniques
2. 1/3 of full scale compressor tests
3. Establishment of performance evaluation methods

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Slide 7 — 7

日本原子力研究開発機構 Japan Atomic Energy Agency — GTHTR300

Helium Compressor Aerodynamics R&D

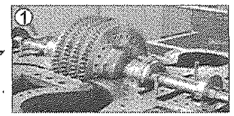
The Results (1/3)

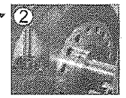
1. Proposal of original design techniques

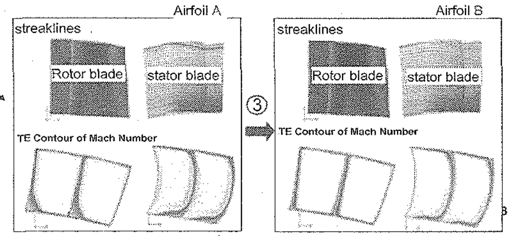
① High performance compressor flowpath: non-intercooled, synchronous, and minimum number of compressor stages

② Tight blade tip clearance: 1.2 mm equivalent in full scale, through a patented shaft-bearing system

③ 3D blade airfoil: shown to eliminate boundary layer flow separation on blade







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Slide 8 — 8

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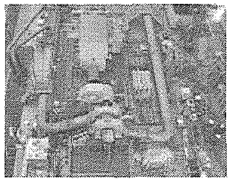
Helium Compressor Aerodynamics R&D

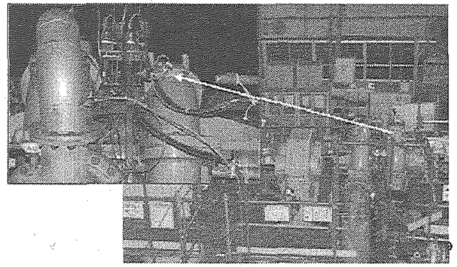
The Results (2/3)

2. 1/3 of full scale compressor tests
1) Internal flowpath boundary layer measurements
2) Airfoil performance measurements
3) Inlet/outlet casing geometry performance measurements
4) Compressor efficiency and surge margin

Helium compressor test rig



Detailed internal flowpath measurement of aerodynamic variables



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Slide 9

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Helium Compressor Aerodynamics R&D

The Results (3/3 A)

3. Establishment of performance evaluation methods

A. Throughflow method

- ❑ Test measurements
- ❑ Additional test-calibrated CFD data
- ❑ Performance predication model is significantly improved over existing air-compressor-experience based model

B. Reynolds Correlation method

- ❑ Extensive test measurements
- ❑ Viscous CFD analytical insights to identify flow regimes
- ❑ Correlation of efficiency with Reynolds number, Re^{-n}, subject to critical Reynolds number

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Slide 10
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日本原子力研究開発機構 Japan Atomic Energy Agency GTHTR300

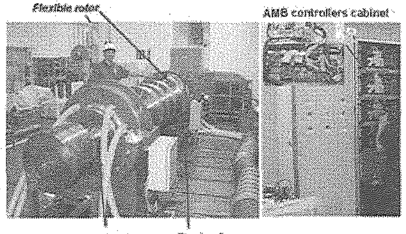
Helium Turbomachine: Additional R&D Needs

- ❑ **Compressor aerodynamics R&D:** documentation of design data base to be done
- ❑ **Turbine aerodynamics R&D:** turbine test section partially constructed…
- ❑ **Magnetic bearing design & control:** test stand being commissioned, test programs planned
- ❑ **Brayton cycle helium gas loop:** designed and partially constructed…

1/3 scale magnetic bearing levitated rotor on test stand

Test rig specification:
- ❑ 5 ton rotor, 3600 rpm
- ❑ Four vibration modes in operating speed range (the world first heavy duty flexible MB rotor)
- ❑ Tight bearing and rotor clearance control
- ❑ Conventional and advanced MB control algorithms

Based on the above specification, the test rig is now undergoing commissioning tests.



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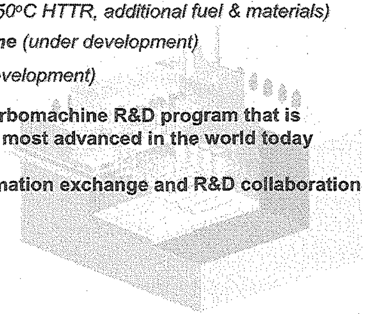
日本原子力研究開発機構 Japan Atomic Energy Agency GTHTR300

Summary

- ❑ **Three pillars of the VHTR system technologies:**
  - ✓ *The VHTR reactor (the 950°C HTTR, additional fuel & materials)*
  - ✓ ***The helium turbomachine** (under development)*
  - ✓ *The IS process (under development)*
- ❑ **JAEA has ongoing helium turbomachine R&D program that is unique, comprehensive, and most advanced in the world today**
- ❑ **JAEA welcome further information exchange and R&D collaboration with KAERI colleagues**



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Slide 12

日本原子力研究開発機構 Japan Atomic Energy Agency — 超高温ガス炉 GTHTR300 series

#2-3 VHTR Cogeneration System : Development of High Temperature Valve

Tetsuo Nishihara

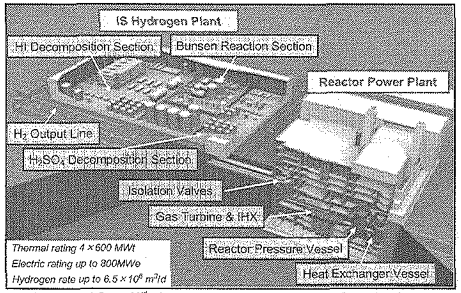
1st JAEA/KAERI Information Exchange Meeting on HTGR and Nuclear Hydrogen Technology

August 28, 2006

日本原子力研究開発機構 Japan Atomic Energy Agency — 超高温ガス炉 GTHTR300 series

VHTR Cogeneration System

- Hydrogen plant is connected to the IHX by the secondary helium pipe.
- It shall be designed, constructed, operated and maintained as a general chemical plant.
- Isolation valves are provided in the secondary helium pipe.



Ref. X. Yan et al, Proc. of 3rd Information Exchange Meeting on Nuclear Production of Hydrogen

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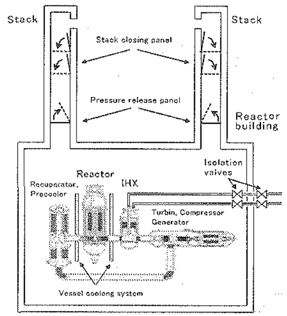
日本原子力研究開発機構 Japan Atomic Energy Agency — 超高温ガス炉 GTHTR300 series

Necessity of the High temperature Valve

- To ensure the performance of reactor confinement from the viewpoint of nuclear safety
  - Secondary helium pipes penetrate the reactor confinement.
  - Safety performance of the secondary helium pipe in the hydrogen plant to contain the helium gas can not be expected in an accident state.
  - An accidental release of the radioactive materials through the secondary helium pipe shall be prevented as the IHX heat transfer tube is ruptured.
  - Isolation valves shall be installed on the secondary helium pipes to maintain the performance of reactor confinement.

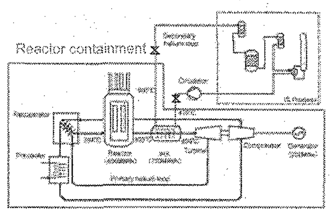


Ref. S. Katanishi, et al., Trans. At. Energy Soc. Japan., 2[1], 55 (2000).

日本原子力研究開発機構 Japan Atomic Energy Agency — 超高温ガス炉 GTHTR300 series

Necessity of the High temperature Valve

- Structural integrity of the IHX heat transfer tube shall be ensured against dangerous material ingress.
  - In the IS process, some explosive and corrosive materials are treated as reactants.
  - Operation pressure of the IS process is lower than one of the secondary helium to prevent such materials from flowing into the secondary helium loop as the heat transfer tube of chemical reactor is cracked.
  - However a scenario that the secondary helium pressure decreases and then the heat transfer tube of the chemical reactor is cracked induces such materials ingress.
  - Isolation valves shall be closed to prevent damage of the IHX heat transfer tube by such materials.

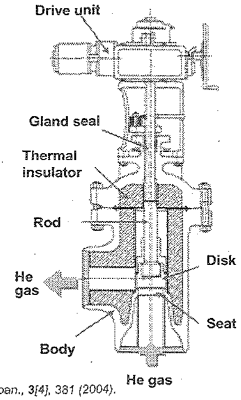


Ref. X. Yan et al, Proc. of 3rd Information Exchange Meeting on Nuclear Production of Hydrogen

日本原子力研究開発機構
Japan Atomic Energy Agency
超高温ガス炉 GTHTR300 series

Design requirement

- Structure
  - Lowering the mean temperature of body to be able to use a carbon steel.
  - Minimizing the thermal deformation of body, rod, seat and disk to keep the dimensional accuracy.
  - Easing the maintainability of seat and disk.
- Material
  - Coating seat and disk to prevent baking.
- Performance
  - Long-term operation
  - Low leak rate of helium gas from seat and gland

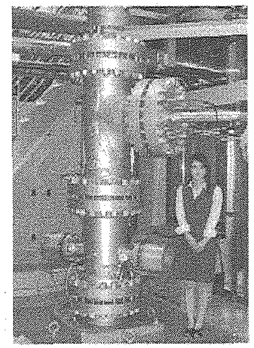


Ref. T. Nishihara, et al., Trans. At. Energy Soc. Japan., 3[4], 381 (2004).

日本原子力研究開発機構
Japan Atomic Energy Agency
超高温ガス炉 GTHTR300 series

Mock-up test

- Mock-up model has 100mm of nominal inner diameter of valve seat manufactured by Utsue Valve and Mitsuibishi Heavy Industries.
- Maximum seat temperature is 900℃.
- Maximum helium pressure is 4MPa.
- Basic performance is verified.
  - Structural integrity
  - Seal performance (three times shutdown test at 900℃)
  - Maintainability (recover the seal performance after polishing the seat surface)



Ref. N. Sakaba, et al., Proc. of , WHEC2006, S04-043, Lyon, France, (2006).

1.2.2 Present Status of VHTR PSA in Korea

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Summary

In developing a very high temperature reactor (VHTR) for a hydrogen generation in Korea, we expect the PSA will play an important role to improve the safety and economy of a VHTR. We attempt to establish two kinds of PSA technologies, one is to develop a risk-informed design framework for the VHTR and the other is to resolve the unique technical issues in the VHTR PSA. For establishing a risk-informed design framework, a paradigm shift is required among the researcher, designer and regulatory. It means that a major role of responsibility for nuclear safety transfer from regulatory to utility. We identified several problems in the risk-informed design such as a safety & performance goals for a VHTR, event selection criteria, risk due to a hydrogen facility and quality control in the PSA. Our effort to establish a risk-informed design framework is ongoing. We identified two kinds of issues in VHTR PSA; one is about a PSA framework and the other is about unique technical issues on VHTR. For a PSA framework, we should resolve the methodology, the reliability & initiating event frequency data, the definition of the end state of accident sequence in the event tree, the consequence analysis and the external events (Fire, seismic, flood). For technical issues, we are ongoing to resolve the reliability of the passive systems and the digital I&C systems and the human reliability. We are establishing our detailed research plan step by step under our VHTR schedule. PSA technology and tools for VHTR PSA are under development according to the master plan of VHTR development. We think one of the most importance thing for successful VHTR PSA is an international incorporation for risk assessment area.

1st JAEA/KAERI Information Exchange Meeting on VHTR System
August 28-30, 2006

Present Status of VHTR PSA in Korea

2006. 8. 28

Seok-Jung Han & Joon-Eon Yang

Korea Atomic Energy Research Institute

Contents

2

1. Introduction

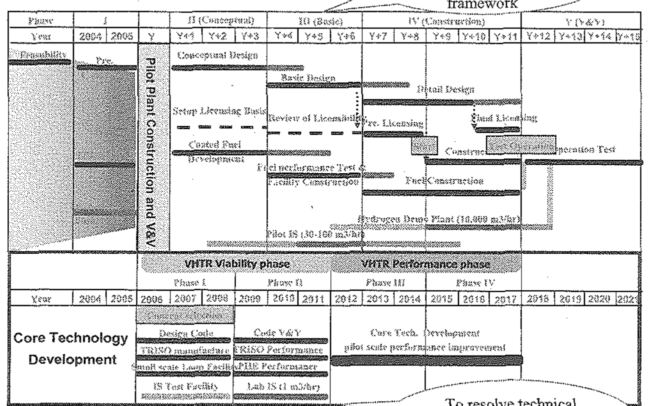
- A research on hydrogen conversion reactor has started at KAERI from 2004 (Fig. 1).
  - Primary candidate: VHTR for the purpose of hydrogen conversion
  - Two major master plans:
    1. Design and construction project
    2. Core technology development project
- Motivation:
  - PSA technology → an effective/efficient tool for enhanced safety and economic
    - Balance between enhanced safety and economical needs
  - Risk information for design and development of VHTR system
- **Objectives:**
  - Framework for the risk-informed design
  - Technological issues of PSA for VHTR

3

Master Plans of the Project

Fig.1

To establish a risk informed design framework



To resolve technical issues on VHTR PSA

2006.2

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General Activities

- Integrated safety assessment division
  ~35 specialized experts for PSA
- LWR PSA experiences
  - Internal PSA: full scope (Yonggwang Units 3&4; Ulchin Units 3&4)
  - External PSA: partly engagement (Seismic, Fire, Flooding)
  - Low power and shutdown PSA: full scope (Yonggwang units 5&6)
  - Level 2 & 3 PSA
  - CANDU PSA
- Codes
  - AIMS: Integrated PSA code package
    - KIRAP for Level I PSA
    - CONFAS for ET edition and Level II PSA
  - FTREX for cutset generation engine (one of the fastest codes in the world)
  - KIND for reliability database system
  - Etc
- Other application areas
  - Chemical (Petrol) plants risk assessment
  - Domestic train rail safety assessment
  - New plants PSA (Hydrogen conversion Rx, Next generation Rxs)
- Research parts
  - Integrated code system
  - A full scope PSA model for Ulchin units 3&4
  - Specific Reliability database for domestic nuclear sites
  - Human reliability
  - Level III PSA methodology
  - Risk-informed application
  - And related more detailed technique of PSA

5

2. Roles of PSA in VHTR Development

- Importance of risk information
- RID: an aggressive approach to use the risk information
  - A useful technique for taking a balance between enhanced safety and economical need (Fig. 2)
- What we do now:
  - **To develop a risk-informed design framework for the Korean VHTR**
  - To resolve technical issues on the VHTR PSA

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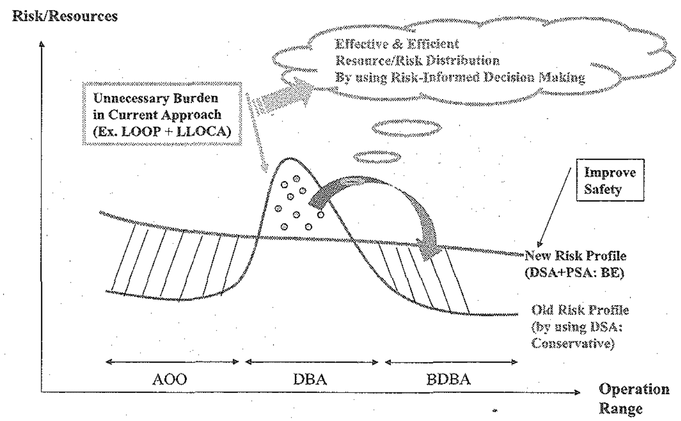
Note: Basic Concept of Risk-informed Decision Making

Fig.2



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3. Risk-Informed Design Framework

- Relationship with the regulatory framework
- Responsibility for nuclear safety:
  - Regulatory → Utility
- Proposed approaches:
  - D-RAP (Design-Reliability Assurance Program) proposed by IAEA
  - A research project supported by US DOE
  - PBMR licensing approach by South Africa & Exelon proposal
  - A research program for the generation IV reactor
  - Risk-informed regulation framework by US NRC
  - etc
- Basic structure of risk informed design framework (Fig.4)

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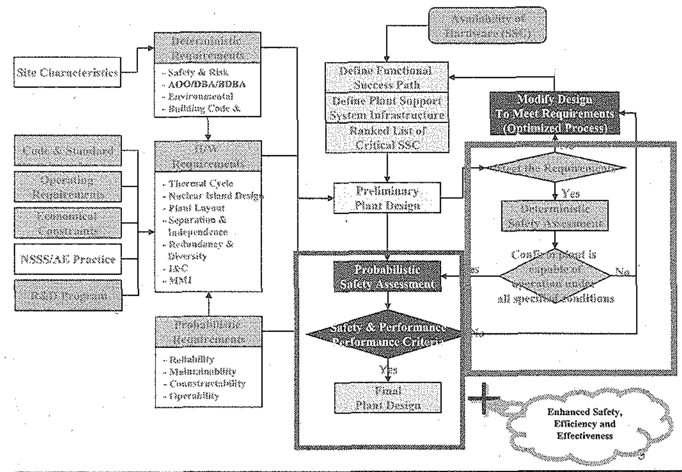
Conceptual Framework for RID

Fig.4



Note: Relationship with Regulatory Framework for VHTR

- Regulation & licensing problem
  - Less experience
  - Weakness of licensing process
- Preparation of regulation body to accept a probabilistic approach (Paradigm shift)
  - Necessary of iterative process depends on regulation

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Related Issues for RID

- Safety & performance goals for a VHTR
- Event selection criteria
- Risk due to a hydrogen facility
- Quality control in PSA

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Note: VHTR Characteristics (Table 1)

- Large difference to LWR
  - Coolant (liquid vs. gas)
  - Similarity :
    - Loss of pressure boundary
    - Loss of forced circulation
  - Difference
    - No safety injection system (not applicable: 10CFR50.46 ECCS Rule → DBA)
    - No coolant makeup except very small LOCA or leakage cases
- No need residual heat removal (independent shutdown cooling system)
  - Indirect cycle (Intermediate loop)
- Simplified safety functions
  - Reactivity control
  - Residual heat removal
  - No necessity of inventory makeup functions
  - Radiation release control

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Note: VHTR Characteristics

Table 1

	Safety Function	VHTR	Remarks
Prevention	Inherent Safety Features	- Low Power Density - Strong Negative Feedback - Strong Fuel Configuration (Coated Particle) - Large Heat Capacity of Graphite Core	ATWS / Return to Power
	Reactivity Control	Reactor Control & Protection System	
	Coolant Makeup	Helium Supply System	Leak & Pressure Conserve Function
	Auxiliary Cooling System	Auxiliary Cooling System Direct Vessel Cooling System Heat Bypass to Ground	
	Long Term Cooling	N/A	Possible Indirect Cooling for HCU
Mitigation	**10CFR50.46 ECCS Rule***	N/A	N/A
	General Design Criteria (10CFR50 App. A)	Single Failure Criteria	N/A to Passive System (with loss of off-site power)
	Containment (10CFR50 App. A)	Confinement Purge System Emergency Air Purification System	LWR <-> GCR N/A

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Safety & Performance Goals for a VHTR

- Safety goals (regulatory or public)
  - Use of the Generation IV reactor' safety goals
- Performance goals (utility or developer)
  - Very higher performance to compete with other power systems for hydrogen production
- Quantitative or qualitative ?

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Events Selection Criteria

- Selection of AOO/DBA/BDBA
  - Difference between LWR <-> VHTR
- Event categorization for design and regulation (Fig. 5)
- Selection factors
  - Event frequency
  - Consequential impact

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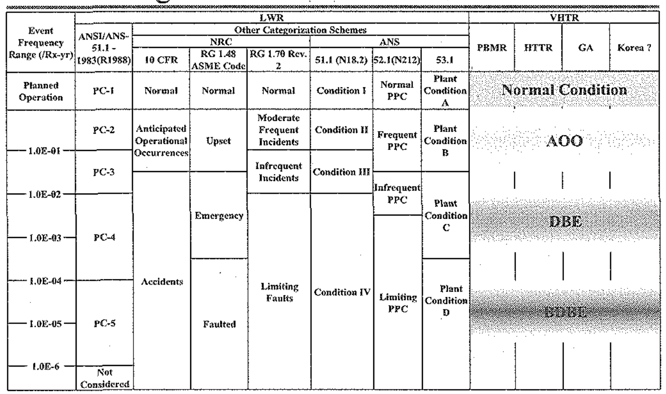
Event Categories

Fig.5



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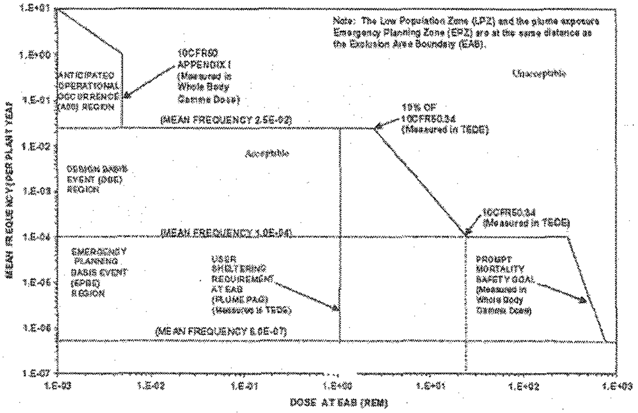
Ex) Risk Criteria Chart for GA VHTR

Fig.6



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Risk due to a Hydrogen Facility

- A different type of risk (Hydrogen vs. Radiation)
  - Rare experience of this type risk estimation
  - Coupled effects due to nuclear and hydrogen facilities
- Qualitative/quantitative identification of the risk from hydrogen
  - Search and review of historical data of hydrogen accidents
  - Identification of risk facts from hydrogen
  - Quantification of specific risk factors

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PSA Quality

- Inherent issue of PSA
  ←→ quality assurance (QA) or quality control (QC)
- PSA Quality:
  - Methodology (Procedure),
  - Modeling,
  - Level of detail,
  - Coverage scope etc
- Approach:
  - To develop a PSA model to meet essential features of PSA quality
  - To use iterative process

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4. Technical Issues in the VHTR PSA

- PSA framework
  - Methodology
  - Reliability & initiating event frequency data
  - Definition of ET accident sequence end state
  - Consequence analysis
  - External events (Fire, seismic, flood)
- Technical issues
  - Passive systems
    - Definition of passive system reliability
    - Quantification method
  - Digital systems
    - H/W and S/W reliability
  - Human reliability

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PSA Methodology

- Essential features of PSA are useful in VHTR PSA.
  - Event tree/fault tree approach
  - Minimal cutset generation
  - Dose rate and fatality estimation etc
- Several kinds of the terminology and technology for the LWR PSA are not applicable in the VHTR PSA.
  - Classification of assessment levels
    - Level 1 PSA (core damage estimation)
    - Level 2 PSA (radiation release estimation)
    - Level 3 PSA (fatality estimation)
  - Definition of sequential end states
    - Core damage state (CDF)
    - Containment state (LERF, LLRF)
- An adequate PSA procedure (methodology) should be developed for VHTR.

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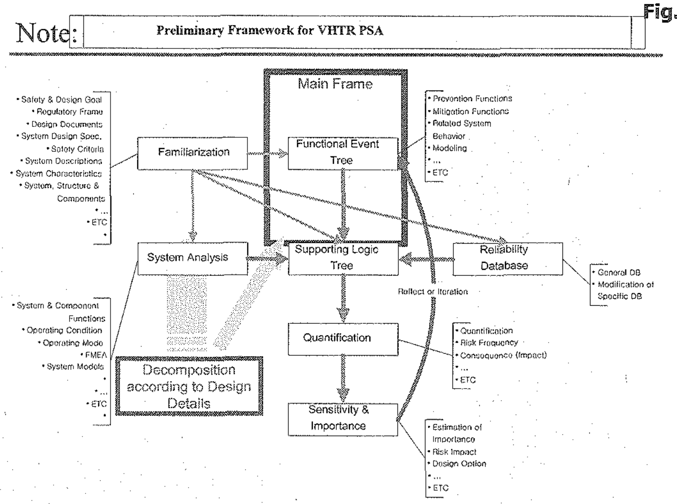
Note:

Fig.7



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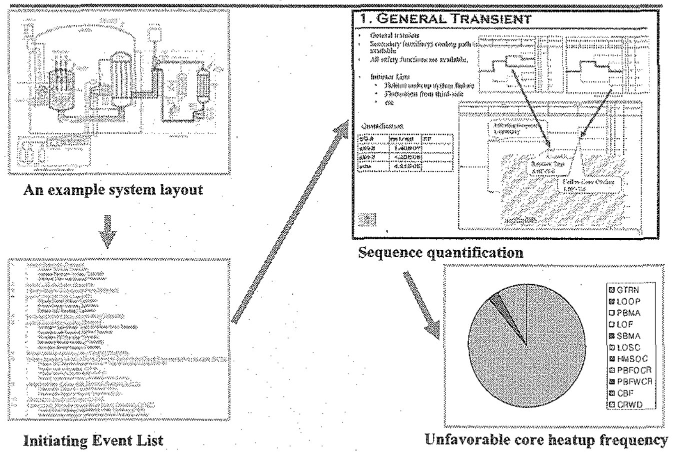
Note: An example study

Fig.8



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ET End State Definition

- Different characteristics of core damage state (PWR vs. VHTR)
  - No catastrophic core damage
- Preliminary approach:
  - To consider consequential impact
  - To use GA and PBMR PSA approach as a preliminary method
- Categorization by consequential states (GA):
  - Primary Pressure Boundary (PPB) Status
  - Core Cooling Status
  - Corrosion Attack Status
  - Reactor Shutdown Status
  - Confinement Status

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Reliability Data

- Gathering qualified data
  - No qualified reliability data because of rare experiences
- Typical procedure for reliability data (Fig.9)
  - Three different kinds of reliability data
- Reliability database system:
  - Classification
  - Data generation with Bayesian update & CCF
  - Comparison with other database
- Related databases
  - GA database (GCR reliability data bank status report, 1978)
    - Components Lists, CCF, Maintenance
  - German database (to be scheduled)

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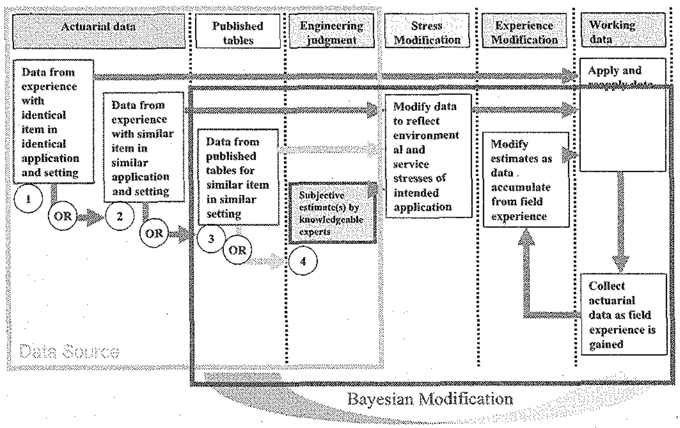
General Procedure for Reliability Database

Fig.9



From P.L. Clemens, JACOBS Severdrup

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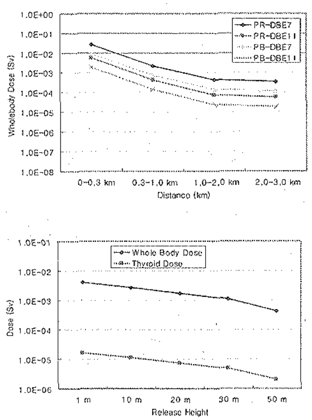
Consequence Analysis

- Essential and last step of VHTR PSA
  - The release of radioactive material
  - Their frequencies of occurrence
- The results of consequence analysis
  - Radiological consequences such as fatalities and injuries
  - Risk to the public
  - Can be used in demonstrating compliance with regulatory criteria
- Assessment and application area
  - Exposure doses as a function of distance to determine EAB
  - Sensitivity analysis for important source terms release parameters



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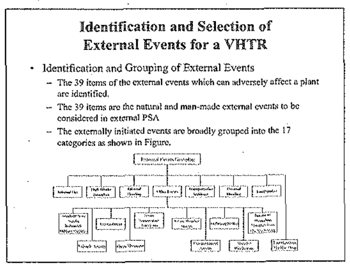
External Events

- An integrated treatment method of external events has being developed now.
  - Mapping table approach: internal PSA model * external event mapping table structure
  - This expended approach will be used in the VHTR PSA.
- Preliminary study:
  - Identification
  - Selection



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Technical issues

- Passive systems
  - Definition of passive system reliability
  - Quantification
- Digital system
  - Digital instrument and control system
  - S/W and H/W reliability estimation
- Human reliability
  - Operation procedure
    - Function based procedure
    - Symptom based procedure
  - Man-machine interface
  - Operators response under accident condition
    - Mission estimation
    - Stress level
    - Step in procedure
    - etc

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5. Future Plan

- Establishment of risk-informed paradigm for nuclear system safety
- Establishment of a detailed research plan under VHTR schedule.
- Main R&D areas:
  - VHTR PSA framework
  - Inherent technical issues for VHTR

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6. Concluding Remark

- PSA technology and tools are under development according to the master plan of VHTR development.
- Unresolved issues
  - Consensus for risk-informed applications
  - Reliability data
  - System behavior /description / etc
- International communication
  - Information exchange
  - Reliability database

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1.2.3 Hydrogen Production Costs of Various Primary Energy Sources

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Summary

The limited resource and environmental impacts of fossil fuels are becoming more and more serious problems in the world. Consequently, hydrogen is in the limelight as a future alternative energy due to its clean combustion and inexhaustibility and a transition from the traditional fossil fuel system to a hydrogen-based energy system is under considerations. Several countries are already gearing the industries to the hydrogen economy to cope with the limitations of the current fossil fuels.

Unfortunately, hydrogen has to be chemically separated from the hydrogen compounds in nature such as water by using some energy sources. In this study, the hydrogen production costs of major primary energy sources are compared in consideration of the Korean situations. The evaluation methodology is based on the report of the National Academy of Science (NAS) of U.S.

The results may be summarized as follows:

•The fossil fuels are susceptible to the price variation according to the oil price and the material price, and the hydrogen production cost also depends on the carbon tax.

•The hydrogen production cost from the renewal energy sources such as the wind, solar, and biomass are much more expensive(greater than 4~6 times) when compared with the hydrogen production from coal or natural gas. On the other hand, the production cost by nuclear energy is lower than that of natural gas when the oil price is over about $50/barrel. It means that nuclear energy has a high potential for the hydrogen production in the future.

1st JAEA/KAERI Information Exchange Meeting on VHTR System

Hydrogen Production Costs of Various Primary Energy Sources

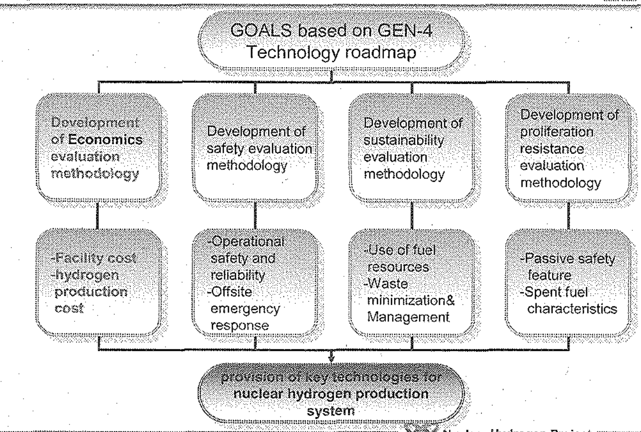
2006. 8. 28

Nuclear Hydrogen Project
KAERI

J. H. Choi, K. Y. Lee, J. H. Chang

Korea Atomic Energy Research Institute

Goals based on GEN-4 Technology Roadmap



Nuclear Hydrogen Project

Researches for Cost & Economics Estimation

1.G4-ECONS Version 1.0 (Economic Modeling working Group, May 2006)
2.The Hydrogen Economy (National Academy of Science, 2004)
3.Survey of the Economics of Hydrogen Technologies (National Renewable Energy Laboratory, Sep 1999)
4.Modular Gas-Cooled Reactor Economics (J. S. Thomas Oct. 1991)
5.Production of Hydrogen by Nuclear Energy (K.R. Schultz, 2003)
6.Nuclear Energy Options for Hydrogen and Hydrogen-Based Liquid Fuels Production (B.Yildiz et al, 2003)

1.Evaluation of Hydrogen Cost (Tetsuo NISHIHARA et al. JAERI-Tech 2005-038)
2.Cost Estimation of Hydrogen and DME Produced by Nuclear Utilization System II (Tetsuo NISHIHARA et al. JAERI-Tech 2004-057)
3.Cost Estimation of Hydrogen and DME Produced by Nuclear Utilization System (Tetsuo NISHIHARA et al. JAERI-Tech 2003-076)
4.Study on the Fuel Cycle Cost of Gas Turbine High Temperature Reactor(GTHTR300) (Masanobu TAKEI, Kazuhiko KUNITOMI et al. JAERI-Tech 2002-089
5.Study on Commercial HTGR Hydrogen Production System (Tetsuo NISHIHARA et al. JAERI-Tech 2000-046)

→ They did not use the values in consideration of the Korean situations

Nuclear Hydrogen Project

Current Status

Today's topic

➤ The Hydrogen Economy

- Report written by National Research Council and National Academy of Engineering of The National Academies
- Natural Gas, Coal, Nuclear, Grid-based Electrolysis, Biomass, Wind, Solar
→$/kg H2

→ Completion of evaluation

➤ G4-ECONS Version 1.0

- A Generic EXCEL-based Model for Computation of the Projected Levelized Unit of Electricity Cost (LUEC) from Generation 4 Reactor System
- PWR (Open, Partially closed), JSFR Open, PBMR Open
→ mills/kwh or $/MWh

→ On going

Nuclear Hydrogen Project

Assumptions Considered for Cost Estimation
- Based on the NAS Report-

Hydrogen Production Technologies considered in the NAS Report

- ✓Natural Gas – Steam Reforming
- ✓Coal – Coal Gasification
- ✓Nuclear – Thermal Splitting of Water
- ✓Biomass – Biomass Gasification
- ✓Electrolysis – Electrolysis of Water
- ✓Wind Energy – Wind-Turbine-Based Electrolysis
- ✓Solar Energy – Photovoltaic(PV) Solar-based Electrolysis

Nuclear Hydrogen Project

Assumptions for Cost Estimation

1. Future Optimism Option (2020 year)
2. Plant size for Hydrogen Production
   - Natural gas, Coal, Nuclear: Central station (1200ton/day H2, load factor 90%)
   - Biomass: Midsize(24 ton/day H2, load factor 90%)
   - Grid-based Electricity: Distributed size (480kg/day, load factor 90%)
   - Wind Power: Distributed size (1.2ton/day, load factor 20%(Japan), 28%(Youngdeok wind power plant)
   - PV Solar: Distributed size (2.4ton/day, load factor 20%(Japan))
3. Site Specific Factor (tax, labor cost, weather): 110% of U.S Gulf Coast cost
4. CO2 disposal cost: $ 10 /ton
5. Carbon Tax: $ 50 /ton

Nuclear Hydrogen Project

Future Optimism

- Meaning
  - the based on technological improvements that may be achieved if the appropriate R&D are successful.
- Fixed parameters of Current technology/ Future technology options
  - Material cost (cf. excluded Biomass)
  - Grid-Based Electricity (cf. power generation prices of wind energy and solar energy decrease greatly.)

cf. Capital costs decrease greatly due to the application of the developed technology

Nuclear Hydrogen Project

Input Parameters relative to Korea Situation (Material Cost)

- Material cost
  - Natural gas: 294.3 $ /ton (average cost in 2004)
    NAS: 226.8 $ /ton
  - Coal: 54 $ /ton (average cost in 2004 [1])
    NAS: 32.28 $ /ton
  - Nuclear: 4.61 $ /MWhr (Nuclear fuel cycle cost, JAERI[1])
    - Ore cost: 0.6 $ /MWhr
    - Conversion/Enrichment/fabrication: 3.13 $ /MWhr
    - Waste disposal: 0.88 $ /MWhr
    - NAS: 5 $/MWhr
  - Biomass: 35.58 $ /ton (NAS cost)

1)Takei, M. et al, Study on the Fuel Cycle Cost of Gas Turbine High Temperature Reactor, GTHTR-300, JAERI -Tech 2002-089

Nuclear Hydrogen Project

Input Parameters Considered for Korea Situation (Electricity)

- Grid-supplied Electricity
  - For industry: 60.23$/MWhr (2004.12.31 in Korea)
    NAS: 45$/MWhr
  - For Commercial: 96.85$/MWhr(2004.12.31in Korea)
    NAS: 70$/MWhr
- Wind Power Electricity
  - Electricity generated using wind turbine: 90$/MWhr (Cheju Haeng-won)
    NAS: 60$/MWhr(Current), 40$/MWhr(Future)
  - Technology Development Factor: apply to 40/60
    →applied generation cost: 60$/MWhr
- Electricity from ...: 98$/MWhr(NAS cost)

(callout) ... generated and an increase in the turbine's capacity factor

(callout) the wind-electrorysis-hydrogen system could be substantially optimized.

Nuclear Hydrogen Project

Hydrogen Production Costs
- Future Optimism-

Natural Gas

1.Capital costs

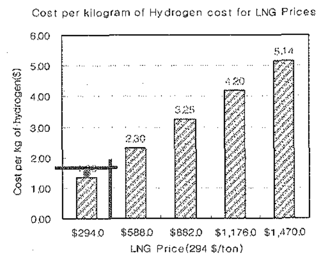
- Hydrogen 1200ton/day- Process units=263 M$
- General facilities(20%), Eng. Permiting&Startup(10%), Contignecy(7%), Working capital, Land&Misc(7%)

US Gulf Coast Capital Cost: 387 million $
Site Specific Factor 110%: 426 million $

2.Hydrogen production cost

- Variable costs
  - Non-fuel variable O&M: 426 M$*1%
  - LNG Cost: 294.3 $/ton(2004 yr)
  - Electricity(65,938kW): 60.23 Won/kWh
- Fixed operation cost : 426 M$*5%
- Capital Charge : 426 M$ *15.9%
- Carbon tax : 0.02$/kgH2(0.51Mton/yr)
- CO2 disposal : 0.08$/kgH2(3.1Mton/yr)

1.36 $ /kg H2



2005. 6. LNG Cost
= 425 $/ton[1]

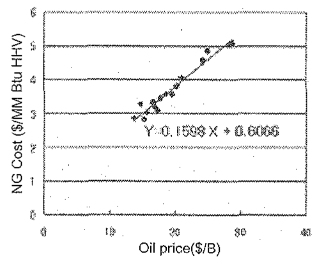
1.78$/kgH₂

1) Energy focus 2005.10

Nuclear Hydrogen Project

Cost of Natural gas with different Oil costs

Year	LNG($/Ton)	Oil($/B)
1990	209.95	20.95
1991	184.19	19.42
1992	184.53	18.55
1993	173.33	16.59
1994	155.87	15.55
1995	159.21	17.32
1996	196.66	20.11
1997	197.78	20.34
1998	146.79	13.72
1999	165.34	16.91
2000	259.64	28.22
2001	250.68	24.87
2002	235.33	24.24
2003	261.50	28.73
2004	294.30	36.15



SOURCE: SK Institute of Technology in Korea, 2005

Nuclear Hydrogen Project

Coal

1.Capital costs

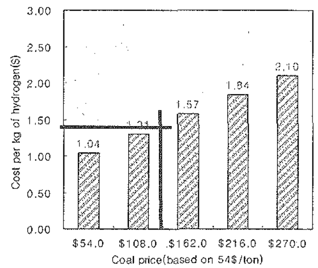
- Hydrogen 1200ton/day- Process units=515 M$
- General facilities(30%), Eng. Permiting&Startup(10%), Contignecy(10%), Working capital, Land&Misc(7%)

US Gulf Coast Capital Cost: 809 million $
Site Specific Factor 110%: 889 million $

2.Hydrogen production costs

- Variable costs
  - -Non-fuel variable O&M: 890 M$*1%
  - -Coal Cost: 54 $/ton(2004 yr)
  - -Electricity(88,098kW): 60.23 Won/kWh
- Fixed operation cost : 890 M$*5%
- Capital Charge : 890M$ *15.9%
- Carbon tax : 0.03$/kgH2(0.87 Mton/yr)
- CO2 disposal : 0.15$/kgH2(5.8 Mton/yr)

1.10 $/kg H2



2004. 8. soft coal price from Australia = 57 $/ton

2005. 7. soft coal price from Australia = 125 $/ton

1.43$/kgH2

Nuclear Hydrogen Project

Nuclear(1/2)

1.Capital costs

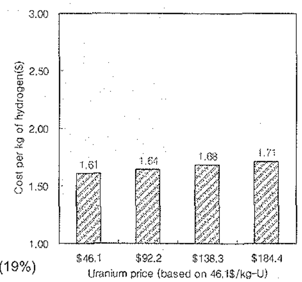
- Hydrogen 1200ton/day- Process units=1674 M$
- General facilities(10%), Eng. Permiting&Startup(10%), Contignecy(7%), Working capital, Land&Misc(7%)

US Gulf Coast Capital Cost: 2243 million $
Site Specific Factor 110%: 2467 million $

2.Hydrogen production costs

- Variable costs
  - -Non-fuel variable O&M: 2467 M$*1%
  - -Oxygen Byproduct : 10 $/ton
  - -Fuel cycle cost: 4.61 $/MWh
    uranium cost(13%),conv./enrich./fab.(68%),disposal(19%)
  - -Decommission: 2467 M$*1%
- Fixed operation cost : 2467 M$*5%
- Capital Charge : 2467M$ *15.9%

1.61 $ /kg H2

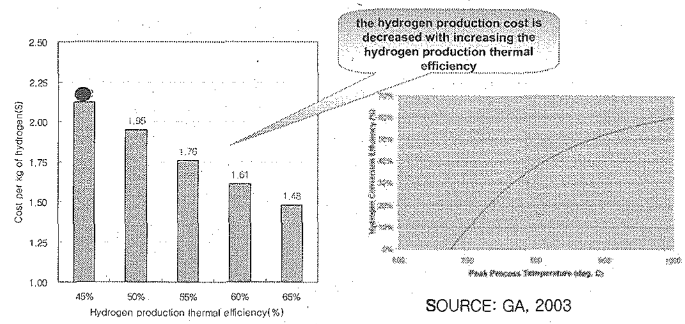


2006. 6. Uranium price = 112 $/kg-U[1)]

1) NCF No.35 2006.8

Nuclear Hydrogen Project

Nuclear(2/2)



SOURCE: GA, 2003

*****The most important thing to decrease the hydrogen production cost is to increase the hydrogen production thermal efficiency

Nuclear Hydrogen Project

Biomass

1.Capital costs
- Hydrogen 24ton/day- Process units=35.1 M$
- General facilities(30%),
  Eng. Permiting&Startup(10%), Contignecy(10%),
  Working capital, Land&Misc(7%)

US Gulf Coast Capital Cost: 55 million $
Site Specific Factor 110%: 60.5 million $

2.Hydrogen production cost
- Variable costs
  - -Non-fuel variable O&M: 60.5 M$*1%
  - -Biomass cost : 35.58 $/ton (NAS)
  - -Electricity(4,742kW): 60.23 Won/kWh
- Fixed operation cost : 60.5 M$*5%
- Capital Charge : 60.5 M$ *15.9%
- Carbon tax : -0.21$/kgH2(0.12 Mton/yr)
- CO2 disposal : 0.17$/kgH2(0.13 Mton/yr)

2.35 $ /kg H2

Land for CS(394,000ton/yr): 3129.5km²
(cf. Cheju city: 1848km²)

The CO2 taken from the atmosphere whole growing the biomass would greatly exceed the residual amount released back in to the atmosphere at the time of hydrogen production

Nuclear Hydrogen Project

Electrolysis

1.Capital costs
- Hydrogen 0.48ton/day- Process units=0.36 M$
- General facilities(20%),
  Eng. Permiting&Startup(10%), Contignecy(10%),
  Working capital, Land&Misc(5%)

US Gulf Coast Capital Cost: 0.52 million $
Site Specific Factor 110%: 0.57 million $

2.Hydrogen production costs
- Variable costs
  - -Non-fuel variable O&M: 0.57 M$*1%
  - -Electricity(946kW): 96.85 Won/kWh (commercial rate)
- Fixed operation cost : 0.57 M$*2%
- Capital Charge : 0.57 M$ *14%
- Carbon tax : 0.21$/kgH2(2,400ton/yr)

the reason is why hydrogen production cost is high is that electricity is high due to application of commercial rate.

5.41 $/kg H2

Nuclear Hydrogen Project

Wind Energy

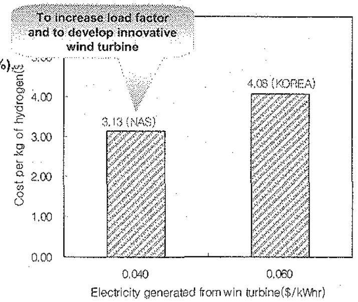
- Load factor: 20%, 28%(Youngdeok, Japan = 20%), cf:Cheju Haengwon load factor 26%~27%

1.Capital costs
- Hydrogen 1.2ton/day- Process units=0.56 M$
- General facilities(20%),
  Eng. Permiting&Startup(10%), Contignecy(10%),
  Working capital, Land&Misc(5%)

US Gulf Coast Capital Cost: 0.81 million $
Site Specific Factor 110%: 0.89 million $

2.Hydrogen production costs
- Variable costs
  - -Non-fuel variable O&M: 0.89 M$*1%
  - -Electricity(2,365kW): 90 Won/kWh (Haengwon)) *2/3= 60 won/kWh
- Fixed operation cost : 0.89 M$*2%
- Capital Charge : 0.89 M$ *14%

4.08 $/kg H2(load factor 28%),
4.57 $/kg H2(load factor 20%)



Land for CS(394,000ton/yr): 337km² (cf. Seoul: 605.5km²)

Nuclear Hydrogen Project

Solar Energy

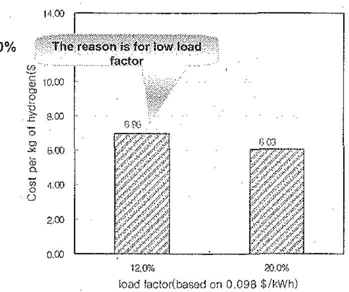
Load factor: 20%(Japan = 12%), Land for CS(394,000ton/yr): 64km²(=1,500 tokyo domes)

1.Capital costs
- Hydrogen 1.2ton/day- Process units=0.9 M$
- General facilities(20%),
  Eng. Permiting&Startup(10%), Contignecy(10%
  Working capital, Land&Misc(5%)

US Gulf Coast Capital Cost: 1.3 million $
Site Specific Factor 110%: 1.43 million $

2.Hydrogen production costs
- Variable costs
  - -Non-fuel variable O&M: 1.43 M$*1%
  - -Electricity(4,729kW): 98 Won/kWh (NAS)
- Fixed operation cost : 1.43 M$*2%
- Capital Charge : 1.43 M$ *14%

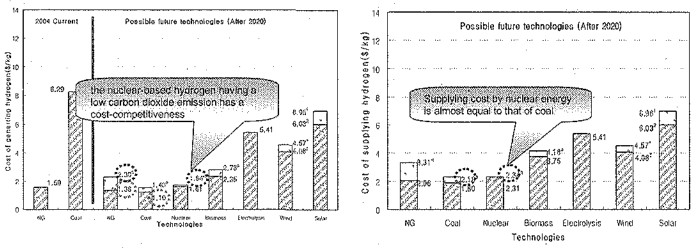
6.03 $ /kg H2



➢ Innovative technology for solar PV is required to raise the economics of solar energy.

Nuclear Hydrogen Project

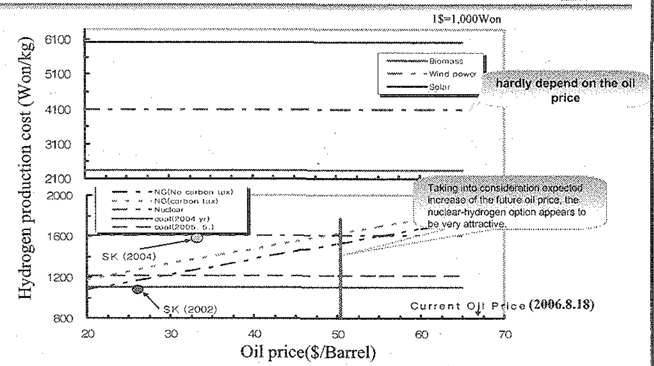
Costs of Generating/ supplying Hydrogen



1. a is the hydrogen production cost by increasing 100%
2. In the case of wind, * shows 20% load factor, + shows 28% load factor
3. In the case of solar, 1 shows 12% load factor, 2 shows 20% load factor

Nuclear Hydrogen Project

Costs of generating Hydrogen according to Variation of Oil Price



1. SK : Naphtha method (200Ton/d, carbon imputed cost: $50/ tonne C)
2. Coal price: $54/Ton(2004), $74/Ton(2005.5, based on CIF)
3. Carbon imputed cost for natural gas: $50/Ton
4. Current Oil Price: $ 67.66/bbl(Dubai, 2006.8.18)

Nuclear Hydrogen Project

G4-ECONS

➢ G4-ECONS Version 1.0

- A Generic EXCEL-based Model for Computation of the Projected Levelized Unit of Electricity Cost (LUEC) from Generation 4 Reactor System
- PWR (Open, Partially closed), JSFR Open, PBMR Open
  → mills/kwh or $/MWh

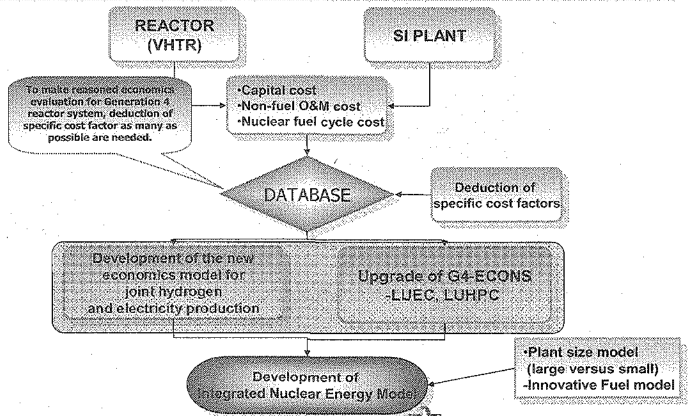
On going

1. Study on basic data used in G4-ECONS
   - user's manual, related reports, program mechanism, equation used in the program

2. Under Modification & estimation *to other* GEN4 reactor systems.

Nuclear Hydrogen Project

Proposal



Nuclear Hydrogen Project

1.2.4 Introduction of the HTTR

Yoshihiro KOMORI

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Summary

To enhance nuclear energy application to heat process industries, the Japan Atomic Energy Agency (JAEA) constructed a high-temperature gas-cooled reactor named High-Temperature Engineering Test Reactor (HTTR) at the Oarai Research and Development Center of JAEA. Using the HTTR, reactor performance and safety demonstration tests have been conducted as planned.

The HTTR is a graphite-moderated and helium gas-cooled reactor with 30 MW of thermal power, which is the first HTGR in Japan. The reactor core is composed of graphite prismatic blocks. Fuels are inserted in the blocks as a shape of cylindrical graphite compacts in which tri-isotropic (TRISO)-coated fuel particles with UO_2 kernel are dispersed. Helium gas of the HTTR coolant is circulated at a pressure of 4 MPa, and via an intermediate heat exchanger, high temperature heat can be transferred to the hydrogen production process.

The first criticality of the HTTR was achieved in 1998, and the full power operation of 30 MW was attained in 2001 with a reactor outlet temperature of 850°C. Safety demonstration tests have been conducted since 2002. The high-temperature operation of 950°C was successfully done in April 2004.

In the presentation, the structure, major specification and the history of the HTTR are briefly introduced.

Introduction of HTTR

- Recent Activities -

August 28, 2006

Yoshihiro KOMORI

Department of HTTR
Oarai Research and Development Center
Japan Atomic Energy Agency

Establishment of technology basis for HTGR

To pursue the feasibility of commercialization

Midterm Goal by MEXT : (Ministry of Education, sports culture and science////

R&D on HTGR and hydrogen production Technology

To diversify nuclear energy utilization

- ◆ Establish technology basis for HTGR that can be high temperature heat source and power generation method with excellent economic efficiency and
- ◆ Establish technology basis on hydrogen production by HTGR

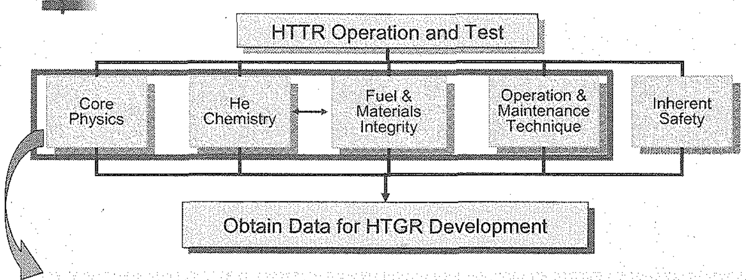
Midterm Plan of JAEA (October 1, 2005 to March 31, 2010)

R&D on HTGR and Hydrogen Production Technology

To establish technology basis on HTGR : (Related to HTTR operations and tests)

- ・Obtain data to on core burn-up properties, He impurity behavior, Integrity of High-temp. or in-pile Components by **950℃/50days HTTR Operation**
- ・Demonstrate excellent inherent safety of HTGR by **HTTR safety demonstration test**

HTTR Long High-temp. (50days/950℃) Operation



- ・Core Physics : Excess reactivity and other core physics parameters changes by fuel burn-up
- ・He Chemistry : Impurities behavior at high temperature under radiation environment; Performance of primary He purification system
- ・Fuel and materials Integrity : FP release, High temp. component (IHX), In-core components (Gr core support and reflectors)
- ・Operation and maintenance technique : Control of primary coolant (Leak, purification,--)

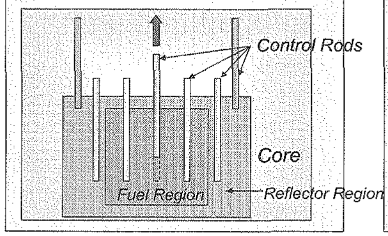
HTTR Safety Demonstration Test

(since 2002 ~)

*To **demonstrate inherent safety** characteristics of HTGR and obtain data for **validation of safety analysis code***

Reactivity Insertion Test

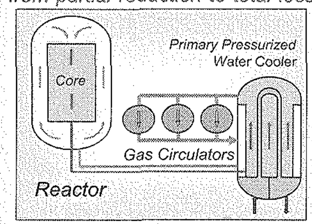
Increase of reactivity by withdrawal of the central pair of control rods



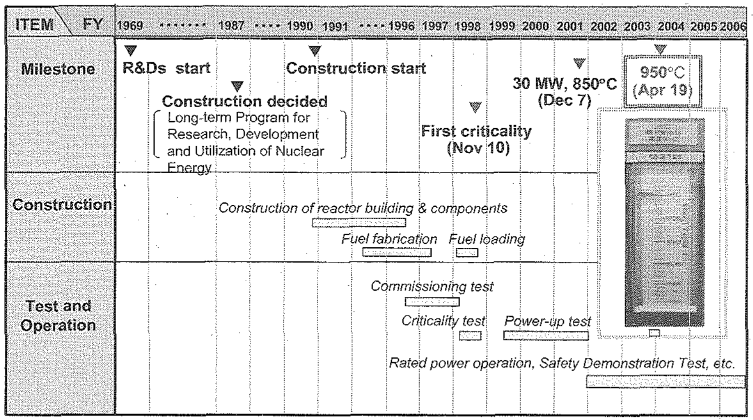
Coolant Flow Reduction Test

Reduction of primary coolant flow rate

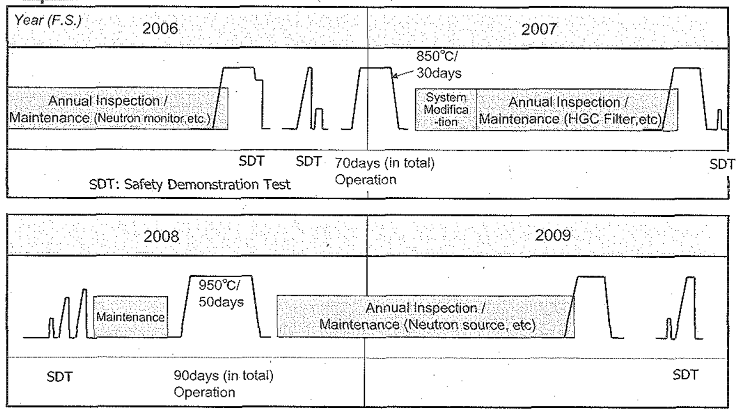
from partial reduction to total loss



Construction, Test and Operation of the HTTR

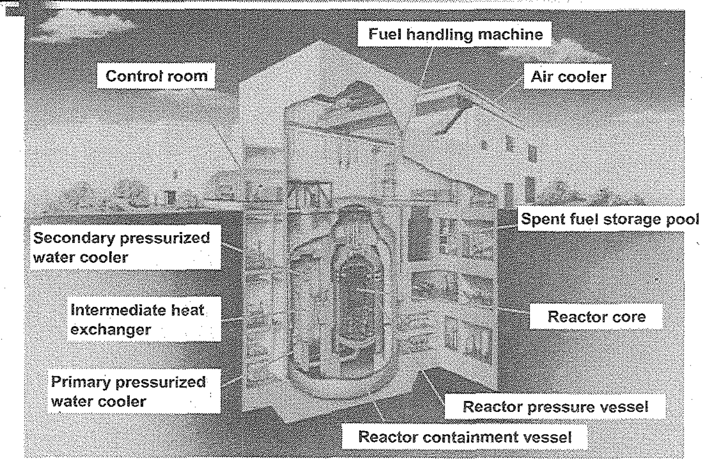


HTTR Operation Schedule (Tentative)



To obtain and accumulate data of operation and maintenance for HTGR

Bird's-eye View of HTTR Reactor Building



Major Specification of HTTR

Thermal power	30MW
Average power density	2.5MW/m^3
Outlet coolant temperature	850°C/950°C
Inlet coolant temperature	395°C
Primary coolant pressure	4MPa
Direction of coolant flow (core)	Downward
Moderator / Reflector	Graphite
Core height	2.9m
Core diameter	2.3m
Fuel	Low enriched UO_2
Uranium enrichment	3 ~ 10% (Ave. 6%)
Fuel element type	Prismatic block
Pressure vessel	2 1/4Cr-1Mo steel 13m(H) × 6m(ID)
Containment vessel	Steel containment 30m(H) × 18.5m(ID)

1.3 Session 3 VHTR design codes and analytical works

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1.3.1 Overview of VHTR Design Code System and Future Test Plan Using HTTR

Tetsuaki TAKEDA and Yukio TACHIBANA

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Summary

High temperature gas-cooled reactor (HTGR) has currently strong interests of development worldwide. Besides its broad economical appeals resulting from unique high temperature capability, the reactor provides inherent and passive safety and aims at enhanced safety goal. JAEA has successfully built and operated the 30 MWt High Temperature Engineering Test Reactor (HTTR). JAEA is now performing development and validation of the analytical codes for the design and safety assessment aiming at the development of HTGR that has a high inherent safety and economy. These analytical codes will be verified by using the experimental data of the HTTR and of the out-of-pile test facilities. As for the experiment, we have been performing the HTTR safety demonstration test that is a reactivity insertion (control rod withdrawal) test, a coolant flow reduction test, and a loss of forced cooling (gas circulators trip) test.

Enhancement of evaluation method for characteristics of a Very High Temperature Reactor (VHTR) has been studied to establish the VHTR technology in JAEA. In particular, a safety demonstration tests have been carried out to demonstrate inherent safety features of the VHTR using a High Temperature Engineering Test Reactor (HTTR) with which simulated abnormal status. In addition to that, safety analysis tools have been validated using the HTTR data. Appropriate safety margin can be assumed in the VHTR design by the safety analysis tools whose validation was carried out using the actual reactor data. These tools allow the design of the VHTR which is the one of the Generation-IV reactor type with high cost performance and high safety feature.

Following issues have been carried out to contribute the future's VHTR design; (1) Development of a nuclear-thermal hydraulics coupling code, (2) Development of the evaluation code for an amount of fission products and of impurities in order to prevent installing excess equipments for removing impurities or protecting tritium permeation, (3) Development of the safety analysis tools in order to eliminate constructing the containment vessel or develop of the inherent cooling system of the reactor vessel, and (4) Establishment of the evaluation method for high temperature equipments and for strength and life time of the structures.

A characteristic of reactor caused by neutron behavior is called nuclear characteristics which are a temperature coefficient, a power distribution, and so on.

The nuclear characteristics must be evaluated with high accuracy by nuclear calculations before a reactor design is carried out. JAEA has plan that different two calculation codes are used for the nuclear calculations in accordance with purpose. One is a diffusion code based on a diffusion theory and another is a Monte Carlo code based on a transport theory. These codes have been modified and the validated using the HTTR experimental data.

The numerical analysis code was developed to analyze the reactor dynamics including the flow behavior in the HTTR core. We used a conventional method, which uses a one-dimensional flow channel model and a reactor kinetics model with a single temperature coefficient taking into account the temperature variation of the core. However, it was found that there is a slight difference between the analytical results and the experimental ones; therefore, we have modified this code to use a model with four parallel flow channels and twenty temperature coefficients in the core.

The safety demonstration test consists of the control rod withdrawal test, the test of partial loss of primary coolant flow, the test of complete loss of primary coolant flow and the test of function loss of the vessel cooling system. As for the control rod withdrawal test by withdrawing the central control rod to insert the reactivity, the tests of initial reactor power of 15MW and 18MW have been performed. The test in the initial reactor power of 24MW will be performed at the end of 2006. As for the test of partial loss of primary coolant flow by tripping one or two gas circulators out of three gas circulators circulating the primary coolant and reducing the revolution of gas circulator, the tests of initial reactor power of 9MW and 18MW have been performed. The test in the initial reactor power of 24MW will be performed at the end of 2006 and the test of 30MW will be performed in the beginning of 2007. The test of partial loss of primary coolant flow by tripping one or two gas circulators out of three gas circulators is performed as the ATWS simulation test. As for the test of complete loss of primary coolant flow and the test of function loss of the vessel cooling system, the licensing by the government is in progress and the details of the test are under planning. The test of complete loss of primary coolant flow is also performed as the ATWS simulation test. The data obtained in the safety demonstration test are used to the code validation and the study to improve the simulation accuracy is in progress. As for another test using the HTTR in the future, the continuous high temperature operation for about 50 days and the performance test to study the operation of the heat utilization system are under planning. In the continuous high temperature operation, the capability of the steady and long-term reactor operation will be confirmed, and the data necessary to develop the commercial HTGR concerning the core burn-up performance, the purity control of primary coolant, performance of high temperature components, etc. will be accumulated.

#4-1

Overview of VHTR Design Code System and Future Test Plan using HTTR

Presented by Tetsuaki TAKEDA and Yukio TACHIBANA

HTGR Performance & Safety Demonstration Group
Nuclear Science and Engineering Directorate
Japan Atomic Energy Agency

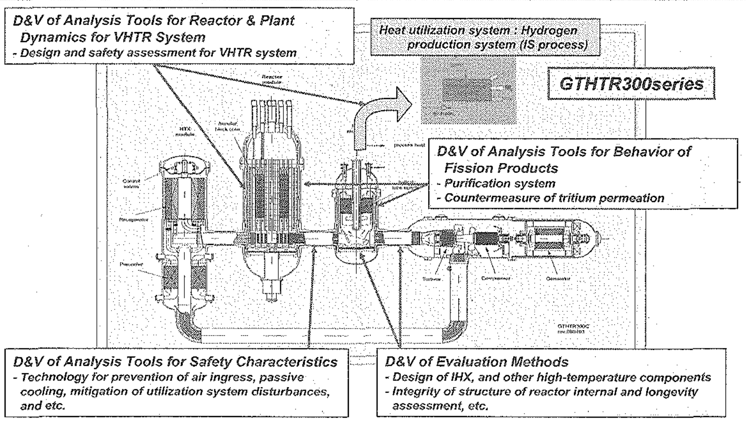
1st JAEA/KAERI Information Exchange Meeting on HTGR & Nuclear Hydrogen Technology
Oarai Research & Development Center, August 28 - 30, 2006

Contents

- Overview of design methods development and validation
  - Current status of analysis tools development and validation
  - Example of results by these analysis tools
  - Activity of the CFD analysis for the VHTR system
- Concluding remarks

1

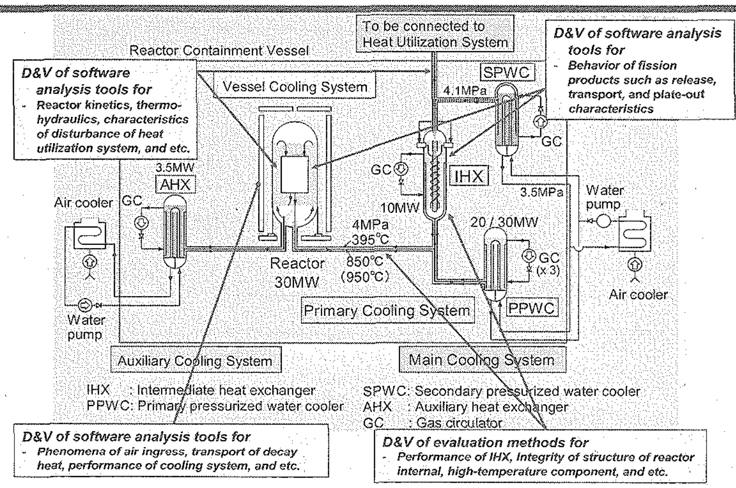
Design methods development and validation



Goal : Development and validation of analysis tools for design and safety assessment of commercial VHTR as one of Generation-IV reactor system.

2

Analysis tools validation by HTTR tests



3

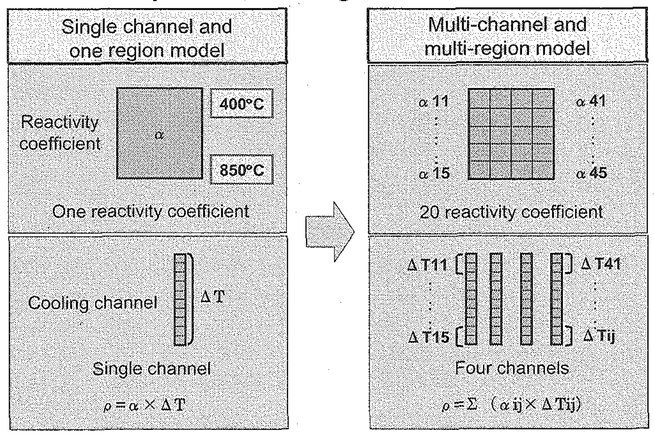
Analysis tools to be developed and validated

- Reactor and plant dynamics
  - Development of analytical model simulating co-generation system during off-normal and normal transients
  - D&V of plant dynamics code coupled with computational fluid dynamics (CFD) code
- Static analysis for evaluations of criticality and power distribution
  - D&V of diffusion-theory and Monte Carlo codes
- Fuel behavior and fission product release
  - Development of analytical model simulating fuel oxidation during depressurization accident and fission product releases from high burn-up fuel
- Fission product transport
  - D&V of analysis tools of fission product plate-out on the surface of primary components
  - D&V of analysis tools of tritium and hydrogen permeation in co-generation system
- Safety characteristics
  - D&V of analysis tools of decay heat removal, air ingress phenomena, and graphite oxidation during depressurization accident

4

Reactor and plant dynamics (1)

Adoption of multi-region core model



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Static analysis for evaluations of criticality (1)

Development of diffusion-theory and Monte Carlo codes and validation of its by HTTR test data

- Analysis tools
  - Modify diffusion-theory code, SRAC, and compare with Monte Carlo codes, MVP and MVP-BURN.
  - In addition to that, these analytical results compare with HTTR data
    - Results by modified SRAC are in good agreement with that by MVP
- Nuclear data
  - Validate JENDL, ENDF, and JEFF by HTTR data
    - Value of keff by JENDL-3.3 is in good agreement with HTTR criticality data

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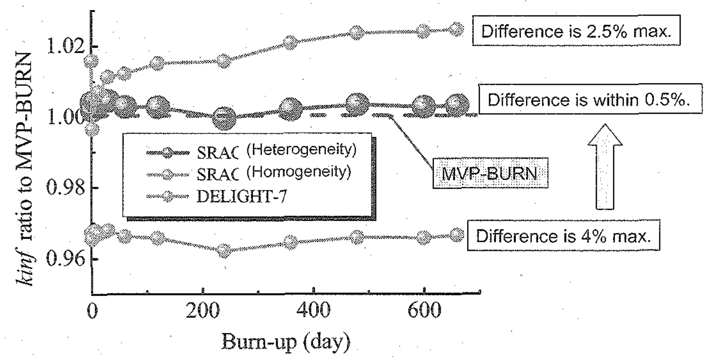
Static analysis for evaluations of criticality (2)

Improvement of diffusion-theory code, SRAC

- Improved treatment of double heterogeneity



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Fuel behavior and safety characteristics

Development or modification and validation of fuel behavior code

- Air ingress during the depressurization accident
  - Air ingress by diffusion and natural circulation was considered.
  - Validation of the model was carried out by comparison between experimental results obtained using an air ingress simulation apparatus and analytical results.
- Oxidation behavior of coated fuel particles
  - Composition of SiO_2 film on the surface of the coated fuel particles.
  - Validation of this oxidation behavior is necessary.

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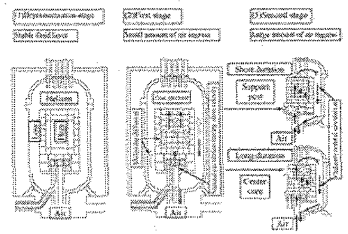
Safety characteristics (1)

- When the primary-pipe rupture accident occurs, the high-pressure helium gas coolant in the reactor is forced out into the reactor container through the breach.
- Gas pressure should become balanced between the inside and outside of the reactor vessel after a few minutes.
- Air ingress phenomena in HTGR is known to follow two sequential phases, starting with molecular diffusion and very weak natural circulation of gas mixture and, natural circulation of air develop suddenly as once sufficient buoyancy is established.
- Therefore, it is very important to make sure that the air ingress accident cannot seriously oxidize the graphite fuel elements to release the radioactive materials from the reactor core to the environment nor severely damage the graphite components to loose the integrity of the reactor internals.



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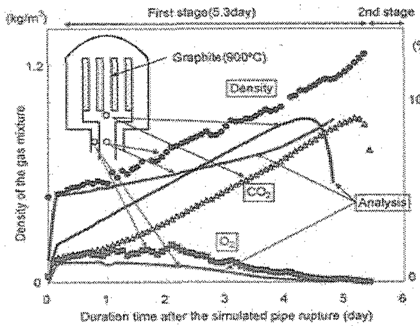
Safety characteristics (2)

Air ingress in experimental apparatus



Duration time of the first stage is shortened by the localized natural convection

The production of the gas by the graphite oxidation doesn't influence duration time of the first stage.

An analytical result was verified by the experiment.

The analysis of the concentration of each component gas for a long time can be possible.

It succeeded in the analysis of duration time of the first stage

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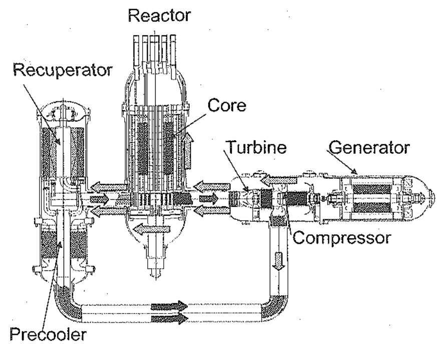
Safety characteristics (3)

Major design specifications of GTHTR300

Reactor power	600 MWt
Reactor outlet temp.	850ºC
Reactor inlet temp.	587ºC
Turbine input pressure	~7.0 MPa
Turbine mass flowrate	439 kg/s
Fuel type	Prismatic Average fuel
enrichment	14 wt%
Average power density	5.8 MW/m³
RPV inner diameter	7.6 m
Net plant efficiency	45.8%
Economy	
Capital	1800US$/KWe
Electricity	3.8US cents/kWh



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Safety characteristics (4)

Analytical condition

- *Assumed to be guillotine double pipe rupture between the reactor and the turbine vessel.*
- *The location of the break point is assumed to 0.7m from the RPV.*
- *The temperature change with time and location was given by another analytical results of the reactor core temperature in the depressurized accident condition.*
- *This is defined as the analytical condition A.*
- *The analytical condition B is the case of setting a helium canister in the top space of the recuperator.*
- *The means that if we adopt the canister, helium gas will be released after the accident automatically and continuously.*
- *We assumed that the volume of the canister is about 6 times of the top space in this preliminary evaluation.*

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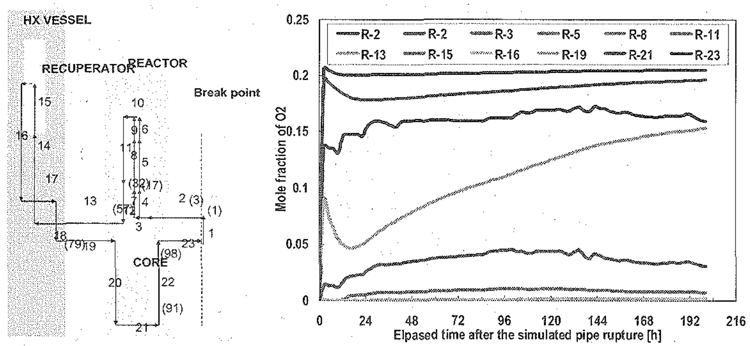
Safety characteristics (5)

Time variation of the mole fraction of Oxygen (Analytical condition B)



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Safety characteristics (6)

Air ingress analysis in GTHTR300

- *Just after the pipe rupture, air will flow into the lower plenum located below the break point.*
- *Helium gas exist in the upper side from the break point in the reactor and recuperator, and air exist in the lower side from the break point.*
- *Because a stable stratified layer will be established, the buoyancy by density difference of helium will be not enough force to generate natural circulation and to enter air into the reactor.*
- *In the first stage of the accident, the molecular diffusion and the natural circulation of the gas mixture having the very slow velocity limit the air ingress.*
- *In the second stage of the accident, the ordinary natural circulation of air throughout the reactor limits the air ingress.*
- *The duration time of the air ingress by molecular diffusion would increase due to the existence of the recuperator in the GTHTR300.*
- *In the passive safe technology developing, if the canister filled with helium can be equipped at the top space of the recuperator and continuously released a small amount of helium to the reactor, it is possible to prevent air ingress.*

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Activity of the CFD analysis for the VHTR system

- *It is necessary to predict the temperature of the RPV and concrete for the HTTR safety demonstration test*
- *Numerical model is 1/6 region of the HTTR core.*
- *HTTR core, inner structure of the RPV, VCS, and the concrete vessel has been modeled in this analysis.*
- *STAR-CD and FLUENT will be used as the CFD analysis code for this problem.*
- *It will be necessary to develop a thermal radiation model for the RPV and reactor containment.*

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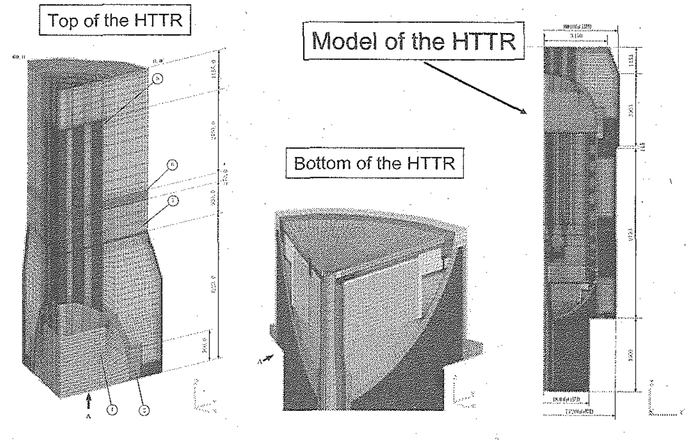
Mesh status of HTTR model (1)



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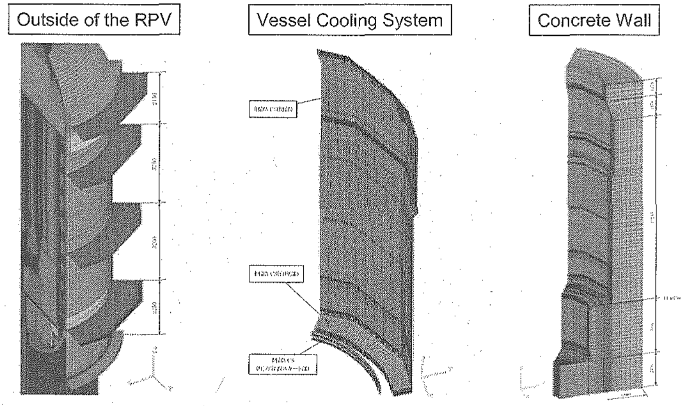
Mesh status of HTTR model (2)



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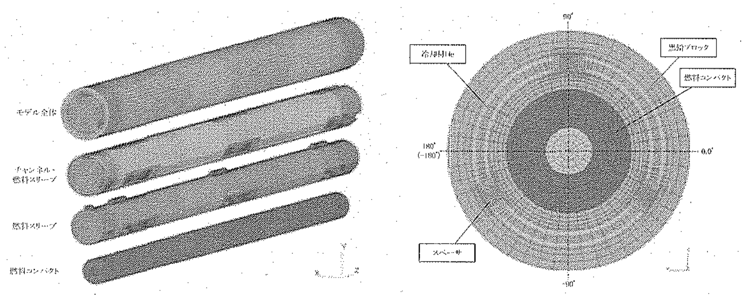
Fuel channel of the HTTR core

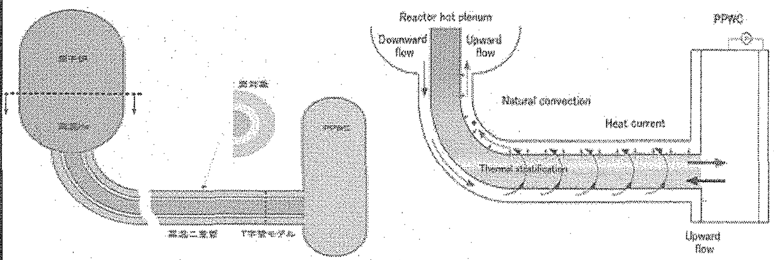
- We are performing the comparison between the numerical results of the CFD code and results of DNS.
- We are also compared these numerical results with the experimental data of the out-of-pile and HTTR tests.



21

Example of the structural integrity of the double coaxial pipe

- To analyze the thermal stress of the double coaxial pipe between the RPV and PWC



- To obtain the temperature distribution in the transient condition

→ We predict the temperature varies by natural convection with loss of forced cooling accident

We can improve the system design from the economical point of view.

22

Concluding remarks

- *Future plan*
  - *Develop and modify analysis tools for design and safety assessment of the VHTR system in consideration with VHTR roadmap.*
  - *Validate and improve the analysis tools by the HTTR test data.*
  - *We are planning to perform not only safety demonstration tests but also rated power operation of 950 °C using the HTTR aiming to verify the inherent safety features and to improve the safety evaluation technologies of VHTR.*
- *International collaboration*
  - *JAEA are willing to perform the multilateral collaborative study under the GIF framework.*
  - *JAEA are also willing to join the coordinated research project under the IAEA.*
  - *We are now discussing the possibility of performing the bilateral collaboration study such as US/Japan (I-NERI, DOE/JAEA), France/Japan (CEA/JAEA), Korea/Japan (KAERI/JAEA), and etc.*
  - *JAEA will provide the HTTR data to develop and validate analysis tools for VHTR system development.*
  - *JAEA are willing to accept your proposal of new HTTR tests not only under the GIF framework but also the bilateral framework.*

24

#4-2

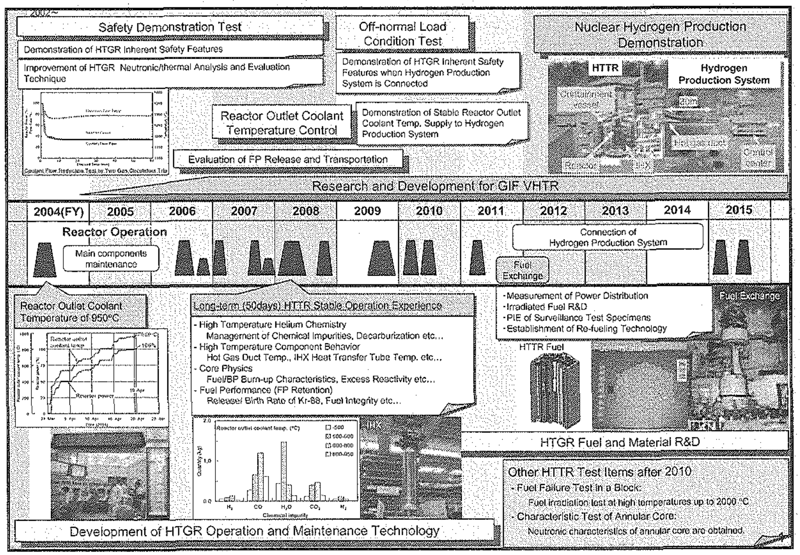
1st JAEA/KAERI Information Exchange Meeting on HTGR and Nuclear Hydrogen Technology, August 28 - 30, 2006

Overview of VHTR Design Code System and **Future Test Plan using HTTR**

August 29, 2006

Tetsuaki Takeda and **Yukio Tachibana**

Japan Atomic Energy Agency



Near-term plan of HTTR operation and tests

FY2006: Reactivity insertion tests (control rod withdrawal tests) and coolant flow reduction tests at high power level

FY2007: Long-term rated (850°C) operation (30 days)
Loss of forced cooling test at low power level

FY2008: Long-term high temperature (950°C) test operation (50 days)
Loss of forced cooling test at high power level
Vessel cooling system stop test (1 out of 2)

FY2009: Loss of forced cooling test at full power
Vessel cooling system stop test (2 out of 2)

(Note: Japanese FY2006 starts in April 2006 and ends in March 2007.)

2

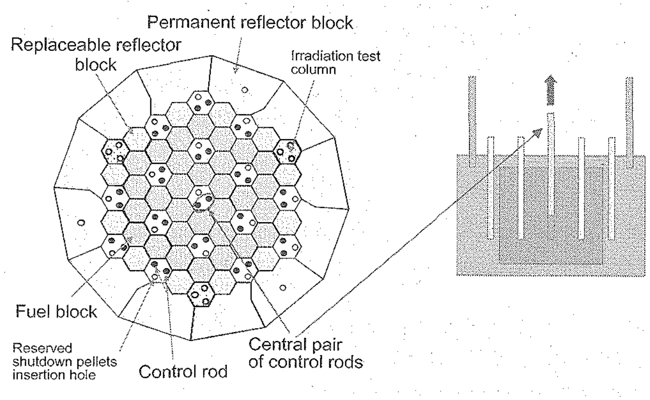
Reactivity insertion test
- Control rod withdrawal test -

Test conditions

Reactor power	30% - 80%
(30%, 50% and 60% tests has been conducted)	
Control rods to be withdrawn	Central pair (16 pairs (total))
Withdrawal speed	1 and 5 mm/s
Withdrawal distance	10mm - 40mm
Reactor power control system	Disabled
Reactor outlet coolant temperature	
Initial	Below 850℃
During Test	Below 950℃

3

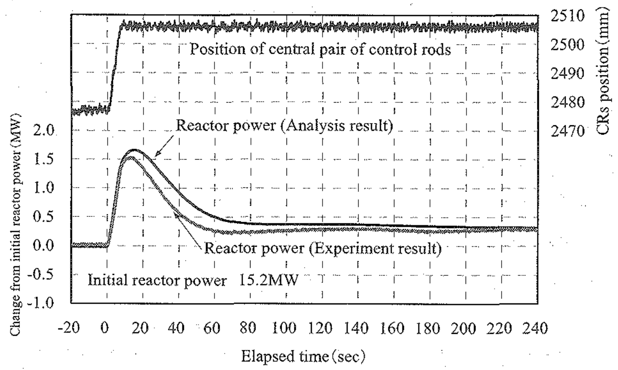
Control rod withdrawal test



Arrangement of control rods

4

Control rod withdrawal test



S. Nakagawa et al., Nuclear Engineering and Design 233 (2004) 301–308.

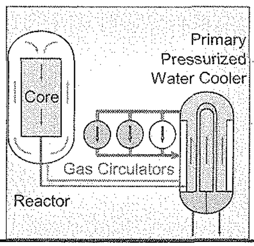
5

Coolant flow reduction test

- Trip of one and two out of three gas circulators -

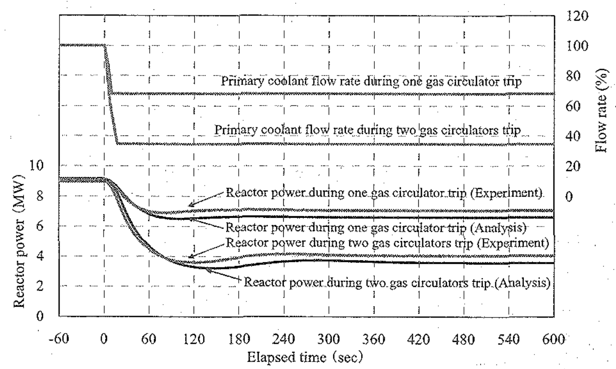
Test conditions

Reactor power	30% - 100%
(30% and 60% tests has been conducted)	
Gas circulators to be stopped	1 or 2 (out of 3)
Reactor power control system	Disabled
Reactor outlet coolant temperature	
Initial	Below 850°C
During Test	Below 950°C
Scram set point of flow rate	
	93% → 27%



6

Trip of one and two out of three gas circulators



S. Nakagawa et al., Nuclear Engineering and Design 233 (2004) 301–308.

7

Loss of forced cooling test
- Trip of all the three gas circulators -

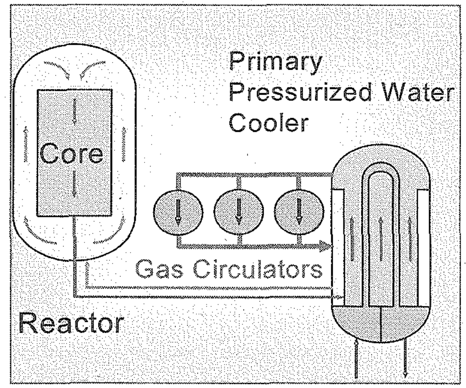
Test conditions

Reactor power	30% - 100%
Gas Circulators to be Stopped	3 (All the GCs)
Reactor power control system	Disabled
Reactor Outlet Coolant Temperature	
Initial	Below 850℃
During Test	Below 950℃

Reactor scram due to decrease of primary coolant flow rate
Bypassed during test

8

Trip of all the three gas circulators



9

Vessel cooling system stop test

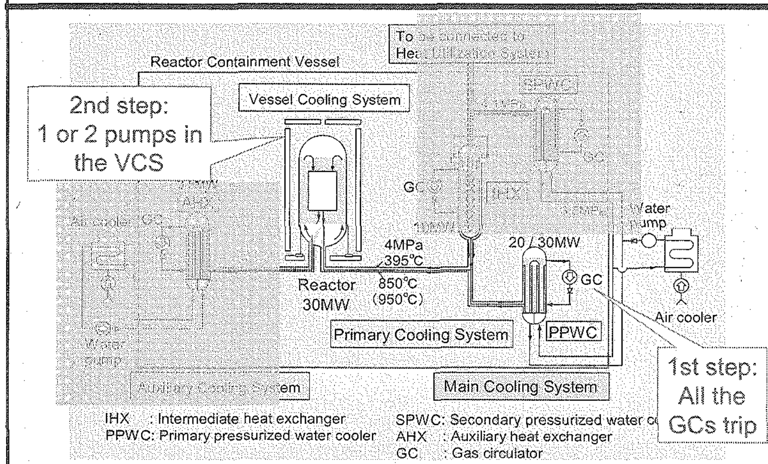
Test conditions

Reactor power	30%
Gas circulators to be stopped	3 (All the GCs)
VCS pumps to be Stopped	1 or 2
(VCS as an engineered safety feature has two pumps)	
Reactor power control system	Disabled
Reactor outlet coolant temperature	
Initial	about 320℃

Reactor scram due to decrease of primary coolant flow rate
Bypassed during test

10

Vessel cooling system stop test



11

1.3.2 Development of Nuclear Design Code System for the Analysis of VHTR Cores

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Summary

There are many challenges in VHTR core analysis such as double heterogeneity of fuel, a strong core/reflector spectral interaction, a spectral interference between the fuel blocks or the spectral zones. Double heterogeneity of fuel can cause 3~4% error in k_{eff} if it is ignored. The spectrum in a fuel block or in a spectral zone is strongly influenced by the reflector as well as the neighboring fuel block or spectral zone.

We developed a two-step procedure to resolve these problems. In the first step, two-dimensional (2-D) transport lattice calculation is performed and few-group equivalent cross-sections are generated. The double heterogeneity of fuel was removed by transforming doubly heterogeneous fuel elements into equivalent singly heterogeneous fuel elements with Reactivity-equivalent Physical Transformation (RPT) method. Spherical pebbles are transformed into equivalent cylindrical fuels by using Equivalent Cylindrical fuel Model (ECM) for pebble type VHTR core analysis. A simple spectral geometry was introduced to capture the core/reflector spectral interaction and the equivalent cross-sections are generated with the help of Equivalence Theory (ET). The number of neutron energy groups and the group boundary was optimized for environment-independent few-group cross-sections. In the second step, three-dimensional (3-D) diffusion calculation is performed with the equivalent corss-sections generated in the first step for core physics analysis and simulation.

Based on the two-step procedure, we are developing KAERI own VHTR core analysis code system for both prism type and pebble bed type VHTR. Currently, we are using HELIOS code for the 2-D lattice calculation in the first step but we are developing a new 2-D lattice physics code LIBERTE. We adopted MASTER code as the 3-D diffusion core simulation for prism type VHTR. We are also developing a new 3-D diffusion core simulation code for pebble bed type VHTR. We verified our code system against many benchmark problems with full heterogeneities of fuel elements such as prism type NGNP problem, prism type GT-MHR problem, pebble box problem, and PBMR-400 problem. The two-step solutions of our code system were compared with Monte Carlo solutions. Comparison showed an excellent agreement between the two solutions.

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Development of Nuclear Design Code System for the Analysis of VHTR Cores

Presented at 1st JAEA/KAERI Information Exchanging Meeting on HTGR and Nuclear Hydrogen Technology
August 28-30, 2006

Hyun Chul Lee
Korea Atomic Energy Research Institute

KAERI

Introduction

- **Objective**
  - Develop KAERI own VHTR Core Analysis Code System (Prism Type & Pebble Bed Type)
- **Challenges in VHTR Core Analysis**
  - Fuel double heterogeneity
    - 3~4 % error in k_{eff} if ignored
  - Strong core/reflector spectral interaction
  - No asymptotic spectrum
    - Long diffusion length
    - Environment dependent spectrum

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Methodologies and Procedures

- **Methodologies**
  - Reactivity-equivalent Physical Transformation (RPT)
    - Treats fuel double heterogeneity
    - Transforms heterogeneous fuel zone into homogeneous fuel zone
    - Enables to use conventional transport lattice codes
  - Equivalent Cylindrical Fuel Model (ECM) for Pebble Type Fuel
    - Transforms spherical pebble fuels into cylindrical fuels
    - Enables to use conventional 2-D lattice code for pebble core analysis
  - Spectral Geometry and Equivalence Theory
    - Captures the strong core/reflector interaction
    - An infinite slab or mini core spectral geometries are used to generate equivalent cross-sections
  - Energy Group Structure Optimization
    - Multi-group (6-10 Groups)

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Methodologies and Procedures

- **Procedures**
  - 2-Step Procedure
    - Well proven for the LWR core analysis
    - Step 1 : 2-D Transport lattice spectrum calculation
      - *Simple spectral geometry*
      - *Generate Equivalent cross-sections with the help of equivalence theory*
    - Step 2 : 3-D Diffusion core calculation
      - *3-D diffusion calculation with the cross sections generated in the 1st step*
    - Cf. VSOP adopted an iteration between local spectrum calculation and the global core calculation .
- **Code Systems for VHTR Core Analysis**
  - 2-D Transport Lattice Codes
    - HELIOS Code
    - Developing a lattice code : LIBERTE
  - 3-D Diffusion Core Simulation Codes
    - MASTER-GCR for prism type VHTR
    - Developing a new code for pebble-bed type VHTR

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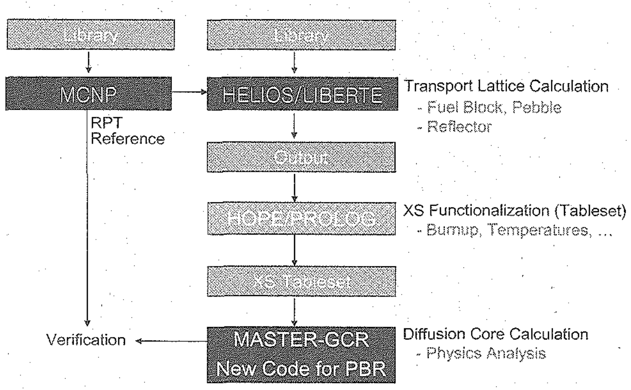
Code Systems for VHTR Core Analysis



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Verifications

- **Prism Type VHTR**
  - GT-MHR Core
  - NGNP Core
- **Pebble Bed Type VHTR**
  - Pebble Box Problem
  - PBMR-400 Core
- **MC results with doubly heterogeneous model was taken as the reference solution**

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Methodologies

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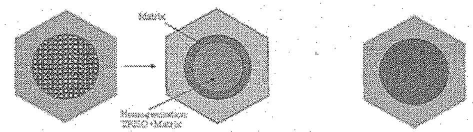
Reactivity-Eq. Physical Transformation

- **Heterogeneous fuel zone → Homogeneous fuel zone**
  - Enables to use conventional transport lattice codes



RPT

Volume Weighted Homogenization

Method	Four factors and % Error				k_{inf} (pcm)
	η	f	p	ε	
Reference (r_f=0.62cm)	2.07779	0.99218	0.70450	1.00075	1.45344
VWH	0.38	0.0	-5.55	-0.01	-3766
RPT (r_{rpt}=0.38cm)	0.00	0.00	0.00	0.00	1.4

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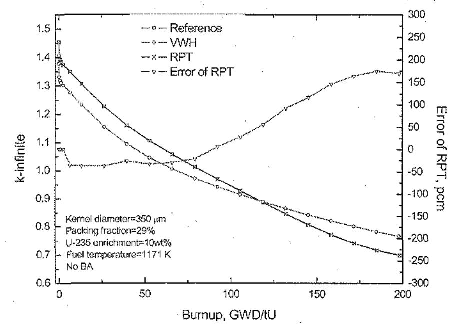
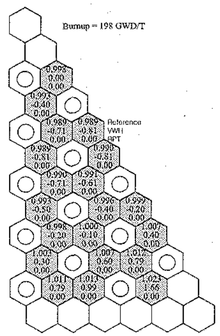
Reactivity-Eq. Physical Transformation

- Prism Type Fuel





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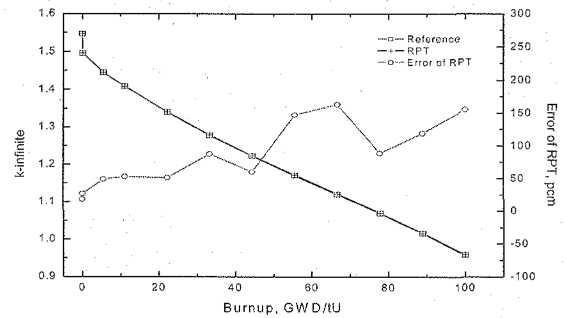
Reactivity-Eq. Physical Transformation

- Pebble Type Fuel



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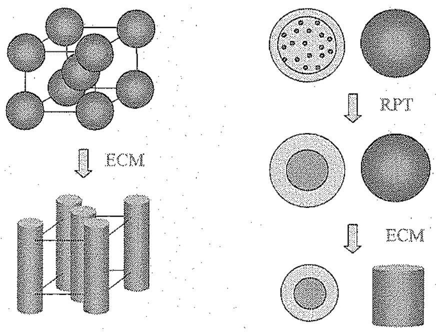
Equivalent Cylindrical Fuel Model (ECM)

- Spherical Fuels → Cylindrical Fuels
  - Enables to use conventional 2-D lattice code for pebble core analysis



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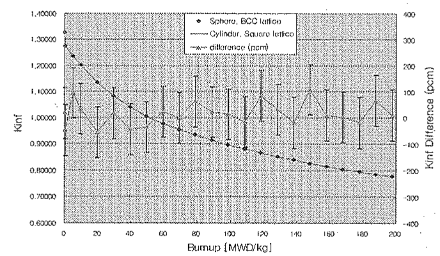
Equivalent Cylindrical Fuel Model (ECM)

- Single Pebble

Cell Geometry	k_{inf}	Diff. (pcm)
Spheres in BCC (Reference)	1.32476 ± 0.00012	-
Cylinders (ECM)	1.32504 ± 0.00012	+28



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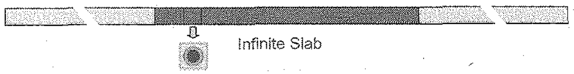
Spectral Geometry and Equivalence Theory

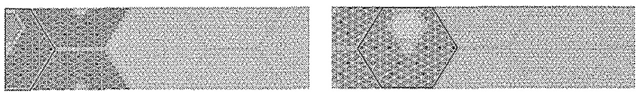
- Spectral Geometry for Pebble Bed Type VHTR

Infinite Slab

- Spectral Geometries for Prism Type VHTR



Infinite Slab



Mini Core

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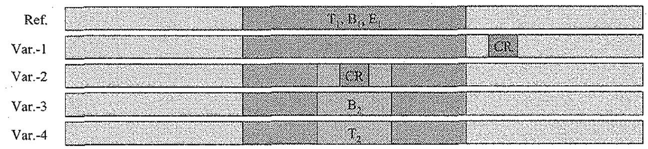
Energy Group Structure Optimization

- Group Structure for Environment-indep't XS's
  - State variable changes in a zone affect the neutron spectrum in the neighboring zones
    - State variables : CR insertion, Burnup, Enrichment, Temperature…
  - Localize the XS changes caused by the state variable changes.
    - State variable changes in a zone should affect the XS's only in the zone.
  - Determine the energy group boundaries so that the XS's and reaction rate changes in the neighboring zones remain small.



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Verifications

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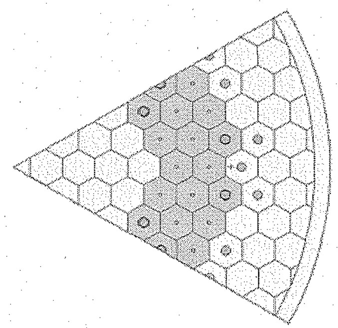
Verification – NGNP

- Doubly Heterogeneous Uranium-fueled Core



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Verification – NGNP

- Case A : XS from Single Block
- Case B : XS from Mini Core
- Equivalent Reflector XS from Infinite Slab Core

Burnable Poison	Temp. (K)	Reactivity Difference (pcm)		
		MCNP*	MASTER [Case A]	MASTER [Case B]
No	300	1.42671	+179	-170
	600	1.40045	+189	-125
	900	1.37714	+83	-150
Er2O3 (6 /block)	300	1.20107	+255	-52
	600	1.14972	+22	-83
	900	1.08220	-136	-153
Er2O3 (12 /block)	300	1.02538	113	+395
	600	0.96401	-531	+257
	900	0.88432	-1208	-91

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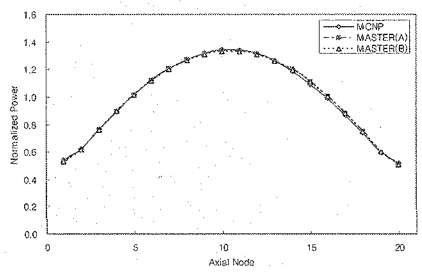
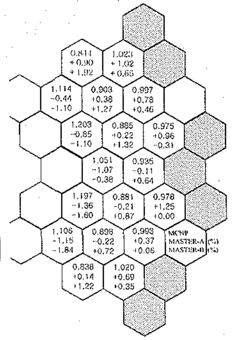
Verification – NGNP

- Results – Power Distribution
  - No BP, 300K





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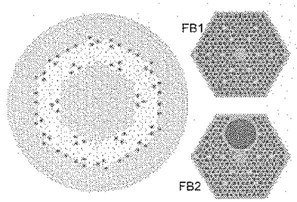
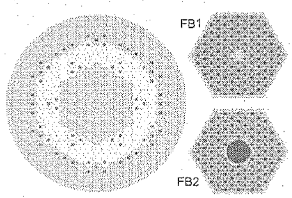
Verification – GT-MHR

- Doubly Heterogeneous Plutonium-fueled Core
- GT-MHR Core : six variants depending on the axial arrangement of Fuel Blocks
- Simplied Core : 1/6 symmetry, all FBs are fresh with central hole



GT-MHR Core



Simplied Core

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Verification – GT-MHR

- Results – k_{eff}

Case	Code	Temp. (K)		
		300	600	900
Varinat-1 BOC1	MCNP	1.18487	1.18659	1.17630
	MASTER Δρ (pcm)	+126	-248	-239
Varinat-2 EOC1	MCNP	1.11045	1.12598	1.12871
	MASTER	+305	-83	-230
Varinat-3 BOC2	MCNP	1.19266	1.19088	1.17874
	MASTER Δρ (pcm)	+80	-240	-249
Varinat-4 EOC2	MCNP	1.13342	1.14591	1.14484
	MASTER Δρ (pcm)	+114	-254	-301
Varinat-5 BOC3	MCNP	1.16326	1.16916	1.16155
	MASTER Δρ (pcm)	+124	-276	-244
Varinat-6 EOC3	MCNP	1.09269	1.11491	1.12356
	MASTER Δρ (pcm)	+331	-76	-316
Simple Core BOC	MCNP	1.51490	1.49188	1.46528
	MASTER Δρ (pcm)	-525	-580	+403

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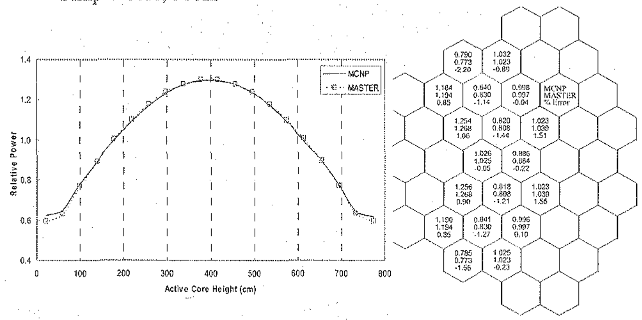
Verification – GT-MHR

- Results – Power Distribution
  - Simple Core, 300K



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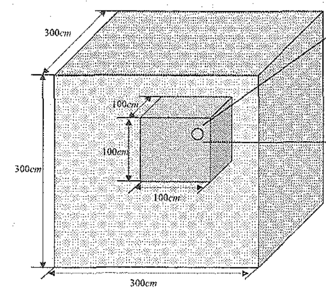
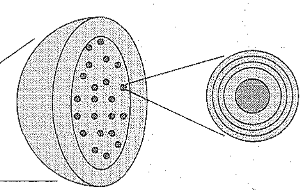
Verification – Pebble Box Problem

- IAEA CRP5 Pebble Box Problem
  - CASE6, CASE7 : Doubly Heterogeneous, Graphite-Reflected





Pebble Packing Fraction	%	61.0
Heavy Metal Loading	g/pebble	9.0
Enrichment	%	9.6
Pebble Diameter	*cm*	6.0
Fuel-free Zone Thickness	*cm*	0.5
Fuel Kernel Diameter	*μm*	500

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Verification – Pebble Box Problem

- Results - Summary

CASE	Method	Item	300K	800K	1200K	800K 1200K[1]
6	MC	k_{eff}	1.02618	0.97190	0.93421	0.96100
	2-Step Diff.	k_{eff} Error (pcm)	+259	+72	+446	-66
		Power Error[2] (%)	5.6	4.7	4.0	4.9
7[3]	MC	k_{eff}	0.68306	0.65089	0.62909	0.64190
	2-Step Diff.	k_{eff} Error (pcm)	-31	-185	+49	-303
		Power Error[2] (%)	2.3	1.9	1.8	2.0

1) : UO2 kernel temperature
2) : Relative power density error along the *x*-axis, RMS
3) : An impurity of 10 ppm B-10 is added in the graphite reflector

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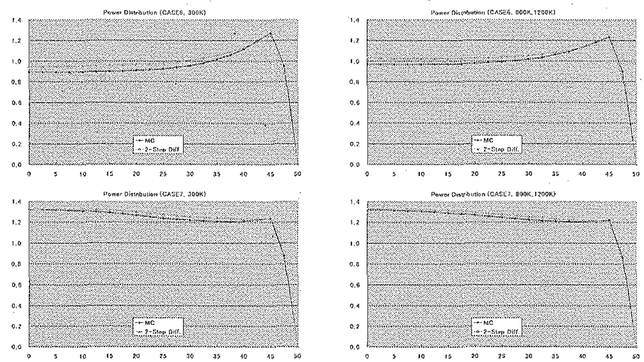
Verification – Pebble Box Problem

- Results – Power Distribution along the X-axis



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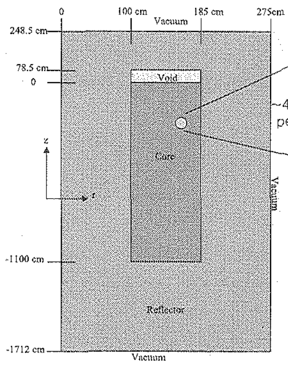
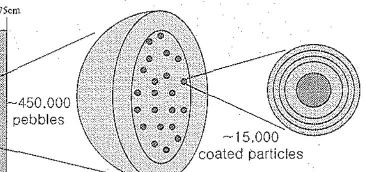
Verification – PBMR-400

- Doubly Heterogeneous PBMR-400





Temperature	K	300
Pebble Packing Fraction	%	61.0
Heavy Metal Loading	g/pebble	9.0
Enrichment	%	5.76
Pebble Diameter	cm	6.0
Fuel-free Zone Thickness	cm	0.5
Fuel Kernel Diameter	μm	500

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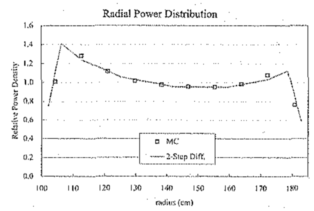
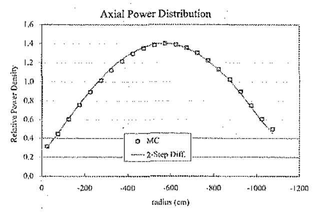
Verification – PBMR-400

- Results

MC		2-Step Diffusion	
k_{eff}	Std. Dev. (pcm)	k_{eff}	k_{eff} Error (pcm)
1.31486	17	1.31488	+2





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Conclusions

- The two-step procedure for VHTR core analysis has been developed.
  - Very accurate and practical in the VHTR core analysis
  - Resolved almost all the technical issues in the VHTR core analysis including double heterogeneity treatment.
- International Collaborations
  - NHJDC with GA (USA)
    - Block and core optimization for prism type VHTR
  - JRC with INET (China)
    - Compilation of HTR-10 experiment data
  - INERI Project with ANL (USA)
    - Development of neutronics analysis code for block type VHTR.
  - OECE/NEA PBMR-400 Benchmark
  - IAEA CRP-5 Benchmark

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Conclusions

- Collaboration with JAEA (Hopefully)
  - New Work Package proposed by JAEA in GIF
    - Double heterogeneity treatment
    - Monte Carlo depletion
    - Whole core transport calculation
    - Experiment data for code verification
  - Old Experiment Data
    - The first criticality experiment data for code verification

1.3.3 Thermo-Fluid and Safety Analysis Code System for VHTR

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Summary

This presentation intends to introduce the KAERI's thermo-fluid and safety analysis code system for the VHTR development. KAERI has planned to design the NHDD (Nuclear Hydrogen Demonstration Development) system, which is the scaled-down demonstration plant of about $200MW_{th}$ capacity for the nuclear hydrogen production. The reactor outlet temperature of 950 °C is a target value and the inlet temperature of about 400~590 °C and the system pressure of 40~70 bar are considered. The iodine-sulfur thermo-chemical process will be used for the hydrogen production.

In order to apply this NHDD system design, KAERI has developed several kinds of design analysis tools such as LILAC code for the CFD analysis, GAMMA for the air/water ingress analysis, MARS-GCR for the system thermo-fluid and safety analysis, MIDAS-GCR for the fission product/graphite dust/tritium transport analysis, and HyPEP for the layout and plant efficiency analysis. These codes must have the capabilities to handle the key phenomena of the VHTR design such as the radiation heat transfer, the multi-dimensional heat conduction, the contact heat transfer, the graphite chemical reaction and the multi-component gas fluid dynamics, etc., which are high-ranked phenomena by PIRT analysis. The specific code characteristics, some code V&V calculations and the application results are presenting the existing capabilities and the future development plans of each code.

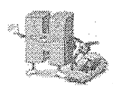
In addition, some experimental programs for the application of thermo-fluid code models and code V&V are introduced. The SNU pebble bed core experiment has the air open test loop for the observations of a turbulent flow during the normal operation and a natural convection flow during the accident condition. The contact conduction test is installed in the vacuum chamber in order to exclude the effects of natural convection and gas conduction. KAIST PCHX experiment has the purpose to obtain the effectiveness, friction factor and heat transfer coefficient of PCHX. KAIST also has the graphite oxidation test loop for the air-ingress analysis. This loop is available at any time. KAERI is preparing the high temperature gas loop for the purpose of the thermal fluid dynamics and plant dynamic tests. KAERI is participating in the international experimental database such as IAEA and GIF programs for the code-to-experimental benchmark. Finally, KAERI addresses the in-depth collaboration with JAEA for the common benchmark of the codes through the information exchange of the software technology and the existing HTTR experimental database.

1st JAEA/KAERI Information Exchange Meeting on VHTR System

Thermo-Fluid and Safety Analysis Code System for VHTR

August 28-30, 2006, Japan

Jisu Jun (*junjisu@kaeri.re.kr*)



KAERI - NHDD Project 1

CONTENTS

KAERI - NHDD Project 2

I. Thermo-Fluid & Safety Codes for NHDD

- NHDD System: Scaled-Down Demo. Plant (~ 200MW_{th})
  - Operating Conditions : T_{out}=950°C, T_{in}=400~590°C, P_{sys}=40~70 bar
  - Hydrogen Production Options : Iodine-Sulfur Thermo-Chemical
- Development of Design Analysis Tools
  - Computational Fluid Dynamics : LILAC
  - Air & Water Ingress : GAMMA
  - System Thermo-Fluid and Safety : MARS-GCR
  - Fission Product/Graphite Dust/Tritium Transport : MIDAS-GCR
  - System Layout and Plant Efficiency : HyPEP
- Development of Next Generation Tool (planned)
  - Multi-D System Thermo-Fluid/Safety, 3-D Kinetics and Confinement Analysis Code coupled with CFD code
  - Hydrogen Explosion Analysis Code

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Thermo-Fluid & Safety Code Requirements

- Key Phenomena for VHTR : PIRT (I-NERI project)
  - Multi-dimensional Fluid Dynamics in Core, Plenums, ...
  - Thermodynamic and Transport Properties of Coolants: He, N2, MS, ...
  - Power Distribution and Reactivity Feedback
  - Gas Convection Heat Transfer: Forced, Mixed and Free
  - Radiation Heat Transfer
  - Multi-dimensional Heat Conduction
  - Contact Heat Transfer
  - Graphite Chemical Reaction and Multi-Component Gas Fluid Dynamics
  - System Component Performance
  - Fission Product and Dust Transport and Plate-out

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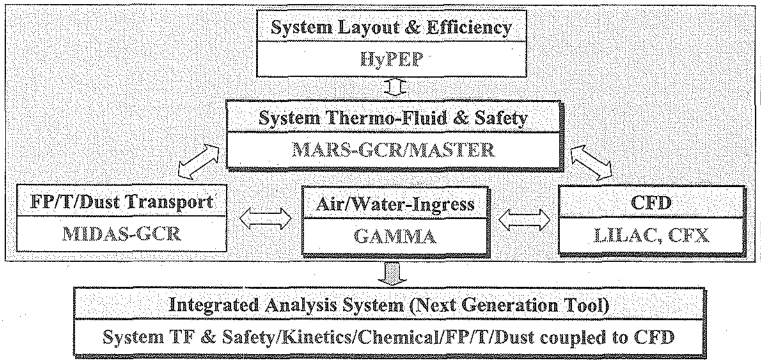
Thermo-Fluid & Safety Analysis Tools



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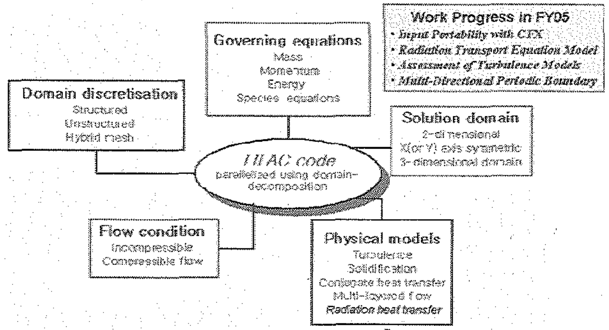
II. Computational Fluid Dynamics: LILAC

- Commercial CFD Codes: CFX & FLUENT
- In-house CFD Code: LILAC (under Development)



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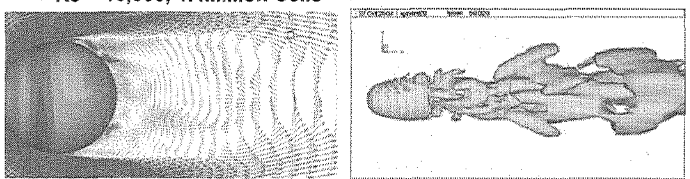
Turbulence Models in LILAC

- Steady Flow
  - High Re : Standard $\kappa-\varepsilon$ Model
  - Low Re : Launder-Sharma $\kappa-\varepsilon$ and Wilcox $\kappa-\omega$ Model
- Unsteady Flow
  - URANS (Unsteady Reynolds-Averaged Navier-Stokes) Model
  - RANS-LES (Large Eddy Simulation) Hybrid Model
- RANS-LES to a Turbulent Flow around Sphere
  - Re = 10,000, 1.4Million Cells



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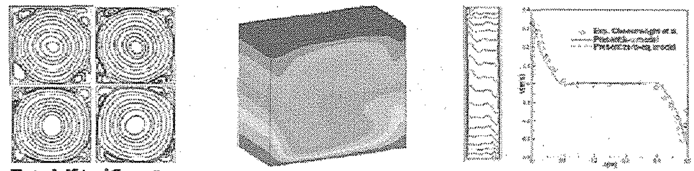
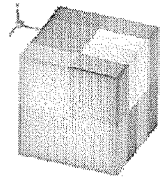
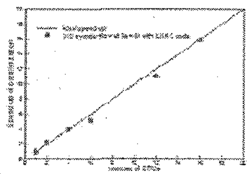
V&V of LILAC

- V&V: Natural Convection Problem



- Parallel Computation
  - Platform: Windows-PC, Linux-PC, Supercomputer

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III. Air & Water Ingress Analysis : GAMMA

- Thermo-Fluid and Chemical Reaction behaviors in a multi-component mixture system related to an air-ingress accident in a VHTR
  - Developed under I-NERI (KAIST/KAERI/SNU & INL)
  - Extension to Water-Ingress Analysis is being studied

TH Phenomena	GAMMA Features
Multi-D 1-ϕ Fluid Dynamics	1-ϕ One-D and Multi-D Porous Media Hydrodynamics
Multi-Gas Species Model	Species Conservation (N_2, O_2, CO, CO_2, H_2O) Gas Properties for Pure and Mixture Fluids
Convection Heat Transfer	Gas Heat Transfer Package Wall-to-Fluid and Pebble-to-Fluid Models
Radiation Heat Transfer	Radiosity Model
Multi-D Heat Conduction	Multi-D Porous Media Model (Effective Conductivity)
Graphite Chemical Reaction	Bulk and Surface Reactions
Molecular Diffusion	Multi-Component Diffusion
Choking Model	Improved Choking Model
Component Models	Circulator Model

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V&V of GAMMA

- GAMMA Code Assessment : Good agreement

Test	Test Facility	Phenomena
Natural Circulation	NACOK natural convection test	Natural convection in a pebble bed
Molecular Diffusion	Duncan & Toor's experiment	Multi-component molecular diffusion
	Inverse U-tube single/multiple channel tests	Binary molecular diffusion and natural convection
	Vertical slot exp.	Local circulation effect on molecular diffusion
Chemical Reaction	Ogawa's circular tube test	Chemical reactions in a IG-110
	Takahashi's annular tube test	Chemical reactions in a IG-110
	VELUNA pebble bed test	Chemical reactions in a pebble bed
Air Ingress	Inverse U-tube air ingress exp.	Molecular diffusion(MD), natural convection (NC), and chemical reactions(CR)
	HTTR-simulated air ingress exp.	MD, NC, and CR Multi-D effect on air ingress process
Heat Removal	SANA-1 afterheat removal test	Pebble temperature distributions: steady power tests and power ramp up/down tests
	HTTR RCCS mockup test	Air convection and radiation in a reactor cavity
	SNU RCCS test	Air convection and radiation in a reactor cavity

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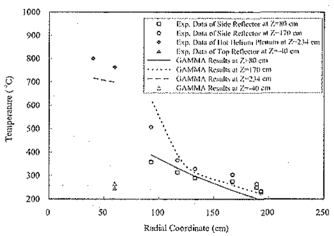
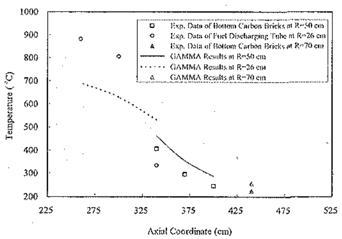
V&V of GAMMA

- HTR-10 Steady State Temperature (IAEA CRP-5)
  - Core Peak Temperature ($T_{Fuel-max}$=929°C) is below Safety Limit
  - Generally, Good Agreement with Measurements
  - Large Deviation near Bottom Reflector and Fuel Discharging Tube Zones



Radial Temperature Distribution



Axial Temperature Distribution

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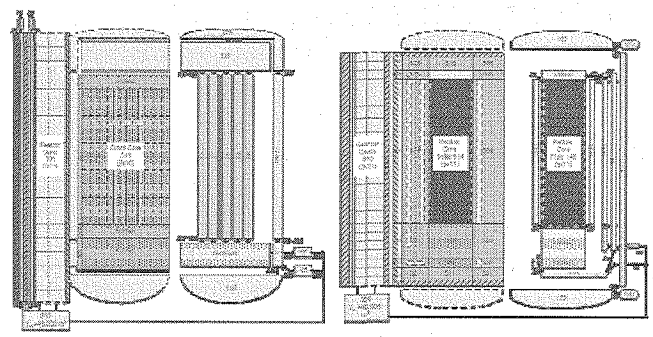
Application of GAMMA

- LPCC Analysis Model



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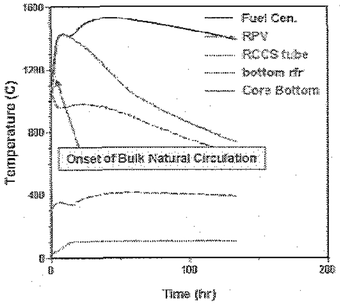
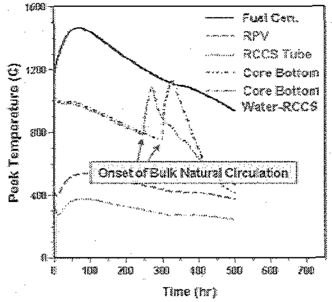
Application of GAMMA

■ **Air-Ingress Analysis Results**

- No Significant Fuel Temperature Rise by Air-Ingress (V_{air} = 50,000m^3)



Pebble Bed Reactor



Prismatic Modular Reactor

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IV. System Thermo-Fluid and Safety : MARS-GCR

■ **System Thermo-Fluid and Accident Analysis**

- RELAP5 as Backbone: Modernized, Restructured and Improved

TH Phenomena	MARS-GCR Features
Multi-D 1-/2-ϕ Fluid Dynamics	2-ϕ One-D and Multi-D Porous Media Model with Diffusion Terms
Numerical Method/Matrix Solver	Semi-Implicit/Two-Step/Direct or Iterative Solver
Coolant Properties	Table Search (He, N_2, O_2, CO, CO_2, H_2O, D_2O)
Convection Heat Transfer	Gas and Water Heat Transfer Package
Multi-D Heat Conduction	2-D in Cylinder, General Model is being developed
Radiation Heat Transfer	RELAP5 Model
Contact Heat Transfer	SNU $k_{eff}(P, T)$ Model
System Component Models	Turbine, Circulator, Pump, Valves, ...
Core Specific TF Models	Heat Transfer & Pressure Drop in Pebble Core
Coupled Analysis	MASTER (3-D Kinetics) and CONTAIN
User Interface	Graphic Users Interface ViSA

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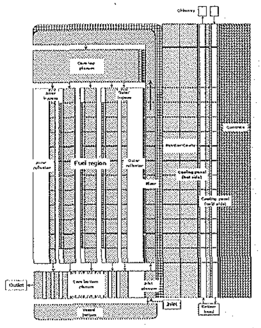
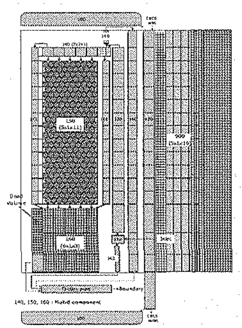
Application of MARS-GCR

■ **HPCC Analysis Model**



PMR



PBR

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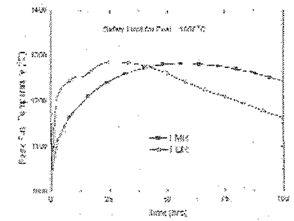
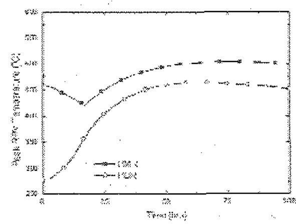
Application of MARS-GCR

■ **HPCC Analysis Results**

- Maximum Fuel and RPV Temperatures are within Safety Limit
- Slower Core Heat-up in PMR due to Large amount of Graphite
- Higher RPV Temperature in PMR due to Higher Initial Temperature (No RPV Cooling)



Peak Fuel Temperature



Peak RPV Temperature

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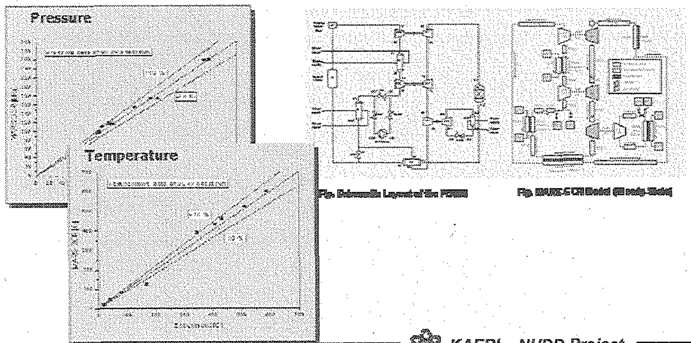
V&V of MARS-GCR

- **PBMM PCU Performance Benchmark (IAEA CRP-5)**
  - Steady state results showed good agreement



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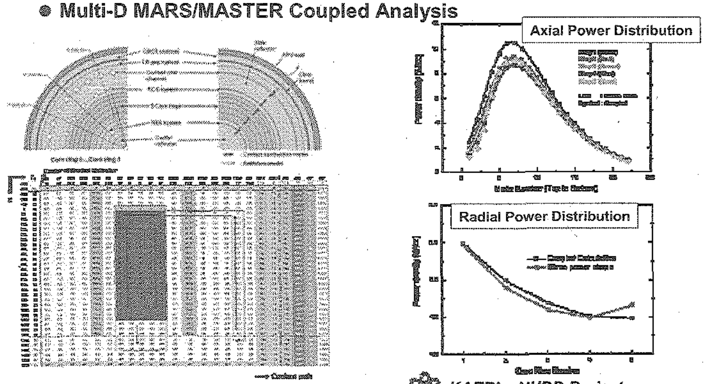
V&V of MARS-GCR

- **OECD/NEA PBMR-400 Benchmark (Exercise 3)**
  - Multi-D MARS/MASTER Coupled Analysis



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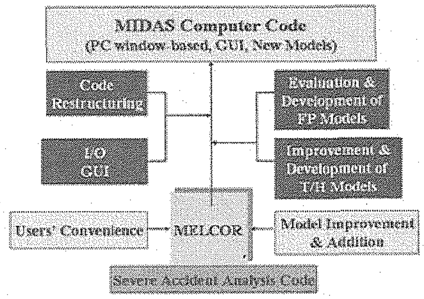
V. FP/Dust/Tritium Transport : MIDAS-GCR

- **FP, Dust and Tritium Transport Analysis**
  - Improved Version of MELCOR for PWR Severe Accident Analysis
  - Adaptation for VHTR FP and Dust Transport Analysis is in Progress
  - Extension to Tritium Transport Analysis is being studied in collaboration with GA (USA)



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MIDAS-GCR

- **Tritium Transport Modeling Strategy in MIDAS-GCR**
  - Tritium is regarded as one of Fission Product Species
  - Tritium Generation
    - Tritium Generation Models or Time-dep't-Table Input
  - Tritium Transport over the System
    - Bulk Flow: Thermo-Mechanical Equilibrium with Vapor
    - Diffusion: Need New Model (Accident Conditions)
  - Tritium-specific Models (Use GA Models)
    - Recoil Model
    - Leakage from Coolant Loops (User Input)
    - Removal by Purification System (User Input)
    - Chemisorption on Graphite (Temkin & Myer)
    - Permeation through Heat Exchangers (Arhenius)

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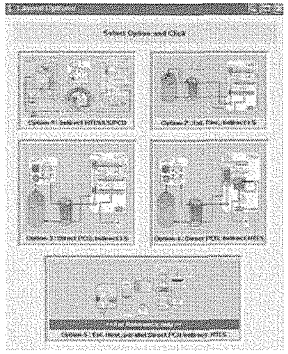
VI. System Layout and Plant Efficiency : HyPEP

- HyPEP: System Layout & Hydrogen Efficiency Analysis
  - Steady-State Energy Balance and Efficiency Analysis
    - *Hard-wired Analysis Version: 5 System Configurations*
  - I-NERI (ANL/INL/KAERI)
    - Develop a Generalized Network Version
      - Drag-and-Drop Features
      - Component & Sizing Models
      - Efficiency Models
      - Cost Models



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Models in HyPEP

- VHTR/IHX Module
  - Calculates mass flow rate of the primary helium, the electric power requirement of the primary helium circulator and the primary to secondary heat transfer
- PCU Module
  - Calculates the Brayton cycle efficiency
  - Consists of the gas turbines, recuperator, pre- and inter-coolers, compressors, and AC power generators
- HTES Module
  - Calculates the hydrogen production efficiencies and yields
  - Consists of the HX, the electolyser, the condenser, the separator, the H2 and water supplies, and the helium circulator
- I-S Module
  - Calculates the hydrogen production efficiencies and yields
  - Consists of the HX, a H2SO4 decomposition unit, a HI composition /decomposition unit, Bunsen reaction unit, a water pump and a helium circulator

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Application of HyPEP

- System Operating Conditions and Efficiencies
  - Good agreement with ASPEN analysis for I-S by GA and KAERI's HTES calculations

VHTR		
Power	[illegible]	MW
Core Outlet Pressure	[illegible]	bar
Inlet Temperature	[illegible]	°C
Outlet Temperature	[illegible]	°C
Core Pressure Drop	[illegible]	bar
Primary Loop ΔP (excl. IHX ΔP)	[illegible]	bar
Blower Efficiency	[illegible]	%
IHX		
Primary Side ΔP	1	bar
Secondary Outlet Pressure	[illegible]	bar
Secondary ΔP	[illegible]	bar
Primary to Secondary average ΔT	[illegible]	°C
Heat Transfer efficiency	[illegible]	%
I-S System		
Heat Exchanger ΔP	[illegible]	bar
Heat Exchanger Efficiency	[illegible]	%
Helium Blower Efficiency	[illegible]	%
Thermal Energy Requirements (kJ/mol H2)		
Bunsen Reaction	[illegible]	kJ/mol-H2
H2SO4 Decomposition	[illegible]	kJ/mol-H2
HI Concentration/Decomposition	[illegible]	kJ/mol-H2
Electric Energy Requirements (kJ/mol-H2)		
Bunsen Reaction	[illegible]	kJ/mol-H2
H2SO4 Decomposition	[illegible]	kJ/mol-H2
HI Concentration/Decomposition	[illegible]	kJ/mol-H2

PCU		
[illegible]	[illegible]	°C
Turbine efficiency	[illegible]	%
Turbine pressure ratio	[illegible]	
Compressor efficiency	[illegible]	%
Recuperator efficiency	[illegible]	%
Generator [illegible]	[illegible]	
HTES		
Chemical formula: [illegible]		
Primary Side HX and electrolyser heater total ΔP	[illegible]	bar
Secondary Side HX and electrolyser heater total ΔP	[illegible]	bar
HX Primary to Secondary ΔT	[illegible]	°C
Electrolysis Efficiency	[illegible]	%
HX and Electrolyser Heater Efficiency	[illegible]	%
AC/DC converter efficiency		%
Helium Circulator Efficiency	[illegible]	
Condenser Efficiency	[illegible]	%
Condenser Outlet Pressure	[illegible]	bar
Condenser Outlet Temperature	[illegible]	°C
H2 supply Pressure	[illegible]	bar
H2 supply Temperature	[illegible]	°C
H2 supply Compressor Efficiency	[illegible]	%
H2O supply Pressure	[illegible]	bar
H2O supply Temperature	[illegible]	°C
H2O Supply Pump Efficiency	[illegible]	%

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VII. Experimental Programs

- SNU Pebble Core Experiment
  - 2-D Thermo-Fluid Dynamics for Pebble Bed Core
- KAIST PCHX Experiment
  - Thermo-Fluid Test of Printed Circuit Heat Exchanger (Heatric PCHE)
- KAIST Graphite Oxidation Experiment
  - Graphite Oxidation Test for Air-ingress Analysis
- KAERI High Temperature Gas Loop Test
  - Small Scale Helium Test for Thermo-Fluid Dynamics and Plant Dynamics
- International Experimental Database
  - Available Data in Int'l programs (IAEA, Gen-IV ..) will be used for the Thermo-Fluid Code Models and V&V

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SNU Pebble Core Experiment

Experiment	SNU Pebble Core Experiment
Fields of application	• 2-D Thermo-Fluid Dynamics for Pebble Bed Core
Main Characteristics	• Rectangular planar channel for downward air flow • Experiment for CFD code validation • Flows over a cylinder and cylinder bundle using cylindrical heating elements • Fluid flows and heat transfer relevant to effects of turbulence • Hotwire and K-type thermocouple for velocity and temperature measurements
Deliverables /Outcomes	• Streamwise velocity profiles over cylindrical obstacles • Heater surface temperature distribution relevant to flow separation and turbulent mixing • Pressure drop through the channel
Need for Improv'nt	• Three-dimensional velocity measurement system
Status/Schedule	• Construction finished by Feb. 2005 • First step experiments finished by Feb. 2006
Originator	• SNU and KAERI
Conditions for Avail.	• Conditional
Codes validation and/or Organization using the facility	• Comparison of characteristics for turbulence models in CFD (CFX-5.7) code • SNU and KAERI

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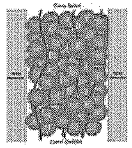
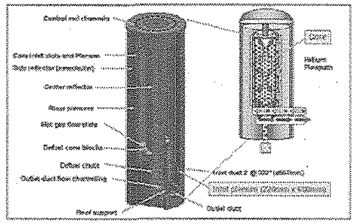
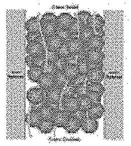
SNU Pebble Core Experiment

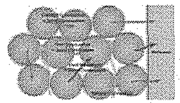


Task 1: *Turbulent flow during normal operation*

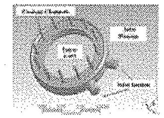




Task 2: *Natural Convection during Accident condition*



Task 3: *Contact conduction*



Task 4: CFD Analysis *Inlet plenum Optimization*

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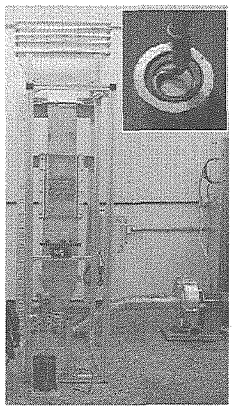
SNU Pebble Core Experiment

- Thermo-Fluid Test Facility
  - Air Open Loop at atmospheric pressure
  - Vertical channel with suction blower
  - Wind tunnel at the inlet
  - 2-D Pebble Cylindrical heaters (d=4cm) with power up to 100W
  - Measurements
    - Streamwise velocity around pebbles (hotwire)
    - Surface temp. of pebbles (K-type T/C)
    - Pressure drop (DP transmitter)
- Contact Conduction Test
  - Contact Area & Contact Pressure between Graphite Bodies

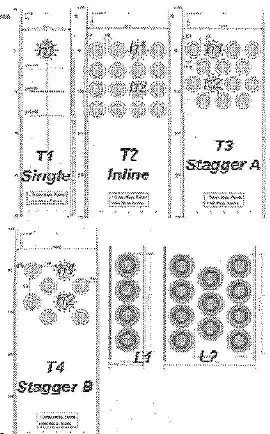


KAERI - NHDD Project 27

SNU Pebble Core Experiment

- Test Matrix

Case No.	Description	U_{in} [m/s]	Re_{in}	Re_{max}	Q_{each} [W]	No. Heater	Q" [W/m²]
T1-1	Single	5	1.20E4	2.22E4	30	1	3573
T1-2	Single	10	2.40E4	4.44E4	30	1	3573
T1-3	Single	15	3.60E4	6.64E4	30	1	3573
T2-1	Inline	10	2.40E4	1.34E5	30	16	3573
T3-1	Stagger A	10	2.40E4	1.14E5	30	14	3573
T4-1	Stagger B	5	1.20E4	2.98E4	30	8	3573
T4-2	Stagger B	10	2.40E4	5.93E4	30	8	3573
T4-3	Stagger B	15	3.60E4	8.95E4	30	8	3573
L1	One-line (L1)	0	-	-	30	4	3573
L2	Zigzag (L2)	0	-	-	10	11	1191



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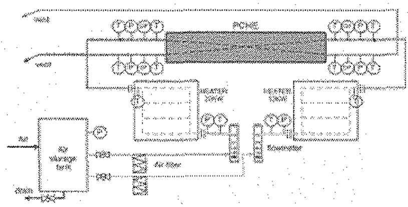
KAIST PCHX Experiment

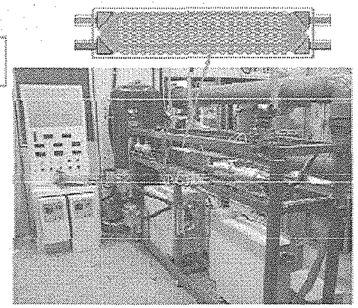
Experiment	Printed Circuit Heat Exchanger Thermal-Hydraulic test
Fields of application	▪ Thermo-Fluid Dynamics (IHX)
Main Characteristics	▪ Laminar flow at semicircular wavy channels ▪ High inlet temperature (~800℃) ▪ High effectiveness ▪ Temperature (~800℃), Pressure(~33bar), flow rate (125kg/h)
Deliverables /Outcomes	▪ Effectiveness ▪ Friction factor ▪ Heat transfer coefficient ▪ DP, P, T, mass flow rate
Need for improvement	▪ Not necessary
Status / Schedule	▪ Air test is on-working ▪ Helium test is planned for 2006
Originator	▪ KAIST (Korea Advanced Institute of Science and Technology)
Conditions for Avail.	▪ Conditional
Codes validation and/or Organization using the facility	▪ Using CFD code are available for validation of PCHE TH performance and different channel shape tests are available

KAERI - NHDD Project 29

KAIST PCHX Experiment

Experimental Facility



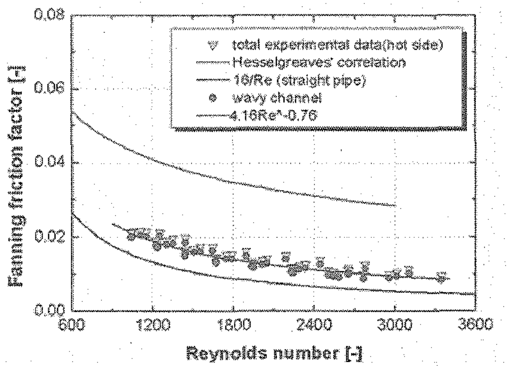


	primary loop	secondary loop
loop type	open	open
Working Fluid	air	air
heat load (kW)	20	10
Range	Laminar	Laminar

KAERI - NHDD Project 30

KAIST PCHX Experiment

Fanning Friction Factor



KAERI - NHDD Project 31

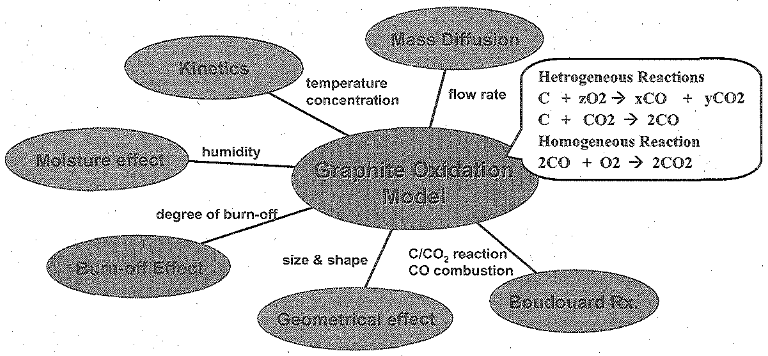
KAIST Graphite Oxidation Experiment

Experiment	Graphite Oxidation Test Loop for Air-ingress Analysis
Fields of application	▪ Air-ingress (Chemistry and Transport)
Main Characteristics	▪ Separate and integrated effect test for graphite oxidation (temperature, velocity, gas concentration, moisture) ▪ Analysis of gases ▪ Direct heating method by induction heater (direct control of graphite surface temperature) ▪ Non-contact measurement of graphite temperature by IR- temperature sensor ▪ Including moisture supply and control system ▪ Temperature (550~1400℃), O_2 concentration (0~100%), CO concentration (0~20%), CO_2 concentration (0~20%), flow rate (120 SLPM), Moisture (Rh 0~70% at 23℃)
Deliverables /Outcomes	▪ Rate of reaction between graphite and gases (O_2, CO_2, He, ...) ▪ Activation energy of graphite oxidation ▪ Order of reaction of graphite oxidation ▪ Concentration of product gases of graphite oxidation ▪ Mass transfer coefficient in graphite oxidation ▪ Moisture effect on the graphite oxidation
Need for Improv'nt	▪ Not necessary
Status / Schedule	▪ On working (available at any time)
Originator	▪ KAIST (Korea Advanced Institute of Science and Technology)
Conditions for Avail.	▪ Conditional
Codes validation and/or Organization using the facility	▪ If the test-section is modified, various air-ingress tests are available for validation of graphite oxidation model in safety analysis codes.

KAERI - NHDD Project 32

KAIST Graphite Oxidation Experiment

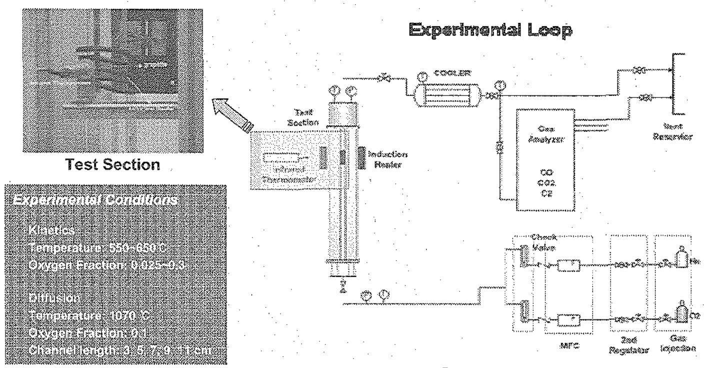
■ Scopes of Study



KAERI - NHDD Project 33

KAIST Graphite Oxidation Experiment

■ Experimental Facility



Experimental Conditions

Kinetics
Temperature: 550~650°C
Oxygen Fraction: 0.025~0.3

Diffusion
Temperature: 1070°C
Oxygen Fraction: 0.1
Channel length: 3, 5, 7, 9, 11 cm

KAERI - NHDD Project 34

KAERI High Temperature Gas Loop

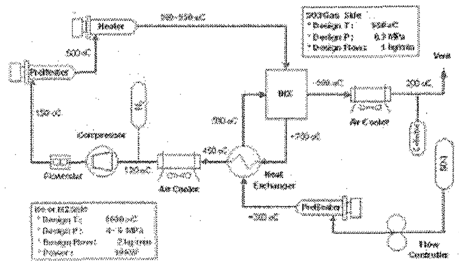
Experiment	Small Scale Helium Test Loop
Fields of application	▪ Thermo-Fluid Dynamics and Plant Dynamics
Main Characteristics	▪ 150kW thermal fluids and component test loop ▪ Loop operating conditions ▪ Primary loop: Helium at T_{exit}/P/W = 950°C/4~6 MPa/30 kg/min ▪ Secondary loop: SO_3 at T_{exit}/P/W = 900°C/2 MPa/15 kg/min ▪ Steady state thermal fluid tests ▪ Transient loop performance tests ▪ Intermediate heat exchanger tests
Deliverables /Outcomes	▪ Heat transfer ▪ Pressure drop ▪ Transient thermal fluid dynamics: P, T, W, ...
Need for improvement	
Status / Schedule	▪ Conceptual design in 2006 ▪ Loop construction in 2008
Originator / Cooperation	▪ KAERI
Conditions for Avail.	
Codes validation and/or Organization	▪ Test results will be used for the development and assessment of thermo-fluid models for system dynamics analysis codes

KAERI - NHDD Project 35

KAERI High Temperature Gas Loop

■ High Temperature Gas Loop

- N_2-SO_3 Loop (10~20kW, 2006): PHE
  - -> He-SO_3 (150kW, 2008): PHE, Material, Basic Thermo-Fluid
  - -> He-SO_3 (>500kW, 2011): PHE, Material, Thermo-Fluid, Safety, Components



KAERI - NHDD Project 36

Summary and Proposal

- Analytical and Experimental Effort for NHDD has been introduced
- Proposals for KAERI/JAEA Collaboration
  - KAERI: Provide the Software Technology
  - JAEA: Provide the Existing HTTR and Experimental Database for Code Models & V&V
  - Common Benchmark of the Codes and Relevant Technologies

KAERI - NHDD Project 37

1.4 Session 4 VHTR fuel and materials

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1.4.1 Overview of R&D on VHTR Fuel

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Summary

The high quality of HTTR fuel is shown. For the 1st loading fuel, Average through-coatings and SiC failed fractions were 2×10^{-6} and 8×10^{-5}, corresponding the criteria, 1.5×10^{-3} and 1.5×10^{-4}, respectively. Fuel performance of the first loading fuel of the HTTR has been investigated. The fractional release of Kr-88 as a function of the volume averaged fuel temperature was as low as 1×10^{-8} at about 1100°C (full power operation), and in good agreement with the calculation under the assumption that no additional failure of the particle occurred. Therefore, it was supposed that almost no additional failure was occurred during the irradiation.

The SiC fuel might be used in VHTR, however, the ZrC fuel would improve the performance of VHTR due to its higher resisitivity to high temperature and the corrodion by Pd than SiC. And now the ZrC coated fuel is been developed. First, We are optimizing deposition condition for larger scale coater. In the previous research in JAEA, ZrC coated fuel were developed with laboratory scale.Enlarging the coater scale affects the quality of ZrC-coating layer, because the temperature un-uniformity of the coating region become large. Therefore, the parametric tests, such as temperature and gas flow rate, etc. are being carried out. Second, we are developing the inspection technologies. ZrC is oxidized and do not form the passive state. So we can not burn the particles to remove PyC layer for the inspection of ZrC layer. For example, plasma etching technology of PyC is been developed now. Third, further irradiation data should be obtained because present data is up to about 4.5% FIMA. Irradiation test of ZrC material will be carried out in the framework of I-NERI collaboration between US and Japan.

Overview of R&D on VHTR Fuel

Presentation for

1st JAEA/KAERI Information Exchange Meeting on HTGR and Nuclear Hydrogen Technology

J. Aihara, S. Ueta, A. Yasuda, H. Ishibashi, T. Takayama and K. Sawa

High Temperature Fuel and Material Group

Japan Atomic Energy Agency (JAEA)

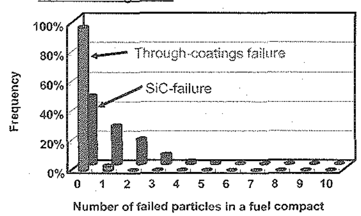
August 29, 2006

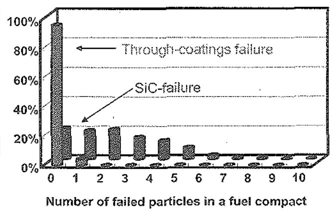
Contents

1. High quality of SiC coated fuel
2. Development of VHTR fuel

1. High quality of SiC coated fuel

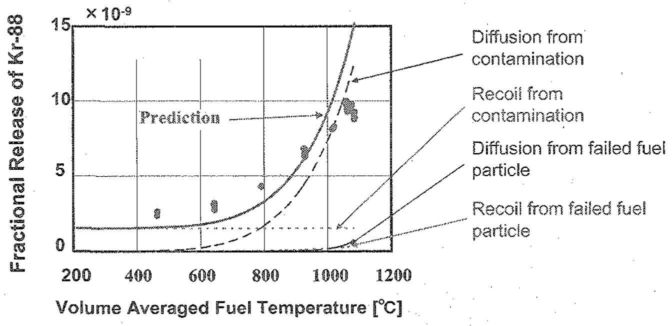
Fabrication Results of the 1st- and 2nd-Loading Fuel of the HTTR





- Low as-fabricated failure fractions were achieved.
  - Through-coatings failure fraction (criteria : 1.5×10^{-4}) :
    1st : 2×10^{-6} 2nd : 2×10^{-6}
  - SiC-failure fraction (criteria : 1.5×10^{-3}) :
    1st : 8×10^{-5} 2nd : 1.7×10^{-4}

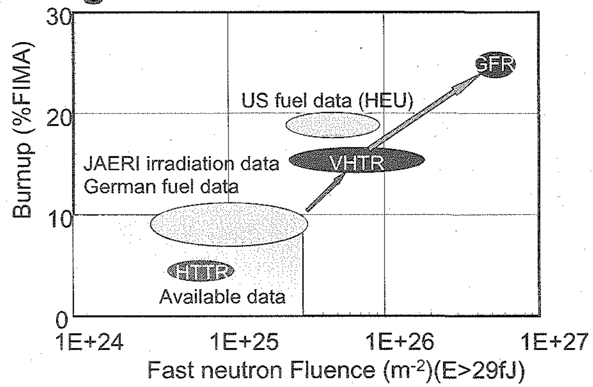
Fuel Performance in HTTR (Normal Operating Condition)



Additional failure of the fuel particles should hardly occur during irradiation

2. Development of VHTR fuel

Target of Future HTGR Fuels



● **Burnup extension are needed**

(GIF,etc. :ATR, HFR, HFIR, etc.)

For the Development of Fuel for VHTR

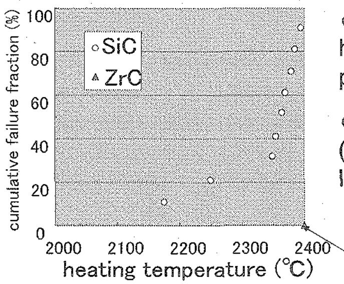
1. Fabrication technique development of SiC coated fuel particles for high burnup and high temperature
   * Thicker SiC layer
   * (higher packing fraction of fuel compact)

2. Additional irradiation test

3. Model development

In addition,
Advanced fuel particle development
(now we are doing)

Limitation of SiC Fuel



Cumulative failure fraction of the fuel particles with post irradiation heating test

J. Am. Ceram. Soc., 75 (1992) 2985.

- Cannot be used at very high temperatures due to phase transformation of SiC.
- Corrosion by Pd (transuranium nuclides has larger yield)

ZrC:
- Higher heat resisitivity than SiC
- No corrosion by Pd

ZrC-Coated Fuel Development (On-going)

- Optimization of deposition condition for larger-scale coater.

Enlarging the coater scale affects the quality of ZrC-coating layer, because the temperature distribution of the coating region become large.

- Development of inspection technologies.

ZrC is oxidized and do not form the passive state.

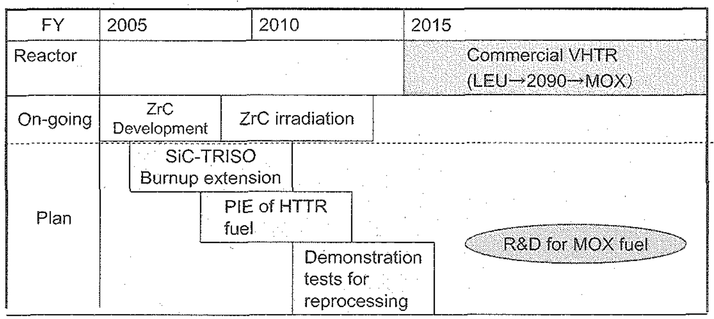
So we can not burn the particles to remove PyC layer for the inspection of ZrC

→ For example, plasma etching of PyC

- Irradiation test

irradiation test of ZrC material will be carried out in the framework of I-NERI collaboration between US and Japan

Road Map for HTGR Fuels Development



Conclusions

1. We can produce SiC coated fuel particles with high quality.
   The SiC fuel might be used in VHTR.
2. We are now developing ZrC coated fuel particles.
   The ZrC fuel may improve the performance of VHTR.

1.4.2 Over View of VHTR Ceramic Materials Development in JAEA

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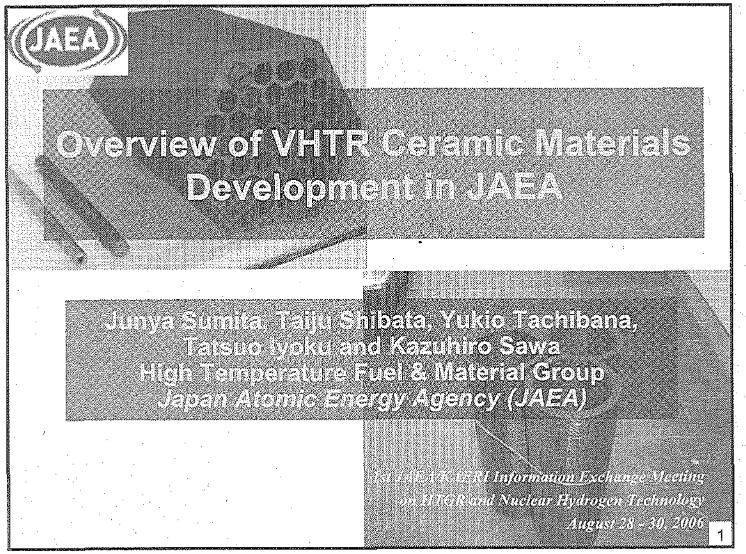
Summary

JAEA has established the technological basis for HTGR. For metallic material, since the maximum metal temperature of HTTR reaches 900°C, JAEA has developed heat and corrosion resistant super alloy, Hastelloy XR. For in-core graphite components, JAEA has developed the nuclear grade IG-110 graphite. It is fine-grained and isostatic-pressed isotropic graphite which has excellent mechanical properties and stability against neutron irradiation. The IG-110 (IG-11) is a candidate grade for in-core graphite components of VHTR. The IG-430 graphite, advanced grade, is also a candidate. Since neutron fluence and temperature of VHTR core are higher than HTTR, it is necessary to evaluate the integrity of graphite components at such a severe condition. For this purpose, development of damage evaluation method and accumulation of irradiation data are necessary.

From the viewpoint of lifetime extension of graphite component, it is important to evaluate the degradation of them. The residual stress due to the irradiation creep, temperature gradient and so on, limits the lifetime of graphite components and the oxidation damage due to quite small amount of impurities in a coolant degrades the strength of them. We are now developing the non-destructive evaluation method, NDE method, to evaluate the residual stress and oxidation damage of graphite. These methods must contribute to extent the lifetime of the graphite components.

As advanced materials for the VHTR, ceramic composite materials are candidates due to thier excellent thermal stability as well as high strength. A two-dimensional carbon fiber reinforced carbon-carbon composite (2D-C/C composite, CX-270G) has been studying for the application to control rod element. Since the 2D-C/C composite has great anisotropy in thermo-mechanical properties in with- and across- fiber directions, it is necessary to consider the anisotropy for developing design methodology and to develop the evaluation method for the anisotropic irradiation effects. It is, hence, important to accumulate irradiation data of C/C composite at high fluence and temperature as well as graphite materials.

In the presentation, typical R&D results on graphite and C/C composite are explained and irradiation test plans for graphite and C/C composite including possible international cooperation in GIF are also explained.

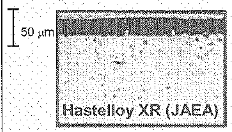


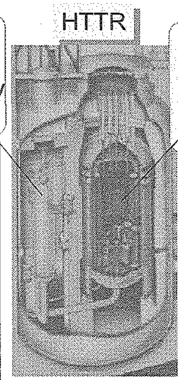
Materials R&D for the HTTR

Metallic Material
- Development of heat and corrosion resistant super alloy

Hastelloy XR

Cross-sectional Views after Corrosion Test (1000℃, 10000hrs, in helium gas)





Graphite material
- Development of high grade graphite
- Design Guideline for graphite components

➢Core components

IG-110 graphite (Toyo Tanso)
- Fine-grained, ・Isotropic,
- Grain size : 20 μm, ・High strength,

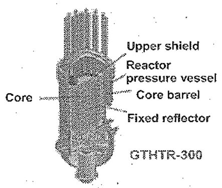
➢Core support structures

PGX graphite
- Medium-to-fine-grained,
- Grain size : 800 μm,

2

R&D items for VHTR

Component	HTTR	VHTR	R&D
Fuel block Reflector	Isotropic nuclear grade graphite (IG-110)	IG-110(IG-11) (primary) IG-430 (advanced)	Irradiation data, Lifetime extension
Control rod element	Alloy 800H	C/C composite SiC/SiC composite	Design methodology Irradiation data



	VHTR	HTTR
Power density	5.8 MW/m^3	2.5 MW/m^3
Burn-up	150～200GWD/t	22GWD/t
Fluence	6 × 10^{25}n/m^2	1.5 × 10^{25}n/m^2

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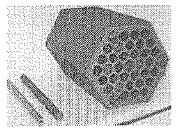
Typical properties of ceramic materials

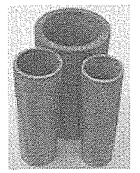
	IG-110[1] graphite	PGX[1] graphite	IG-430[2] graphite	CX-270G[3] C/C composite
Bulk density(Mg/m^3)	1.78	1.73	1.82	1.63
Mean tensile strength(MPa)	25.3	8.1	37.2	167(//)
Mean compressive strength(MPa)	76.8	30.6	93.5	69(//), 89(⊥)
Young's modulus(GPa)	7.9	6.5	10.7	81(//)
Mean thermal expansion coefficient (293～673K) (10^{-6}K)	4.06	2.34	3.97	0.2(//), 10.8(⊥) (RT～1273K)
Thermal conductivity(W/(m·K))	80 (673K)	75 (673K)	154 (RT)	129(//), 26(⊥) (RT)

(//) : Parallel to lamina, (⊥) : Perpendicular to lamina

1)M.Ishihara, et. al., JAERI-M 91-153(1991).
2)A private letter
3)T.Sogabe, et. al., JAERI-Research 2002-026(2002).



Fuel block for HTTR (Toyo Tanso IG-110)



2-D C/C composite pipes for control rod element (Toyo Tanso CX-270G)

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Contents

1. **Research on graphite**
2. Research on C/C composite

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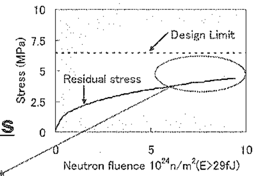
Development of NDE methods for graphite components

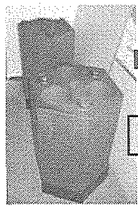
Residual stress limits the lifetime of graphite components
- Irradiation creep, •Temperature gradient, etc.

Oxidation damage degrades the strength
- Impurities in coolant



With increasing neutron fluence, residual tensile stress appear to increase and saturate.

Application NDE methods



Integrity check

Reactor

⇨ **Contribute the lifetime extension of the graphite components**

- Micro-indentation
- **Ultrasonic wave propagation**

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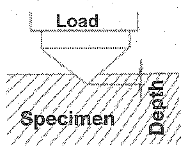
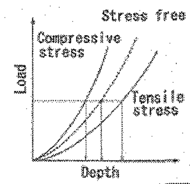
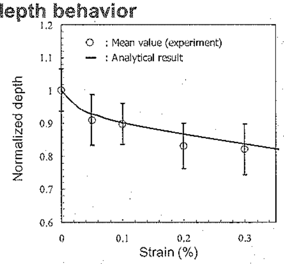
Micro-indentation method





The indentation depth
- ✓Decreases under compressive condition
- ✓Increases under tensile condition

Stress condition affects the indentation load-depth behavior



J Sumita, et. al., Proceedings of ICONE14-89384 (2006).

It is possible to evaluate residual stress from the relationship indentation load- depth behavior

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Contents

1. Research on Graphite

2. Research on C/C composite

8

Application of C/C composite to control rod element

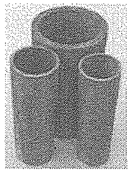
Ceramics composite material

- C/C composite, •SiC/SiC composite, etc.

2D-C/C composite CX-270G (TOYO Tanso)

Fabrication cost and process

But, 2D-C/C composite has great anisotropy



2-D C/C composite pipes for control rod element (Toyo Tanso CX-270G)

Application C/C composite to control rod element

○Development of design methodology
- **Irradiation data**
- **Strength prediction model (with irradiation effect)**
- **Structural design code**
- **Demonstration test**

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Strength prediction method

Fracture model : based on the Competing risk theory

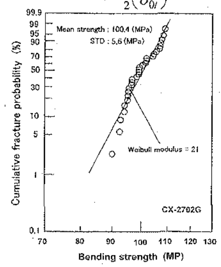
Application to three point bending strength prediction

Risk of rupture for three point bending strength : R_{3b}

$$R_{3b} = R_t + R_c + R_\tau \quad (1)$$

R_t, R_c, R_τ : risk of rupture for tensile, compressive and shear fracture mode

$$R_t = 2\int_0^{l}\int_0^{\frac{l}{2}}\left(\frac{\sigma_t}{\sigma_{0t}}\right)^{m_t} bdxdy \qquad R_c = 2\int_0^{l}\int_0^{l}\left(\frac{\sigma_c}{\sigma_{0c}}\right)^{m_c} bdxdy \qquad R_\tau = 2\int_0^{l}\left(\frac{\sigma_\tau}{\sigma_{0\tau}}\right)^{m_\tau} lbdy \quad (2)$$



Mean three-point bending strength : 100.4MPa

Prediction using Cometing Risk Model

Predicted strength : 94MPa

Develop the model considering irradiation effect

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Demonstration test by HTTR

Standpipe closure

Irradiation standpipe

RPV

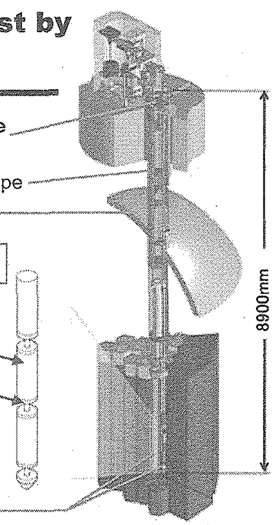
Prototype of control rod element

Control rod sheath

Connecting rod

Materials: C/C, SiC/SiC (superplastic ceramics)

Irradiation unit



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Plan for irradiation test

➢Irradiation test using JOYO

Irradiation start : 2008 ~

Temperature : 1000℃, Fluence : ~2×10^{26}(n/m^2, E>29fJ)

Material : graphite (IG-110, IG-430), C/C composite (CX-270G)

PIE start : 2010 ~

PIE : dimensional change, bending strength, thermal conductivity, CTE, etc.

➢Irradiation test in GIF

HIFR, PETTEN, OSIRIS, HANARO, etc.

➢Surveillance test of HTTR graphite

Specimens, blocks

Surveillance test start : 2011~

Examination : dimensional change, bending strength, thermal conductivity, CTE, etc.

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Summary

- ✓JAEA has established the technological basis for HTGRs on metallic materials Hastelloy XR and graphite materials IG-110.
- ✓Study on non-destructive method is carrying out to aim at the life extension of graphite components.
- ✓JAEA is developing design methodology of composite materials for control rod element application.
- ✓JAEA has irradiation plans of graphite and composite materials for VHTR.

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1.4.3 Development of HTGR Fuel Technology in Korea: Current Status

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Summary

In the HTGR fuel technology development, R&D of technologies relevant to the TRISO fuel and component materials is one of the important tasks in the respect of reactor safety.

KAERI has been devoted to develop the fundamental technologies for TRISO coated particle fuel, which include the fabrication of uranium kernels, coating technology for buffer, IPyC, SiC and OPyC, and for their respective material characterization. This presentation deals with the R&D works currently being carried out for the development of fabrication technology for coated particle fuels, including the previous feasibility study and experience on the coating technology. It also deals with the fuel performance model and analysis code development and the preliminary studies on the design of irradiation test device and PIE of coated particle fuel.

1st JAEA / KAERI Information Exchange Meeting on HTGR
and Nuclear Hydrogen Technology

Development of HTGR Fuel Technology in Korea: Current Status

August 28-30, 2006

Choong-Hwan JUNG*, Ji-Yeon PARK, Young-Woo LEE
chjung1@kaeri.re.kr
Nuclear Materials Technology Development, Div.
Korea Atomic Energy Research Institute

KAERI 1

Content

- Brief explanation of

1. Status of Fuel Technology (1) - Kernel preparation
2. Status of Fuel Technology (2) - SiC-TRISO coating technology
3. Status of Fuel Technology (3) - ZrC coating technology
4. Status of Fuel Technology (4) - Code development & Plan for irradiation test/PIE

* Future work & Joint Collaboration Proposal
(Collaborations with JAEA)

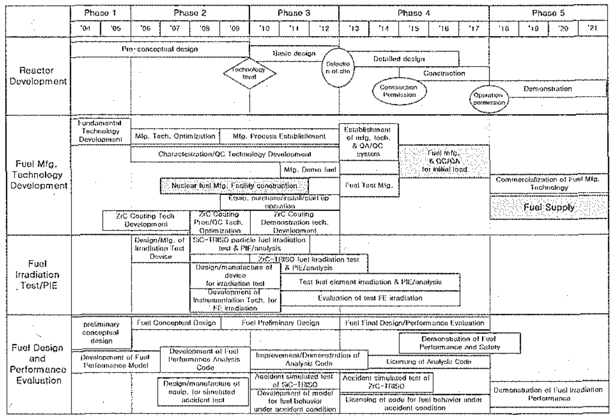
KAERI 2

Background

1. **Started in 2004, "Nuclear Hydrogen Production Technology Development and Demonstration (NHDD) Project" is in its first phase and currently being carried out for the purpose of 'Preliminary Conceptual Design and Development of Core Technology of Very High Temperature gas-cooled Reactor (VHTR) for Hydrogen Production' in Korea.**
2. **As a part of this NHDD Project, R&D works for the development of coated particle fuel technology are currently being carried out.**
3. **These technology development for kernel mfg. and PyC and SiC coating as well as their respective characterization techniques.**
4. **Fuel element mfg. technology will be developed from 2007 on.**

KAERI 3

Overall Brief Activities (Long-term R & D Plan)



KAERI 4

Current HTGR fuel R&D activities

❑ **Current activities (fuel mfg.-related)**
- Development of kernel fabrication and coating technology in Lab-scale
- Development of respective **characterization techniques of TRISO-coated elements**
- Start of ZrC coating technology development
- Performance modeling and code development
- Establishment of quality inspection standards (density, PSA, porosity, sphericity)

❑ **Near-term future activities (fuel mfg.-related, within ~5 years)**
- Preparation of small quantity of various types of improved coated (PyC, SiC, ZrC) **particle** fuel specimens with the laboratory-scale equipment
- Start of irradiation test of prepared coated particle fuel specimens in HANARO research reactor in KAERI
- **Start of ZrC-TRISO coating technology development**

❑ **Participation in Gen-IV Program on VHTR fuel-relevant technologies**
- ZrC coating technology
- Preliminary design of irradiation test and PIE
- Analytical codes and D-base for material properties

KAERI 5

1. Status of Fuel Technology - Kernel preparation

KAERI 6

1. Status of Fuel Technology (1) - Kernel

❑ **Kernel Preparation**

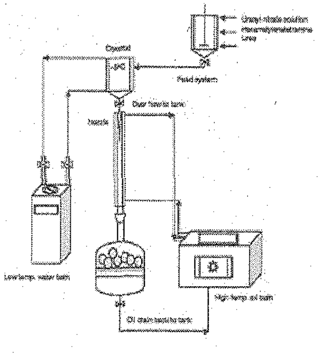
* Installation of Lab.-scaled Gelation Apparatus
- a simple flow diagram & a schematic process flow for the apparatus arrangement were established,
- a laboratory scale apparatus mostly with glassware was constructed with a capacity of 50gU/batch

* Preliminary tests on ADU sphere preparation (*internal, external and total gelation*)

- Experimental matrix preparation on with test variables

- Establishment of optimum condition for ADU sphere preparation

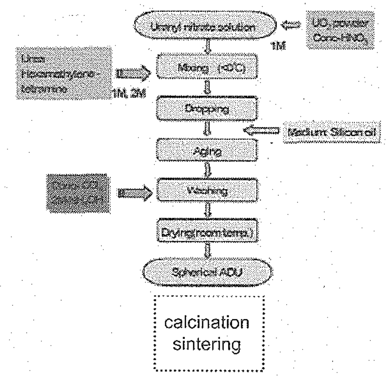
- Possibility of preparation of UO2 and/or UCO by different sintering techniques

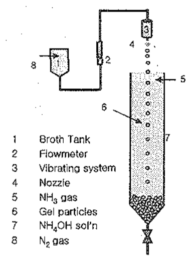


Schematic flow with its apparatus arrangement

KAERI 7

1. Status of Fuel Technology (2) - Kernel

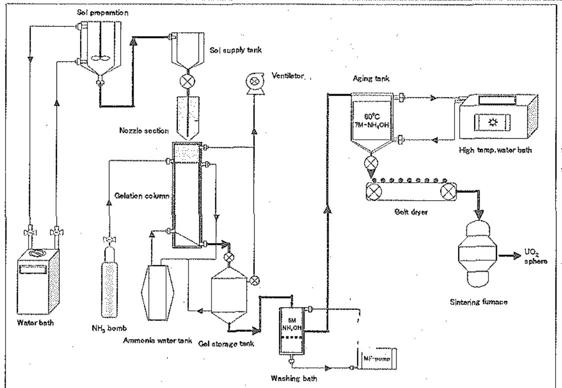




Flow diagram for the internal gelation

KAERI 8

1. Status of Fuel Technology (3) - Kernel



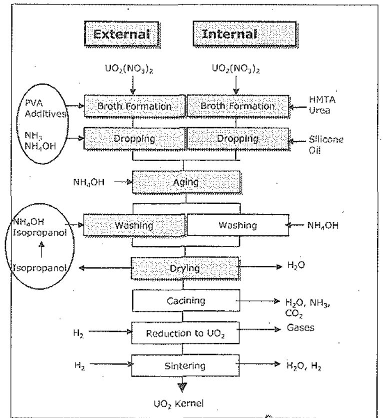
Schematic Diagram of External Process

* Similar apparatus
* Lab-scaled set up (20g)

KAERI 9

1. Status of Fuel Technology (4) - Kernel

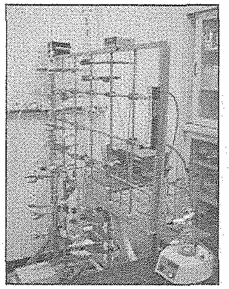
- (U_3O_8) ADUN : 2.9~3.5 Mole-U/L
- Urea : 8 Mole/L (or Solid)
- PVA : 80 g/L dissolved
- Nozzle diameter : Φ0.7 mm
- Vibration Frequency :110 Hz, Amplitude :180
- NH_4OH (Gelation) : 5~7 Mole/L
- Aging time : 60°C, 1 Hr (5~10 Mole/L, NH_4OH)
- Drying : RT, under Air



KAERI 10

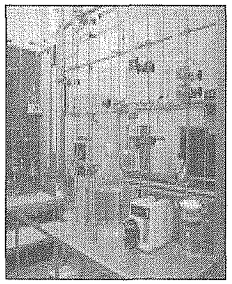
1. Status of Fuel Technology (5) - Kernel

Internal Gelation

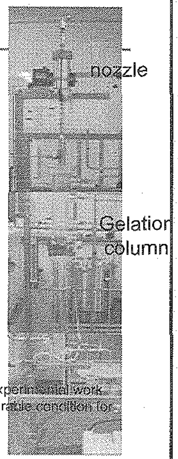


Construction of the Lab. sol-gel arrangement for internal gelation.

External Gelation



External gelation was constructed and experimental work is being carried out in order to find a desirable condition for gel formation,

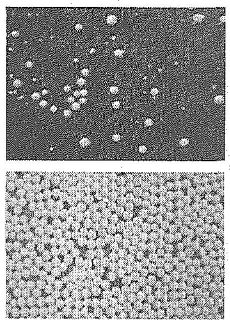


Photographs of gelation equipments for microsphere preparation

KAERI 11

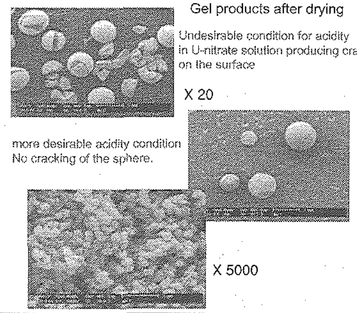
1. Status of Fuel Technology (6) - Kernel

Photograph of ADU microspheres prepared with Internal Gelation



gels formed by internal gelation after washing and before drying.

Gel products after drying

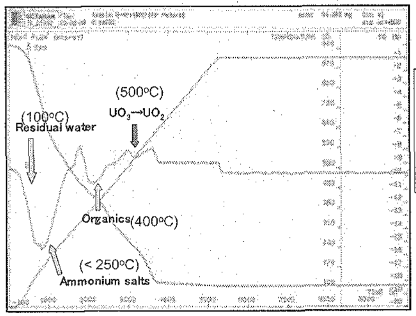


- **morphology of the dried gel products depends not only on the** condition of the formation of the gel **but** on the drying condition
- **careful control of** the atmosphere and temperature **is required for more desirable morphology of the dried gel product.**

KAERI 12

1. Status of Fuel Technology (7) - Kernel

Calcination of Gelled product



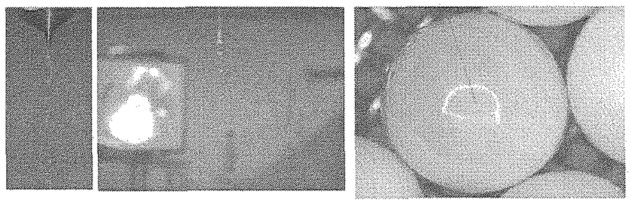
TGA results obtained, with the gel products calcined in Ar-H2 gas mixture atmosphere. The reaction in the calcination was terminated at a temperature lower than 600°C, with removal of residual water in the first step and then the decomposition of ammonium salts and other organics and finally UO_3 phase is reduced to UO_2.

This formation of UO_2 was confirmed by X-ray diffraction.

KAERI 13

1. Status of Fuel Technology (8) - Kernel

Gel formation by External gelation



Nozzle System Improvement (nozzle shape changing)

Droplets formation by External gellation

Photograph of ADU microspheres prepared with External Gelation

KAERI 14

Summary

- ❑ **Installation of Lab.-scaled Gelation Apparatus**
- ❑ **Preliminary tests on ADU sphere preparation**
  (internal, external and total gelation)
- ❑ **Experimental matrix preparation on with test variables**
  (calcination, DTA/TG, nozzle shape)
- ❑ **Establishment of optimum condition for ADU sphere preparation** **(organic, nozzle shape, aging, drying)**

KAERI 15

2. Status of Fuel Technology - SiC-TRISO coating technology

KAERI 16

2. Status of Fuel Technology (1) -coating

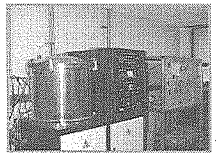
❑ Coating technology

- Installation of laboratory FB-CVD (3 set) coating equipment
- Simulated coating experiment by use of ZrO_2 spheres
- Characterization of each coating layers (buffer, PyC, SiC)
- Simulated spouting experiment by use of ZrO_2
- Design and Mfg. of ZrC coating equipment including chloride decomposer

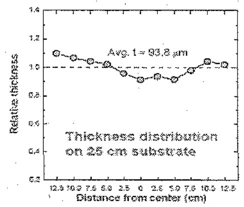
KAERI 17

Develop. of SiC for Advanced Nuclear Reactor (previous results on NMTD) -1

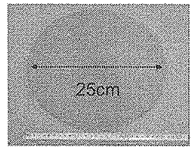
Large Area SiC CVD up to 30cm for Semiconductor Indus.

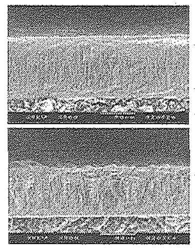


CVD reactor



Thickness distribution on 25 cm substrate





inside

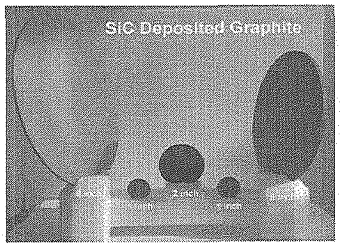
outside

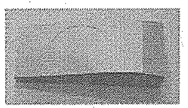
Microstructures of CVD SiC layers

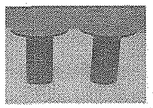
KAERI 18

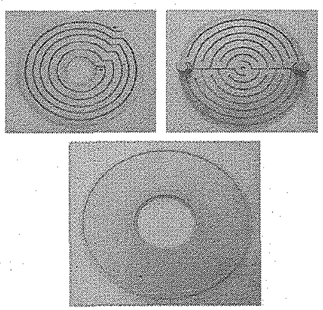
Develop. of SiC for Advanced Nuclear Reactor (previous results on NMTD) -2

Various CVD SiC-coated components





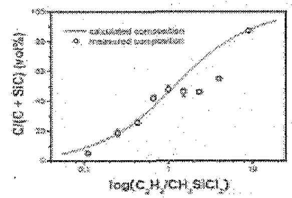


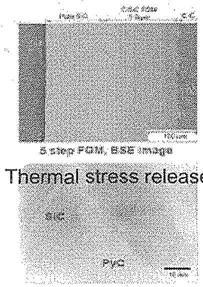


KAERI 19

Develop. of SiC for Advanced Nuclear Reactor (previous results on NMTD) -3

Fabrication of C/SiC FGM Layers by LPCVD





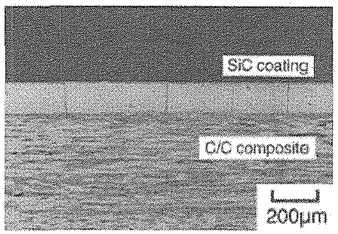
Thermal stress release

HRTEM image of C/SiC (50 vol.% SiC)

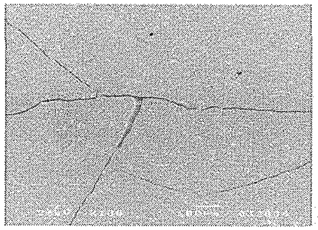
KAERI 20

Develop. of SiC for Advanced Nuclear Reactor (previous results on NMTD) -4

Oxidation Protective SiC Coating for C/C Composites



cross-section


plane-view

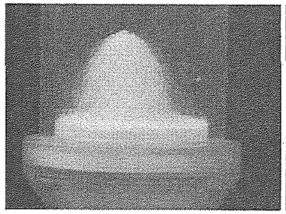
$\alpha_{C/C} < 1.0 \times 10^{-6}/K$

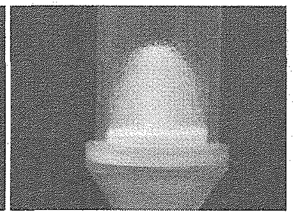
$\alpha_{SiC} = 4.5 \times 10^{-6}/K$

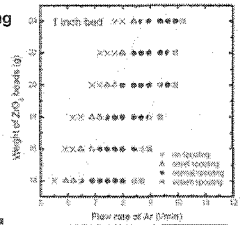
Introduction of C/SiC functionally graded materials (FGM) to reduce the thermal expansion mismatch (CVD, CVR, Melt infiltration, Pack cementation, etc.)

KAERI 21

Spouting Modes of ZrO_2 Beads

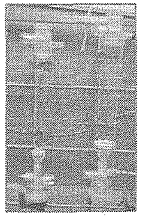

Normal spouting

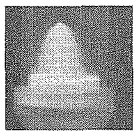

Violent spouting

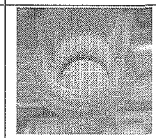
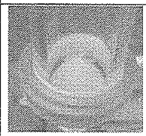
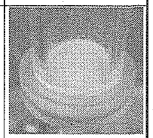


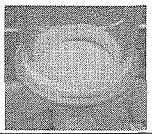
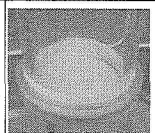
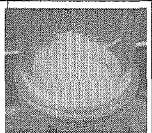
- In order to visibly observe the formation of a fluidized bed with particles of about 600μm in diameter,
- Simulation test was carried out to optimize the formation of the fluidized bed, using a transparent annular column of about 2 inches inner diameter and ZrO2 beads.
- Design of the inlet nozzle for carrier gas plays an important role in the design of fluidized bed (FB) CVD furnaces.

22


Simulation Test Apparatus



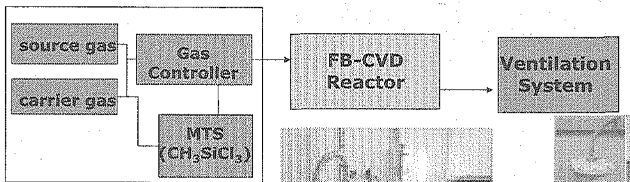
Ar flow rate (slm)	7.6	9.0	11.1
Mode of Fluidization (ZrO_2: 18g)			
	loss	normal	violent

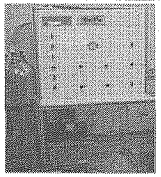
Ar flow rate (slm)	20.9	23.6	25.0
Mode of Fluidization (ZrO_2: 117g)			
	loss	normal	violent

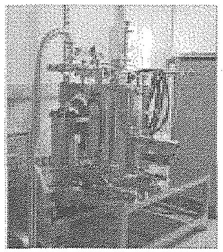
KAERI 23

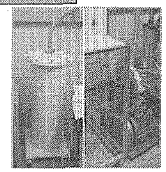
2. Status of Fuel Technology (2) -coating

Fluidized-Bed CVD Coater



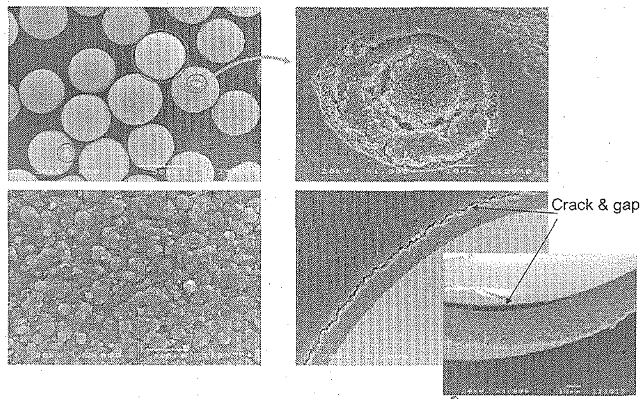

Gas supply control console





KAERI 24

Results SiC Coating *(previous)*

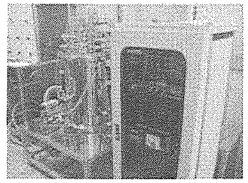


KAERI 25

2. Status of Fuel Technology (3) *-coating*

Parameter Studies

Buffer	Ar + C_2H_2 Conc. of C_2H_2: 50~80% Total flow: 1600~2500 sccm Dep. Temp.: 1200°~1300°C
Inner PyC	Ar + C_2H_2 + C_3H_6 Conc. of hydrocarbon: 30% Total flow: 2000 sccm Dep. Temp.: 1300°C
SiC	Ar + H_2 + CH_3SiCl_3 H_2/MTS = 50~100, Ar/H_2 = 1 Total flow: 2000~5000 sccm Dep. Temp.: 1460°~1550°C
Outer PyC	Same as inner PyC



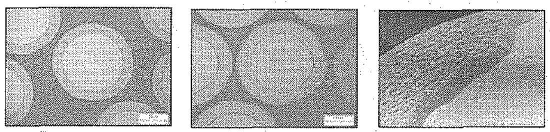
Fluidized bed CVD reactor

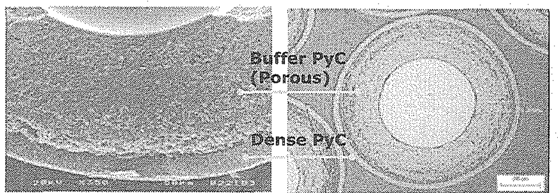
ZrO_2 loading per batch: 7~18g
Bed diameter: 25 mm
Nozzle diameter: 1~3 mm
Angle of the cone: 30°~75°
Continuous coating without unloading after coating each layer

KAERI 26

2. Status of Fuel Technology (4) *-coating*

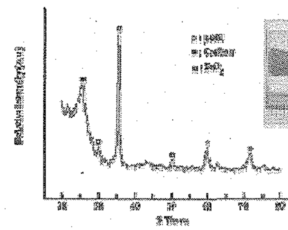
- Optimization of TRISO coating conditions for buffer PyC, dense PyC, and SiC using ZrO_2 simulant kernel



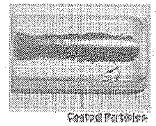


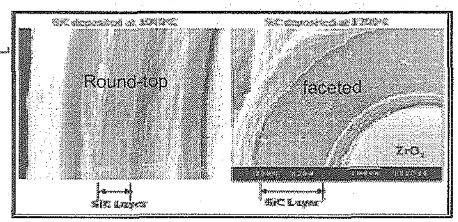
KAERI 27

2. Status of Fuel Technology (5) *-coating*



Phase Analysis of PyC/SiC/PyC layers



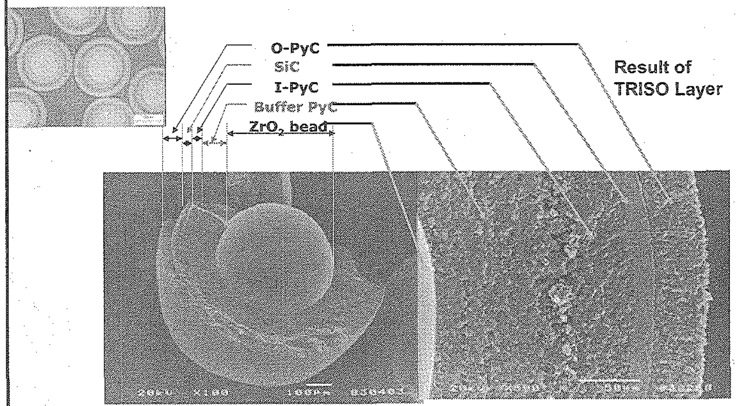


ZrO_2 kernel coated with PyC/SiC/PyC layers

Different morphology with deposited temperature

KAERI 28

2. Status of Fuel Technology (6) - coating



KAERI 29

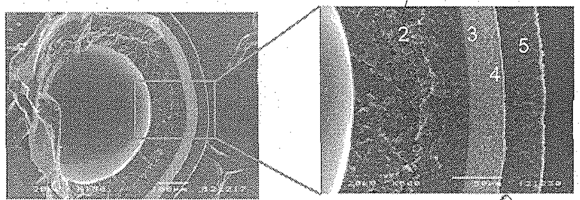
2. Status of Fuel Technology (6)

SiC TRISO - Current Status

- Buffer: 75~80% C_2H_2, 2000 sccm, 1250°C
- Dense PyC: 30% C_2H_2+C_3H_6, 2000 sccm, 1300°C
- SiC: H_2/MTS=50, 3000 sccm, 1500°C

EDS results of coated layer

Spectrum	C	Si
2	99.73	0.27
3	25.22	74.78
4	26.04	73.96
5	99.89	0.11



KAERI 30

Summary

❑ Coating technology

- Installation of laboratory FB-CVD coating equipment
- Simulated coating experiment by use of ZrO_2 spheres
- Characterization of each coating layers (buffer, PyC, SiC)
- Simulated spouting experiment by use of ZrO_2 spheres

KAERI 31

3. Status of Fuel Technology - ZrC coating technology

KAERI 32

3. Status of Fuel Technology - ZrC

- Limitation of SiC
  - can't be used at HT than designed HTGR (currently)
- Failure of SiC coating layer **in triso coated fuel particles**
  - higher performance of fission product retention of the TRISO at high temperatures
  - Attacked chemically by fission product palladium yield from Pu-239
    SiC + 2Pd (Pu-239) → **Pd2Si** + C : melting point 1398°C
  - Cs-137 release
  - Phase transition and pyrolysis above 1700°C
- ZrC
  - High Melting temperature (3540°C) & thermodynamic stability
  - Non Pd corrosion
  - Non coating layer damage up to 2400°C
  - Good-compatibility with structural metals
- ZrC is candidate to replace the SiC coating layer of the triso coated fuel particles

KAERI 33

ZrC coating methods

- **Physical Vapor Deposition**
  - PLD (pulsed laser deposition)
  - Sputtering
- **Chemical Vapor Deposition**
  - Fluidized bed CVD
  - HTCVD
    - Chloride process ($ZrCl_4$)-coventional process, single solid source
    - Bromide process ($ZrBr_4$)- advantage for stoichiometric deposition, toxic process
    - Iodide process (ZrI_4) –low temperature coating (1100°C), nonstoichiometric deposition

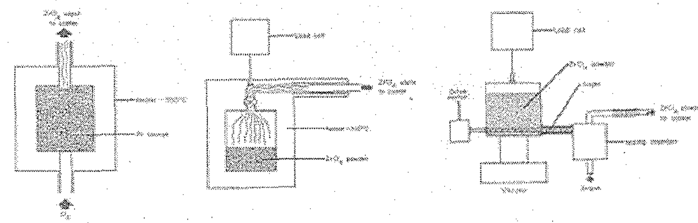
KAERI 34

- **Three ZrC coating methods**
  - Iodide process
    - **Low temperature deposition**
    - Carbon deposition decreased with increasing H_2 supply rate.
      - Suppression of C formation by H_2
    - Zr deposition showed no simple correlation with the H_2 supply rate
  - Chloride process
    - Stiochiometric ZrC : CH_4
    - C-ZrC carballoy, graded portion of the co-deposited C-Zr
      - C_3H_6+$ZrCl_4$: very little ZrC
      - C_3H_6 flow gradually increase or decrease
  - Bromide process
    - The ZrC monophase region exists in a wide composition range of the feed gas mixture
    - Two inhibitor co-exits : H_2, CH_4
    - $ZrBr_4$, CH_4: C/Zr ratio of the deposits to 1.0 and increase the amount of deposition in the ZrC-C two phase region

KAERI 35

$ZrCl_4$ Sublimation ?

- **Chloride process**



$ZrCl_4$ reactor | $ZrCl_4$ vaporizer (Load cell controlled) | $ZrCl_4$ powder feeder (Auger feeder)

Point : → constant supply of $ZrCl_4$ to reactor

KAERI 36

3. Status of Fuel Technology - ZrC

Development of Advanced Fuel, ZrC TRISO

- On-going Activities (2005~)

- **Thermodynamic calculation by SOLGASMIX-PV for screening of parameters**
- **Design and manufacture of ZrC coating system (sublimation system)**
- **Preliminary coating experiments using disc shape substrates (1", 2")**
- **Planning on evaluation of irradiation effects by ion beam**

- Next R&D

* Optimization of deposition condition for FB-CVD coater
* Investigation of microstructure of ZrC coated layer (stoichio., failure, density)
* Modification of ZrCl4 sublimation system for larger-scale coater
* Hydrocarbon pyrolysis behavior → Stoichiometry and density of ZrC

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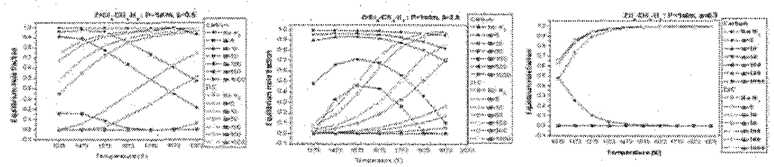
Thermodynamic Equil. Calculation by SOLGASMIX-PV

- **Screening the coating process parameters for the known Zr-source material such as Chloride, Bromide, Iodide based on the thermodynamic calculation**
- **Calculation of the equilibrium composition by direct minimization of the Gibbs energy of a system**
- Considering process parameters for CVD coating

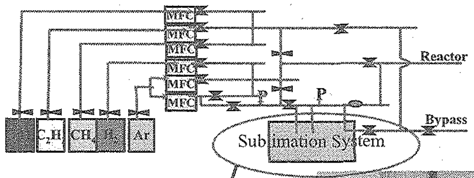
→ α : Input Gas Ratio of H_2/(Zr-source gas+CH_4) ; ($ZrCl_4$ or $ZrBr_4$ or ZrI_4),
β : Input Gas Ratio of Zr/(C+Zr) , Total Pressure, Deposition Temperature, Flow Rate

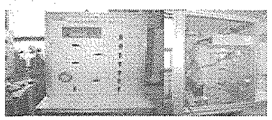


KAERI 38

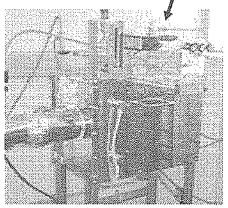
ZrC Coating System

- 2 inch coater
- Chloride Process

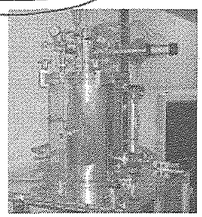




Gas Supplying System



$ZrCl_4$ Sublimation System



Reactor

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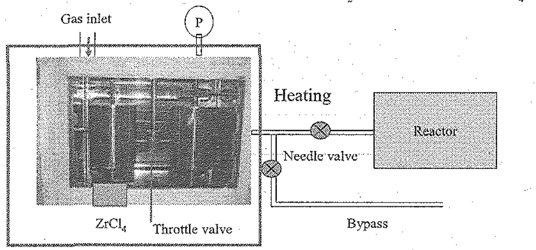
Concept of Zr source Sublimation & Supplying System in the KAERI-Chloride Process system

•Output gas = input gas + generation $\frac{P_{ZrCl_4}}{P_{vessel_2}} = \frac{Q_{ZrCl_4}}{Q_{carrier} + Q_{ZrCl_4}}$



* Control of ZrCl4 pressure
* Control of continuous of ZrCl4 flowing

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Experimental conditions

Sample ID	α	β	H_2-C (sccm)	Ar-C (sccm)	$ZrCl_4$ (sccm)	CH_4 (sccm)	T(℃)	Time (min)	P (torr)	Thickness (㎛)
Z-01	4	0.5	50		50	50	1300	60	10	0.5
Z-02	4	0.8	128		128	32	1400	60	10	
Z-03	4	0.8	128		128	32	1400	180	10	
Z-04	5	0.8		50	108	27	1400	180	10	
Z-05	5	0.6		30	81	54	1400	180	10	19
Z-06	5	0.6		30	81	54	1500	180	10	12
Z-07	5	0.6		30	81	54	1400	180	100	
Z-08	5	0.8		30	108	27	1400	30	10	3
Z-09	5	0.8		30	108	27	1400	180	10	4.6

→ α : Input Gas Ratio of H_2/($ZrCl_4$ gas+CH_4)
β : Input Gas Ratio of Zr/(C+Zr)

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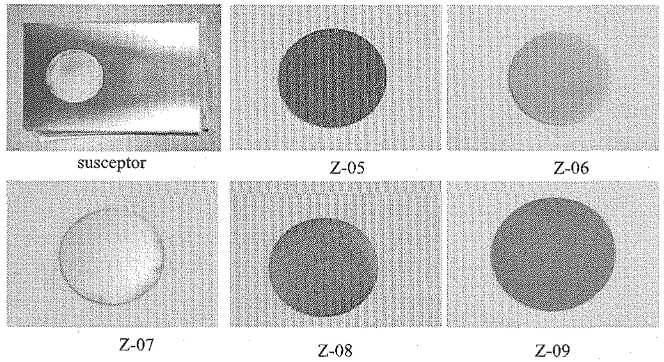
Images of specimens



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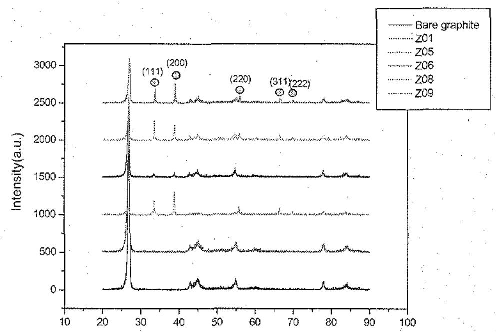
XRD and EDA results



Sample ID	α	β	Ar-C (sccm)	$ZrCl_4$ (sccm)	CH_4 (sccm)	T(℃)	Time (min)	P (torr)	Thickness (㎛)
Z-05	5	0.6	30	81	54	1400	180	10	19
Z-08	5	0.8	30	108	27	1400	30	10	3

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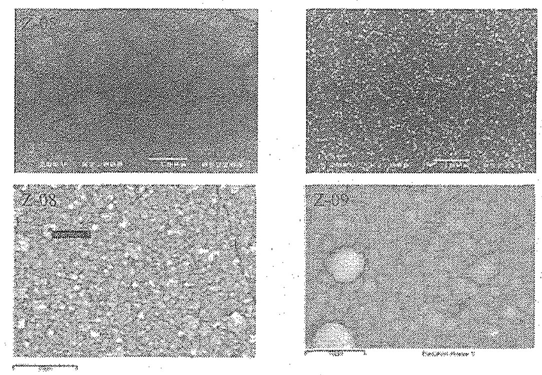
SEM image-surface



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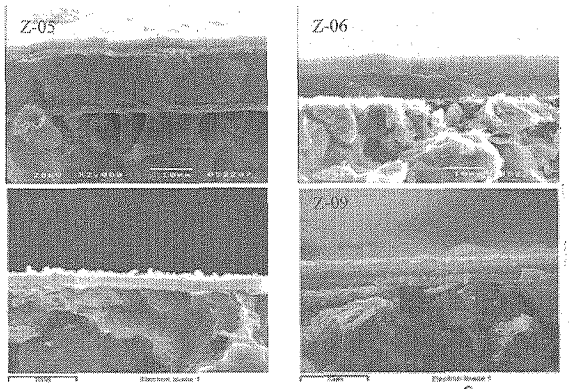
SEM image (cross-section)



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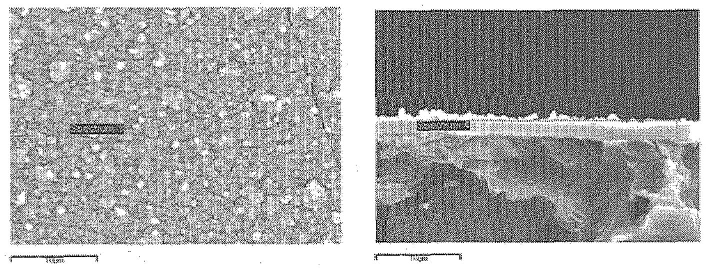
Selected area EDS spectrum of ZrC coated layer



SEM-EDS (at %)

Spectrum 3 Zr : 9.44 % C : 88.7 %

Spectrum 4 Zr : 14.77 % C : 84.02 %

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Summary

- Thermodynamic calculation by SOLGASMIX-PV
- Design and manufacture of ZrC coating system (sublimation system)
- Preliminary coating experiments using disc shape substrates (1", 2")
- Planning on evaluation of irradiation effects by ion beam

- Next R&D
* Optimization of deposition condition for FB-CVD coater
* Investigation of microstructure of ZrC coated layer (stoichio., failure, density)
* Hydrocarbon pyrolysis behavior → Stoichiometry and density of ZrC
* Modification of ZrCl4 sublimation system for larger-scale coater

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4. Status of Fuel Technology (4)
- Code development & Plan for irradiation test/PIE

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4. Status of Fuel Technology (1)

☐ Quality inspection techniques

- Standard ceramography (density, porosity, grain..)
- Installation of PSA (particle size analyzer) equipment
- Anisotropy to be measured by Photo spectrometry (PyC)
- Densities by sink float method
- X-ray micro-radiography (NDE)

- Establishment of Quality Inspection Standards (TR)

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4. Status of Fuel Technology (2)

☐ Develop. of Fuel Performance Analysis Code

- Performance Model development
- COPA(COated Particle fuel Analysis) code

TRISO particle Mechanical behavior (TRISO- stress anal.) : COPA-MECH
TRISO particle Failure : COPA-FAIL
TRISO particle Temperature profile : COPA-TEMTR
TRISO coating layer cracking/separation : COPA-ABAQ

Pebble Temperature : COPA-TEMPEB
Block Temperature : COPA-TEMBL
Fission Product Release : COPA-FPREL
Fuel Material properties : COPA-MPRO

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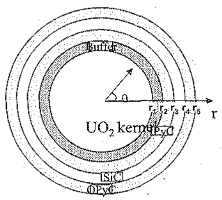
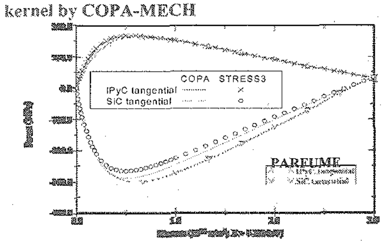
4. Status of Fuel Technology (3)

Coated particle Mechanical behavior Model(COPA-MECH)

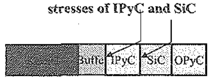
☐ Prediction of stress variation in PyC and SiC layers with Irradiation-induced densification, swelling and creep
☐ Participation in benchmarking in IAEA/CRP-6



☐ Max. Stresses of IPyC and SiC in a TRISO with 500 μm kernel by COPA-MECH



Points with maximum tangential stresses of IPyC and SiC



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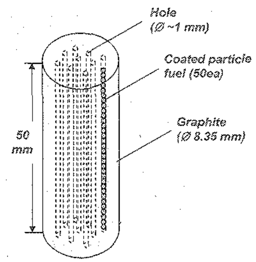
4. Status of Fuel Technology (5)

Irradiation test device to be developed 2005-2007



1. Non-instrumented Capsule
2. Zircaloy-4 tube (graphite rod)
   - OD 9.50 mm, ID 8.35 mm
   - Length 200 mm
   - Atmosphere : He, 1 atm
   - 3 rods (9 holes/each rod, 450 ea)
3. Total No. of particles : 1,350 ea
4. UO_2 weight : ~ 0.93 g (~ 0.80 g U-base)

	Kernel	Buffer	IPyC	SiC	OPyC
Material	UO_2	PyC	PyC	SiC	PyC
Enrichment (wt%U-235)	12	-	-	-	-
Diameter (μm)	500	-	-	-	-
Thickness (μm)	-	95	40	35	40
Density (g/cc)	10.5	1.0	1.9	3.2	1.85
Weight (g)	0.00068	0.00036	0.00036	0.00060	0.00044

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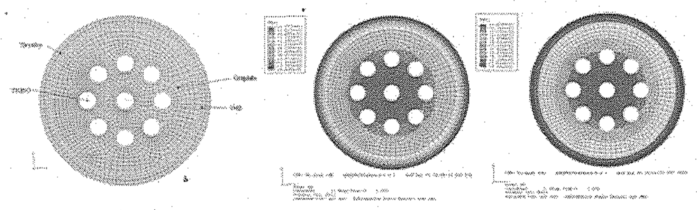
IV. Plan for Irradiation test/PIE

Temp. distribution Preliminary analysis



Geometrical modeling | Cladding : zircaloy-4 | Cladding : Stainless Steel

Future Work

- Capsule design/fabrication
- HANARO core analysis / T distribution analysis

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Future work & Joint Collaboration Proposal

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V. International Collaboration Activities

- ❑ Participation in IAEA-CRP activities (2002)
  "Conservation and application of HTGR Technology: Advances in HTGR Fuel Technology" ; CRP-6
- ❑ Participation in Gen-IV Program for VHTR system (2005)
  - Irradiation test and PIE
  - Material properties /Code benchmark
  - Advanced coating technology
- ❑ GA (USA) / KAERI JDC (2005)
- ❑ Possible International Co-operation
  for early establishment and the improvement of
  - kernel fabrication technology
  - coating technology
  - fuel element mfg. technology
  - characterization and fuel materials analysis
- ❑ Possible Joint Irradiation Test
  of the fuel prepared via process improvement and with improved properties

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Joint Collaboration Proposal (JAEA)

❑ Possible International Co-operation

- Kernel fabrication technology and analysis (...)
- Advanced coating technology
  * *Information exchange for process development*
  * coating process parameter study of ZrC-TRISO
    improvement of poor quality of buffer PyC coating layer;
    → homogeneous density distribution along radial direction
    → the improved process and analysis results
  * development of ZrC coating technology (chloride, bromide)
    → deposition process and equipment
    → characterization methods of ZrC layer (stichio, density..)
  * share the irradiation experience data for HTTR fuel (ZrC)

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1.5 Session 5 IS process development

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1.5.1 Development History of Hydrogen Production Technology in JAEA

Ryutaro HINO and Yoshiyuki INAGAKI

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Summary

As part of the development of the hydrogen production processes, laboratory-scale experiments of a high-temperature electrolysis of steam (HTES) had been carried out with a practical electrolysis tube with 12 solid-oxide cells connected in series. Using this electrolysis tube, hydrogen was produced at the maximum density of 44 Ncm^3/cm^2h at a electrolysis temperature of 950 °C. Thereafter, to improve hydrogen production performance, a self-supporting planar electrolysis cell with a practical size (80 x 80 mm^2 of electrolysis area) was fabricated. In the preliminary electrolysis experiment carried out at 850 °C, the planar cell produced hydrogen at the maximum density of 38 Ncm^3/cm^2h, and the energy efficiency was almost as high as that obtained with the electrolysis tube at 950 °C. However, both electrolysis tubes and planar cells did not keep their integrity in one thermal cycle. Durability of the solid-oxide cell against the thermal cycle is one of the key issues of HTES.

In the presentation, the history of HTES development including its experimental results is explained and the reason why should be discontinued the HTES development overview of the HTTR project is briefly given with emphasis on the return on the investment.

1st JAEA/KAERI Information Exchange Meeting
on HTGR and Nuclear Hydrogen Technology
Oarai, 28-30 August, 2006.

Development History of Hydrogen Production Technology in JAEA

Ryutaro Hino and Yoshiyuki Inagaki
Japan Atomic Energy Agency (JAEA)

Contents

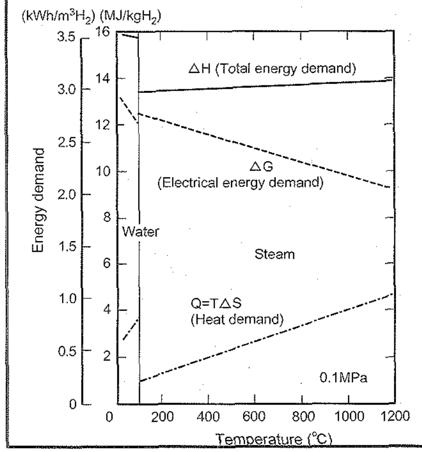
1. High-temperature electrolysis of steam
- 1989 – 1991 Tubular cell
- 1992 – 1995 Planner cell

2. Steam reforming of methane
- 1992 – 1994 Catalyst test
- 1994 – 1996 Design of out-of-pile demonstration test facility
- 1997 – 1999 Construction
- 2000 – 2003 Demonstration test

3. Thermochemical water splitting
- from 70's – 1990 Study on several thermochemical processes
- from 1990 – IS process

1

1. High-temperature Electrolysis of Steam - Energy demand for water and steam electrolysis -



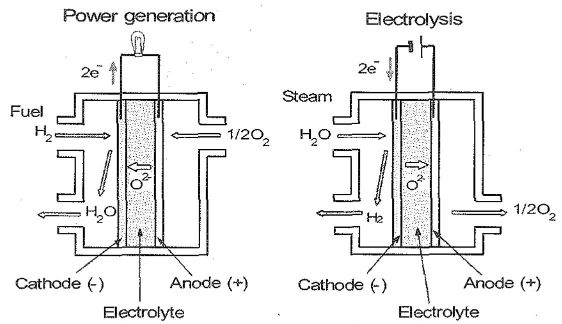
The total energy demand (ΔH) for water and steam decomposition is the sum of the Gibbs energy (ΔG) and the heat energy (TΔS).

The electrical energy demand, ΔG, decreases with increasing temperature; the ratio of ΔG to ΔH is about 93 % at 100 °C and about 70 % at 1000 °C.

The HTES can produce hydrogen with lower electric power than the conventional water electrolysis.

2

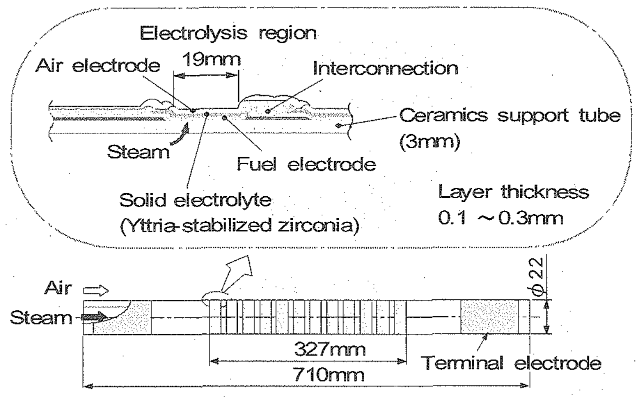
Principle of High-Temperature Electrolysis of Steam - Reverse reaction of solid oxide fuel cell -



	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	$H_2 + 1/2O_2 \rightarrow H_2O$	$H_2O \rightarrow H_2 + 1/2O_2$

3

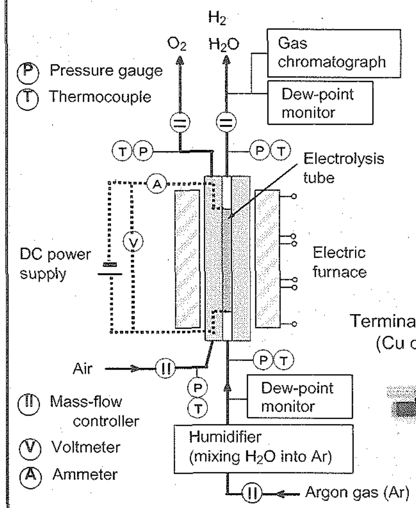
Structural Drawing of Electrolysis Tube with 12 Electrolysis Cells (Tubular type cell)

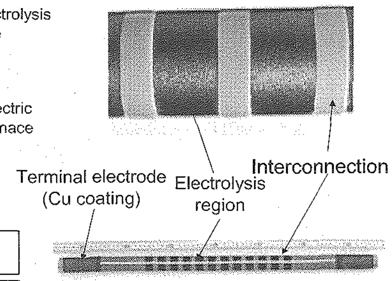


Electrolysis tube had been developed for SOFC.

4

Schematic Diagram of Experimental Apparatus and Outer-View of Electrolysis Tube



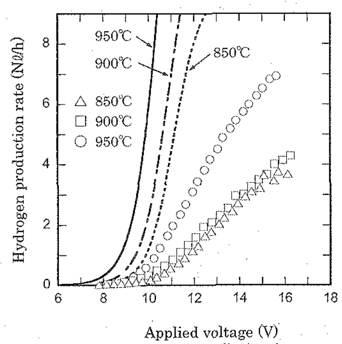


Electrolysis tube had been developed for SOFC.

5

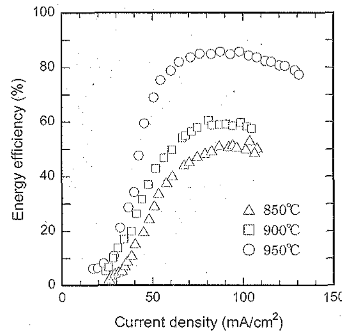
Test Results Obtained with Electrolysis Tube

To increase H_2 production performance, steam should be supplied directly to fuel electrode without support tube.



Relation between applied voltage and hydrogen production rate

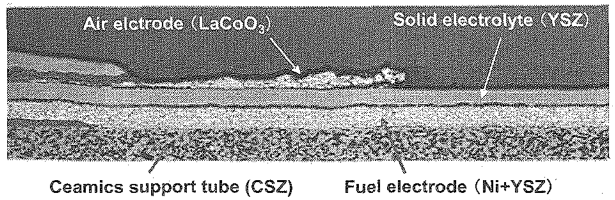
Energy efficiency = LHV of generated hydrogen / Applied power

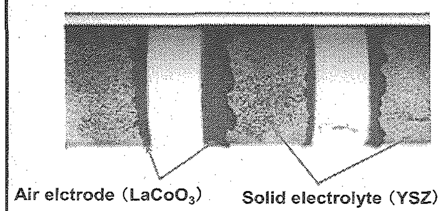


Relation between current density and energy efficiency

6

Outer View of Electrolysis Tube after One -Thermal Cycle



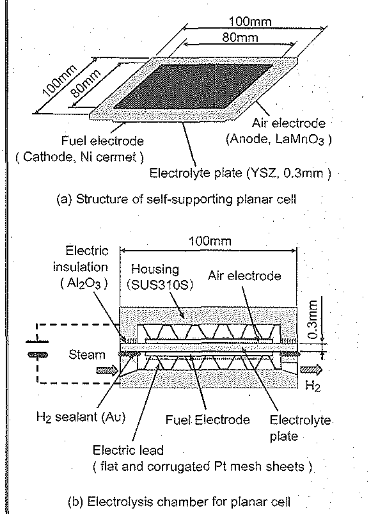


After one-thermal cycle operation, it was observed that large parts of the anode layers had been separated from the electrolyte layers.

This indicates that the durability of the cell against thermal cycles, especially the durability of the air electrode (anode) layer, is one of the key issues of HTES.

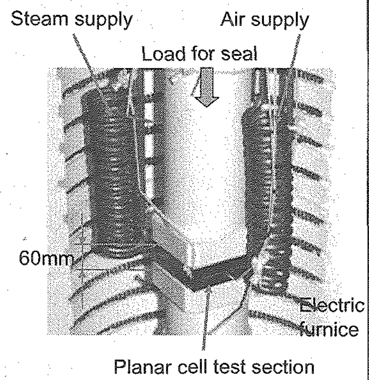
7

Self-Supporting Planar Cell



(a) Structure of self-supporting planar cell

(b) Electrolysis chamber for planar cell

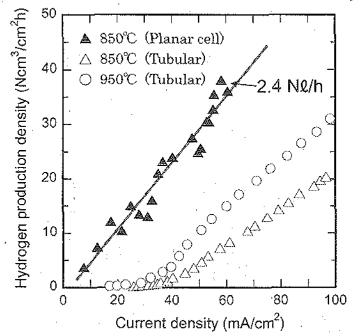


Planar cell test section

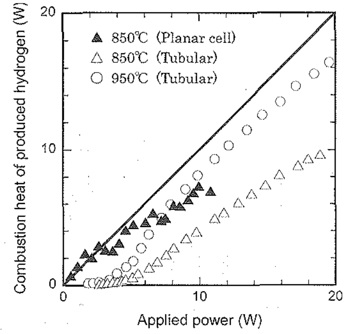
8

Test Results Obtained with a Planar Cell

The planar cell showed a good energy efficiency: the energy efficiency of the planar cell was around 0.73 at 2.4 Nℓ/h, which was almost the same value of the electrolysis tube obtained at 950 ℃, which was 0.79.



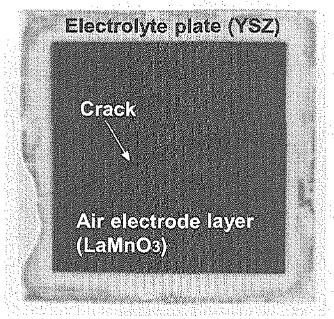
Relation between current and hydrogen production densities



Relation between applied power and combustion heat of generated hydrogen

9

Outer View of Self-Supporting Planar Cell after One-Thermal Cycle



After the experiment, a crack crossing the cell was observed, which could have been caused by the thermal expansion due to the Joule heating.
In designing a module consisting of stacked planar cells, special relief structures against the thermal expansion should be installed, which are also seem to be necessary for providing both seal and electric insulation performances.

10

Key Engineering Issues on High-Temperature Electrolysis of Steam

- To increase energy efficiency, ohmic loss of the cell is should be reduced by
  - ・thinning electrolyte and electrode layers with keeping strength
  - ・reducing contact resistance between electrode and lead plate (planar cell)
- To increase durability against thermal cycling, it is necessary to raise bonding force of the anode layer to the electrolyte layer while considering thermal expansion difference of these layers.

⇩

In those days (about 10 years ago), long-term developments was expected to be needed to solve above issues.
Considering the return on the investment, we decided to halt the study on the high-temperature electrolysis of steam.

⇩

The INL team (Leader : Steve Herring) is developing this technology by using remarkable progressed planar cells, and show much better experimental results than ours.
Though they are trying to solve issues above mentioned, it would be very hard to establish mass-production technology as an industrial hydrogen process.

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Contents

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2000 – 2003 **Demonstration test**

3. Thermochemical water splitting

from 70's – 1990 **Study on several thermochemical processes**

from 1990 – **IS process**

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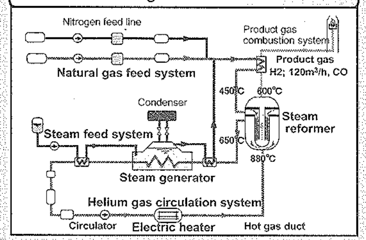
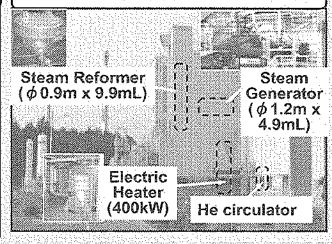
2. Steam Reforming of Methane
- Out-of-pile demonstration for HTGR hydrogen production -

Feature of test facility
- ➢Simulate key components downstream from IHX
- ➢Heat helium with electric heater instead of nuclear reactor
- ➢Perform test as the same temp. and press. conditions as those of HTTR, and 1/30 flow rate

Schematic Diagram of Simulation Test



Outside view



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Simulation Test on Controllability

➢ Experimental condition
- Helium gas temperature at steam reformer (SR) inlet : 840°C
- Helium gas pressure at SR inlet : 4.1MPa

➢ Experimental procedure

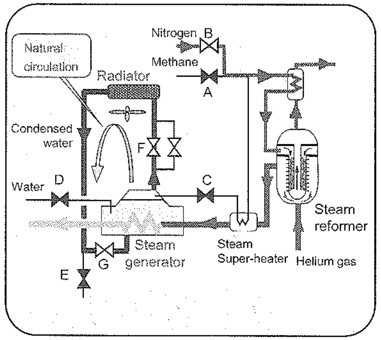
(1) Stop methane feed to SR
: close stop valve A

(2) Start nitrogen feed to SR
: open stop valve B

(3) Stop steam feed to SR
: close stop valve C

(4) Stop water feed to SG
: close stop valve D

(5) Start natural circulation of steam and condensed water between SG and radiator
: close stop valve E
and open stop valve F and G



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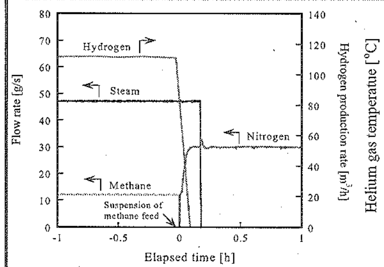
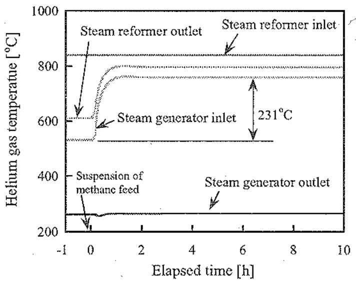
Simulation Test Results on Controllability

The steam generator (SR) could work well as an auxiliary heat sink so as to mitigate the fluctuation of helium-gas temperature from the hydrogen facility.





Fluctuation range of helium gas temperature at SG outlet
: -5.5 ~ +4.0°C

Ref.: H. Ohashi et al., "Development of Control Technology for HTTR Hydrogen Production System with Mock-up Test facility –System Controllability Test for Loss of Chemical Reaction," Nucl. Eng. Des., to be published

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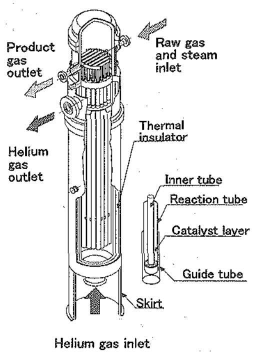
R&D on High Temperature Chemical Reactor

Objective : Development of high temperature chemical reactor (For SO_3 decomposition reactor of IS Process)



Technical problem

(a) Enhancement of He heat transfer
→ Fin installed at outer surface of chemical reactor tube
(b) Enhancement of heat utilization efficiency
→ Bayonet-type reaction tube
(c) Countermeasure against thermal expansion of reaction tube
→ Bayonet-type

Current status

Performance test of the chemical reactor with single reaction tube has been carried out in simulation test.

Ref.: T. Nishihara et al., "Flow scheme and Controllability of the HTTR Hydrogen Production System," JANS, Vol.2, No.4, 517-524 (2003), in Japanese

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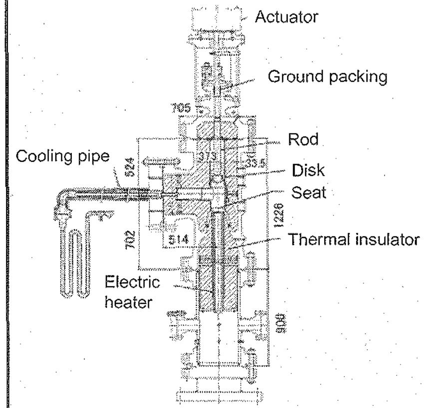
Mock-up Model



Main Specifications
- Type : Angle valve
- Scale : 1/2
- Pressure : 4.5MPa
- Temperature : 900℃
- Inner diameter of seat : 100mm
- Thickness of internal thermal insulator : 117～129.5mm

Ref.: Y. Inagaki et al., "Research and Development on System Integration Technology for Connection of Hydrogen Production System to HTGR," Nucl. Tech., to be published in Feb., 2007

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1.5.2 Status of IS Process Development

Gab-Jin HWANG and Ki-Kwang BAE

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Summary

In Korea, the Nuclear Hydrogen Development and Demonstration Project have started since 2004. Among thermochemical cycles to produce hydrogen from water, IS (Iodine-sulfur) process was selected to connect to VHTR (Very High Temperature Gas Cooled Reactor). In the KIER (Korea Institute of Energy Research), IS process is under investigation with KAERI (Korea Atomic Energy Research Institute) and KIST (Korea Institute of Science and Technology). IS process composes of three main reactions, sulfuric acid decomposition, Bunsen reaction, HI concentration/decomposition. Electro-electrodialysis(EED) method is used for concentration of HI and membrane reactor is used for decomposition of HI and separation hydrogen from HI simultaneously. These two methods are focused to improve thermal efficiency.

The small-scale apparatus built up in Nov. 2005. The apparatus was designed to produce hydrogen at the maximum rate of 20Nℓ /h, and is made of glass and Teflon. The operation is carrying out at atmosphere condition. In the small-scale apparatus, the area of EED cell is about $600cm^2$, and 13 numbers of membranes (membrane length, 15cm) pack in membrane reactor. Two membrane reactors were connected to a series. The closed-loop operation was started in May, 2006.

It is carry out the basic research in pressurrized condition for three reactions to design a laboratory scale apparatus ($1Nm^3/h$) which made up metal material in 2006~2008. The lab.-scale apparatus will be built up in 2009, and the closed-loop operation will be carried out in 2010, 2011 to acquire knowledge on process control and to establish the detailed process scheme required for the scale-up experiment. The laboratory scale closed-loop apparatus (reactors, separators, heat exchanger, line, pump etc.) will be fabricated using the materials selected.

Status of IS process development

The 1th JAEA-KAERI Information Exchange Meeting on HTTR and Nuclear Hydrogen Technology
2006.8.28~8.30

2006. 8. 29

Gab-Jin Hwang & Ki-Kwang Bae

Hydrogen Energy Research Group
Korea Institute of Energy Research

한국에너지기술연구원

Hydrogen project to go to hydrogen economy in Korea

○ 21C Frontier High Efficiency Hydrogen Production, Storage, Utilization Research Development Project (2003.10~2013.3., MOST)
- Hydrogen production : Steam Methane Reforming, Electrolysis, Biological method, Photocatalystic method, Thermochemical water-splitting method using solar heat
- Hydrogen Storage : Metal hydride, nano-materials etc.
- Hydrogen Utilization : Linear engine, Hydrogen sensor (except Fuel Cell)
- Budget : 10 BWon/year (2006)

→ First hydrogen refueling station open in Korea (2006.8.25)

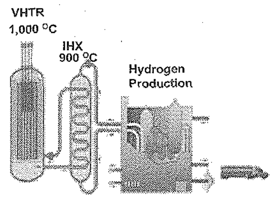
○ Hydrogen & Fuel Cell Development Project (2004.4~2009.3., MOCIE)
- Hydrogen production : Hydrogen refueling station using fossil fuel
- Fuel cell vehicle
- Fuel cell for home use
- Power generation using Fuel cell
- Budget : 40 BWon/year (2006)

○ Nuclear Hydrogen Production Development Demonstration Project (2004.3~2011.3., MOST)
- VHTR & IS process development
- Budget : 10 BWon/year (2006)

Why need nuclear hydrogen production in Korea?

To satisfy hydrogen-demand after 2020, large scale nuclear hydrogen production method is the most promising system

- Hydrogen-demand in 2020 : 18.87 BNm^3/hr [1)]
- Solving method of Environmental problem such as CO_2 emission
  - Carbon tax (25\$/t-CO_2, 2006.1.)
  - Korea is expected to join Kyoto protocol in 2013
- Hydrogen production using fossil fuel is one of now very useful method
  - release CO_2 gas, need CO_2 capture etc.



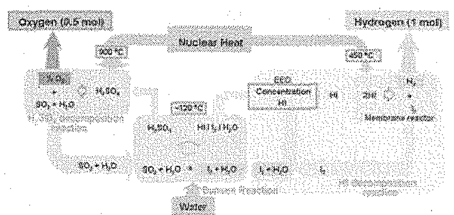
1) http://www.h2fc.or.kr/

→ **"Nuclear hydrogen production"**

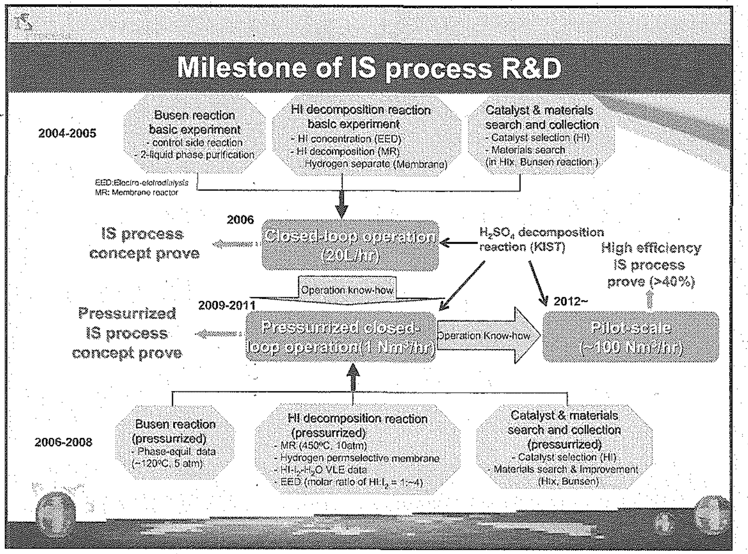
IS (iodine-sulfur) Process

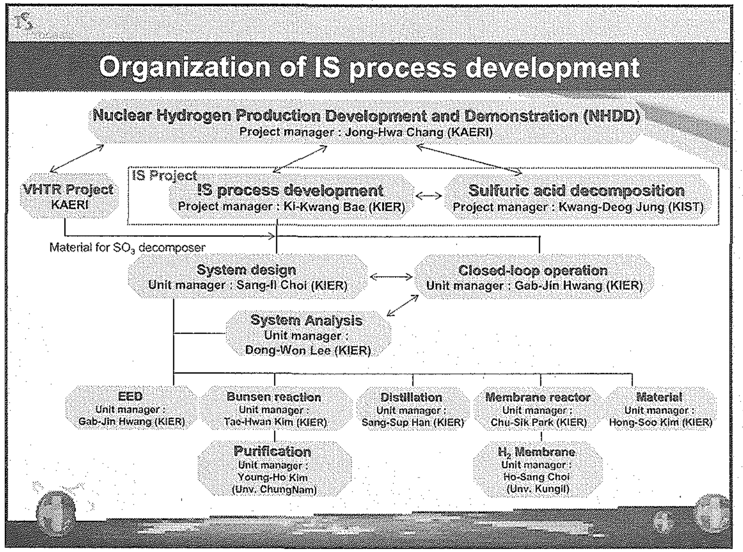
$2H_2O + I_2 + SO_2$	~ 100°C →	$2HI + H_2SO_4$	(exothermic)
$2HI$	400 ~ 500°C →	$H_2 + I_2$	(endothermic)
H_2SO_4	~ 850°C →	$H_2O + SO_2 + (1/2)O_2$	(endothermic)

Using nuclear heat without CO_2 emission



Merit
- High efficiency (target : >40%)
- Closed-cycle (no by-products)
- Large scale hydrogen production
- Low hydrogen production cost





IS process development in pressurrized condition

○ Core technology development in Bunsen reaction

Sulfuric acid phase; HIx phase

$SO_2 + 16\ H_2O + 1\sim9\ I_2 \rightarrow [H_2SO_4 + 4\ H_2O] + [2\ HI + 2\sim8\ I_2 + 10\ H_2O]$

- Reactor design
  - ⦿ Reactor & separator optimization

-2-liquid phase separation & purification technology development to optimize reaction condition

- Side reaction control technology development
  - ⦿ Restrain of H_2S and S formation

$H_2SO_4 + 8HI \rightarrow 4I_2 + 4H_2O + H_2S$

$6HI + H_2SO_4 \rightarrow 3I_2 + 4H_2O + S$

IS process development in pressurrized condition

○ Core technology development in HI decomposition reaction

Electro-electrodialysis; Distillation

$[2\ HI + 2\sim8\ I_2 + 10\ H_2O] \rightarrow$ [HI concentration] $\rightarrow$ [HI/(I_2+H_2O) separation]

Membrane reactor

$\rightarrow$ [HI decomposition & separation] $\rightarrow H_2$

- Reactor design for high performance & large scale treatment
  - ⦿ Electro-electrodialysis cell
  - ⦿ Membrane reactor

- Security of VLE data for HI-I_2-H_2O composition

IS process development in pressurrized condition

○ Core technology development of closed-loop operation

- Control technology development without loss of recycled I_2 and SO_2 in process
- Maintenance technology development of steady state
- Process improvement & process analysis for IS process establishment
- Operation technology development connect with He loop

→ **Closed-loop operation in atmosphere pressure (20L/hr)**
⊙ **Verify of electro-electrodialysis + distillation + membrane reactor system**

→ **Lab.-scale (1Nm^3/hr) closed-loop operation in pressurrized condition**
⊙ **Verify of optimum process**
⇨ Process improvement (efficiency) : heat exchanger etc.

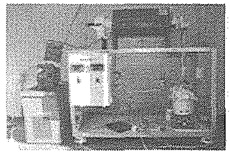
→ **Pilot-scale (100Nm^3/hr) closed-loop operation in pressurrized condition**
⊙ **Verify of high efficiency IS process (>40%)**

IS process development in pressurrized condition

○ Core technology development in catalyst and materials

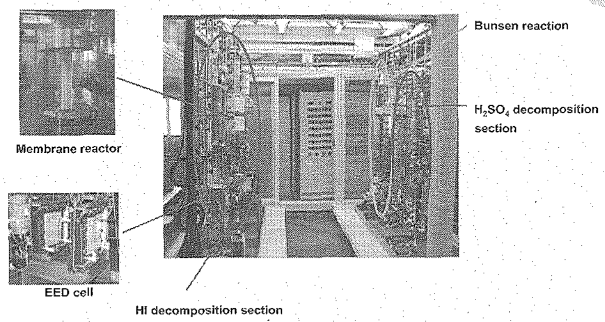
- Catalyst selection for HI decomposition

- Material search and improvement in HIx and Bunsen reaction condition



Material corrosion test in HIx gaseous mixture

Closed-loop operation apparatus (~20ℓ/hr-H_2)



Status of closed-loop operation

○ Sulfuric acid decomposition section was preliminary operated to 3 times with the assistance of KIST

○ HI decomposition section will be operated in next month (2006.9.)

○ Bunsen reaction section : 2006. 10.

○ Closed-loop operation : 2006. 11. ~

1.5.3 Overview of IS Process Development in JAEA

Kaoru ONUKI, Shinji KUBO, Atsuhiko TERADA, Jin IWATSUKI, Hiroyuki OKUDA, Seiji KASAHARA, Nobuyuki TANAKA, Yoshiyuki IMAI, Hiroki NOGUCHI, Nariaki SAKABA, and Ryutaro HINO

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onuki.kaoru@jaea.go.jp

Summary

JAEA has been conducting research and development on thermochemical IS process for hydrogen production from water. Laboratory-scale hydrogen production of 1 NL/hr was completed in 1997, where closed-cycle operation conditions such as to suppress the occurrence of side reactions was demonstrated. In 2004, bench-scale hydrogen production was demonstrated for one week with the hydrogen production rate of 30 NL/hr owing to the developed methodology for controlling the closed-process and to the developed process monitoring methods. As the next stage of process development, a pilot test is under planning, where hydrogen production will be demonstrated by a test apparatus made of industrial materials using an electrically-heated helium gas as the heat source. At present, various studies are under way for the pilot test, which covers development of components, development of codes, etc.

Overview of IS Process Development at JAEA

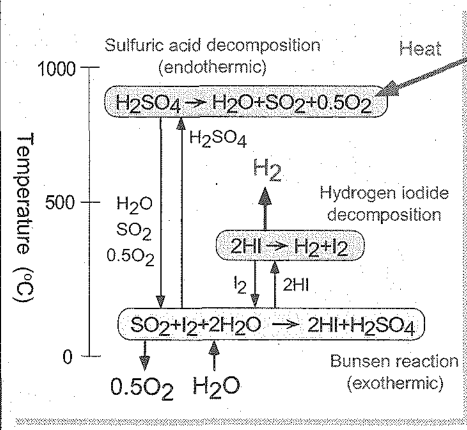
1st JAEA/KAERI Information Exchange Meeting, Oarai, August 28-30, 2006.

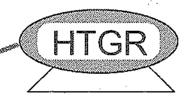
K. Onuki, S. Kubo, A. Terada, J. Iwatsuki, H. Okuda, S. Kasahara, N. Tanaka, Y. Imai, H. Noguchi, N. Sakaba, and R. Hino

Nuclear Applied Heat Technology Division
Nuclear Science and Engineering Directorate
Japan Atomic Energy Agency (JAEA)

Hydrogen production from water

Thermochemical IS Process





- produces hydrogen by water splitting using heat of lower than 1000°C
- needs no feed of reactants except water (closed cycle)

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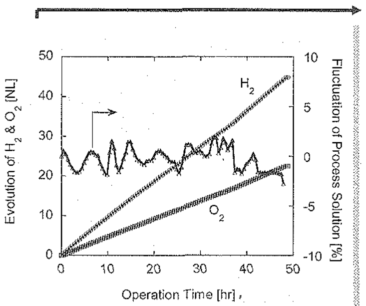
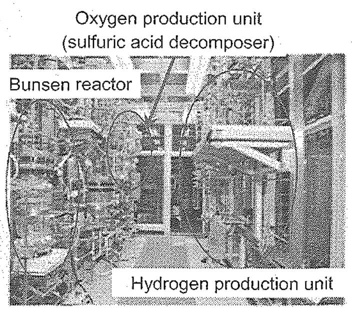
Hydrogen production tests at JAEA



Lab. Test (1NL/h)
showed the possibility of continuous closed-loop hydrogen production based on the enlarged chemical data base.

Bench Test (1999-2004)
developed the process control method under modified conditions using an glass apparatus.

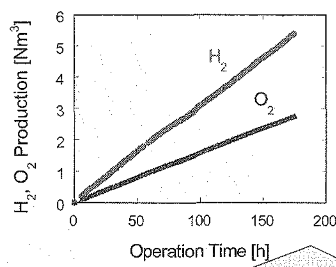


Ref) S. Kubo et al., Proc. GLOBAL 2005, Tsukuba, Japan, Oct. 9-13, 2005, Paper No.474. 3

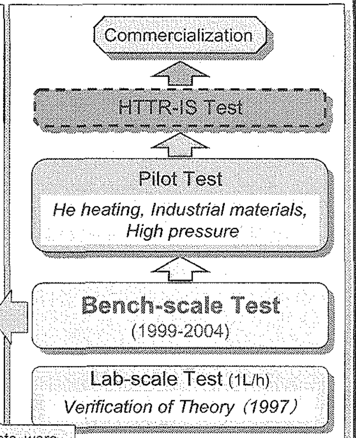
Results of Bench Test and ...

Completion of Hydrogen Production (June, 2004)

Continuous hydrogen production was successfully achieved with the hydrogen production rate of ca. 31NL/h for 1week.

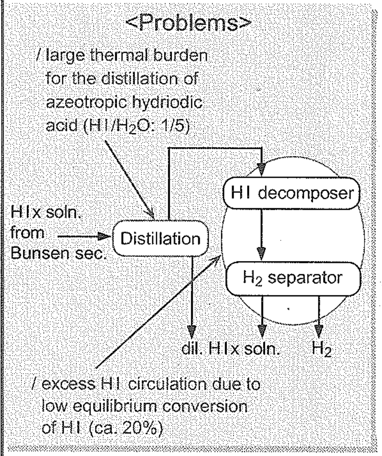


Automatic control system with ultra-sonic detectors etc. were developed for the control of the Bunsen reaction.



Ref) S. Kubo et al., Proc. GLOBAL 2005, Tsukuba, Japan, Oct. 9-13, 2005, Paper No.474. 4

For efficient H_2 production,



<Approach>

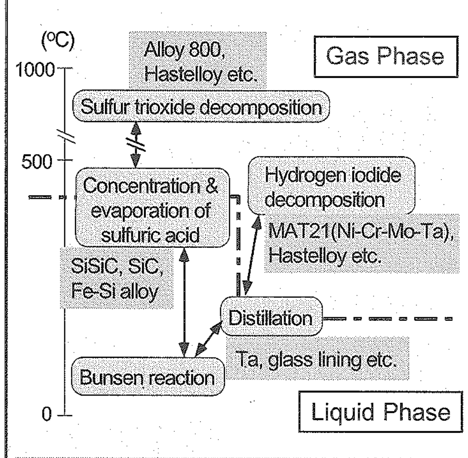
(1) Extractive distillation
Destroy the azeotrope with H_3PO_4

(2) Reactive distillation
Shift the azeotropic composition at elevated pressure (e.g. 20bar).
Carry out the decomposition in the distillation column.

(3) Membrane separation
Preconcentrate the HIx soln. by electrodialysis or pervaporation.
Enhance the one-pass conversion by membrane reactor.

5

As for the materials of construction,



Candidate materials has been screened by corrosion tests in the process condition.

R&D is required for the components used in the boiling sulfuric acid environments.

ex) hybridization of corrosion resistant material and pressure resistant material

6

Next step : Pilot Test

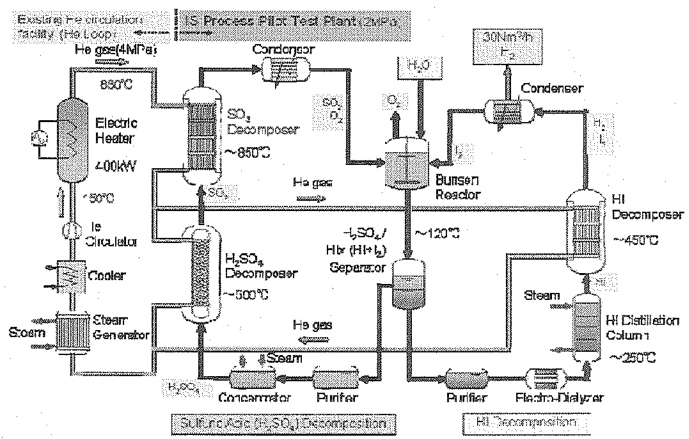
On the basis of the hydrogen production test results and know-how obtained with the bench-scale test apparatus and other R&Ds

	Bench-scale Test	*Pilot Test*	HTTR-IS Test nuclear demonstration
Hydrogen production rate	~ 0.03 m³/h	~30 m³/h	~1000 m³/h
Heat supply	Electrical heater	Heat exchanger with helium gas (Electrical heater 0.4MW)	Heat exchanger with helium gas (Nuclear heat 10MW)
Material of chemical reactors	Glass	Industrial material (SiC, coated)	Industrial material
Pressure of chemical process	Atmospheric pressure	High pressure (up to 2MPa)	High pressure (up to 2MPa)

To develop the components and to confirm continuous hydrogen production under simulated HTGR operation conditions.

7

Pilot test plant (tentative)



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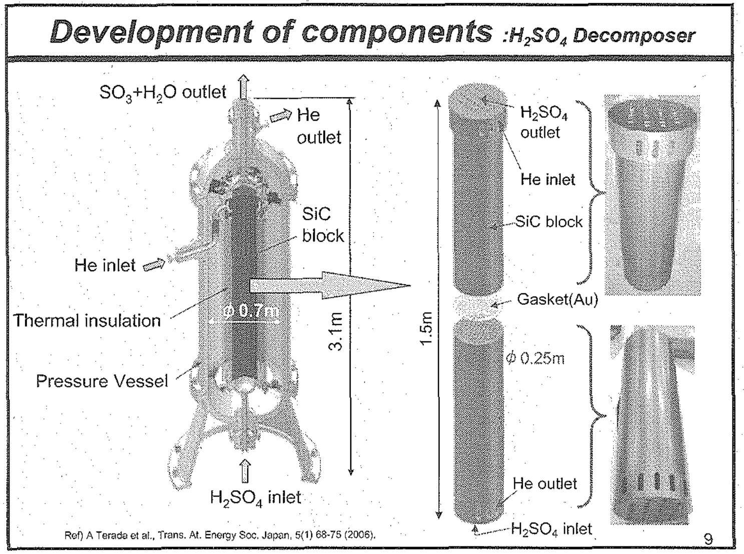
Development of components :H_2SO_4 Decomposer
SO_3+H_2O outlet
He outlet
SiC block
He inlet
Thermal insulation
φ 0.7m
3.1m
Pressure Vessel
H_2SO_4 inlet
1.5m
H_2SO_4 outlet
He inlet
SiC block
Gasket(Au)
φ 0.25m
He outlet
H_2SO_4 inlet
Ref) A Terada et al., Trans. At. Energy Soc. Japan, 5(1) 68-75 (2006).
9

1.5.4 Corrosion of Selected Materials in Sulfuric Acid for IS Process Application

Dong-Jin KIM, Hong Pyo KIM, Hyuk Chul KWON, Han Hee LEE, Woo Seog RYU and Yong Wan KIM

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Korea Atomic Energy Research Institute (KAERI)
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Summary

Some results of corrosion test for various materials in liquid sulfuric acid were presented. According to JAEA and GA reports, they recommended Fe-Si, SiC and Si_3N_4 as candidate materials in concentrated sulfuric acid of high temperature. However, there are some limitations for these materials. Ceramics such as SiC and silicon nitride is very brittle. Therefore, optimum material should be still found(or developed), considering corrosion resistance, machinability and so on. For this goal, various materials were tested by using immersion method and polarization method at KAERI.

In boiling 50wt% H_2SO_4, Pt, Ta, Zr and SiC showed excellent corrosion resistance. In boiling 98wt% H_2SO_4, Fe-Si and SiC showed excellent corrosion resistance while Pt and Ta showed intermediate corrosion resistance. From the corrosion rate for Fe-Cr alloys obtained in boiling 98wt% sulfuric acid, we found that the corrosion rate was decreased with the Cr content. The high corrosion resistance of the Fe-Cr alloys in most environments is attributed to an enrichment of the Cr in the passive film on the Fe-Cr alloys. In spite of Cr enriched passive film, corrosion rate is still too high for application. From the corrosion rate for Fe-Si alloys obtained in boiling 98wt% sulfuric acid, it was found that the corrosion rate was decreased with the Si content leading to the conclusion that Si is essential to corrosion resistance in concentrated sulfuric acid of high temperature.

Corrosion rate of Fe-Si and SiC decreased with time and finally the weight gain was observed. From the surface composition analysis, it was observed that the composition of the specimen after corrosion test includes oxygen meaning that passive film is formed in corrosion environment.

From the polarization curves for various alloys in 30wt% sulfuric acid and 50wt% sulfuric acid at room temperature, the measured current density decreased as the Si content increased. From the analysis of the polarization curve, through the stable passivation, the smaller passive current was passed with the Si content leading to low corrosion rate. Using polarization test, corrosion behavior of various materials can be evaluated and hence the materials can be screened easily as a function of the temperature, concentration and impurity.

For commercial plant which is operated for a long time, energy efficiently and safely, the material having corrosion resistance and ductility or toughness should be found with much effort. So, a collaborative research will be needed for this goal. Collaborative research can be a kind of periodical information exchange, round robin test for the same task or complementary research having the separate tasks.

Corrosion of Selected Materials in Sulfuric Acid for IS Process Application

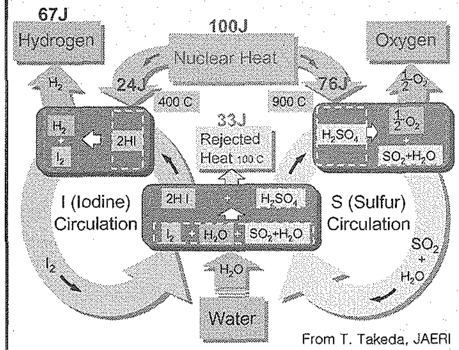
JAEA, Japan
Aug. 28~30

Dong-Jin Kim*, Hong Pyo Kim, Hyuk Chul Kwon, Han Hee Lee, Woo Seog Ryu and Yong Wan Kim

Korea Atomic Energy Research Institute

KAERI — Assessment of corrosion characteristics and development of remedial technology in nuclear materials 1

Iodine-Sulfur Process



$2HI \rightarrow H_2+I_2$

$H_2SO_4 \rightarrow 1/2O_2 + SO_2+H_2O$

$+ \quad I_2+SO_2+2H_2O \rightarrow 2HI+H_2SO_4$

$H_2O \rightarrow H_2+1/2O_2$

From T. Takeda, JAERI

KAERI — Assessment of corrosion characteristics and development of remedial technology in nuclear materials 2

Iodine-Sulfur Process

- **Bunsen Reaction**
  - $9I_2 + SO_2 + 16H_2O \rightarrow (2HI + 10H_2O + 8I_2) + (H_2SO_4 + 4\ H_2O)$ @ 120°C
  - Bunsen reaction, proceeds exothermically in the liquid phase and produces two immiscible aqueous acid phases.
- **HI Decomposition**
  - $2HI \rightarrow H_2 + I_2$ @ 220°C
  - HI decomposition step with a small endothermic heat reaction.
- **Sulfuric Acid Decomposition**
  - $H_2SO_4 \rightarrow SO_2 + H_2O + 1/2\ O_2$ @ 850°C
  - major endothermic reaction for releasing water, oxygen and sulfur dioxide; it takes place in vapor phase in a catalytic reactor above 850°C.

KAERI — Assessment of corrosion characteristics and development of remedial technology in nuclear materials 3

Sulfuric Acid Decomposition

- **H_2SO_4 from the Bunsen Reactor Part**
- **H_2SO_4 Concentration**
- **H_2SO_4 Evaporation**
- **H_2SO_4 Decomposition : SO_2 to the Bunsen Reactor Part**

⇓

→ Very corrosive working conditions

Careful selection of materials is needed.

: must satisfy the *corrosion resistance* and *fabrication ability(machinability)*

KAERI — Assessment of corrosion characteristics and development of remedial technology in nuclear materials 4

Candidate Materials for Sulfuric Acid Decomposition

Environment	Temp(°C)	JAERI	GA
Liquid H_2SO_4	125-180	▪ Zr(<120°C) ▪ Ta ▪ Glass lining	▪ Glass lining ▪ Teflon ▪ SiC ▪ Hastelloy B2
Liquid H_2SO_4	180-420	▪ Fe-Si ▪ SiC ▪ Si_3N_4	▪ Fe-Si ▪ SiC ▪ Si_3N_4

What should we consider for application?

- Corrosion resistance
- Formability(ductility)
- Thermal conductivity
- Economics

→ Need of optimum material

KAERI Assessment of corrosion characteristics and development of remedial technology in nuclear materials 5

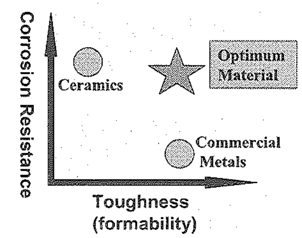
Sulfuric Acid Decomposition

▪ KIST proposed process

60°C 36% H_2SO_4 → 190°C 80% H_2SO_4 → 290°C 95% H_2SO_4 → 400–500°C 5atm H_2SO_4 → 650°C 5atm H_2O+SO_3 → 850°C 5atm $H_2O+SO_2+1/2O_2$

← Concentration → | ← Evap. → | ← Decomposition →

- Material for *lab scale facility* will be determined to the end of 2006.(100NL/hr)
- Material for *pilot scale facility* will be determined to the end of 2008.(100Nm³/hr)



KAERI Assessment of corrosion characteristics and development of remedial technology in nuclear materials 6

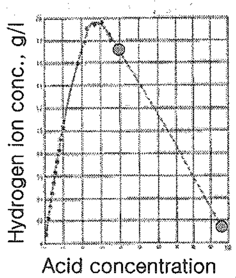
Experimental Environments

▪ Liquid sulfuric acid

- ➢ 125°C 50wt% H_2SO_4
- ➢ 320°C 98wt% H_2SO_4

➢ Immersion test

➢ Polarization experiment
: fast prediction and the mechanism
: various concentrations and temperatures



KAERI Assessment of corrosion characteristics and development of remedial technology in nuclear materials 7

Experimental Conditions

▪ Candidate Materials

- ➢ Fe-Cr
- ➢ Fe-Si
- ➢ Fe base stainless steel
- ➢ Ni base alloy
- ➢ Ta, Zr, Ti
- ➢ Noble metal (Pt, Ir, Ru)
- ➢ SiC

Machinability as well as corrosion resistance is very important
→ Corrosion test is needed for commercial alloys

KAERI Assessment of corrosion characteristics and development of remedial technology in nuclear materials 8

Materials

Ni base | Fe-Cr | Stainless

Design	Material	Composition (wt%)						density (g/cm³)
		Cr	Ni	Fe	Mo	Al	Mn	
C	Alloy718	17	50	33	-	-	-	8.19
D	alloy X 750	15	80		-	-	-	8.28
E	alloy 600	15.2	75	9.15	-	-	-	8.47
F	alloy 690	30	63	7	-	-	-	8.19
G	Hastelloy X	21	52	18	9	-	-	8.22
H	N08	10	-	87	1	-	-	7.82
I	T91	9	-	87	1	-	-	7.82
M	PM2000	20	-	73	-	4.5	-	7.25
N	MA956	20	-	73	-	4.5	-	7.25
R	HT 9							7.8
J	316	16	11	68	3	-	-	8.00
K	304	18.5	9.5	70	-	-	2	8.03
L	alloy 800	20	31	47	-	-	-	7.94
O	sus 329	26	7.5	61	3.5		1.5	7.45
P	sanicro 28	27	31	37	3		2	8.02
Q	Alloy 904L	20.05	24.2	50	4.25		1.46	8.13

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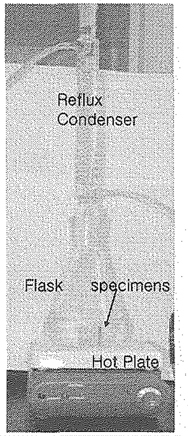
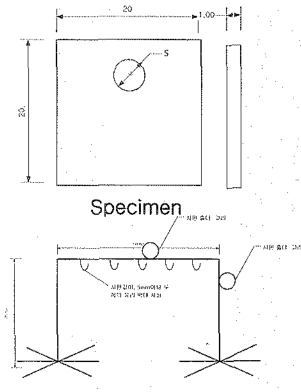
Immersion Test System





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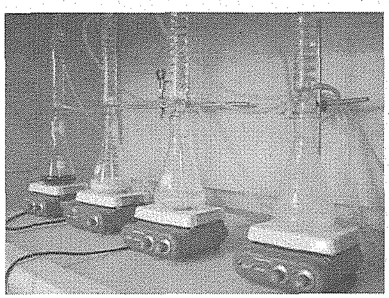
Immersion Test in Sulfuric Acid



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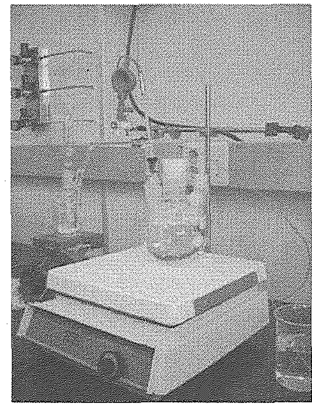
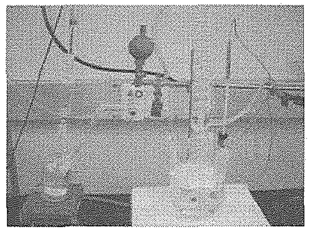
Polarization Test





- Salt bridge
- Sweep rate : 5mV/s
- EG&G 273A

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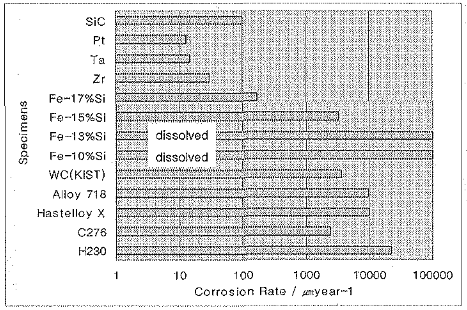
Corrosion in 50wt% H_2SO_4 at 125°C



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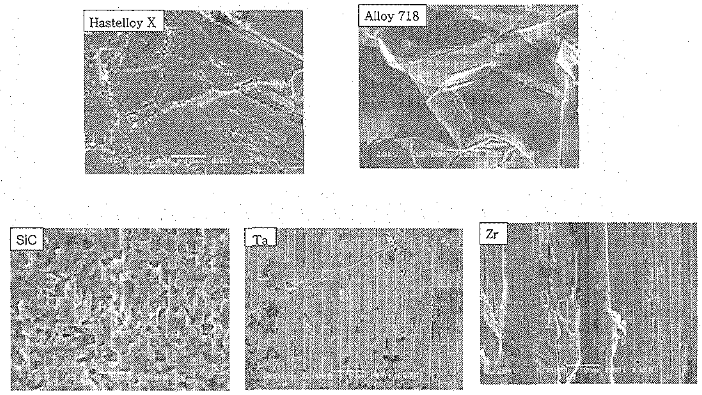
Assessment of corrosion characteristics and development of remedial technology in nuclear materials 13

SEM Images of the Corroded Surface Tested in Boiling 50wt% H_2SO_4 at 125°C



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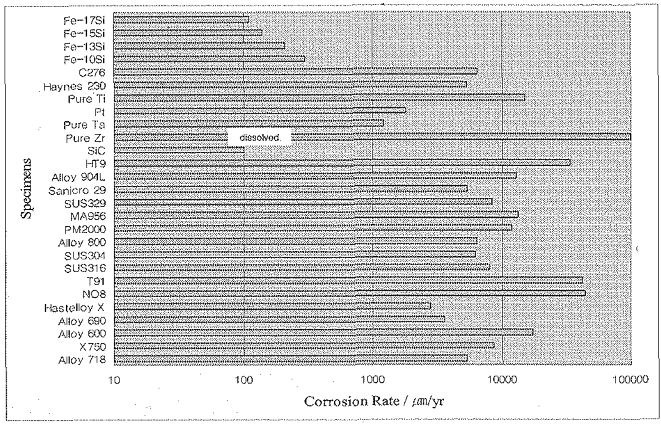
Corrosion in 98wt% H_2SO_4 at 320°C



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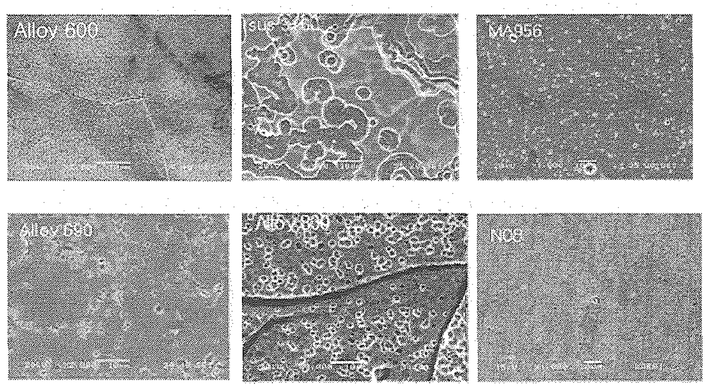
Assessment of corrosion characteristics and development of remedial technology in nuclear materials 15

SEM Images of the Corroded Surface Tested in Boiling 98wt% H_2SO_4 at 320°C



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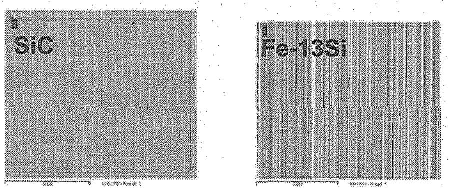
Assessment of corrosion characteristics and development of remedial technology in nuclear materials 16

SEM Images of the Corroded Surface Tested in Boiling 98wt% H_2SO_4 at 320°C



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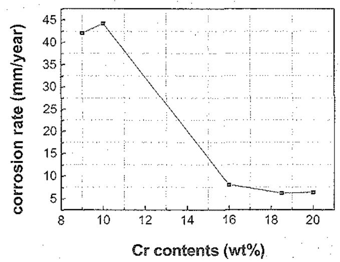
Corrosion of Fe-Cr Alloy in 98wt% H_2SO_4 at 320°C



Corrosion rate decreases with the Cr content but it is still too high for use.

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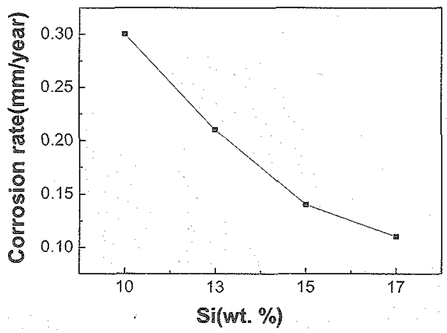
Corrosion of Fe-Si Alloy in 98wt% H_2SO_4 at 320°C



Corrosion rate decreases with the Si content.
→ Si is needed for corrosion resistance

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Corrosion in 98wt% H_2SO_4 at 320°C

Fe-Si

Duration (day)	Specimen	Fe-13Si	Fe-15Si	Fe-17Si
1	Weight change(g)	-0.0021	-0.0029	-0.0008
	Corr. rate(mm/year)	0.2565	0.3116	0.1133
10	Weight change(g)	-0.0003	-0.0023	-0.0004
	Corr. rate(mm/year)	0.0055	0.051	0.0057
30	Weight change(g)	-0.0002	+0.0006	-0.0011
	Corr. rate(mm/year)	0.0012	-	0.0051
60	Weight change(g)	-0.0009	-0.0018	+0.004
	Corr. rate(mm/year)	0.0028	0.0066	-
90	Weight change(g)	-0.0011	+0.0072	+0.0079
	Corr. rate(mm/year)	0.0022	-	-
120	Weight change(g)	+0.0126	+0.0106	+0.0202
	Corr. rate(mm/year)	-	-	-

SiC

Duration (day)	Specimen	RBS
1	Weight change(g)	-0.0004
	Corr. rate(mm/year)	0.0763
10	Weight change(g)	+0.0002
	Corr. rate(mm/year)	-
30	Weight change(g)	+0.0016
	Corr. rate(mm/year)	-
60	Weight change(g)	+0.0258
	Corr. rate(mm/year)	-
90	Weight change(g)	+0.0354
	Corr. rate(mm/year)	-
120	Weight change(g)	+0.0595
	Corr. rate(mm/year)	-

Corrosion rate decreases with the test time.

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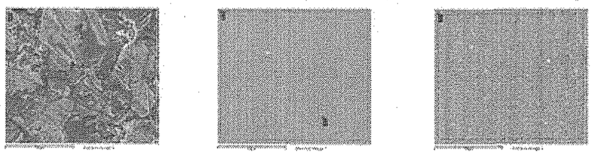
Corrosion in 98wt% H_2SO_4 at 320°C(Fe-13Si)

Before test / 10 days / 30 days



Before test:

Spectrum	Si	Fe	Total
1	22.9	77.1	100.00

10 days:

Spectrum	O	Si	Fe	Total
1	49.4	21.1	29.5	100.00
2	52.1	21.4	26.5	100.00

30 days:

Spectrum	O	Si	Fe	Total
1	51.6	22.4	26.0	100.00

Passive film formation during a corrosion test and thickness increase with the time

→ Corrosion suppression

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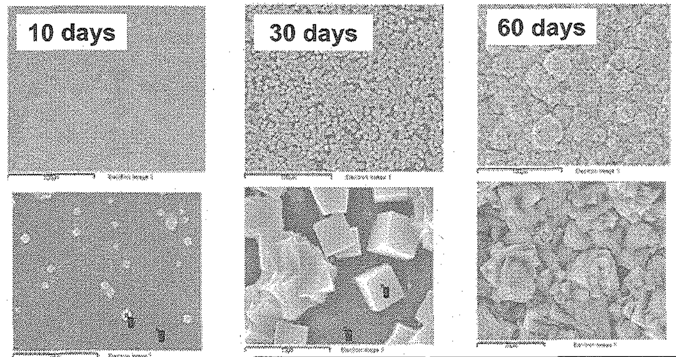
Corrosion in 98wt% H_2SO_4 at 320°C(SiC)



10 days:

	C	O	Si
1	26.72	19.45	53.83
2	38.06		61.94

30 days:

	C	O	Si
1	8.46	38.35	53.20
2	23.13	8.60	68.27

Si enrichment on SiC → SiO_2 formation → coverage increase of SiO_2 with the immersion time

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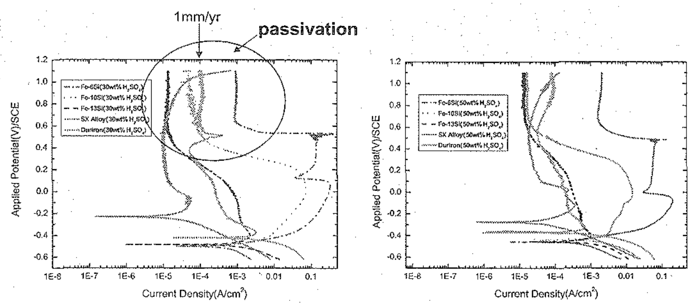
Polarization Test(30wt%/50wt%)



➢ The measured current density decreases with the Si content.

➢ Through the stable passivation, the small current is just passed leading to low corrosion rate.

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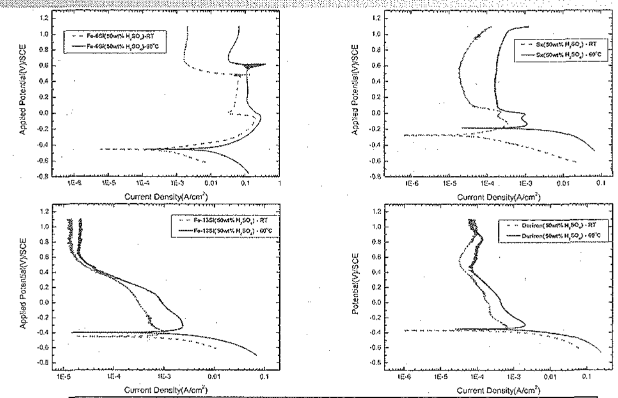
Polarization Test(50wt%, RT/60°C)



➢ Using polarization test, corrosion behavior can be evaluated and various materials can be screened easily.

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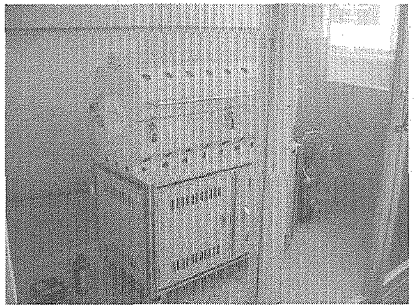
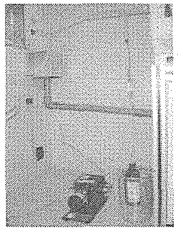
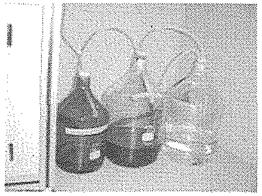
H_2SO_4 Decomposition Test Apparatus

$H_2SO_4 \rightarrow SO_3 + H_2O$ above 600°C
$SO_3 \rightarrow SO_2 + 1/2\, O_2$ above 850°C

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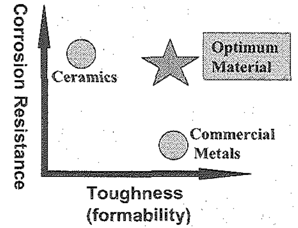
Summary and Proposal

- Corrosion in a liquid sulfuric acid which is the severest environment for the IS process is being performed by using an immersion test and a polarization test for various commercial alloys. According to a corrosion under a sulfuric acid decomposition environment, apparatus was assembled and various materials are being assessed.

→ main issue in liquid sulfuric acid :



➢ To find optimum material for commercial plant, many works are needed.
→ Need of collaborative research
: information exchange, round robin test, complementary research

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1.5.5 Ion Beam Enhanced Adhesion of Ceramic Film Coated on Metallic Substrate and Its Applicability to Nuclear Hydrogen Production

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Summary

The effects of ion beam mixing of the SiC film coated on metallic substrates were studied, aiming at developing highly sustainable materials at above 1173 °K in SO_3/SO_2 ambience. Firstly, ~50 nm thick SiC films were deposited by e-beam evaporative method on stainless 316 L, Inconel 800H, Inconel 690, and Hastelloy X substrates, followed by the 100keV N ions bombardment to mix the interfacial region. After ion beam mixing, additional 500 nm thick SiC film was deposited onto the ion bombarded SiC film. Samples with and without N ion beam mixing were immersed in 50% H_2SO_4 solution for 1 hour with heating the solution up at 573 °K. The film in the as-deposited sample was completely removed during the immersion, while the N ion beam mixed sample exhibited no detachment of the deposited film. The corrosion of non-ion-beam-mixed sample initiated from non-deposited metallic surface and then propagated to the film deposited region, flaking-off the film from the edge. The interface formed by ion beam mixing seems to be protective against the corrosion. The SiC film/metallic substrates were heated up to 1223 °K. The film deposited on the stainless steel substrate was completely peeled off, while the films deposited on Ni-based alloys all sustained. This is due to less difference of thermal stresses between the SiC film and Ni based alloys than between the SiC film and stainless steels. The best materials combination in our experimental scheme seems to be the SiC fim and the Hastelloy X, because their thermal properties are more similar than for the other materials combinations.

Ion Beam Enhanced Adhesion of Ceramic Film Coated on Metallic Substrate and Its Applicability to Nuclear Hydrogen Production

Korea-Japan Nuclear Hydrogen Production
Information Exchange Meeting
Held in Mitto, Japan

August 28 – August 30, 2006

J. W. Park, Y. W. Kim, J. H. Chang
Korea Atomic Energy Research Institute

KAERI

Background

- **Production of Hydrogen**
  - **Nuclear energy as a primary energy source**
    - Stable energy source - Environmentally harmless
  - **High temperature gas-cooled reactor (HTGR)**
    - High level of safety
    - Ability to supply heat of very high temperature up to 950 °C
  - **Iondine-sulfur (IS) cycle**
    - The sulfuric acid (H_2SO_4) is decomposed, generating SO_2/SO_3 gases
      → **Extremely corrosive environment**
- **Required materials for the sulfuric acid decomposer**
  - Sustainability at the temperature as high as 950 °C
  - High corrosion resistance in SO_2/SO_3 environment at the temperature as high as 950 °C

The best materials are questioned.

2

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Materials issue

Materials selection:
> **Ceramics:** - High corrosion resistance - Poor mechanical properties at HT.
> **Metals:** - Good mechanical properties at HT - Not so protective against corrosion

To surmount the materials problem
> New materials development:
> ***Surface modification of metallic materials*** ← This work

Methods of surface modification for this application
> Ceramic coating → problematic in the adhesion between two dissimilar materials
> Ions beam implantation → Not sufficient for corrosion protection in this application

This work
> **Ceramic (SiC) coating on the metals (stainless steels and Ni-based alloys) and then ion beam mixing (IBM) at the interfacial region**

Some benefited properties by IBM
1) Intermixing
2) Enhanced inter-diffusivity
3) Relieving the stresses in the film
4) Generation of new alloy layers

3

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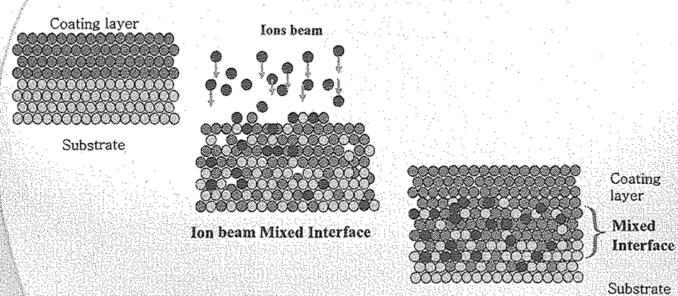
Ion beam mixing



- Reduce abrupt interface → Reduce residual stresses in the film

- Enhance adhesion → Protect the film detachment at HT

4

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Experimental scheme

➢**Sample preparation**

• **Metallic substrates:** SUS 304, SUS316L, Alloy 680H, Alloy 690 and Hastelloy-X were cut to be 20 mm(W) x 20 mm(L) x 5 mm (T) and then were polished on all the surface to have the surface-roughness (Ra) less than 0.05μm

•**1st SiC thin film coating**

- ~ 500eV energy Ar ion beam bombardment before deposition
- Electron beam evaporative deposition :
  ~ 50nm thick film on the metallic substrate

•**Ion beam bombardment**

- Ions: N and Ar, Ion energy: 70 - 150 keV, Ion dose: $1 \times 10^{17} \sim 2 \times 10^{17}$ ions/cm^2

•**2nd SiC film deposition : ~ 500nm thick**

Corrosion
Electrolytic Etching (10% oxallic acid), 50% sulfuric acid corrosion at 300 °C for 1hr

Characterizations
- **Auger depth profiling/elemental mapping**
- **Optical Microscopy/SEM**

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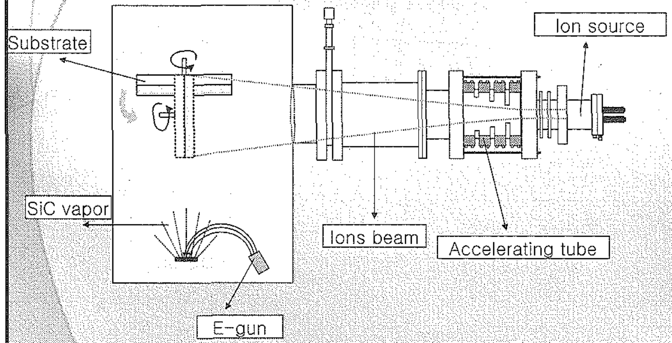
Schematic of coating and IBM processes



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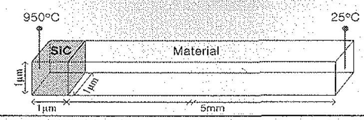
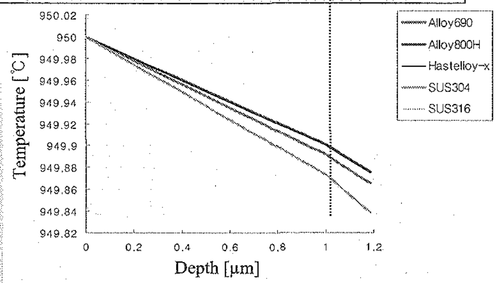
Calculated thermal gradient cross the interface



Equation: one dimensional heat diffusion problem
C.ρ.(δT/δt)=δ/δx.(K.δT/δx) + P(X,t),
C, ρ, and K = specific heat, density, and thermal conductivity; P(x,t): source term: 950 degree C

· **Thermal gradient:**



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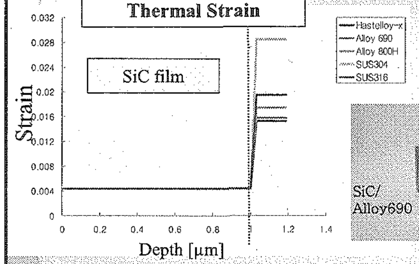
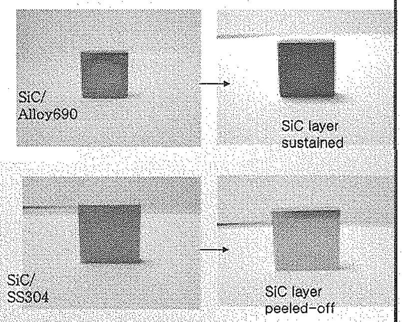
SiC film sustainability at 950℃(w/o IBM)

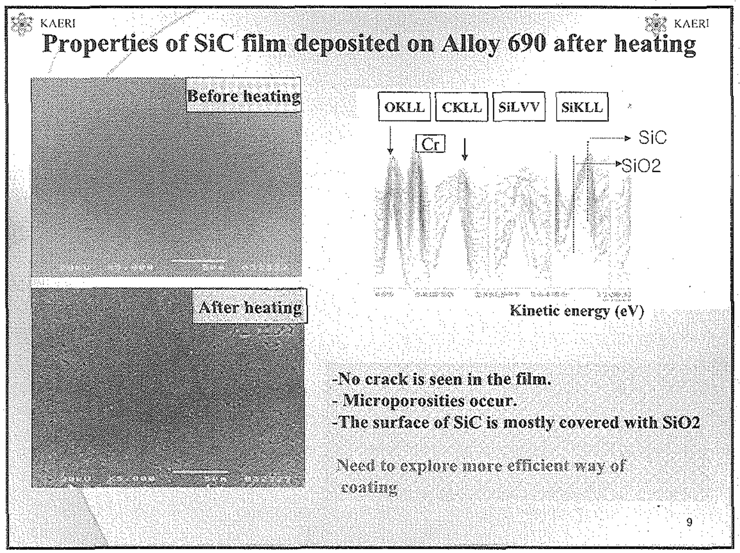


After heating up to 950℃ for 3 hrs in air



The best materials combination : SiC film and Hastelloy X, because their thermal properties are more similar than the other materials combination.

8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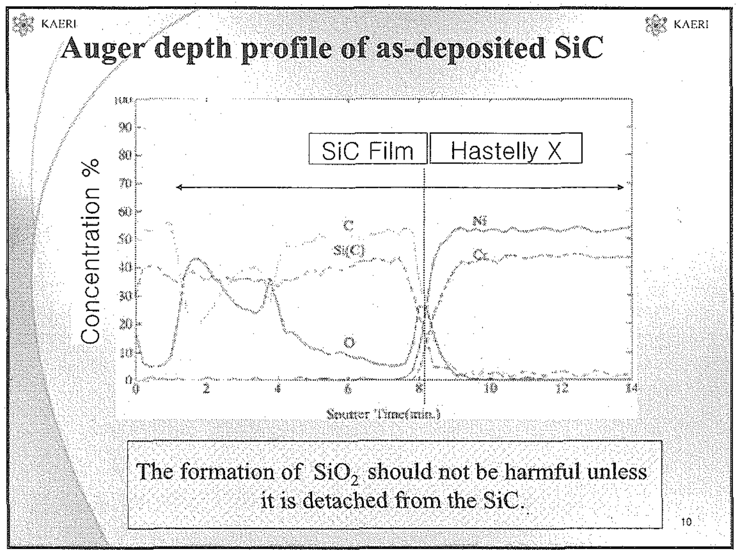
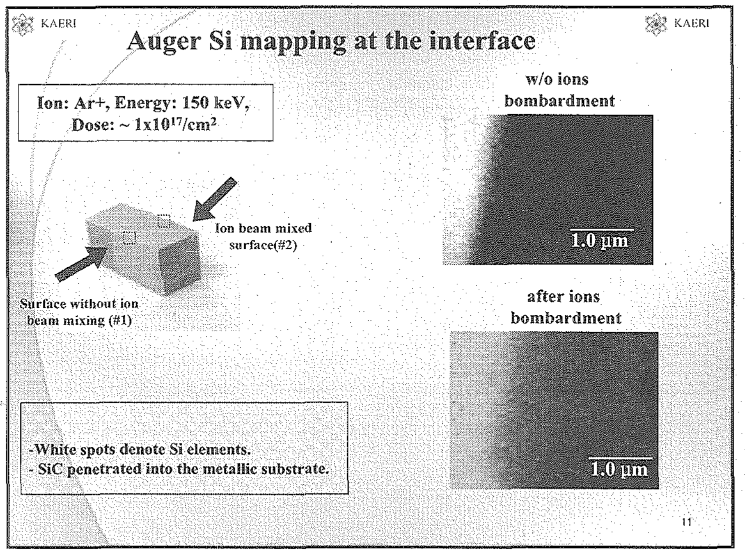
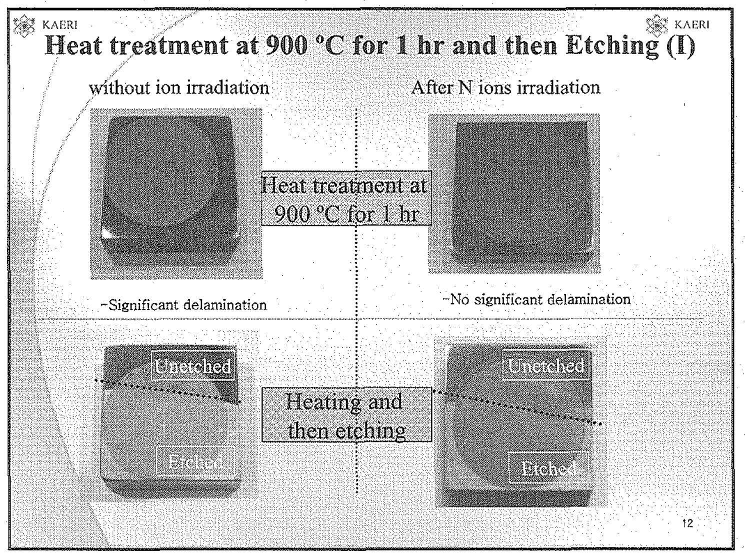
Properties of SiC film deposited on Alloy 690 after heating
Before heating
After heating
OKLL
CKLL
SiLVV
SiKLL
Cr
SiC
SiO2
Kinetic energy (eV)
-No crack is seen in the film.
- Microporosities occur.
-The surface of SiC is mostly covered with SiO2
Need to explore more efficient way of coating
9


KAERI
Auger depth profile of as-deposited SiC
SiC Film
Hastelly X
Concentration %
C
Si(C)
O
Ni
Cr
Sputter Time(min.)
The formation of SiO2 should not be harmful unless it is detached from the SiC.
10


KAERI
Auger Si mapping at the interface
Ion: Ar+, Energy: 150 keV, Dose: ~ 1x10^17/cm^2
Ion beam mixed surface(#2)
Surface without ion beam mixing (#1)
w/o ions bombardment
1.0 μm
after ions bombardment
1.0 μm
-White spots denote Si elements.
- SiC penetrated into the metallic substrate.
11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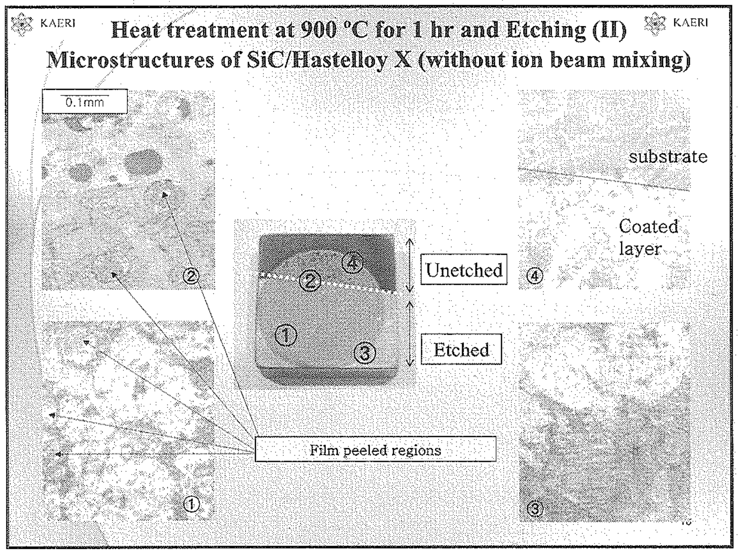
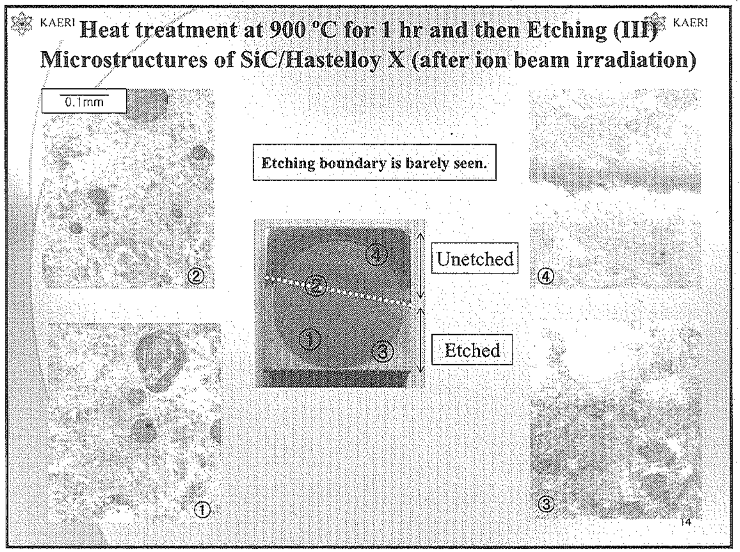
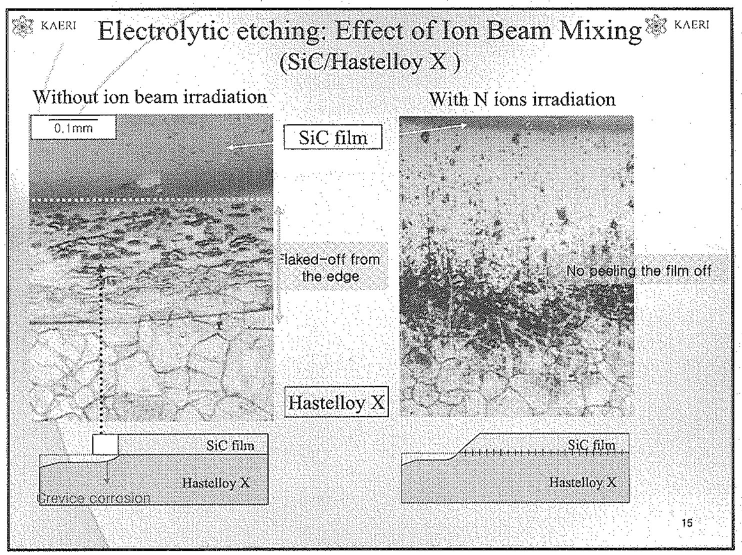
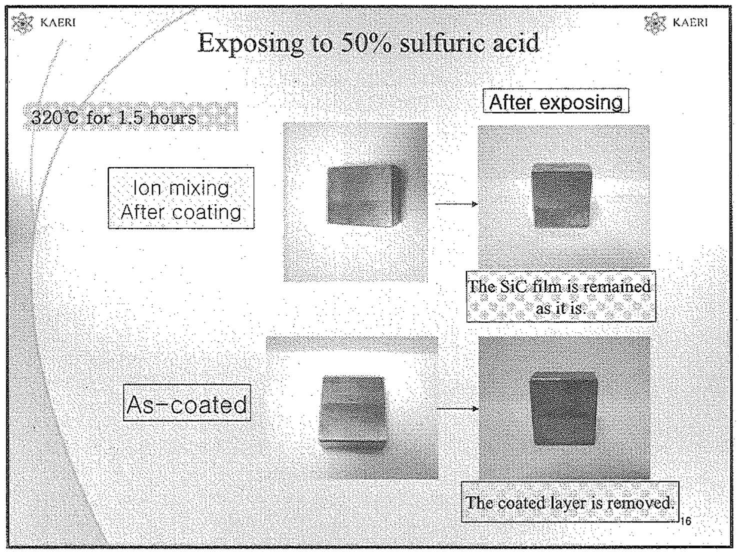
Heat treatment at 900 °C for 1 hr and then Etching (I)
without ion irradiation
After N ions irradiation
Heat treatment at 900 °C for 1 hr
-Significant delamination
-No significant delamination
Unetched
Etched
Heating and then etching
Unetched
Etched
12


KAERI
Heat treatment at 900 °C for 1 hr and Etching (II)
Microstructures of SiC/Hastelloy X (without ion beam mixing)
KAERI
0.1mm
Unetched
Etched
Film peeled regions
substrate
Coated layer
①
②
③
④


KAERI
Heat treatment at 900 °C for 1 hr and then Etching (III)
Microstructures of SiC/Hastelloy X (after ion beam irradiation)
KAERI
0.1mm
Etching boundary is barely seen.
Unetched
Etched
①
②
③
④
14


KAERI
Electrolytic etching: Effect of Ion Beam Mixing
(SiC/Hastelloy X)
KAERI
Without ion beam irradiation
With N ions irradiation
0.1mm
SiC film
Flaked-off from the edge
No peeling the film off
Hastelloy X
SiC film
Hastelloy X
Crevice corrosion
SiC film
Hastelloy X
15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Exposing to 50% sulfuric acid
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320℃ for 1.5 hours
After exposing
Ion mixing
After coating
The SiC film is remained as it is.
As-coated
The coated layer is removed.
16

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Future plans

1. Experiment in more real environment (H_2SO_4 decomposer at >900℃)
2. Development of a multiple process of coating and ions beam bombardment : coating → IBM→ coating → IBM→ ……..→ final coating
3. Find alternative coating and substrate materials (e.g. Al2O3, TiO2 etc. as coating materials and Haynes… as the substrate materials)
4. International collaborative works

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Summary

- Thin layer(50nm thick) coating of SiC on a metallic substrate followed by ions beam bombardment produces a highly adherent interface.
- The ion bombardment generates effective mixing the coated layer with the substrate at the interface.
- The interface between SiC and metals (Ni-based alloys in this work) produced by ions beam mixing is protective of the corrosion.
- It is suggested that multiple process of coating and ions beam bombardment will provide more sustainable interface against the thermal stresses.
- Coating and IBM should be done in the same vacuum chamber to prevent the oxidation (SiO2) of SiC from the surface.

Acknowledgements : This study is being supported through Nuclear Hydrogen Project and Proton Engineering Frontier Project sponsored by The Ministry of Science and Technology, Republic of Korea.

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1.5.6 Corrosion Test Results Obtained under H_2SO_4

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Summary

The IS process uses corrosive chemicals such as sulfuric acid and iodine under high temperature up to 900°C. To construct a pilot test plant, it is necessary to fabricate chemical reactors, pipelines etc. by using corrosion resistant materials. In JAEA and other organizations, corrosion tests in IS process environments have been carried out using test-pieces of commercially-available materials. These tests clarified the followings. In the gas phase, and in the sulfuric acid and iodine environment, as well, refractory alloys such as Alloy800 and MAT21 show relatively good corrosion resistance. In the liquid phase, no alloy has been found which shows enough corrosion resistance in the liquid phase conditions. Materials that showed good corrosion resistance are exotic materials such as glass, Ta, Zr, and Si-SiC.

From the corrosion point of view, biggest issue in the construction of pilot plant lies in the fabrication of sulfuric acid decomposer. The component handles concentrated sulfuric acid solution of around 90wt%, at the temperature of 200 to 400°C, under the pressure of 2MPa. Concerning this problem, we devised a concept of the decomposer featuring ceramic heat exchanger made of silicon carbide. Thermal stress analysis and test fabrication of the ceramic block has shown its feasibility. However, there still remain hurdles concerning the materials to be used in the pipes and headers which contact with hot sulfuric acid.

For evaluating the corrosion resistance of candidates, we are using a special autoclave which can examine the immersion tests in high temperature acidic solution. We plan to examine the immersion test in high temperature sulfuric acid (90wt%, 200~400°C, 2MPa) by using the autoclave, and to complete the tests within this fiscal year

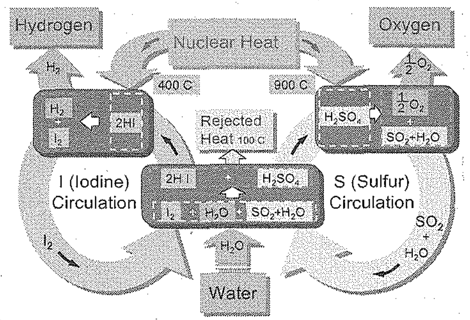
Corrosion Tests in Sulfuric Acid

1st JAEA/KAERI Information Exchange Meeting,
Oarai, August 28-30, 2006

Nobuyuki Tanaka and Hirokazu Suwa
Nuclear Applied Heat Technology Division
Nuclear Science and Engineering Directorate
Japan Atomic Energy Agency (JAEA)

Thermochemical Iodine-Sulfur (IS) process

- Pyrolysis of water; Heat more than 4000℃
- Combination of 3 chemical reactions

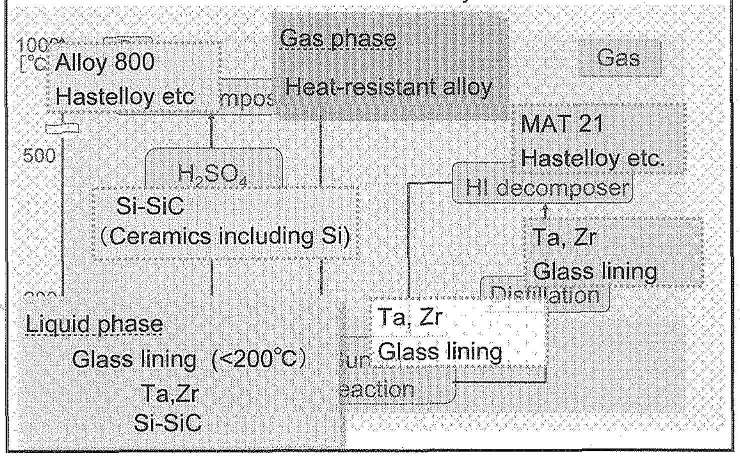


Process fluid:
Sulfuric acid
Hydriodic acid
Temperature:
100~900℃
Pressure:
~2MPa

IS process constitutes corrosive environments for materials.

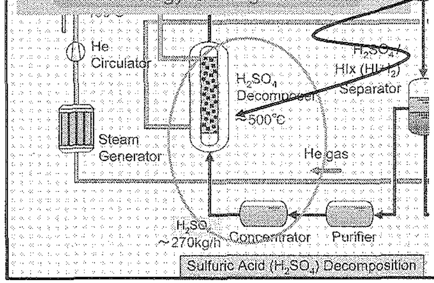
Summary of former knowledge

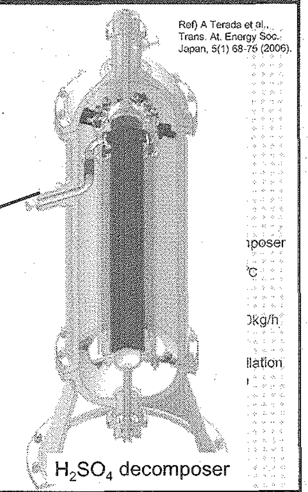
Candidate materials has been screened by corrosion tests.



Corrosion problems in pilot plant

H_2SO_4 decomposer and concentrator (H_2SO_4 90wt%,200~400℃,2MPa)
One of engineering issues to make H_2SO_4 decomposer is to establish service equipments such as pipes and headers.
⇨ Applicability of the coating technology is being examined.





H_2SO_4 decomposer

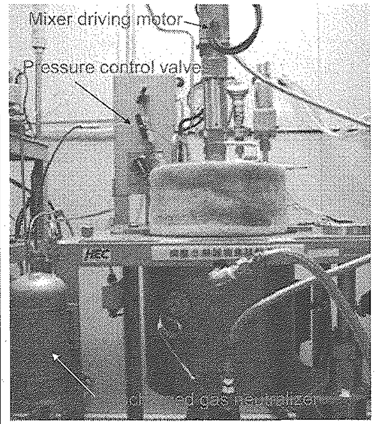
Corrosion problems in pilot plant (contd.)

- Application environment:
  90wt% Sulfuric Acid, 200~400℃, 2MPa
- Main required performances

Thermal resistance
Corrosion resistance
Seal performance etc.

⇨ We examine an application of corrosion resistance coating technology as candidates satisfying these conditions.

Experimental apparatus



Size: 600mmW × 540mmD × 1200mmH

The immersion test of high temperature acid is possible.

Maximum temperature: 500℃

Maximum pressure: 4MPa
[He gas is used for keeping high pressure conditions.]

Inner H_2SO_4 container: SiC

Solution volume: 300 mL
(V/S=15~50 mL/cm²)

During the experiments, solution is stirred to supply fresh solution to the specimen surface.

Ref) N. Tanaka et al, 2006 Annual Meeting of the Atomic Energy Society of Japan, Oarai, Japan, March 24-26, 2006, N45.

Experimental conditions (planned)

Planned corrosion test conditions

Composition	H_2SO_4 90wt%
Temperature	200, 300, 400℃
Immersion time	5, 20, 100 hours
Pressure	2MPa

⇨ The test are under way, and we plan to complete the corrosion tests within this fiscal year.

1.5.7 Design of a NHDD Simulated Gas-Loop for Test of Various SO_3 Decomposers

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Summary

Very high temperature gas cooled reactor technology and IS cycle technology are being developed in KAERI for a nuclear hydrogen production system. The decomposer is a key interfacial component which transfers the heat generated from the nuclear reactor to the hydrogen production loop. This heat exchanger operates at an elevated temperature condition with the corrosive environment. The pressure difference between loops is one of the technical items to be solved in the design of the high temperature process heat exchanger. The heat exchanger is a plate-fin type exchanger in which the plate of Ni-based material is coated with SiC and ion beam mixed to enhance the corrosion resistance. A small gas loop with the capacity of 10kw power test was designed and under construction to investigate the characteristics of the innovative process heat exchanger. The gas loop consists of major components such as graphite heater, gas bearing circulator, hot gas duct, and cooler. Nitrogen gas is used for the primary loop coolant. A complete loop including secondary loop will be constructed till the end of 2007. The structural integrity of the coated layer and some of the preliminary thermo-fluidic characteristic will be investigated in the test. On the basis of the small gas loop technology, a middle sized helium loop of 150kW power is planned be constructed till 2011 in order to perform fundamental thermo-fluidic test and the functional test of the key components.

Design of a NHDD Simulated Gas-Loop for Test of Various SO_3 Decomposers

1st JAEA/KAERI Information Exchange Meeting on VHTR System

2006. 8. 30(Wed.) 9:00, JAEA

Y.W. Kim, S.D. Hong, W.J. Lee, J.H. Chang
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KAERI

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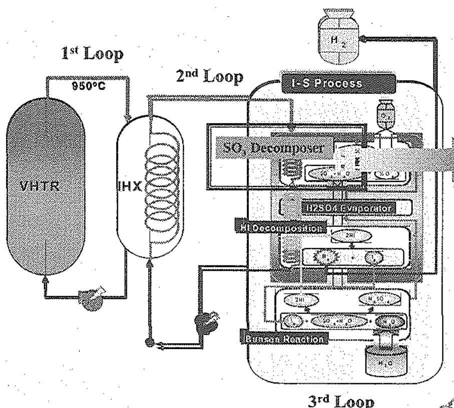
A Key Interface Component - Decomposer



SO_3 Decomposer
Process Heat Exchanger

- High Temperature
- SO_3 Environment
- Pressure Difference Between 2nd and 3rd Loops

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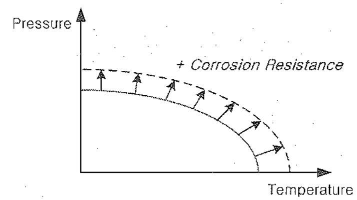
Necessity and Objective

- **Process Heat Exchanger(SO_3 Decomposer) Test**
  - Innovative PHE design needs experimental verifications



- **To Develop the Experimental Technology at Elevated Temperature**
  - A Pre-processor of He loop design
  - Loop component technology

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R&D Plan for Gas Loop & PHE

- **10kW Gas Loop**
  - 2006 : Construction of primary loop (N_2 Gas), Design of PHE for Test
  - 2007 : Construction of secondary loop, Manufacturing of PHE for test
  - 2008 : Process Heat Exchanger Test
- **150kW Gas Loop**
  - 2008 : Loop Design
  - 2009 : Construction of primary loop (He Gas)
  - 2010 : Construction of secondary loop
  - 2011 : PHE, Basic Thermo-fluid experiment and Small scale component test
- **0.5MW Gas Loop (after 2011)**
  - Thermo-fluid and Safety Test, Component Test
- **Collaboration with CEA (HELITE) – under discussion**

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This Gas Loop is

- **High Design Temperature (1000 °C)**
- **High Pressure (up to 6MPa)**
- **Use of SO_3 for Secondary Loop**

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Basic Design Parameters of Loop

- **Power : 10kW(test section), 60kW(total loop capacity)**
- **Primary Loop**
  - Design Temperature : 1000°C
  - Design Pressure : 6MPa
  - Operating Temperature : 50-950°C
  - Operating Pressure : 4MPa
  - Flow Rate : 2 kg/min
  - Working Fluid : N_2
- **Secondary Loop**
  - Design Temperature : 950°C
  - Design Pressure : 1MPa
  - Operating Temperature : Room Temp ~ 900°C
  - Operating Pressure : ~0.1 MPa
  - Flow Rate : 1 kg/min
  - Working Fluid : SO_3

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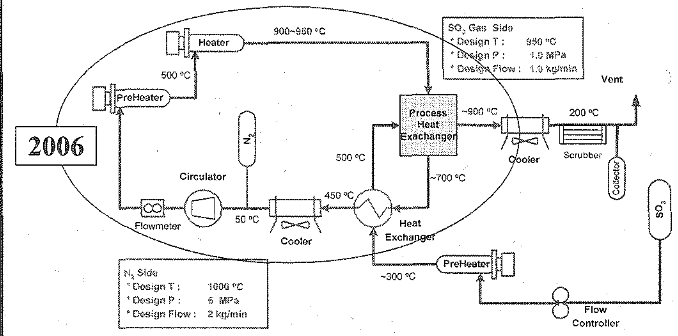
High-Temperature Gas Loop



Schematic Diagram of Small Gas Loop

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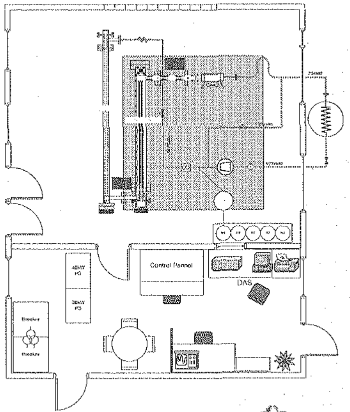
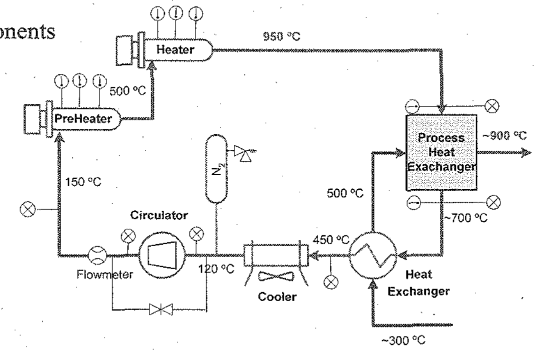
Layout of Gas Loop Lab



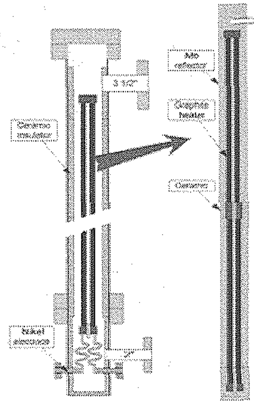
Primary Loop

- Major Components
  - Pre Heater
  - Main Heater
  - Circulator
  - Cooler
  - Hot Gas Duct
  - PHE
  - Sensors
  - Pipes



Main Heater

- **Material : Graphite**
- **Design Characteristics**
  - Internal insulation
  - Cooling of electrodes
  - T/C installation & sealing
  - Emergency shutdown module
- **Design Requirements**
  - Nitrogen inlet temp : 500 °C
  - Nitrogen outlet temp. : ≥ 1000 °C
  - Heater max. temp. : < 1500 °C
  - Design pressure : 6.0 MPa
  - Flow velocity : 2.5m/s



(a) Vessel (b) Heater bundle

Main Heater : Thermal Analysis

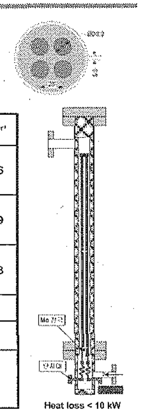
- **Evaluation of heater vessel wall temperature (< 400 °C)**
- **Evaluation of graphite heater temperature (< 1500 °C)**

T/H Performance of the 2X2 bundle heater

N_2 Flow, kg/s		T_{heater}, °C	T_{vessel}, °C	Q_{heater}, kW
0.017	h_{air}=10, ε=0.8, k_{ins}=ub	1316	282.5	14.62
0.026	h_{air}=10, ε=0.8, k_{ins}=ub	1414	307	20.91
0.035	h_{air}=10, ε=0.8, k_{ins}=ub	1443	313	26.58
	ε=0.6	1443	342	26.52
	ε=0.4	1443	385	26.45
	h_{air}=20	1443	262	26.66
	h_{air}=5	1443	342	26.52

N_2 Flow, kg/s		T_{heater}, °C	T_{vessel}, °C	Q_{heater}, kW
0.035	h_{air}=10, ε=0.8, k_{ins}=lb	1451	258	24.66
Worst case	h_{air}=5, ε=0.4, k_{ins}=lb	1451	365	24.49
Worst case	h_{air}=5, ε=0.4, k_{ins}=ub	1443	432	26.33
0.035	helium	> 2000		

ub: upper-bound thermal conductivity of insulator
Lb: lower-bound thermal conductivity of insulator



Main Heater – FIV Evaluation

- **FIV analysis example of a high temperature Heater**
  - Max. Gas velocity of 2.5m/sec in Main Heater
  - Fluidic Elastic Instability
    - Critical velocity : 6m/sec (Based on 8.15Hz)
  - Acoustic
    - Less than 300m/s
  - Vortex Shedding
    - Not Evaluated

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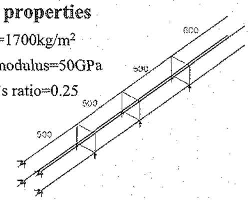
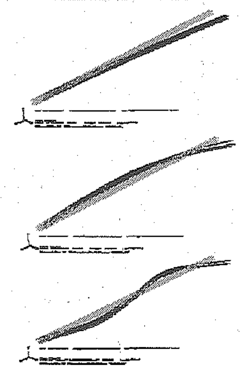
Main Heater – FIV Evaluation

- **FEA : ABAQUS**
- **Model and properties**
  - Density=1700kg/m^2
  - Elastic modulus=50GPa
  - Poisson's ratio=0.25



#	Nat. Frequency (Hz)
1	8.155
2	34.534
3	59.89

Assembly modes



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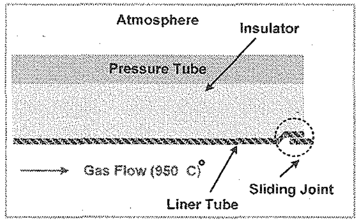
Hot Gas Duct

- **Internal insulation Design**
- **Parameters to design size of a HGD**
  - *Thermal conductivity*
  - *Radiation loss*
  - *External surface area*
  - ...



Internal Insulation Duct

- **Design requirements**
  - Surface temperature; < 300 °C
  - Heat loss per length; < 1.0 kW/m
  - Diameter of flow channel; > 12 mm
  - Thickness of internal insulator; > 27 mm

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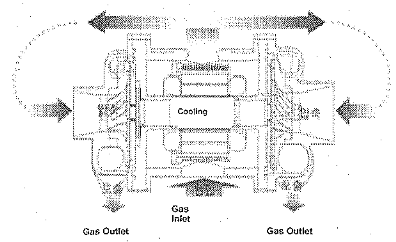
Circulator

- **Design Requirement**
  - High system pressure application (~ 7MPa)
  - Lower inlet temperature is required (< 50 °C)
  - Very high revolution speed (15000-35000 rpm)
  - Maximum flow rate : 0.4kg/s
  - Circulator head : more than 0.3MPa



Details of the Gas Bearing

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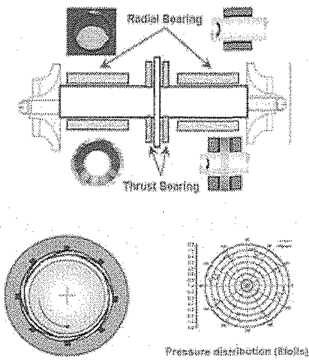
Circulator (cont'd)

- **Key Technology**
  - Gas Bearing
  - Symmetric Rotor (Double Suction)



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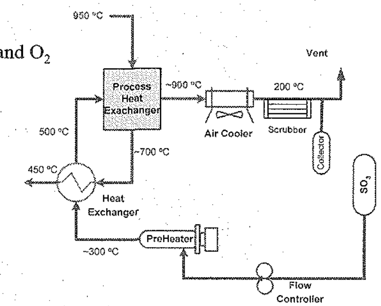
Secondary Loop

- **Secondary Loop**
  - Open loop
  - SO_3 is decomposed into SO_2 and O_2 in the PHE
- **Major Components**
  - Preheater
  - Heat exchanger
  - PHE
  - Cooler
  - scrubber and collection tank
- **Will be constructed in 2007**



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PHE Design – Method of Approach in KAERI

- **Technical Issues**
  - High temperature
  - Corrosive environment
  - Manufacturability

- State of Arts
  - Ceramic
  - High end metal

A Potential Sol. Of KAERI

Coated high end metal
+ Ion beam mixing
Printed Circuit Type and/or Plate Fin Type

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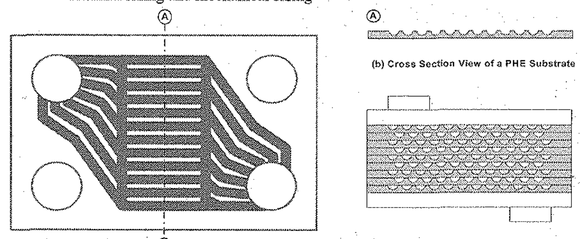
PHE-Printed Circuit Type

- **Design and Manufacturing R&D**
  - SiC coating and ion beam mixing, bonding of PHE
  - Catalyst space
  - Bonding
  - Thermal sizing and mechanical sizing



(a) Top View of a PHE Substrate
(b) Cross Section View of a PHE Substrate
(c) Cross Section View of a PHE Block after Diffusion Bonding the Substrates

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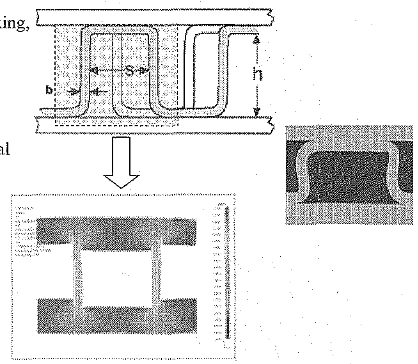
PHE-Plate and Fin Type

- **Design and Manufacturing R&D**
  - SiC coating and ion beam mixing, bonding of PHE
  - Strength evaluation based on pressure and thermal loading (Sensitivity analysis : b, s, h)
  - Thermal sizing and mechanical sizing



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Major Test Items in 10kw Loop

- **Structural Integrity at High Temperature**
  - High temp. behavior of SiC coated surface
  - Short term corrosion/erosion resistance in SO_3 environment
  - Thermal stress and strength
- **Performance of Process Heat Exchanger**
  - Preliminary thermal performance
  - Pressure drop

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At Present

- **Primary Loop is being constructed at KAERI**
- **Process Heat Exchanger is being developed at KAERI**

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R&D Activities on High Temperature Material

- **High Temperature Material Screening**
  - Comparative study for fundamental material properties of various high temperature material was done during last two years
- **Material Test for Alloy 617**
  - Creep Test
  - Creep Test in He environment
  - Fatigue Test at High Temperature
- **Material Test for Modified 9Cr 1Mo**
  - Creep and Fatigue Test for Welded Parts

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R&D Activities on High Temperature Material

	RPV	IHX	PHE*	HGD	CRS
Material Screening	SA508/ Mod.9Cr	X	Metals/ Ceramics	X	X
Material Improve.	X	A617	Surface Treatment	X	X
Design Codification	CFI	He Effect	X	CFI	X
Manufacturing	Welding	Bonding	Bonding Manufac.	Thermal Insulation	C/C SiC/SiC
Database	Creep Fr. Tough.	Creep Fatigue	Corrosion	Fatigue	Property Strength

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R&D Activities on Graphite

- **Comparative and Screening test of Material Properties for Various Graphite**
  - Physical and Mechanical Properties
  - Wear
- **NDT Technology**
- **Irradiation Char.**
- **ASTM RR**
  - Fracture Toughness
  - Oxidation

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R&D Activities on Components

- **High Temperature Component Key Technologies**
  - Compact IHX, Circulator, Hot Gas Duct, Process Heat Exchanger
  - High temp. components integrity
  - With/without on going gas loop technology
- **Major Components Design**
  - Shape/Sizing
  - PHE design development

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R&D Activities on Mechanical Design

- **Component Mechanical Design Method & Tools**
  - Code and Standard Trace : ASME Subsection NH, CC (A617), Code Case N-499…
  - 3-D Digital Modeling : I-DEAS
  - Static/Dynamic Analysis : ABAQUS, ANSYS
  - Non-Linear Analysis for Visco-plasticity and Creep: Modeling based on ANSYS, ABAQUS
- **Graphite Structure Design and Seismic Analysis**
  - Code and Standard Trace : ASME Sec. III Div.2 Subsection CE
  - Graphite Design & Seismic Analysis
    - Core Seismic Modeling
    - Collaboration with GA is under discussion

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1.5.8 Sulfuric Acid Decomposition Process Development in Korea

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Summary

Key technology Development of Sulfric Acid Decomposition was carried out. Catalyst development was investigated for SO_3 decomposition and H_2SO_4 decomposition. Target of 2006-2009 is to develop sulfuric acid decomposer for production of 1000 L/h hydrogen. SO_3 decomposition catalysts were selected in the mechanistic point of view: 1) metal sulfate formation and 2) metal sulfate decomposition. Firstly, metal oxides were selected in thermodynamic calculation. Secondly, metal oxides were selected by TPD experiments of metal sulfates. However, the formation and decomposition of metal sulfates was just prerequisite condition for active catalyst screening. Turnover frequency of metal oxide should be considered further. After selecting metal component, it was supported by various refractory metal oxides such as Al_2O_3 and TiO_2. In activity TiO_2 was active less than Al_2O_3, but expected to be stable more than Al_2O_3. Multicomponent catalysts were almost developed and structural modification will be done to enhance the stability of catalytic systems. For high pressure experiments, pt-lining reactor was installed. The sulfuric acid decomposition experiments will be conducted in high pressure reactor. SO_2-O_2 separation was studied to control release of HI and I_2 in Bunsen reactor. HI and I_2 is harmful as well as expensive. Therefore, the release of HI and I_2 should be prevented perfectly. Various absorbents are prepared and tested. Because temperature ranges of 120~ 500 °C can be available for SO_2 and O_2 separation, if the separation process would be well designed. On the other hand, in-situ analysis tools and algorithm are studied to monitor and control streams of sulfuric acid decomposition.

Sulfuric Acid Decomposition in IS-cycle

Korea Institute of Science & Technology
Environment & Process Technology Division
K. D. Jung & H. Kim
(jkdcat@kist.re.kr)

H_2SO_4 Decomposition Process (2006~)

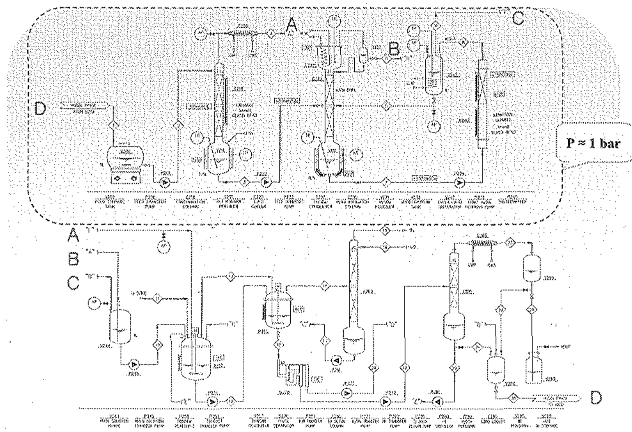
- Development of Pressurized H_2SO_4 Decomposition Units
  - 1st Phase : 2006~2008
  - Target : 1,000 L/h H_2-scale units working at 20 bars & 900℃

- High-Pressure System of H_2SO_4 Decomposition
  - Design of H_2SO_4 concentrator, distillator, decomposition reactor, condenser
  - High pressure/high temperature materials, Sealing components
  - Pelletized catalysts (activity > 90% of equilibrium conversion @ 900℃)
- VLE data of H_2SO_4-Water (0~20 bars)
- SO_2-O_2 Separation
  - Selective absorption in solvents
  - Membrane gas separation
- On-site Instrumental *in-situ* Analysis of H_2SO_4 Decomposition Streams

Experimental Work in Preliminary Phase

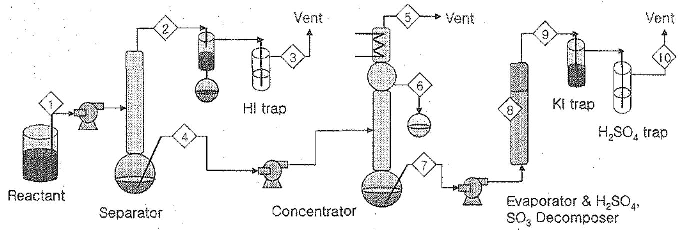
Development of decomposition catalyst - 750~900℃	- Various supported catalysts (activity) - Effects of supporting material, calcination condition - Reaction mechanisms
H_2SO_4 decomposition at ambient pressure	- H_2SO_4 Separation, Concentration, and Decomposition : Design of units Operating conditions for units and an integrated system - Reaction : Quartz Tubular Reactor Cu based pelletized catalyst

Schematic H2SO4 Decomposition System



Lab-scale H2SO4 Decomposition System

KIST



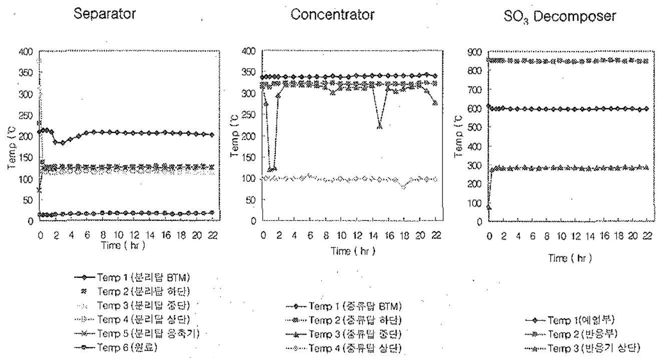
Separating Column		Concentrating Column		Decomposition reactor	
Top	113~118 °C	Top	280~289 °C	1st Reactor	598~599 °C
BTM	190~206	BTM	335~341	2nd Reactor	849~852

Case	Reactant feeding	aq. H_2SO_4 feeding	conc. H_2SO_4 feeding
I	2.57 g/min	1.01 g/min	1.04 g/min
II	5.65 g/min	2.42 g/min	2.01 g/min

Operation of Lab-scale Continuous System

KIST

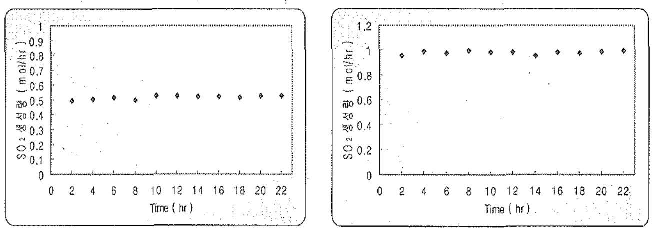
Variation of Temperatures in continuous process (for H_2 = 1.0 mol/h)



H2SO4 Decomposition in Continuous System

KIST

(I) 0.5 mol/h H_2 (II) 1.0 mol/h H_2



(I) H_2SO_4/cat.= 0.218 gmol/h.g_{cat}
H_2SO_4 Conversion to SO_2 = 77.8~83.6%

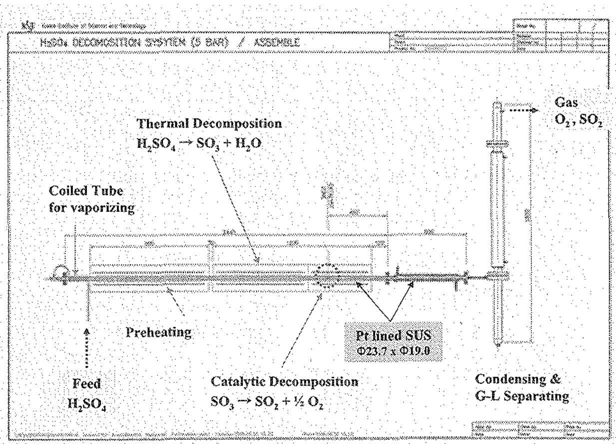
(II) H_2SO_4/cat.= 0.171 gmol/h.g_{cat}
H_2SO_4 Conversion to SO_2 = 79.6~83.1%

Experimental Work in 1st Phase-I

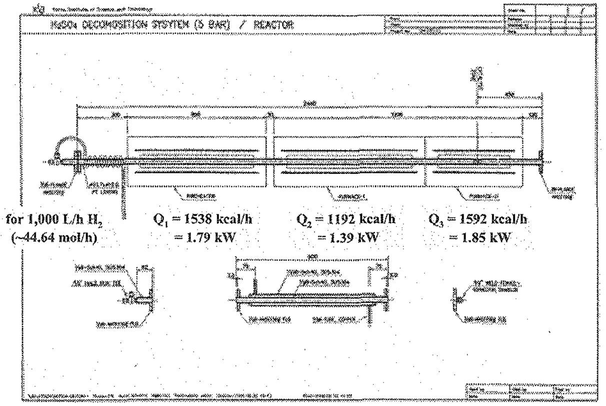
KIST

Reactors for H_2SO_4 decomposition - 5 bars, 900℃	- Pt-lined Tubular Reactor (test for allowable capacity) - Heat exchanger type Multi-tube Reactor (1,000 L/h H_2) - Vertical SiC Reactor (integrated vaporizer and reactor)
Catalyst Development - 800~850℃	- Multi-component supported catalysts (activity) - Structural Modification to prevent the corrosion - Forming catalysts
VLE of H_2SO_4-H_2O - 0~20 bars	- Lab-scale VLE measurement - Empirical equation
SO_2/O_2 Separation - Selective absorption	- Absorbent Selection - Absorption/desorption system
Instrumental Analysis - H_2SO_4, SO_3	- *in-situ* Analysis of H_2SO_4 & SO_3 Concentration with IR, near IR - Spectroscopy Probes and Cells

[1] Pt-lined Medium Pressure Tubular Reactor



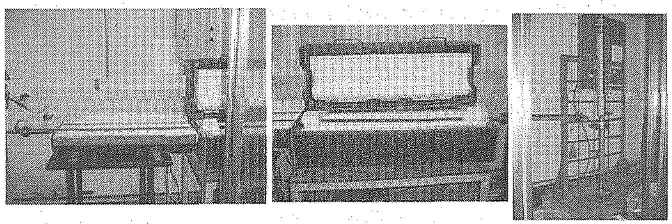
Heaters for Pt-lined Tubular Reactor



* Horizontal reactor because of length

Decomposition Using Pt-lined Reactor

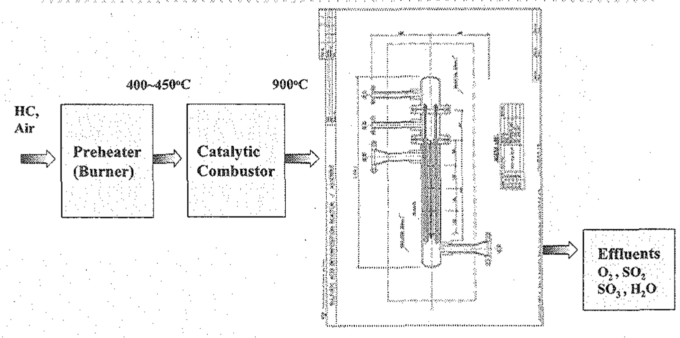
- Pt-lined Tubular Reactor
  - Integration of preheating and decomposition
  - Pressurized reaction (@ 5 bars, 900℃, 20~25 mol/h H_2 expected)
  - Catalytic effect of Pt surface
  - Experimental reactions with pelletized catalysts of $CuCrO_x$, supported $Cu_xFe_yO_z$
  - Design data (allowable flow rate, equilibrium conv., heat required)



Preheater　　Decomposition Reactor　　Separator

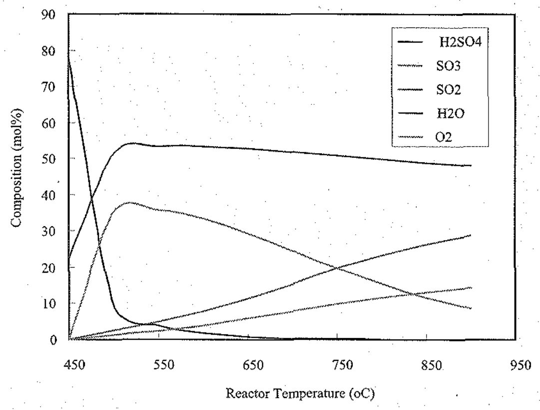
Multi-tube Reactor

- Heat-exchanger type Multi-tube reactor
  - working at 5 bars, 900℃ for 1000L/h H_2 (test material: Inconel or RA330)
  - Units and an integrated system are under designing.



Decomposition Reactor

[2] Sulfuric Acid Decomposition : Composition w.r.t. Rxn T.



Literature Suvey for Catalyst

- ❖ G.A. Catalysts for sulfuric acid decomposition (U.S. patent: 4,314,982)
  ; Two stage catalysts
  - Low temperature decomposition : Pt/TiO2, ZrO below 970 K
  - High temeperature decomposition : Fe2O3 and CuO above 970 K

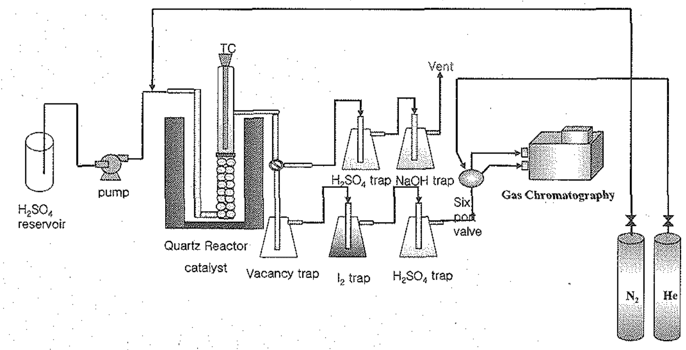
- ❖ JAERI : Pt/Al_2O_3

- ❖ Activity for sulfuric acid decomposition (Bull. of the Chemical Society of Japan, 1977)
  Fe2O3> V2O5 >Cr2O3 > CuO > CoO > TiO2 > NiO > Al2O3

- ❖ Activity for sulfuric acid decomposition (Int. J. Hydrogen Energy, 1989)
  Pt = Cr2O3> Fe2O3> V2O5 >Cr2O3 > CuO > NiO > Al2O3: 4300 h^{-1}

Catalyst Development

- Lab-scale Catalyst Tester



Key Factors for Catalyst Screening in Activity Aspect

$M_xO_y + {}_zSO_3 = M_x(SO_4)_y$: $M_x(SO_4)_y = M_xO_y + ySO_2 + y/2\ O_2$

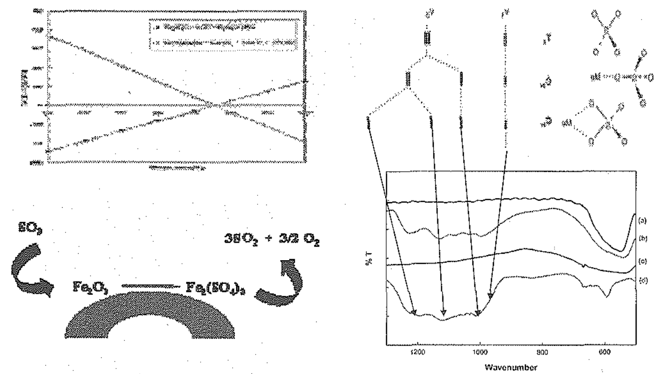
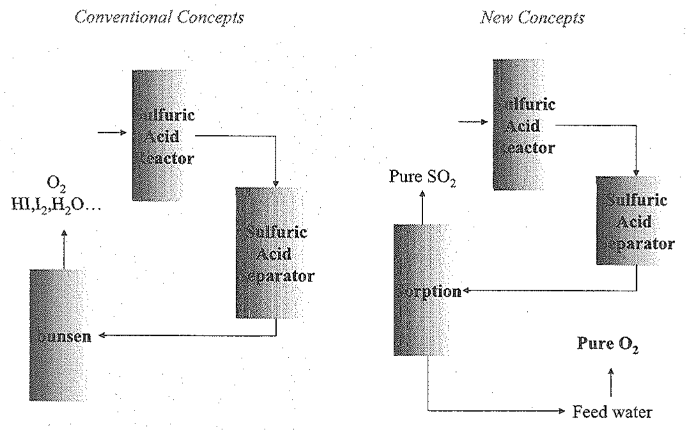


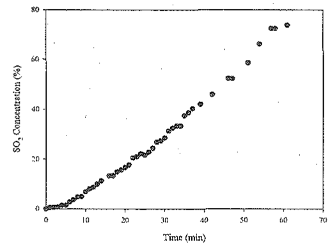
Figure. IR data: (a) Fresh Fe2O3, (b) Fe2O3 after the reaction of SO3 decomposition at 550 oC, (c) Fe2O3 after the reaction of SO3 decomposition 850 oC, (d) Fresh Fe2(SO4)3_xH2O

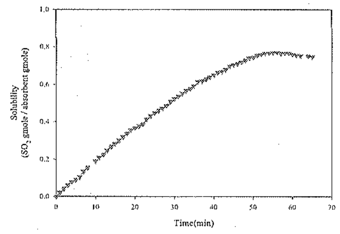
[3] SO2-O2 Separation to Control Minor Components in O2 stream



SO2 Absorption Example

- SO_2 Concentration in Effluent Gas
  - GC analysis
- SO_2 Absorption in DMSO
  - weight change



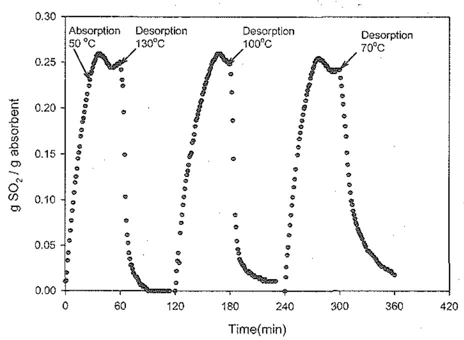


Absorbent : DMSO (dimethyl sulfoxide)

Flow of SO_2/He : 20/10 cc/min, Absorption at 50 ℃

SO2 Absorption/Desorption

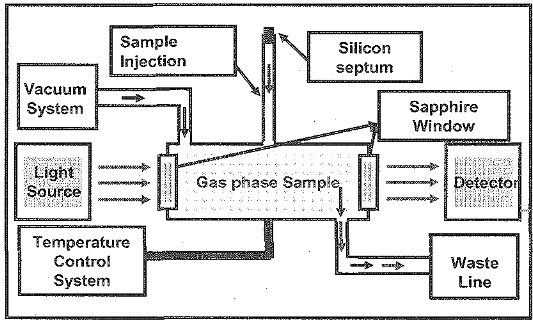
- Effect of Desorption Temperature



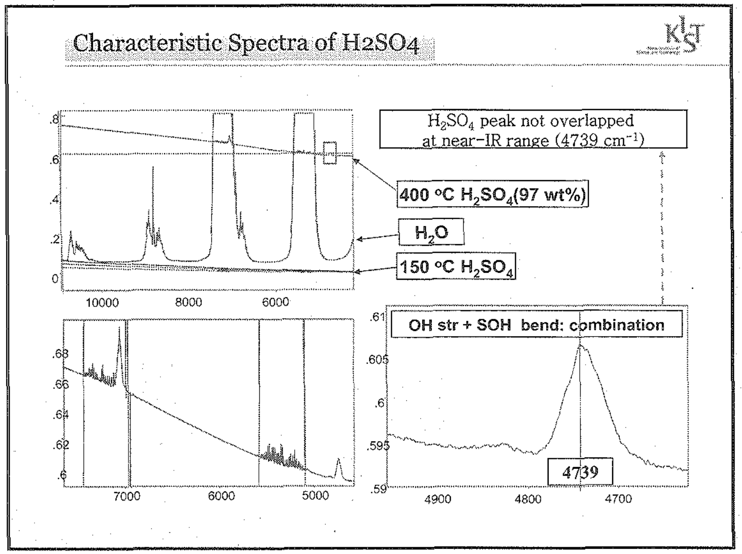
Flow of SO_2/He : 20/10 cc/min, Absorption at 50 ℃

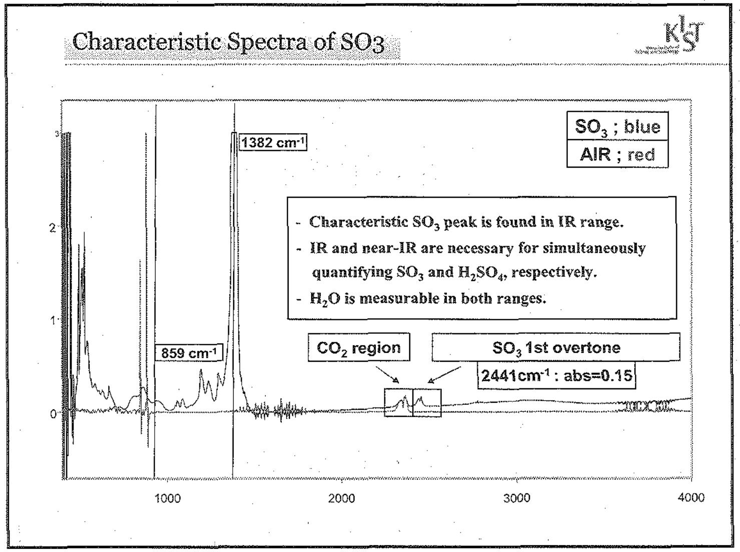
[4] Instrumental *in situ* Analysis

- IR & near-IR Analysis



Advanced Calibration Algorithm using Moment-combined PLS


Characteristic Spectra of H2SO4
H_2SO_4 peak not overlapped at near-IR range (4739 cm^{-1})
400 °C H_2SO_4(97 wt%)
H_2O
150 °C H_2SO_4
OH str + SOH bend: combination
4739
10000
8000
6000
7000
5000
4900
4800
4700


Characteristic Spectra of SO3
SO_3 ; blue
AIR ; red
1382 cm^{-1}
859 cm^{-1}
- Characteristic SO_3 peak is found in IR range.
- IR and near-IR are necessary for simultaneously quantifying SO_3 and H_2SO_4, respectively.
- H_2O is measurable in both ranges.
CO_2 region
SO_3 1st overtone
2441cm^{-1} : abs=0.15
1000
2000
3000
4000

1.5.9 R&D on Sulfuric Acid Decomposition in JAEA

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Summary

JAEA has been conducting R&D on thermo-chemical Iodine-Sulfur (IS) process to produce hydrogen using nuclear thermal energy of high-temperature gas-cooled reactor as the heat source. The hydrogen production method can produce large amount of hydrogen effectively without emitting greenhouse effect gases such as carbon dioxide. JAEA plans to proceed to the pilot test with the hydrogen production rate of $30Nm^3/h$ as the next step of process development. The IS pilot-plant will be constructed using practical industrial materials and driven by high temperature helium gas of 4MPaG.

In the plant, sulfuric acid (H_2SO_4) decomposer is one of the key components, with which H_2SO_4 is evaporated and decomposed into H_2O and SO_3 under high temperature condition of up to 500°C. The decomposer is exposed to severe corrosive condition of H_2SO_4 boiling flow. We proposed a new concept of the H_2SO_4 decomposer which was equipped with a counter-flow type heat exchanger consisting of SiC ceramic blocks. Pure gold gaskets are used as the sealant between SiC blocks. SiC ceramic and gold exhibit excellent corrosion resistance under high temperature H_2SO_4 condition.

3-D thermo-mechanical analyses indicated an enough mechanical strength of the ceramic blocks under the high pressure and high temperature conditions. Also, the satisfactory seal performance was suggested by a test of simulated model under 500°C. Based on these results, a mock-up model of the decomposer, especially the ceramic blocks section, was test-fabricated and its mechanical strength and seal performances were examined against horizontal loading simulating earthquake motion. Structural integrity and fabricability of the H_2SO_4 decomposer were confirmed through the successful completion of these tests.

A H_2SO_4 Thermal-Hydraulic Test Loop was fabricated for measurement of heat transfer characteristics and examination of the H_2SO_4 components. We measured boiling heat transfer coefficient for H_2SO_4 and selected Stephan-Körner correlation for the prediction of heat transfer coefficient. We operated the test loop for one year without significance troubles and accumulated knowledge relating to the operation and the maintenance of H_2SO_4 components.

1st JAEA/KAERI Information Exchange Meeting
on HTGR and Nuclear Hydrogen Technology

R&D on Sulfuric Acid Decomposition in JAEA

August 30, 2006

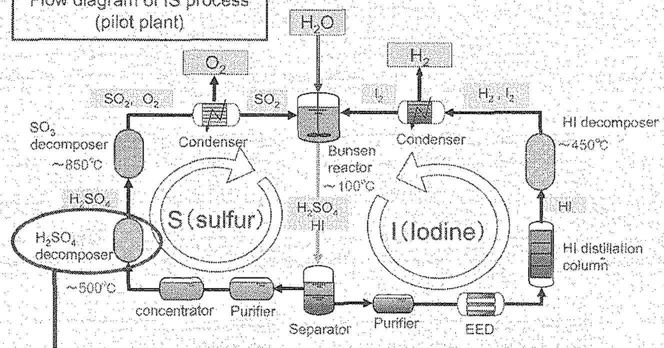
IS Process Technology Group

H. Noguchi, H. Ota, R. Hino

1

Orientation of H_2SO_4 Decomposer

Flow diagram of IS process (pilot plant)



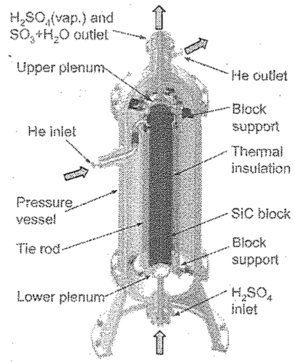
H_2SO_4 (liq.) → H_2SO_4(vap.) and $H_2O + SO_3$
H_2SO_4 is evaporated and H_2SO_4 vapor almost of 40%is decomposed into H_2O and SO_3 in the H_2SO_4 decomposer under high temperature condition up to 500°C.
It is exposed to severe corrosion condition of H_2SO_4 boiling flow.

2

Concept of H_2SO_4 Decomposer

Design condition of H_2SO_4 decomposer

H_2SO_4	Pressure	2 [MPaG]
	Flow rate	4.0 [kg/min]
	Temperature (inlet/outlet)	460 / 435 [°C]
	Concentration	90 [wt%]
	Saturation temperature	455 [°C]
He	Pressure	4 [MPaG]
	Flow rate	5.5 [kg/min]
	Temperature (inlet/outlet)	710 / 535 [°C]
Quantity of exchange heat		82.7 [kW]
Maximum heat flux		80 [kW/m²]
Number of heat transfer channel		32 (H_2SO_4) / 38 (He)
Dimension of heat transfer channel		I.D14.8 [mm] / L 1.5 [m]



Cut away view of H_2SO_4 decomposer

Characteristics
- High temperature
- High pressure
- Severe corrosion condition

A new decomposer concept of a block type heat exchanger made of SiC ceramic was established, which has excellent corrosion resistance and mechanical strength performance.

Ref) A.Terada et al., *J. Atom. Eng. Sci. JPN*, May, Vol.5, No.1 (2006).

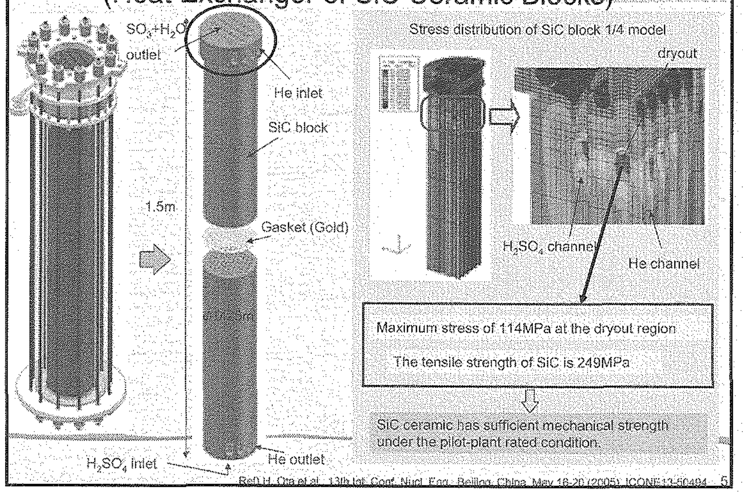
3

Main Tasks of H_2SO_4 Decomposer R&D

- To confirm following feasibility for SiC-made heat exchanger structure :
  - Structural integrity,
  - Seal performance, and
  - Fabricability .
- To make clear design criteria on H_2SO_4 boiling flow :
  - Measurement of boiling heat transfer, and
  - Selection of heat transfer correlation.
- To confirm of applicability of equipments such as pipes, valves, pumps and instrumentation serving to the decomposer.

4

Structure of H_2SO_4 Decomposer (Heat Exchanger of SiC Ceramic Blocks)



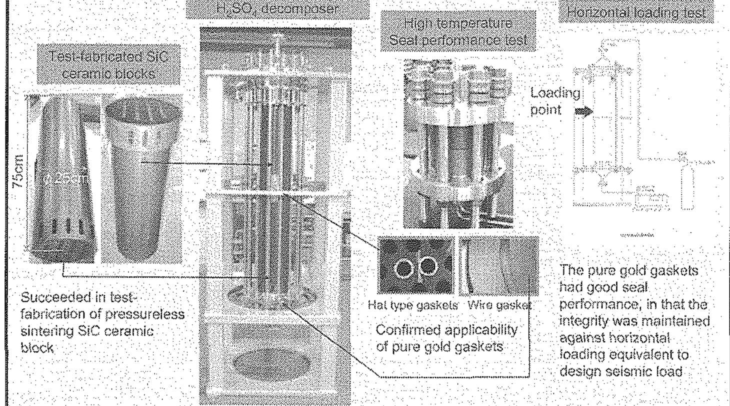
Maximum stress of 114MPa at the dryout region

The tensile strength of SiC is 249MPa

SiC ceramic has sufficient mechanical strength under the pilot-plant rated condition.

Ref) H. Ota et al., 13th Int. Conf. Nucl. Eng., Beijing, China, May 16-20 (2005), ICONE13-50494 5

Test Fabrication of Heat Exchanger Mock-up Model



Succeeded in test-fabrication of pressureless sintering SiC ceramic block

Confirmed applicability of pure gold gaskets

The pure gold gaskets had good seal performance, in that the integrity was maintained against horizontal loading equivalent to design seismic load

The fabricability and structural integrity were confirmed through the test

Ref) H. Noguchi et al., ICAPP'06 Reno, NV, USA, June4-8 (2006), ICAPP06-6166 6

Main Tasks of H_2SO_4 Decomposer R&D

- To confirm following feasibility for SiC-made heat exchanger structure :
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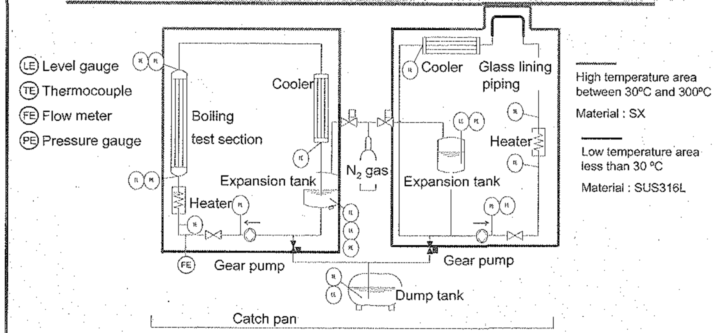
- To confirm of applicability of equipments such as pipes, valves, pumps and instrumentation serving to the decomposer.

7

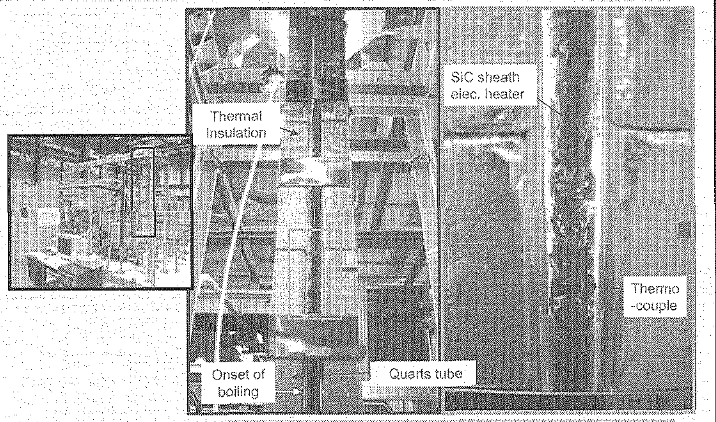
H_2SO_4 Thermal-Hydraulic Test Loop

	Boiling heat transfer test loop	Component test loop
Temperature	30-310 °C	30-320 °C
Pressure	0.05MPaG (max. 0.1MPaG)	0.35MPaG (max. 0.95MPaG)
Flow rate	0.1L/min (max. 2.5 L/min)	0.1L/min (max. 25 L/min)
H_2SO_4 condition	85 - 90 wt% Liquid and vapor	85 - 90 wt% Liquid



Ref) H. Ota et al., 2006 Annual Meeting of the Atomic Energy Society of Japan, Oarai, Japan, March 24-26, N40, pp-592 8

H_2SO_4 Boiling Test

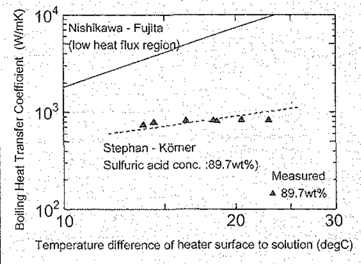


Nucleate boiling in H_2SO_4

Ref) H.Ota et al., 2006 Annual Meeting of the Atomic Energy Society of Japan, Oarai, Japan, March 24-26, N40, pp-592.
J.Iwatsuki et al., 14th Int. Conf. Nucl. Eng., Miami, Florida, July 17-20 (2006), ICONE14-89267.

9

Comparison of Boiling Heat Transfer Correlations



Nishikawa-Fujita correlation (low heat flux)

Higher than experimental results

Stephan-Körner correlation

The correlation for binary mixture could predict experimental results within an accuracy of ±30%

Stephan-Körner correlation is available for prediction of boiling heat transfer coefficient of H_2SO_4-water mixture

Ref) H.Ota et al., 2006 Fall Meeting of the Atomic Energy Society of Japan, Japan, September 27-29

10

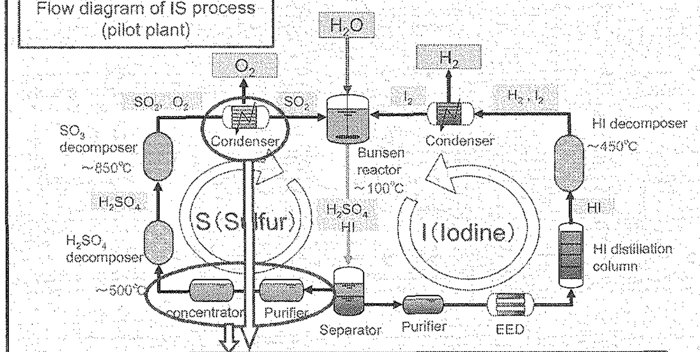
Main Tasks of H_2SO_4 Decomposer R&D

- To confirm following feasibility for SiC-made heat exchanger structure :
  - Structural integrity,
  - Seal performance, and
  - Fabricability .
- To make clear design criteria on H_2SO_4 boiling flow :
  - Measurement of boiling heat transfer, and
  - Selection of heat transfer correlation.
- To confirm of applicability of equipments such as pipes, valves, pumps and instrumentation serving to the decomposer.

11

Orientation of H_2SO_4 component test

Flow diagram of IS process (pilot plant)



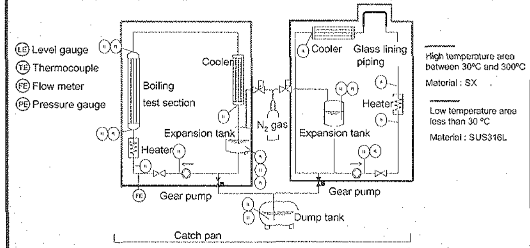
Targets : Components contacting H_2SO_4(liq.), which will be established under severe corrosion condition
Concentration : 50-90wt%, Pressure : 2MPaG, Temperature : 100-400 °C

Objective : To verify soundness of H_2SO_4 components for medium and long term operation

12

H_2SO_4 Thermal-Hydraulic Test Loop

	Boiling heat transfer test loop	Component test loop
Temperature	30-310 °C	30-320 °C
Pressure	0.05MPaG (max. 0.1MPaG)	0.35MPaG (max. 0.95MPaG)
Flow rate	0.1L/min (max. 2.5 L/min)	0.1L/min (max. 25 L/min)
H_2SO_4 condition	85 - 90 wt% Liquid and vapor	85 - 90 wt% Liquid



Actual achievement

Boiling heat transfer test loop
Pump operating time 211h
Hot (~300 °C) holding time 27h
Heat cycles 6 times

Component test loop
Pump operating time 402h
Hot (~300 °C) holding time 153h
Heat cycles 45 times

There was no significant trouble in operating time

Ref) H.Ota et al., 2006 Annual Meeting of the Atomic Energy Society of Japan, Oarai, Japan, March 24-26, N40, pp.592

13

Concluding Remarks

- Structural integrity and fabricability of H_2SO_4 decomposer were confirmed through the test fabrication of the mock-up model of the H_2SO_4 decomposer for the IS pilot-plant
- Stephan-Körner correlation is available for prediction of boiling heat transfer coefficient of H_2SO_4-water mixture.
- Knowledge relating to operation and maintenance of sulfuric acid components has been accumulated through the operation of the H_2SO_4 Thermal-Hydraulic Test Loop

⇩

Future plan

The achievements of those test will be reflected to the IS process pilot-plant design.

14

1.5.10 Catalyst Test of SO_3 Decomposition

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imai.yoshiyuki@jaea.go.jp

Summary

SO_3 decomposition reaction proceeds endothermically at the highest temperature condition in the IS process, in which catalyst is required to attain practical reaction rate.

This study shows the experimental results of catalytic decomposition rate obtained by Pt catalyst supported by Al_2O_3 (1wt%Pt/γ-Al_2O_3). Experiments were carried out under the rated operational temperature of 850°C and rather high space velocity of 32000 h^{-1}, which showed that initial decomposition rate could keep several tens of hours. Also, the catalyst used in one-week continuous hydrogen production experiments with a bench-scale test apparatus was investigated with SEM, EPMA, BET and XRD. The investigation showed the following phenomena; loss of Pt surface area caused by Pt sintering, loss of Al_2O_3 surface area caused by the phase transformation from γ to α, and formation of sulfate on the surface of the catalyst.

Catalyst Test for SO_3 Decomposition

1st JAEA/KAERI Information Exchange Meeting
on HTGR and Nuclear Hydrogen Technology
August 28 - 30, 2006

○Yoshiyuki IMAI and Akihiro KANAGAWA
IS Process Technology Group
Nuclear Applied Heat Technology Division
Nuclear Science and Engineering Directorate
Japan Atomic Energy Agency (JAEA)

1

SO_3 Decomposition

- $SO_3 \rightarrow SO_2 + 1/2O_2$
- **Highest temperature condition in the I-S process (850℃).**
- **Endothermic Reaction.**
  ΔH^0_{1100}=97.2 kJ/mol
- **Catalyst is needed.**
  - **Ex. Pt, Fe_2O_3 etc**

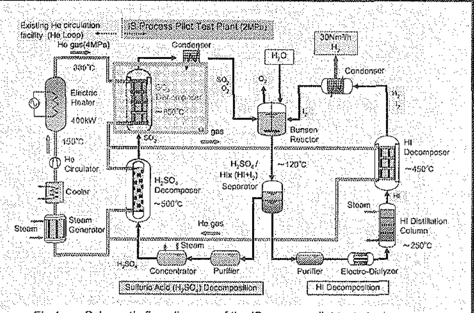


Fig.1 Schematic flow diagram of the IS process pilot test plant

- SO_3 decomposer has to be used under the high temperature condition. So this equipment should be small and have long life.

⇩

it is necessary to find a high performance and <u>long life catalyst</u>.

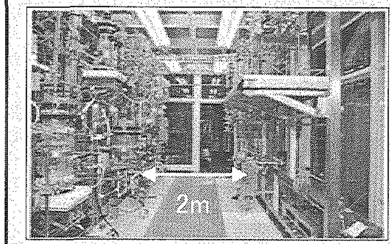
2

Catalyst Test

- In order to develop more stable catalysts,
- Preliminary Examination of used catalyst was carried out <u>to estimate factors of catalyst deactivation.</u>
  - Surface condition and element distribution (SEM, EPMA)
  - Amount of catalyst and surface area on the support (ICP, CO absorption)
  - Support surface area and crystal structure (BET, XRD)
- Durability test to determine the catalyst life.

3

Preliminary Examination of Used Catalyst



Outer view of Engineering test apparatus

- JAEA succeeded in continuous hydrogen production test for one week in 2004.
- Catalyst used for above mentioned engineering test was examined.

Ref) S. Kubo et al., Proc. GLOBAL 2005, Tsukuba, Japan, Oct. 9-13, 2005, Paper No.474.

4

Engineering Test Conditions

- Catalyst : 1wt% Pt／γ-Al_2O_3
- Catalyst size : 3 mm$^{\phi}$ × 3 mm^{L}
- Volume of catalyst: 250 cm^3
- Temperature : 850 ℃
- Sulfuric acid : 90 wt%
- Feed rate : 150 g/h
- Time : 100 h～

SV ≒ 300 h^{-1} << 5000h^{-1}
SV (Space Velocity) ＝Fi／Vc
Fi : process flow rate
Vc : Volume of catalyst

- **Enough quantity of catalyst was filled to keep a stable condition for SO3 decomposition.**

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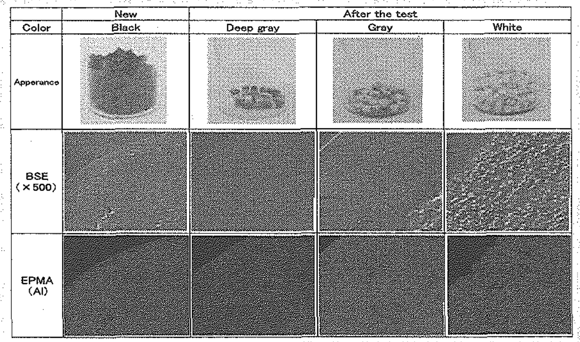
Preliminary Examination for Pt/ γ-Al_2O_3
(Appearance, Surface Condition and Element Distribution)

- Catalyst changed its color from black (original color) into gray or white after the test.
- As its color turns white, catalyst surface becomes rough.



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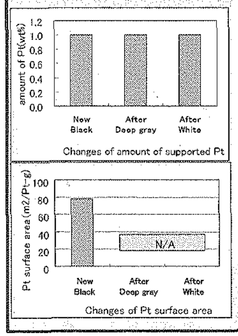
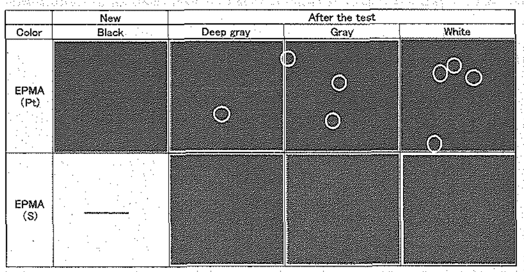
Preliminary Examination for Pt/ γ-Al_2O_3
(Pt Amount, Pt Surface Area and Element Distribution)

- Decline of Pt surface area which is proportional to active site should be caused by Pt sintering with the same amount of Pt on the catalyst.
- Formation of the sulfate also can become the factor of catalyst deactivation.





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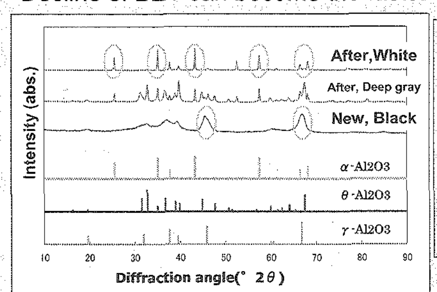
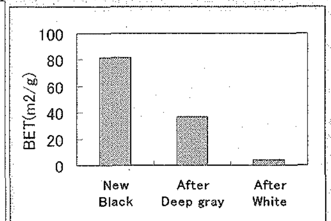
Preliminary Examination for Pt/ γ-Al_2O_3
(Support Surface Area and Crystal Structure)

- The crystal structure of Al_2O_3 support changes from γ-phase (Black) to α-phase (White).
- Support surface area (BET) declines after the test.
- Decline of BET can become the factor of the catalyst deactivation.



Result of XRD

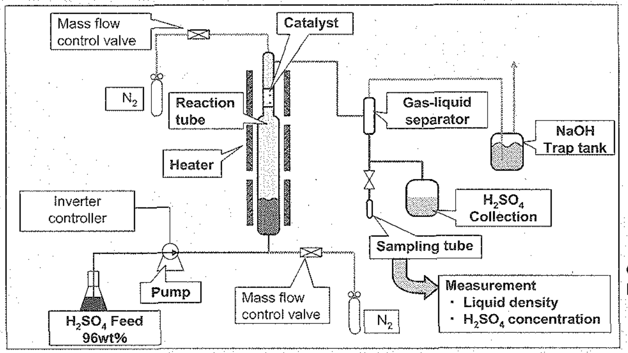


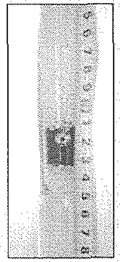
Changes of BET surface area

JAEA 8

Durability Test for Pt/ γ -Al_2O_3

- Main parts are made of glass.
- Catalyst Temp. : 850℃(max), Press. : Atmospheric Pressure
- Space Velocity : 2,000 ~ 50,000 h^{-1}, N_2 as carrier gas





Catalyst bed 1wt% Pt/Al_2O_3 6.5 cm^3

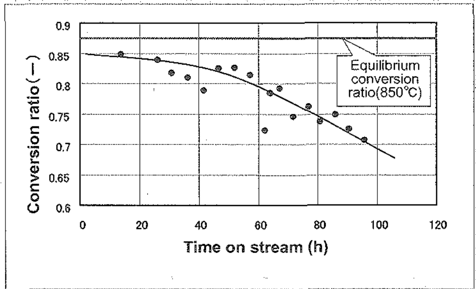
9

Durability of Catalyst (1wt%Pt/ γ -Al_2O_3)

- Catalyst can keep its performance (decomposition rate) for only <u>50 hours</u> at the maximum space velocity in 850℃.
- After 95-hour operation, catalyst color changed to gray.

Test condition

- **Cat. : 1wt%Pt/ γ -Al_2O_3 6.5 cm^3**
- **Temp : 850℃**
- **Feed rate of H_2SO_4 : 207 g/h (96wt%)**
- **Flow rate of N_2 : 1.9 L/min**
- **SV : 32,000 h^{-1}**



10

Concluding Remarks

- Deactivation factors for 1wt%Pt/ γ -Al_2O_3
  - Pt sintering (loss of Pt surface area)
  - Loss of Al_2O_3 surface area caused by the phase transformation ($\gamma \rightarrow \alpha$ -Al_2O_3)
  - Formation of sulfate on the surface of the catalyst
- Life time of 1wt%Pt/ γ -Al_2O_3
  - In the maximum performance condition (850℃, 32000 h^{-1}, atmospheric press.) for the catalyst, the life time is only 50 hours.

11

Future Test Plan

- Test for Pt/SiC catalyst which is not expected to make a phase transformation or sulfate formation.
- SO_3 decomposition test under high pressure (1MPa(G)) condition.

12

1.5.11 Design Code System for IS Process

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Summary

A pilot test program with hydrogen production rate of 30 Nm^3/h was initiated following the successful bench scale test of the IS process. In the program, sensible heat of high-temperature (up to 880°C) and high-pressure (4 MPa) helium gas, which is the same as the HTTR secondary helium gas temperature and pressure, will drive continuous hydrogen production, through which essential engineering data will be acquired to prepare for constructing and operating a nuclear demonstration plant connected with the HTTR (HTTR-IS test).

To design the pilot test plant, it is necessary to carry out following various analyses and estimations:

- Process simulation to make clear state functions in the process and effective functions necessary for improving process efficiency,
- Material selection based on corrosion and SCC estimations,
- Mechanical strength analyses to confirm structural integrity,
- Thermal-hydraulic analyses to improve chemical reaction,
- Safety analyses to make clear countermeasures against fire and explosion accidents.

A design and analysis system based on CAD/CAE system has been almost completed by using commercial codes such as PRO/II, DPS, ABAQUS, Star-CD. Also, to design a Bunsen reactor, a new thermal-hydraulic analysis code coupled with chemical reaction is being developed based on α-flow/MISTRAL, with which it will be possible to estimate time resolved and 3D spatial distribution of design parameters (flow velocity, temperature, concentration, etc). To verify models incorporated in the new analytical code, flow visualization with gas jet bubbles, which simulates internal flow in the Bunsen reactor, is being carried out by using PIV (Particle Image Velocimetry) and PLIF (Planer Laser Induced Fluorescence) systems (DANTEC).

Design Code System for IS process

1st JAEA/KAERI Information Exchange Meeting,
Oarai, August 28-30, 2006

Atsuhiko TERADA, Jin IWATSUKI, Shuichi ISHIKURA, and Ryutaro HINO

Nuclear Applied Heat Technology Division
Nuclear Science and Engineering Directorate
Japan Atomic Energy Agency (JAEA)

Development of Reactor Simulation Code

item／development stage	Bench scale test ⇨	Pilot test ⇨	HTTR IS test
Hydrogen production	~ 50 L/h	~30 m^3/h	~1000 m^3/h
Heat supply	Electric heating	High temperature He gas (electric heating)	High temperature He gas (HTTR nuclear heat)
Material of chemical reactor	glass	Industrial materials	Industrial materials
Process pressure	atmosphere	High pressure	High pressure

⇩

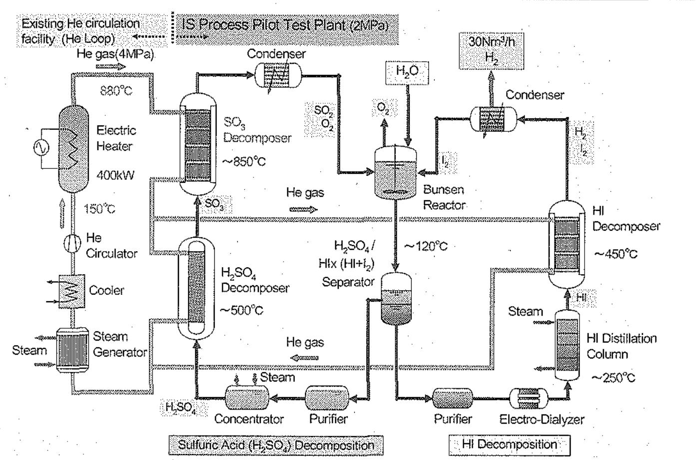
It is necessary for us to prepare a analytical code system for designing the plant scale apparatus.

⇩

Commercial codes are selected to progress the plant design, equipment , etc. efficiently.

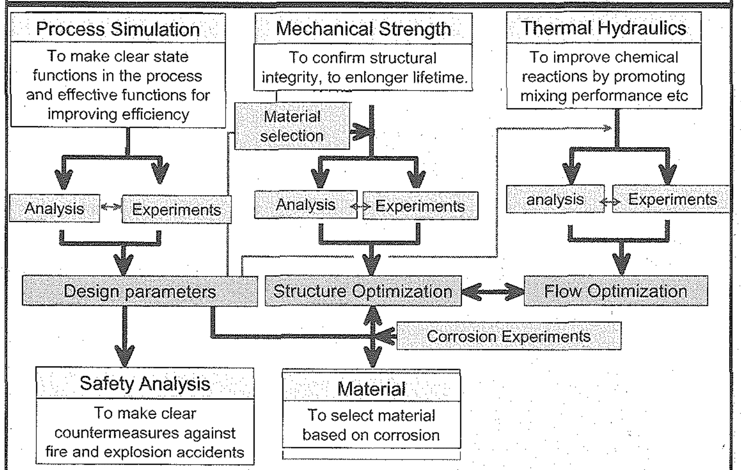
2

Flow Diagram of IS Process Pilot Plant (tentative)



3

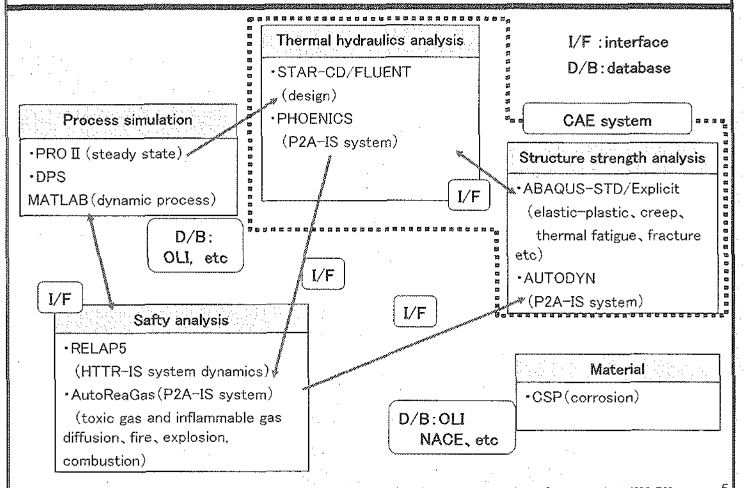
Code System for Designing IS Process Pilot Plant



Ref) A.Terada et al, Proc. 13th Int. Conf. Nucl. Eng., Beijing, China, May 16-20, 2005, ICONE13-50183

4

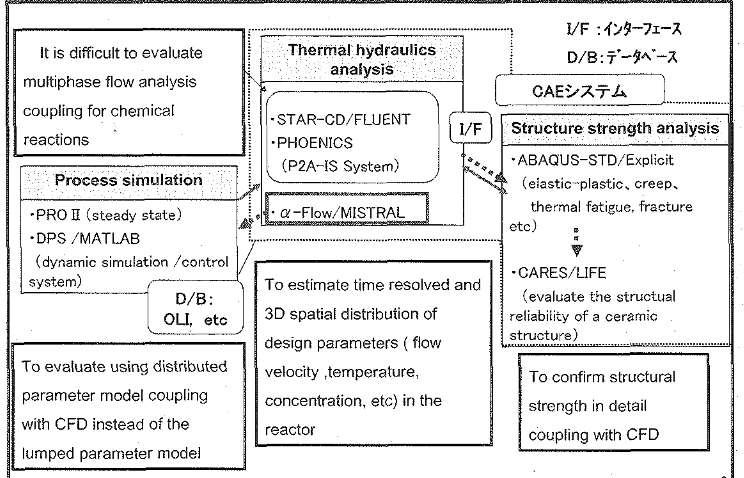
Relationship among Analytical Codes



Ref) A. Terada et al, 2005 Fall Meeting of the Atomic Energy Society of Japan, Hachinohe, Japan, September 13-15, 2005, E26.

5

Improvement of Analytical Codes



6

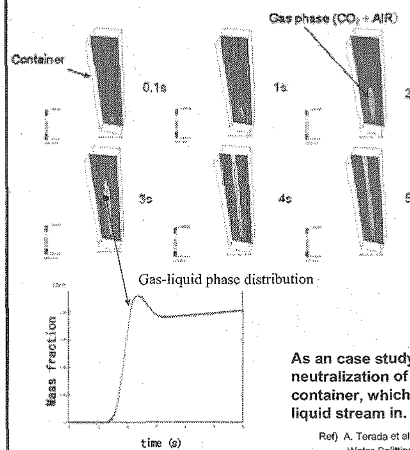
Thermal-Hydraulic Analysis Code Coupled with Chemical Reaction, Especially for Bunsen Reaction

We have developed the thermal hydraulics analysis code based on α-Flow (Mizuho Information & Research Institute)

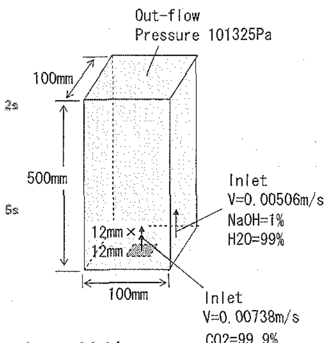
- Basic Conservation equations
  - /Mass and momentum conservation equations(Navier-Stokes equations)
  - /Enthalpy conservation equation
- Multiphase flow model
  - /Eulerian Two-Phase Model
  - /Inter-phase Momentum Transfer
  - /Internal Forces
  - /Energy Transfer
- Chemical reaction model
- Turbulence model
  - /k-ε two-equation model
- Thermophysical properties
  - /Equation of state (density)
  - /Viscosity-temperature relation
  - /Mixture properties etc
- Heat Transfer
  - /Diffusional Flux Relations (Fourier)
  - /Conduction and conjugate heat transfer
- Mass Transfer in Fluid Mixtures
  - /Diffusional flux relations (Fick)

7

Case study (① gas-liquid flow with chemical reaction)



Mass fraction of product (container center



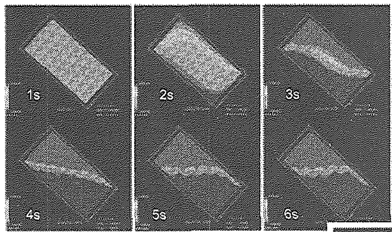
Model

As an case study, We have simulated to neutralization of NaOH with H_2CO_3 in the container, which The CO_2 jet injected into liquid stream in.

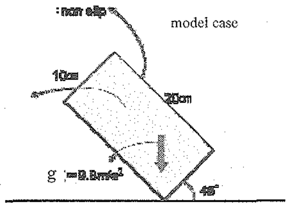
Ref) A. Terada et al, 2006 "Development of Chemical Reactors for Thermochemical Water-Splitting IS Process", Journal of High Temperature Society, 32-1 (2006) 63-68. (in Japanese)

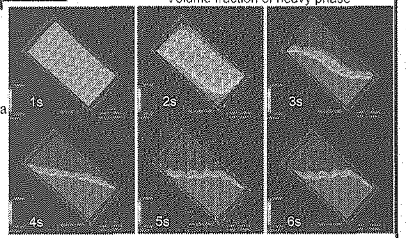
8

Case study (② liquid-liquid separation)



Volume fraction of Light phase





Volume fraction of heavy phase

volume fraction	density	vistcosity
vapor =10%	1.205 kg/m3	1.84e-5 Pa s
Liquid-1 =45%	354.3 kg/m3	1.002e-3 Pa
Liquid-2=45%	1234.6 kg/m3	1.00e-3 Pas

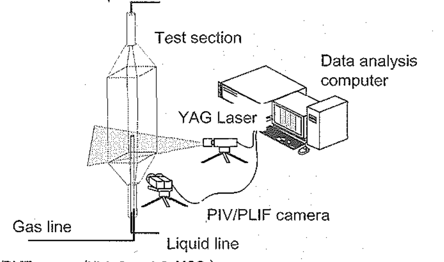
As an case study, we simulate that gas-liquid mixture separates light and heay liquid according to the density difference

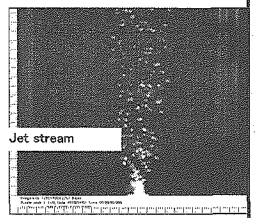
Ref) A. Terada et al, 2006 "Development of Chemical Reactors for Thermochemical Water-Splitting IS Process", Journal of High Temperature Society, 32-1 (2006) 63-68.

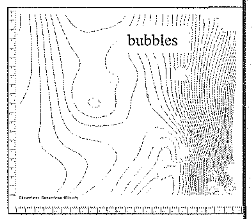
9

Verification of Newly Developed Analytical Code

In order to validate the CFD simulations of gas-liquid flow and reacting flows, bubble flow is presently visualized by using PIV (Particle Image Velocimetry) and PLIF (Planer Laser Induced Fluorescence), which are techniques that can offer whole field information of the mean and fluctuating velocities of both phases and chemical reactants.







PIV/PLIF camera (High Speed C-MOS)
- pixcels : 1280×1024 pixcels
- Interframe time : 100 nsec
- resolution : 10 bit
- Pixcel size : 12 μm×12 μm

ND:YAG laser
- power : 50W (×2)
- Wave length : 532 nm
- Beam diameter : 2.5 mm
- Repetition rate : 10 Hz~50 kHz

Ref) A. Terada et al, 2006 Annual Meeting of the Atomic Energy Society of Japan, Oarai, Japan, March 24-26, 2006, N46.

10

Concluding Remarks

- We have arranged to the analytical code system for IS process pilot plant design.
- To design reactor in detail, especially for the Bunsen reactor, we have been developing a new analytical code, thermal-hydraulic code coupled with chemical reaction.
- The code is being verified with experimental results obtained under gas-liquid flow.

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1.5.12 Development of Dynamic Process Simulator for IS process

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Summary

Development of a dynamic process simulator for the IS process plant was implemented to examine the startup/shutdown procedure and to investigate thermal transition behavior. Main specifications of the simulator are as follows;

- Solver (Object DPS)
  Equation solver type for ordinary differential system
- Properties
  Chemical equilibrium, Vapor-liquid equilibrium, Liquid-liquid equilibrium, Enthalpy, Kinetics
- Flow sheet
  Closed-cycle system, Helium heat exchanger reactors.

Required properties were embedded in the simulator based on the literature or on our experiment results. As for the flow sheet, a simplest model was constructed which features a complete closed-cycle system, conventional distillations for HI and H_2SO_4 concentrations and one-dimensional helium heat exchange reactors. In Trial simulations, main equipments operated without failures, moreover, the complete closed-cycle process heated by helium gas was successfully computed. Modifications are planed to detail the design data and the flow sheet.

Development of Dynamic Process Simulator for IS process

1st JAEA/KAERI Information Exchange Meeting
on HTGR and Nuclear Hydrogen Technology,
Oarai, August 28-30, 2006

Shinji KUBO

IS Process Technology Group
Nuclear Applied Heat Technology Division
Nuclear Science and Engineering Directorate
Japan Atomic Energy Agency (JAEA)

Purpose and specification

Purpose of dynamic simulator

to check startup/shutdown procedure for IS plant

to investigate thermal transition behavior for IS plant

Chief specification of simulator

- Solver (Object DPS)
  Equation solver type for mainly ordinary differential system
- Properties
  Chemical equilibrium, Vapor-liquid equilibrium, Liquid-liquid equilibrium, Enthalpy, Kinetics etc.
- Flow sheet
  Closed-cycle system
  He heat exchanger reactors

Embedded thermodynamic data

○ Vapor-liquid equilibrium
  H_2SO_4-H_2O system → NRTL on existing literature
  HI-I_2-H_2O system → NRTL on existing literature

○ Liquid-liquid equilibrium
  Regressed expression based on experiment results

○ Enthalpy
  Mixing low using pure substance based on existing literature

Required properties were embedded in the simulator based on the existing literature and experiments

Basic flow sheet for simulation

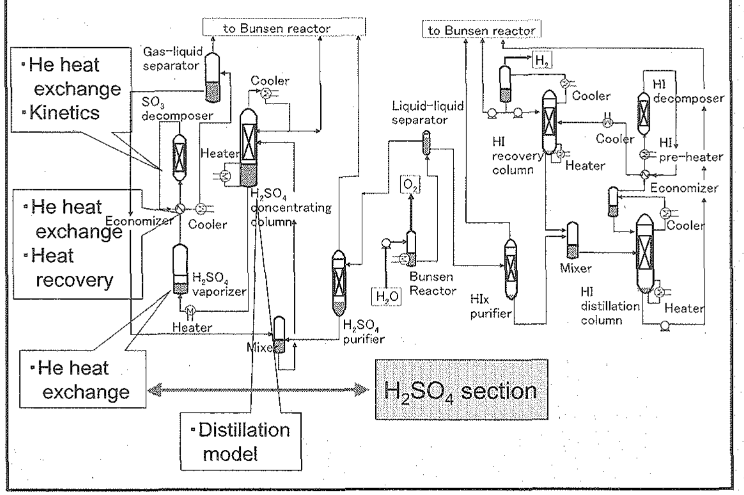
Simplest flow sheet model was constructed for further and detailed modifications

→ Complete closed-cycle system

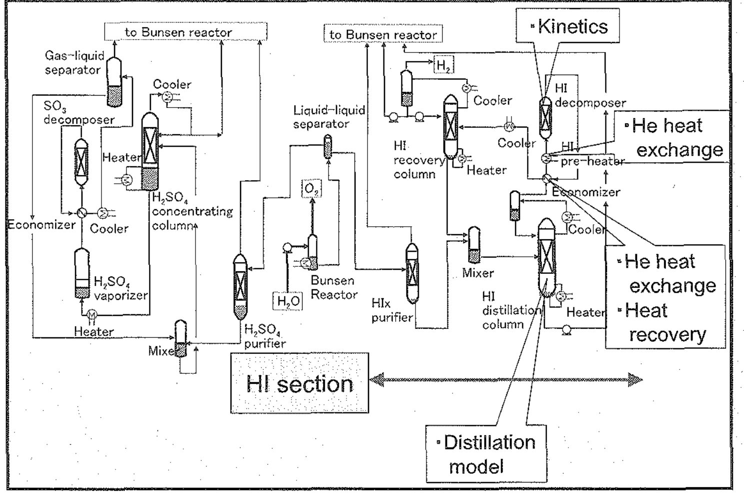
→ Conventional distillation for HI and H_2SO_4 acid concentrations

→ One-dimensional He heat exchange reactors

Flow sheet descriptions (1/2)



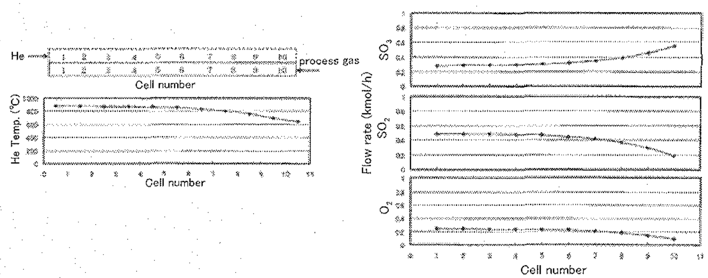
Flow sheet descriptions (2/2)



Trial simulations for main equipments and total system

- Main equipments operated without failure
- Complete closed-cycle process heated by He gas was successfully computed

Temperature distributions and flow rate in SO_3 decomposer



Summary

- Properties required for the dynamic process simulation were embedded into the equation solver.
- Simplest flow sheet model was constructed to realize complete closed-cycle process heated by He gas.
- In trial simulations, the model was successfully computed.
- Modifications are planned to detail design data and flow sheet design.

1.5.13 HTTR-IS program

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Summary

High-temperature reactors (HTRs) are particularly attractive due to their wide industrial application from electricity generation to hydrogen production. The Japan Atomic Energy Agency's (JAEA's) HTTR, which is the first HTR in Japan, attained its maximum reactor-outlet coolant temperature and successfully delivered 950°C coolant helium outside its reactor vessel. A hydrogen production system based on the thermochemical water-splitting iodine sulphur (IS) process is planned to be connected to the HTTR in the near future. This will establish the hydrogen production technology with an HTR, including the system integration technology for connection of hydrogen production system to HTRs. It will probably be the world's first demonstration of hydrogen production directly using heat supplied from an HTR.

The HTTR-IS system design was launched from a conceptual design in 2005. At present, various studies are under way, which covers safety evaluation, thermal efficiency evaluation for the HTTR-IS system, development of components, development of codes, etc. The verification of the hydrogen production by the HTTR-IS system by using heat from a nuclear reactor is greatly expected to contribute to the commercialization of nuclear hydrogen in coming hydrogen society.

1st JAEA/KAERI Information Exchange Meeting on HTGR and Nuclear Hydrogen Technology

HTTR-IS program

30 August 2006

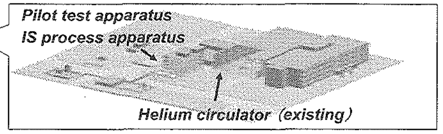
Nariaki Sakaba, Hiroyuki Sato, Hirofumi Ohashi,
Kazuhiko Kunitomi
Japan Atomic Energy Agency

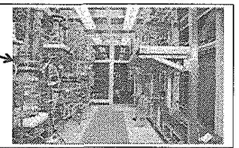
IS Process development in JAEA

Hydrogen production rate (m^3/h)

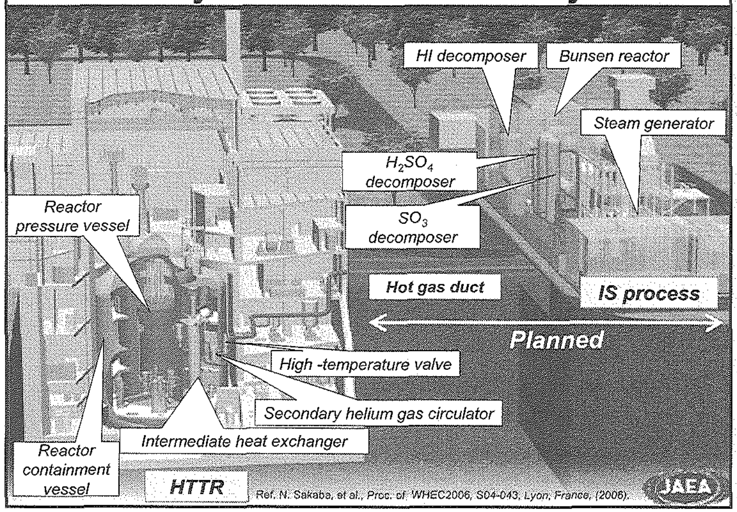
Hydrogen production rate (m^3/h)	Stage
1000	**HTTR-IS test** (after 2010) World's first hydrogen production utilizing heat from nuclear
30	**Pilot test** (design study is underway)
0.03	**Bench-scaled test** (1999-2005)
0.001 (1L)	**Lab-scale test** Verification of theory of the IS process for the first time (1997)

HTTR-IS test verification of economical feasibility
- Obtaining data required for economical evaluation of commercial plant
- Show the way to the commercial plant of satisfying requirements of users



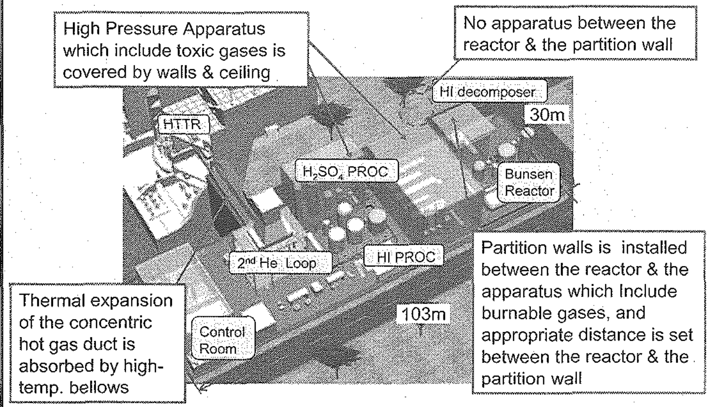


Bird's eye view of the HTTR-IS system



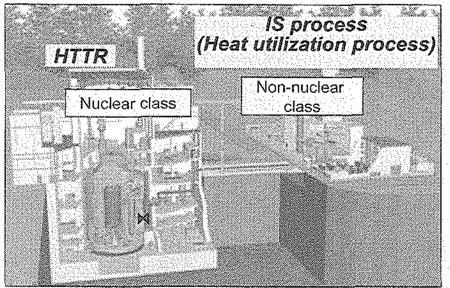
Ref. N. Sakaba, et al., Proc. of WHEC2006, S04-043, Lyon, France, (2006).

Conceptual layout of the HTTR-IS system



Ref. H. Sato, et al., Proc. of SPES2006, OS8-8, Tokyo, Japan(2006).

The HTTR-IS system



- *Establish procedures on safety design and evaluation*
- *Add to experience of construction, operation and maintenance*
- *Establish the control technology for both of IS process and reactor*
- *Establish the technology on key high-temperature components (high-temperature valves, high-temperature bellows etc.)*
- *Verify analysis codes*

Ref. N. Sakaba, et al., Proc. of ICAPP'06, 6024, Reno, US, (2006).

R&D for the HTTR-IS system design

- *The requirement of users should be satisfied or should be shown its way to commercial reactors*
  - *Efficiency, amount and cost of produced hydrogen*
  - *Safety scenario of the connection between a nuclear reactor and a chemical plant*
- *Investigation of possibility of utilization of a non-nuclear class IS system*
- *Separation of IS process from nuclear facilities*
  - *Hydrogen explosion*
  - *Tritium permeation*

Ref. N. Sakaba, et al., Proc. of ICAPP'06, 6024, Reno, US, (2006).

HTTR-IS development schedule

2007	2008	2009	2010
・Basic design ・Design of instrumentation ・Design of control systems	・Detailed design		
	・Safety case studies ・Risk evaluation	・Safety assessment (two years)	
	・Validation of safety analysis codes		
	・Cost evaluation		

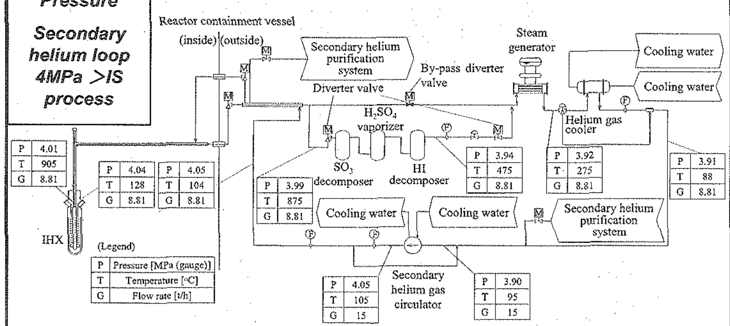
We will complete the HTTR-IS system design until 2010.

Ref. N. Sakaba, et al., Proc. of ICAPP'06, 6024, Reno, US, (2006).

HTTR-IS conceptual design

Pressure

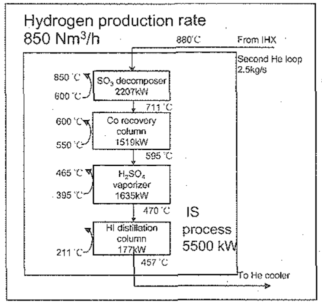
Secondary helium loop 4MPa >IS process

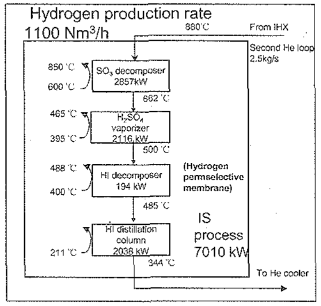


- *During the loss of the heat transfer from secondary helium to the IS process, the IS process is isolated by diverter valves, and the steam generator and the helium cooler remove all the secondary heat.*

Ref. N. Sakaba, et al., Proc. of Annual meeting of AESJ, N49, Oarai, Japan (2006).

HTTR-IS flowsheet evaluation





- H2 production rate over 1,000Nm³/h can be demonstrated by adapting hydrogen permselective membrane in HI decomposer (Thermal efficiency :about 43% or more in the case of electricity generation efficiency of 40% or more)
- Require development and verification of improvements of apparatus such as H2 permselective membrane (Verified in lab scale at present)

Ref. N. Sakaba, et al., Proc. of WHEC2006, S04-043, Lyon, France, (2006).

Expected thermal efficiency

	Unit	The process using components in the bench-scale	HTTR-IS plant (using a HPMR for separation of H_2 in HI
Heat demand	kJ/mol-H_2	4447.4	514.0
Heat for electricity	kJ/mol-H_2	0.0 *	141.9
Total	kJ/mol-H_2	4447.4	655.8
Thermal efficiency (η)	%	6.4	43.6

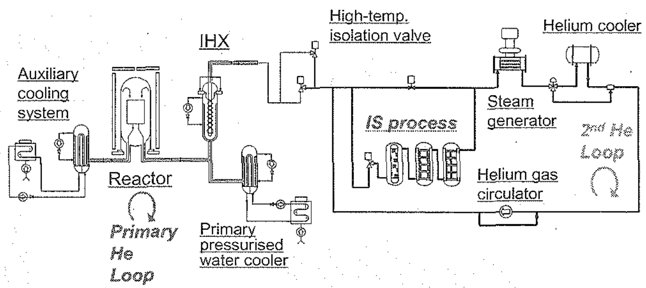
* Not including the electricity for pump and utilities

Thermal efficiency of 44 % and hydrogen production rate of 1,100 Nm³/h are expected in the HTTR-IS system.

Thermal efficiency of the bench scale: Kubo *et al.*, *Nucl. Eng. Des.*, 233(1-3) (2004) 355-362

Ref. N. Sakaba, et al., Proc. of ICAPP'06, 6024, Reno, US, (2006).

Dynamic simulation code development of the HTTR-IS system



Objective

- Calculate the transient behaviour of the HTTR-IS system
- Evaluate the effect of abnormal occurrences caused by the IS process for safety case study

Development status

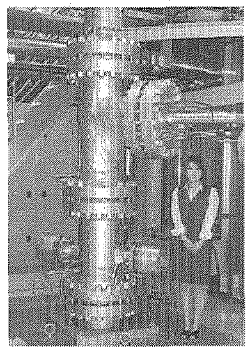
Reactor, primary & secondary system
→ Developed & verified[1)2)]

IS Process
→ Under developing

1) K. Takamatsu, et al., Trans. At. Energy Soc. Japan., 3[1], 76 (2004).
2) H. Ohashi, et al., Nucl. Eng. Des., 236[13], 1396-1410 (2006).

R&D for isolation items

- *Development of high-temperature isolation valve*
- *Development of high-temperature bellows*
- *Estimation of tritium permeation from reactor to hydrogen production system*
- *Countermeasure against hydrogen explosion*
- *Amendment of law, guideline and standards for heat exchanger made by ceramics, etc.*



½ scale model of high-temperature isolation valve

Ref. N. Sakaba, et al., Proc. of WHEC2006, S04-043, Lyon, France, (2006).
Ref. T. Nishihara, et al., Trans. At. Energy Soc. Japan., 2[4], 139 (2003).

Abnormal transients of the HTTR-IS system

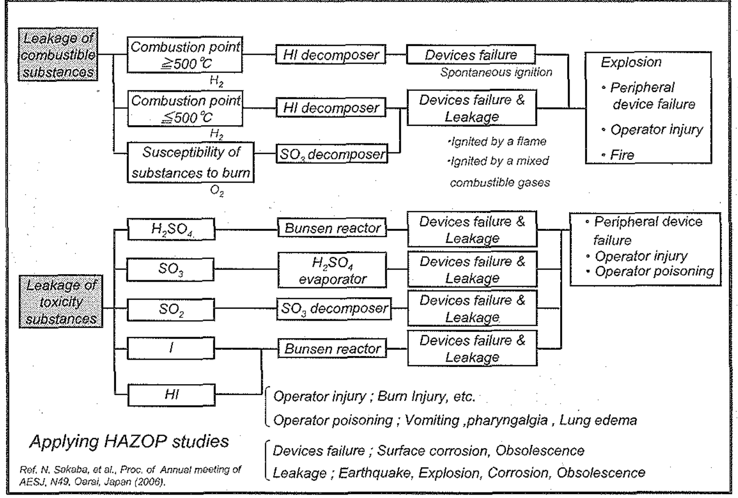
HAZOP studies

A. No influence
B. Fluctuation of operation condition: Without reactor scrum
C. Reactor scrum : No devices failure
D. Devices failure : No leakage or small leakage
E. Vessels and piping rupture
: Leakage of non-combustible substances, non-toxicity substances
F. Vessels and piping rupture : Leakage of combustible substances, toxicity substances (Under the combustion point)
G. Vessels and piping rupture : Leakage of combustible substances
: Hydrogen explosion (Over the combustion point)

HAZOP: Hazard and Operability studies

Ref. N. Sakaba, et al., Proc. of Annual meeting of AESJ, N49, Oarai, Japan (2006).

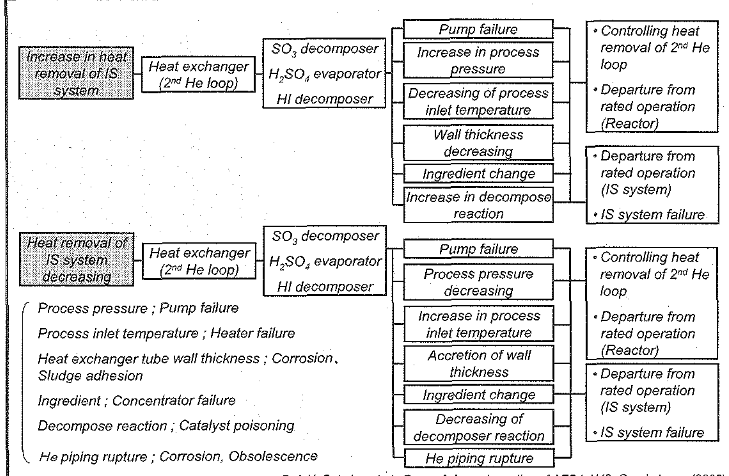
Abnormal occurrences of the HTTR-IS system



Applying HAZOP studies

Ref. N. Sakaba, et al., Proc. of Annual meeting of AESJ, N49, Oarai, Japan (2006).

Abnormal occurrences of the HTTR-IS system (cont'd)



Ref. N. Sakaba, et al., Proc. of Annual meeting of AESJ, N49, Oarai, Japan (2006).

Summary

- JAEA launched a design study of nuclear hydrogen system. (HTTR-IS system).
- Actual high-temperature gas-cooled reactor HTTR will be utilized for hydrogen production.

Future collaboration (Proposal)

- **JAEA will supply reactor conditions e.g. of IHX, secondary helium cooling system.**
- **KAERI will design IS process to be coupled to the HTTR. (JAEA will also continue the HTTR-IS system design.)**

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2 The Briefing of the 1st JAEA-KAERI Information Exchange Meeting on HTGR and Nuclear Hydrogen Technology

The meeting was held at the Oarai Research and Development Center of the Japan Atomic Energy Agency on August 28-30, 2006, per Implementation in July 2006 by the Ministers of Korea (MOST) and Japan (MEXT) to promote collaboration in the field of Nuclear Hydrogen.

JAEA and KAERI mutually showed the status and future plan of the HTTR Project in Japan and the NHDD Project in Korea, respectively.

The meeting was successfully completed with the following major results and conclusions:

1. All of the participants recognized and reaffirmed the necessity of the in-depth cooperation between two organizations including staff involved in the IS process development from KIER and KIST, who are subcontracted institutes of KAERI.
2. It was mutually agreed upon that the cooperation between two projects shall be strengthened by launching cooperative R&D in the framework of the existing JAEA/KAERI Implementation in addition to the general information exchange
3. JAEA stressed the advantage of HTGR with the prismatic core and IS process for hydrogen production in comparison with other candidates for the cogeneration of electricity and hydrogen by nuclear heat. The general philosophy and technical feasibility of the Japanese approach were well understood by the Korean delegation. This will be taken into consideration in the review to be done by the NHDD project team to develop their action plan. Here JAEA supports their technical review so that the Japanese approach or its modification be well incorporated in the Korean NHDD project.
4. The Korean delegation showed an interest in participation in the HTTR Project including the HTTR testing, IS process development and codes validation. JAEA welcomes their participation in the framework of the existing JAEA/KAERI Implementation.
5. It is accepted by JAEA upon request by KAERI that experts from Korea come to the HTTR site as necessary for implementing cooperative R&D.
6. The detailed and specific cooperation subjects will be discussed as soon as possible. The contact persons for this discussion are Mr. T. Takeda for JAEA and Mr. Y. W. Kim for KAERI.
7. The next meeting will be held in Korea next year. The dates and provisional topics will be discussed later.

Appendix 1. Agenda

August 28 (1st day) - HTTR building 4F Conference Room -

8:50	Pick up Korean members at the hotel JAEA bus	Ryutaro Hino (JAEA)
9:40 - 9:50	Welcome Address	Osamu Oyamada (JAEA)
9:50 - 10:15	Self-introduction of Participants	

Session 1 (Overview of projects) Chair: Shusaku Shiozawa (JAEA)

10:15 - 11:05	Overview of HTTR Projects	Shusaku Shiozawa (JAEA)
11:05 - 11:55	Nuclear Hydrogen Projects in Korea	Jonghwa Chang (KAERI)
11:55 - 12:05	Group photograph	
12:15 - 12:55	Lunch at the JAEA's cafeteria	

Session 2 (VHTR system design and related evaluations) Chair: Kazuhiko Kunitomi (JAEA)

13:10 - 14:35	VHTR Cogeneration System: Reactor concept, Turbo machine, High-temp. valve, and GTHTR300C	Kazuhiko Kunitomi (JAEA) Xinglong Yan (JAEA) Tetsuo Nishihara (JAEA)
14:35 - 15:15	Present Status of VHTR PSA in Korea	Seok-Jung Han (KAERI)
15:15 - 15:55	Hydrogen Production Costs of Various Primary Energy Sources	Jae-Hyuk Choi (KAERI)
15:55 - 16:10	Coffee Break	

Site tour (Ryutaro Hino)

16:10 - 16:25	Introduction of HTTR	Yoshihiro Komori (JAEA)
16:25 - 17:40	HTTR	Nozomu Fujimoto (JAEA) Daisuke Tochio (JAEA)
	Test facilities for IS process development	Kaoru Onuki (JAEA)
	Adjourn	
18:00 - 20:20	Welcome party (Asahi Bunshitsu)	JAEA bus
	Welcome address	Osamu Oyamada (JAEA) Takashi Nagata (JAEA)

August 29 (2nd day) - HTTR building 4F Conference Room -

8:50	Pick up Korean members at the hotel JAEA bus	Yoshiyuki Imai

Session 3 (VHTR design codes and analytical works) Chair: Tetsuaki Takeda (JAEA)

9:40 - 10:30	Overview of VHTR Design Code System and Future Test Plan Using HTTR	Tetsuaki Takeda (JAEA) Yukio Tachibana (JAEA)
10:30 - 11:10	Development of a Nuclear Design Code System for the Analysis of VHTR Cores	Hyun-Chul Lee (KAERI)
11:10 - 11:50	Thermal-Hydraulic and Safety Analysis Code System for VHTR	Jisu Jun (KAERI)
12:05 - 12:40	Lunch at the JAEA's cafeteria	

Session 4 (VHTR fuel and materials) Chair: Kazuhiro Sawa (JAEA)

13:00 - 13:15	Overview of R&D on VHTR Fuel	Jun Aihara(JAEA)
13:15 - 13:30	Overview of VHTR ceramic materials Development in JAEA	Junya Sumita (JAEA)
13:30 - 14:10	Development of HTGR Fuel Technology in Korea: Current Status	Choong-Hwan Jung (KAERI)

Session 5 (IS process development) Chair: Kaoru Onuki (JAEA)

14:10 - 14:30	Development History of Hydrogen Production Technology in JAEA	Ryutaro Hino (JAEA)
14:30 - 15:10	Status of IS Process Development	Hwang Gab Jin (KIER)
15:10 - 15:25	Coffee Break	
15:25 - 15:50	Overview of IS Process Development in JAEA	Kaoru Onuki (JAEA)
15:50 - 16:30	Corrosion of Selected Materials in Sulfuric Acid for IS Process Application	Dong-Jin Kim (KAERI)
16:30 - 17:10	Ion Beam Enhanced Adhesion of Ceramic Film Coated on Metallic Substrate and Its Applicability to Nuclear Hydrogen Production	Jae-Won Park (KAERI)
17:10 - 17:40	Corrosion Test Results Obtained under H2SO4	Nobuyuki Tanaka (JAEA)
	Adjourn	

18:00	Leave for Mito	JAEA bus

August 30 (3rd day) - HTTR building 4F Conference Room -

8:50 - 9:30	Pick up Korean members at the hotel JAEA bus	Hiroki Noguchi
Session 5 (Continued)		Chair: Kaoru Onuki (JAEA)
9:40 - 10:20	Design of a NHDD Simulated Gas-Loop for the Test of Various SO3 Decomposers	Yong-Wan Kim (KAERI)
10:20 - 11:00	Performance of Sulfuric Acid Decomposition in Korea	Kwang-Deog Jung (KIST)
11:00 - 12:00	R&D on Sulfuric Acid Decomposition in JAEA	Hiroki Noguchi (JAEA)
12:15 - 12:50	Lunch at the JAEA's cafeteria	
13:10 - 13:40	Catalyst Test of SO3 Decomposition	Yoshiyuki Imai (JAEA)
13:40 - 14:10	Design Code System for IS process	Atsuhiko Terada (JAEA)
14:10 - 14:40	Development of Dynamic Simulation Code	Shinji Kubo (JAEA)
14:40 - 15:00	HTTR-IS program	Nariaki Sakaba (JAEA)
15:00 - 16:00	Discussion	Chair: Masuro Ogawa (JAEA)
	Meeting summary	Shusaku Shiozawa
16:00 - 16:20	Closing Remarks	Shusaku Shiozawa Jonghwa Chang
16:40	Leave for Mito JAEA bus	

Appendix 2. Participants list

Participants	Organization	Area	Affiliation
Jonghwa Chang	KAERI	Project management	Vice President, Nuclear Hydrogen Project
Jae-Hyuk Choi	KAERI	Cost analysis	Post Doctor
Seok-Jung Han	KAERI	PSA	Senior Researcher
Jisu Jun	KAERI	Thermal-hydraulic and safety design	Principal Researcher
Choong-Hwan Jung	KAERI	HTGR fuel	Principal Researcher
Dong-Jin Kim	KAERI	Material (Corrosion)	Senior Researcher
Yong-Wan Kim	KAERI	Gas loop	Principal Researcher, Project Manager
Hyun-Chul Lee	KAERI	Nuclear design	Senior Researcher
Jae-Won Park	KAERI	Material (Corrosion)	Senior Researcher, Project Manager
Gab Jin Hwang	KIER	IS process	Principle Researcher, Hydrogen Energy Research Group
Kwang-Deog Jung	KIST	H_2SO_4 decomposition	Principal Research Scientist
Osamu Oyamada	JAEA	Nuclear Science and Engineering	Director General, Nuclear Science and Engineering Directorate
Shusaku Shiozawa	JAEA	HTTR project	Scientific Consultant
Masuro Ogawa	JAEA	HTTR project	Director, Nuclear Applied Heat Transfer Division
Takakazu Takizuka	JAEA	HTTR project	Supreme Researcher, Nuclear Science and Engineering Directorate
Ryutaro Hino	JAEA	HTTR project	Senior Principal Researcher, Nuclear Science and Engineering Directorate
Yoshihiro Komori	JAEA	HTTR project	Director, Department of HTTR
Tatsuo Iyoku	JAEA	HTTR project	Deputy Director, Department of HTTR
Kozo Kawasaki	JAEA	HTTR project	Deputy Director, Department of HTTR
Yukio Tachibana	JAEA	HTTR project	General Manager, HTTR Project Management Section
Daisuke Tochio	JAEA	HTTR project	HTTR Project Management Section
Kazuhiko Kunitomi	JAEA	Cogeneration system design	Group Leader, HTGR Cogeneration Design & Assessment Group
Tetsuo Nisihara	JAEA	Cogeneration system design	HTGR Cogeneration Design & Assessment Group
Xing Long Yan	JAEA	Cogeneration system design	HTGR Cogeneration Design & Assessment Group
Nariaki Sakaba	JAEA	Cogeneration system design	HTGR Cogeneration Design & Assessment Group
Hiroyuki Sato	JAEA	Cogeneration system design	HTGR Cogeneration Design & Assessment Group
Kazutaka Ohashi	JAEA	Cogeneration system design	HTGR Cogeneration Design & Assessment Group

Tetsuaki Takeda	JAEA	HTTR project and HTGR design code development	Group Leader, HTGR Performance & Safety Demonstration Group
Shigeaki Nakagawa	JAEA	HTTR project and HTGR design code development	HTGR Performance & Safety Demonstration Group
Minoru Goto	JAEA	HTTR project and HTGR design code development	HTGR Performance & Safety Demonstration Group
Kuniyoshi Takamatsu	JAEA	HTTR project and HTGR design code development	HTGR Performance & Safety Demonstration Group
Kazuhiro Sawa	JAEA	HTGR fuel and material	Group Leader, High Temperature Fuel & Material Group
Taijyu Shibata	JAEA	HTGR material	High Temperature Fuel & Material Group
Jun Aihara	JAEA	HTGR fuel	High Temperature Fuel & Material Group
Junya Sumita	JAEA	HTGR material	High Temperature Fuel & Material Group
Shohei Ueta	JAEA	HTGR fuel	High Temperature Fuel & Material Group
Yoshiyuki Inagaki	JAEA	System Integration	Group Leader, HTGR-IS Coupling Technology Group
Kaoru Onuki	JAEA	IS Process	Group Leader, IS Process Technology Group
Shinji Kubo	JAEA	IS Process	IS Process Technology Group
Atsuhiko Terada	JAEA	IS Process	IS Process Technology Group
Jin Iwatsuki	JAEA	IS Process	IS Process Technology Group
Seiji Kasahara	JAEA	IS Process	IS Process Technology Group
Hiroyuki Okuda	JAEA	IS Process	IS Process Technology Group
Nobuyuki Tanaka	JAEA	IS Process	IS Process Technology Group
Yoshiyuki Imai	JAEA	IS Process	IS Process Technology Group
Hiroki Noguchi	JAEA	IS Process	IS Process Technology Group
Hiroaki Ota	JAEA	IS Process	IS Process Technology Group
Akihiro Kanagawa	JAEA	IS Process	IS Process Technology Group
Hirokazu Suwa	JAEA	IS Process	IS Process Technology Group
Masanori Ichiji	JAEA	IS Process	IS Process Technology Group
Mitsunori Yoshida	JAEA	IS Process	IS Process Technology Group

Appendix 3. Session summary by chairmen

Session 1: Overview of projects

It is widely recognized that hydrogen is one of the best energy media and its demand will increase greatly in the near future. However, it is necessary to develop suitable technology to produce hydrogen without CO_2 emission from a view point of global environmental protection. Hydrogen production from water using nuclear energy, especially the high-temperature gas-cooled reactor (HTGR), is one of the most attractive solutions for the environmental issue. JAEA and KAERI are pursuing their nuclear hydrogen research and development programs, HTTR (High-Temperature Engineering Test Reactor) project of JAEA and NHDD (Nuclear Hydrogen Development and Demonstration) project of KAERI, respectively.

The HTTR project investigates technologies on reactor and hydrogen production as well as design of commercial HTGR systems with a prismatic block type core and an Iodine-Sulfur thermochemical hydrogen production process (IS process) plant. The NHDD project aims to construct a 600MWt-HTGR coupled with the IS process to complete the development and demonstration of the nuclear based hydrogen production technology by early 2020. Presently, the prismatic block type and the pebble-bed type cores are under studying.

Session 2: VHTR system design and related evaluations

Aiming to conceptualize practical nuclear hydrogen system, JAEA is carrying out design study on (Very High-Temperature Gas-Cooled Reactor) as well as experimental and analytical works on horizontal-placed helium turbomachine with magnetic bearings and angle-type high temperature stop valve with internal thermal insulation. Presently, JAEA's VHTR cogeneration system involves a helical-type metallic intermediate heat exchanger (IHX) already demonstrated with the HTTR's 950□ high-temperature operation. From economical and technical standpoint of view, JAEA stressed the advantages of the prismatic block type core and the VHTR cogeneration system with the IS process plant (VHTR-IS system), which co-generates high temperature heat with the helical-type IHX and electricity by the horizontal gas-turbine (GT). Korean participants well understood these advantages evaluated based on experiences obtained from the HTTR project.

KAERI has started feasibility study on VHTR system including probabilistic safety assessment (PSA) and estimation of hydrogen production cost. After an intense discussion on the necessity of the PSA, it is agreed upon that the PSA is useful not only for the safety assessment but also for the investment assessment such as elimination of redundant safety systems. In the cost estimation, JAEA suggested to KAERI that it is necessary to take into account of non CO_2 emission, which is a specific feature of nuclear hydrogen production such as by using the IS process.

The VHTR-IS system is competitive with any other system. Especially after 2020, economical competitiveness of the VHTR-IS system will become enhanced with the ever-rising oil price. It was agreed upon that the hydrogen production by the VHTR-IS system is the most promising way after 2020.

Session 3: VHTR design codes and analytical works

JAEA has presented the current status of development and validation of analysis tools including an example of analytical results and an activity of the CFD analysis. Especially, analysis tools are being developed for application to safety assessments on severe accident such as pipe rupture as well as for improvement of a core-physics analysis code based on a diffusion-theory and a Monte Carlo method.

KAERI is developing their core-physics analysis codes applicable to studying both prismatic and pebble-bed cores. KAERI requested the operational data of the HTTR in order to verify their analysis tools and nuclear database. Because the accuracy of analytical results depends on the quality of the nuclear data, it is important to verify the nuclear data by available experimental results. It was felt necessary by meeting participants to obtain and validate the nuclear data by experiments conducted under high-temperature operational conditions. After verification of the analysis tools, KAERI will inform the results as well as their analytical models to JAEA. Also, KAERI is developing safety analysis codes based on CFD for investigating thermal-hydraulic phenomena against air and water ingress accidents, fission product release and dust transport in the primary circuit.

KAERI intends to fully support the HTTR Work Package in the Computational Methods Validation and Benchmarks project of the GIF VHTR system. KAERI proposed to exchange the software technology with experimental data such as the criticality database of the HTTR in the past and future experiment under the bilateral framework.

Session 4: VHTR fuel and materials

JAEA presented current status of their fuels and materials development. As for fuel, fabrication properties of high quality HTTR fuels and fission gas behavior in the HTTR were introduced as well as R&D plan for VHTR fuels, i.e., burnup extension program of TRISO fuel and ZrC-coated particle development. Also, R&D status on non-destructive method such as the micro indentation method to evaluate residual stress in the graphite components was introduced as well as R&D plans for C/C composite material for VHTR control rod.

KAERI introduced R&D status of kernel preparation, SiC-TRISO coating technology, ZrC coating technology, code development, and plan for irradiation and post-irradiation experiments.

Through discussions, JAEA and KAERI agreed to activate information exchange for ZrC coating technologies.

Session 5: IS process development

Research and development on the IS process are in progress at JAEA and in Korea, where three national research institutions, KAERI, KIER and KIST, engage in the R&D. A glass-made apparatus with the capacity of 20 liters hydrogen per hour was set up at KIER and is scheduled to reach the closed-loop operation within this year. KAERI is constructing a 10kW gas loop to examine the highest temperature process heat exchanger, SO_3 decomposer. Works are also underway in areas of process chemistry and materials. The NHDD project plans to complete the present R&D until 2008 and proceed to the next stage featuring a closed-loop operational test under pressurized condition and a larger-scale test using 150kW gas loop.

At JAEA, based on the fruits of bench-scale demonstration in 2004, studies are under way aiming to proceed to the pilot test. Highlighted among the ongoing works on the IS process such as materials and components, catalyst, design codes and process simulator is the successful test-fabrication of ceramic heat exchanger for the sulfuric acid decomposer.

Based on the information exchange in this session and also utilizing a satellite meeting of experts, it was agreed to pursue a possible collaboration between the two research groups.

Discussion:

In the final session of Discussion, it was mutually agreed upon that the cooperation between two projects shall be strengthened by launching cooperative R&D in the framework of the existing JAEA/KAERI Implementation in addition to the general information exchange. The Korean delegation showed an interest in participation in the HTTR Project including the HTTR testing, IS process development and codes validation. JAEA welcomes their participation in the framework of the existing JAEA/KAERI Implementation.

The following subjects were developed as possible future cooperative R&D. In addition, it is expected that some of subjects proposed to the GIF will be conducted, in case GIF does not adopt or GIF agreements are delayed unacceptably.

- Graphite core seismic analysis: TBD
- IS process: Concrete subjects will be discussed in the fields of material, membrane, etc.
- HTTR-IS system common design

It was confirmed that the information exchange is to be continued.

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位	
	名称	記号
面積	平方メートル	m^2
体積	立法メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m-1
密度（質量密度）	キログラム毎立法メートル	kg/m^3
質量体積（比体積）	立法メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
（物質量の）濃度	モル毎立方メートル	mol/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率	（数の）1	1

表５．SI 接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表３．固有の名称とその独自の記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン[(a)]	rad		$m \cdot m^{-1}=1$ [(b)]
立体角	ステラジアン[(a)]	sr[(c)]		$m^2 \cdot m^{-2}=1$ [(b)]
周波数	ヘルツ	Hz		s^{-1}
力	ニュートン	N		$m \cdot kg \cdot s^{-2}$
圧力，応力	パスカル	Pa	N/m^2	$m^{-1} \cdot kg \cdot s^{-2}$
エネルギー，仕事，熱量	ジュール	J	N・m	$m^2 \cdot kg \cdot s^{-2}$
工率，放射束	ワット	W	J/s	$m^2 \cdot kg \cdot s^{-3}$
電荷，電気量	クーロン	C		s・A
電位差（電圧），起電力	ボルト	V	W/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
静電容量	ファラド	F	C/V	$m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$
電気抵抗	オーム	Ω	V/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$
コンダクタンス	ジーメンス	S	A/V	$m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2$
磁束	ウエーバ	Wb	V・s	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
磁束密度	テスラ	T	Wb/m^2	$kg \cdot s^{-2} \cdot A^{-1}$
インダクタンス	ヘンリー	H	Wb/A	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
セルシウス温度	セルシウス度[(d)]	℃		K
光束	ルーメン	lm	cd・sr[(c)]	$m^2 \cdot m^{-2} \cdot cd=cd$
照度	ルクス	lx	lm/m^2	$m^2 \cdot m^{-4} \cdot cd=m^{-2} \cdot cd$
（放射性核種の）放射能	ベクレル	Bq		s^{-1}
吸収線量，質量エネルギー分与，カーマ	グレイ	Gy	J/kg	$m^2 \cdot s^{-2}$
線量当量，周辺線量当量，方向性線量当量，個人線量当量，組織線量当量	シーベルト	Sv	J/kg	$m^2 \cdot s^{-2}$

(a)ラジアン及びステラジアンの使用は、同じ次元であっても異なった性質をもった量を区別するときの組立単位の表し方として利点がある。組立単位を形作るときのいくつかの用例は表４に示されている。
(b)実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号“1”は明示されない。
(c)測光学では、ステラジアンの名称と記号srを単位の表し方の中にそのまま維持している。
(d)この単位は、例としてミリセルシウス度m℃のようにSI接頭語を伴って用いても良い。

表４．単位の中に固有の名称とその独自の記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa・s	$m^{-1} \cdot kg \cdot s^{-1}$
力のモーメント	ニュートンメートル	N・m	$m^2 \cdot kg \cdot s^{-2}$
表面張力	ニュートン毎メートル	N/m	$kg \cdot s^{-2}$
角速度	ラジアン毎秒	rad/s	$m \cdot m^{-1} \cdot s^{-1}=s^{-1}$
角加速度	ラジアン毎平方秒	rad/s^2	$m \cdot m^{-1} \cdot s^{-2}=s^{-2}$
熱流密度，放射照度	ワット毎平方メートル	W/m^2	$kg \cdot s^{-3}$
熱容量，エントロピー	ジュール毎ケルビン	J/K	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1}$
質量熱容量（比熱容量），質量エントロピー	ジュール毎キログラム毎ケルビン	J/(kg・K)	$m^2 \cdot s^{-2} \cdot K^{-1}$
質量エネルギー（比エネルギー）	ジュール毎キログラム	J/kg	$m^2 \cdot s^{-2} \cdot K^{-1}$
熱伝導率	ワット毎メートル毎ケルビン	W/(m・K)	$m \cdot kg \cdot s^{-3} \cdot K^{-1}$
体積エネルギー	ジュール毎立方メートル	J/m^3	$m^{-1} \cdot kg \cdot s^{-2}$
電界の強さ	ボルト毎メートル	V/m	$m \cdot kg \cdot s^{-3} \cdot A^{-1}$
体積電荷	クーロン毎立方メートル	C/m^3	$m^{-3} \cdot s \cdot A$
電気変位	クーロン毎平方メートル	C/m^2	$m^{-2} \cdot s \cdot A$
誘電率	ファラド毎メートル	F/m	$m^{-3} \cdot kg^{-1} \cdot s^4 \cdot A^2$
透磁率	ヘンリー毎メートル	H/m	$m \cdot kg \cdot s^{-2} \cdot A^{-2}$
モルエネルギー	ジュール毎モル	J/mol	$m^2 \cdot kg \cdot s^{-2} \cdot mol^{-1}$
モルエントロピー，モル熱容量	ジュール毎モル毎ケルビン	J/(mol・K)	$m^2 \cdot kg \cdot s^{-2} \cdot K^{-1} \cdot mol^{-1}$
照射線量（X線及びγ線）	クーロン毎キログラム	C/kg	$kg^{-1} \cdot s \cdot A$
吸収線量率	グレイ毎秒	Gy/s	$m^2 \cdot s^{-3}$
放射強度	ワット毎ステラジアン	W/sr	$m^4 \cdot m^{-2} \cdot kg \cdot s^{-3}=m^2 \cdot kg \cdot s^{-3}$
放射輝度	ワット毎平方メートル毎ステラジアン	$W/(m^2 \cdot sr)$	$m^2 \cdot m^{-2} \cdot kg \cdot s^{-3}=kg \cdot s^{-3}$

表６．国際単位系と併用されるが国際単位系に属さない単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86400 s
度	°	1° =(π/180) rad
分	’	1’ =(1/60)° =(π/10800) rad
秒	”	1” =(1/60)’ =(π/648000) rad
リットル	l、L	$1l=1\ dm^3=10^{-3}m^3$
トン	t	$1t=10^3$ kg
ネーパ	Np	1Np=1
ベル	B	1B=(1/2)ln10(Np)

表７．国際単位系と併用されこれに属さない単位でSI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位であらわされる数値
電子ボルト	eV	$1eV=1.60217733(49)\times10^{-19}J$
統一原子質量単位	u	$1u=1.6605402(10)\times10^{-27}kg$
天文単位	ua	$1ua=1.49597870691(30)\times10^{11}m$

表８．国際単位系に属さないが国際単位系と併用されるその他の単位

名称	記号	SI 単位であらわされる数値
海里		1海里=1852m
ノット		1ノット=1海里毎時=(1852/3600)m/s
アール	a	$1a=1\ dam^2=10^2m^2$
ヘクタール	ha	$1ha=1\ hm^2=10^4m^2$
バール	bar	$1bar=0.1MPa=100kPa=1000hPa=10^5Pa$
オングストローム	Å	$1Å=0.1nm=10^{-10}m$
バーン	b	$1b=100fm^2=10^{-28}m^2$

表９．固有の名称を含むCGS組立単位

名称	記号	SI 単位であらわされる数値
エルグ	erg	$1\ erg=10^{-7}\ J$
ダイン	dyn	$1\ dyn=10^{-5}N$
ポアズ	P	$1\ P=1\ dyn \cdot s/cm^2=0.1Pa \cdot s$
ストークス	St	$1\ St=1cm^2/s=10^{-4}m^2/s$
ガウス	G	1 G ^10^{-4}T
エルステッド	Oe	1 Oe ^(1000/4π)A/m
マクスウェル	Mx	1 Mx ^10^{-8}Wb
スチルブ	sb	$1\ sb=1cd/cm^2=10^4cd/m^2$
ホト	ph	$1\ ph=10^4lx$
ガル	Gal	$1\ Gal=1cm/s^2=10^{-2}m/s^2$

表10．国際単位に属さないその他の単位の例

名称	記号	SI 単位であらわされる数値
キュリー	Ci	$1\ Ci=3.7\times10^{10}Bq$
レントゲン	R	$1\ R = 2.58\times10^{-4}C/kg$
ラド	rad	$1\ rad=1cGy=10^{-2}Gy$
レム	rem	$1\ rem=1\ cSv=10^{-2}Sv$
X線単位		$1X\ unit=1.002\times10^{-4}nm$
ガンマ	γ	$1\gamma=1\ nT=10^{-9}T$
ジャンスキー	Jy	$1\ Jy=10^{-26}W \cdot m^{-2} \cdot Hz^{-1}$
フェルミ		$1\ fermi=1\ fm=10^{-15}m$
メートル系カラット		$1\ metric\ carat = 200\ mg = 2\times10^{-4}kg$
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	
ミクロン	µ	$1\mu=1\mu m=10^{-6}m$

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