

JAERI-Conf  
95-011



COLLECTED PAPERS PRESENTED AT THE PANEL DISCUSSION  
ON NUCLEAR HEAT UTILIZATION TECHNOLOGY  
AND ROLE OF MULTIPHASE FLOW RESEARCHES  
AT ICMF '95-KYOTO

June 1995

(Ed.) Yukio SUDO

日本原子力研究所  
Japan Atomic Energy Research Institute

本レポートは、日本原子力研究所が不定期に公刊している研究報告書です。  
入手の問合わせは、日本原子力研究所技術情報部情報資料課（〒319-11 茨城県那珂郡東海村）あて、お申し越しください。なお、このほかに財団法人原子力弘済会資料センター（〒319-11 茨城県那珂郡東海村日本原子力研究所内）で複写による実費頒布をおこなっております。

This report is issued irregularly.

Inquiries about availability of the reports should be addressed to Information Division, Department of Technical Information, Japan Atomic Energy Research Institute, Tokai-mura, Naka-gun, Ibaraki-ken 319-11, Japan.

© Japan Atomic Energy Research Institute, 1995

---

編集兼発行 日本原子力研究所  
印刷 ㈱原子力資料サービス

Collected Papers Presented at the Panel Discussion  
on Nuclear Heat Utilization Technology  
and Role of Multiphase Flow Researches  
at ICMF '95-Kyoto

(Ed.) Yukio SUDO

Department of High Temperature Engineering  
Tokai Research Establishment  
Japan Atomic Energy Research Institute  
Tokai-mura, Naka-gun, Ibaraki-ken

(Received May 8, 1995)

This report collected the papers of 1 keynote lecture and 5 topics presented by 6 panelists and a participant at the panel discussion on Nuclear Heat Utilization Technology and Role of Multiphase Flow Researches. The panel discussion was organized at the 2nd International Conference on Multiphase Flow at Kyoto International Conference Hall on April 5 in 1995, aiming at much better understanding the present status of nuclear heat utilization technology, the importance of nuclear heat utilization, the role of multiphase flow researches in the area of nuclear heat utilization technology as well as the significance of international cooperation on the associated research area especially with the HTTR.

Keywords: Panel Discussion, Nuclear Heat Utilization Technology, Multiphase Flow, 2nd International Conference on Multiphase Flow, International Cooperation, HTTR

ICMF- '95 パネルディスカッション論文集  
— 核熱利用技術と混相流研究の役割 —

日本原子力研究所東海研究所高温工学部

(編) 数土 幸夫

(1995年5月8日受理)

本レポートは、核熱利用技術と混相流研究の役割についてのパネルディスカッションにおいて6名のパネリストと1名のパネル参加者から発表された基調講演1件と5分野のトピックスの論文をまとめたものである。このパネルディスカッションは、1995年4月5日京都国際会議場で開催された第2回国際混相流会議のなかで、核熱利用技術の現状、核熱利用の重要性、核熱利用技術における混相流研究の役割、及びHTTRを利用した国際協力研究の重要性についての理解を深めるために企画された。

## Contents

1. Preface .....	1
2. Program of Panel Discussion .....	3
3. Photographs of the Panel Discussion .....	4
4. Abstracts of Keynote Lecture and Topic Speakers .....	6
5. Keynote Lecture-present Status of Nuclear Heat Utilization Technology and Application of Multiphase Flow Researches .....	13
6. Papers Presented by Topic Speakers .....	41
6.1 Heat Transfer Augmentation by Gas-particle Two-phase Flow .....	42
6.2 Microencapsulated Phase Change Material for Heat Transfer Enhancement .....	65
6.3 Application of Multiphase Flow to Improvement of Nuclear Power Plant Safety .....	94
6.4 Multiphase Flow Importance in Future Nuclear Process Heat Applications : Energy Alcohol by Biomass Gasification with HTR --100	
6.5 Status of IAEA Coordinated Research Program Design and Evaluation of Heat Utilization Systems for the HTTR .....	120
6.6 Application of the Heat Pipe to the Passive Decay Heat Removal System of the Modular HTR .....	142
7. Concluding Remarks .....	156
Acknowledgments .....	158

## 目 次

1. まえがき .....	1
2. パネルディスカッションのプログラム .....	3
3. パネルディスカッション時の写真 .....	4
4. 基調講演と話題提供者の発表アブストラクト .....	6
5. 基調講演－核熱利用技術の現状との混相流研究の応用 .....	13
6. 話題提供者の論文 .....	41
6.1 気固二相流による伝熱促進 .....	42
6.2 相変化物質のマイクロカプセル化による伝熱促進 .....	65
6.3 原子力発電プラントの安全性向上のための混相流技術の応用 .....	94
6.4 将来の核熱利用プロセスにおける混相流の重要性 －高温ガス炉を用いたバイオマスガス化によるアルコール製造 .....	100
6.5 H T T Rを用いた核熱利用システムの設計・評価のための I A E A主催の国際協力活動の現状 .....	120
6.6 モジュール型高温ガス炉の受動的崩壊熱除去システムへの ヒートパイプの適用 .....	142
7. あとがき .....	156
謝 辞 .....	158

## 1. Preface

At present, it is expected that the worldwide population would reach about 10,000 millions in the mid-twenty-first century and then, the increase in worldwide population undoubtedly requires us to enlarge the energy supply and economy scale. However, the massive energy consumption leads us to the depletion of energy resources and the destruction of global environment and therefore, researches and developments have been carried out intensively of clean, economical, stable, safe and abundant energy. We, of course, have various option as the alternative energy against the fossil fuels and it is sure that the nuclear energy by high-temperature gas-cooled reactors (HTGRs) has an strong potential to take a share in the energy supply and heat utilization, being an potential option in the very near future.

The High Temperature Engineering Test Reactor (HTTR), which is a gas-cooled and graphite-moderated reactor, is being constructed at the Oarai Research Establishment of the Japan Atomic Energy Research Institute (JAERI), aiming at establishing and upgrading the HTGR technology basis, innovative basic research on high temperature and the enlargement of nuclear heat utilization. The direct utilization of nuclear energy is necessary and indispensable so that energy efficiency can be markedly increased and the areas in which nuclear energy is utilized can be enlarged as much as possible.

Many engineers and researchers on the multiphase flow have been engaged in nuclear heat utilization technology, applying the multiphase flow technology to it. As typical examples, we can easily list up such technologies as heat transfer enhancement, distant heat transportation, coal gasification, hydrogen production, and so on. It is preferable that the importance of the nuclear heat utilization is much better recognized and that possibility of international cooperation with the HTTR and some more effective contribution to the future significant issues can be given to the researchers and engineers on the multiphase flow. To meet this objectives, the coordinators planned to have the panel discussion on "Nuclear Heat Utilization Technology and Role of Multiphase Flow Researches" on the occasion of The 2nd International Conference on Multiphase Flow, which was held at the International Conference Hall in Kyoto, Japan on April 3 to 7, 1995, with the support of the conference committee chaired by Prof. Akimi SERIZAWA, the University of Kyoto.

The significance of a panel discussion can be derived from the well known

fact that the driving force for progress in science and technology is largely produced in the "dialogue of ideas". An example for this is the principle used in philosophy-and sometimes misused-of "thesis, antithesis, and synthesis". The original meaning of the Greek word "dialogue" is a talk and conversation between two or more partners, in contrast to a monologue, that is talking to oneself.

In science and technology the dialogue of ideas has a 2-fold aspect that is talk between brains, known as theories, and talk between brains and nature, known as experiments. This 2-fold aspect is the base of culture, civilization and economical welfare on mankind.

The objective of this panel discussion was to stimulate progress in the above mentioned topic "nuclear heat utilization technology and role of multiphase flow researches", and therefore to initiate, to intensify, and to discuss conclusively many brainstormings among experts, exchanges of ideas between theoretical and experimental scientists for better understanding, more effective research and development, including demonstration, and finally meaningful application of multiphase phenomena.

For the achievement of this objective of the panel discussion, a general frame for the presentations and the discussions were planned and there were in part 1 the keynote lecture and in part 2 five contributions, being followed by the panel discussion among the panelists and auditorium.

April 20, 1995

The coordinators

Yukio SUDO

Heiko BARNERT



## 2. Program of panel discussion

### Panel Discussion on Nuclear Heat Utilization Technology and Role of Multiphase Flow Researches

Chairmen H. Barnert ( Prof., KFA, Germany )  
Y. Miyamoto ( Director, JAERI, Japan )

#### Keynote Lecture ( Invited )

#### **“Present status of nuclear heat utilization technology and application of multiphase flow researches”**

M. Akiyama ( Prof., Univ. of Tokyo, Japan )

#### Contributions of multiphase flow researches ( 75 minutes )

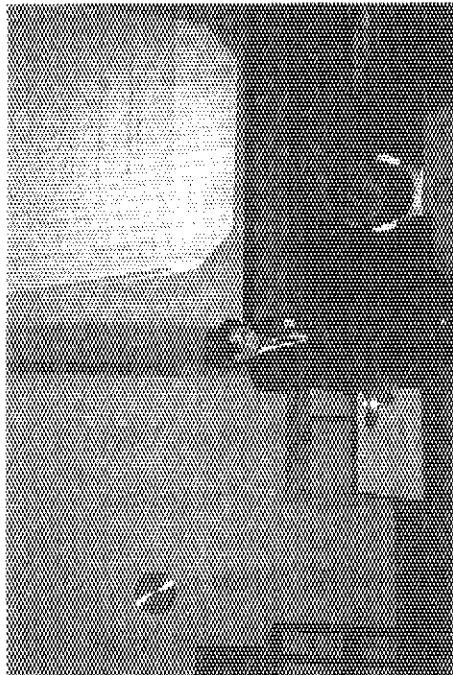
- ① **Heat transfer augmentation by gas-particle two-phase flow**  
A. Shimizu ( Prof., Univ. of Kyushu, Japan )
- ② **Microencapsulated phase change material for heat transfer  
enhancement**  
S. Sengupta ( Prof., Univ. of Michigan, USA )
- ③ **Application of multiphase flow to improvement of nuclear  
power plant safety**  
T. Tanaka ( Director, JAERI, Japan )
- ④ **Multiphase flow importance in future nuclear process heat  
applications energy alcohol by biomass gasification with HTR**  
H. Barnert ( Prof., KFA, Germany )
- ⑤ **Status of IAEA coordinated research program design and  
evaluation of heat utilization systems for the HTTR**  
J. Cleveland ( IAEA )

#### Discussion ( 20 minutes )

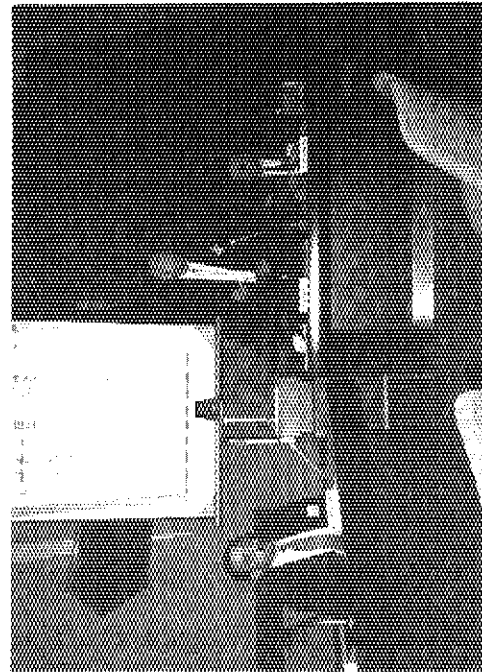
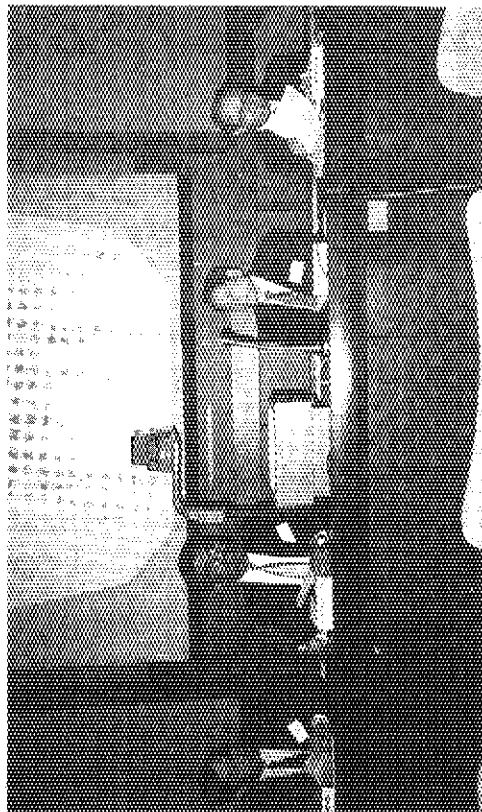
- Question and answers
- Suggestion, Recommendation, Proposal

Coordinators : Yukio Sudo ( JAERI, Japan )  
Heiko Barnert ( KFA, Germany )

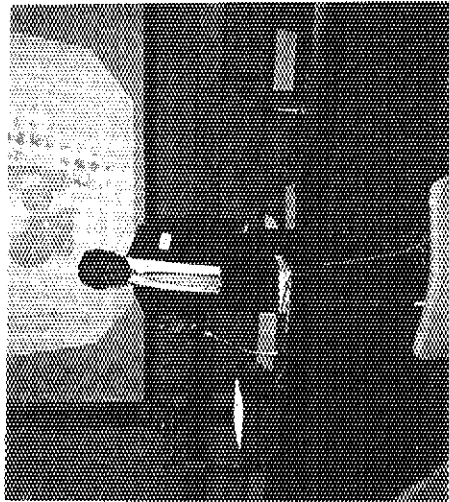
### 3. Photographs of the panel discussion



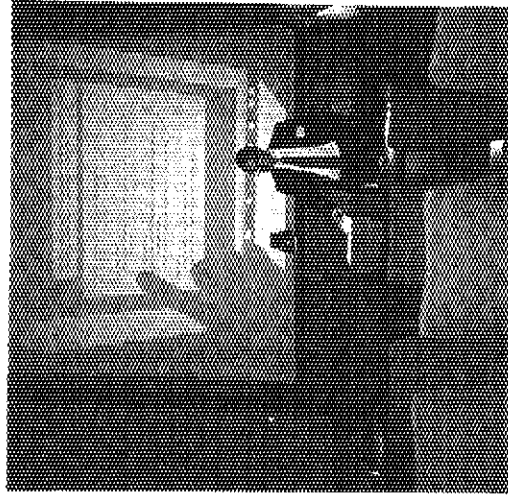
Prof. Akiyama presented the keynote lecture.



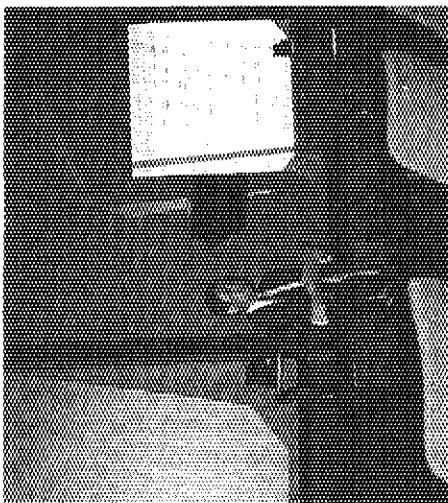
Panel discussion was performed vigorously chaired by Prof. Barnert and Mr. Miyamoto.



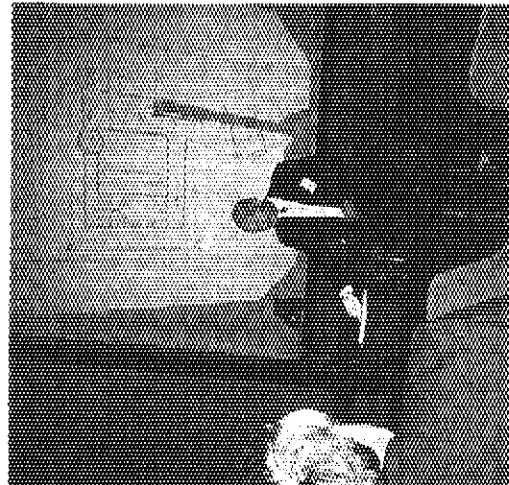
Prof. Sengupta



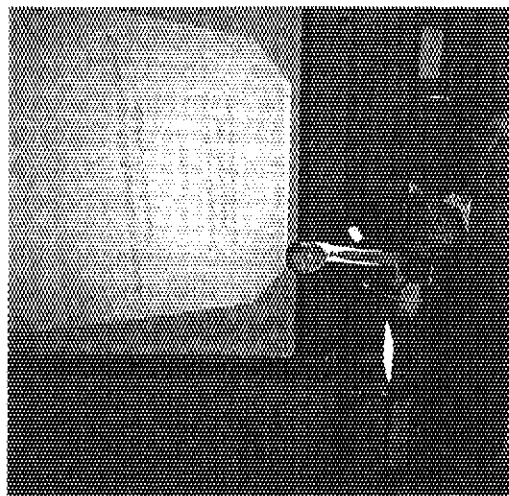
Dr. Cleveland



Prof. Shimizu



Prof. Barnert



Mr. Tanaka

## 4. Abstracts of keynote lecture and topic speakers

### Keynote Lecture

#### Present Status of Nuclear Heat Utilization Technology and Application of Multiphase Flow Researches

Mamoru AKIYAMA  
University of Tokyo, Japan

### ABSTRACT

The mass consumption of energy will lead us to the depletion of energy resources and the destruction of the global environment and especially, the depletion of the fossil fuels endangers continuing the welfare of society. Additional problem is also posed by geographically uneven distribution of the energy resources. When the emission of the pollutants such as ash, lead, SO<sub>x</sub>, NO<sub>x</sub>, and CO<sub>2</sub> exceeds the permissible level of the earth, for example, the excess emission of CO<sub>2</sub> causes the climate change due to the greenhouse effect, and SO<sub>x</sub> and NO<sub>x</sub> result in the corrosive acid rain. Accordingly, it is a serious problem common to mankind that the mass consumption of energy can be made consistent with the environmental preservation. We must solve this problem by all means to keep the sustainable progress of mankind in future.

Research and development (R&D) for clean, economical, stable, safe, and abundant energy should be promoted from the viewpoint of technologies for the stable energy supply and utilization. We have various options as the alternative energy against the fossil fuels: solar energy, geothermal energy, hydropower, nuclear energy and so on. Available natural energy is limited by its stability, quality, quantity, and density and so, it is sure that the nuclear energy by high-temperature gas-cooled reactors (HTGRs) has potential to take a share in the stable energy supply and heat utilization.

The High Temperature Engineering Test Reactor (HTTR) is being constructed at the Oarai Establishment of the Japan Atomic Energy Research Institute, aiming at the first criticality in 1998. The thermal output and the outlet coolant temperature are 30MW and 950°C, respectively. The R&D are also being continued for the future advanced HTGR as new and innovative basic researches. The HTTR project aims at establishing and upgrading the HTGR technology basis, the innovative basic researches and the enlargement of nuclear heat utilization. Almost all nuclear power plants generate electricity in the world, but, the direct utilization of nuclear thermal energy is necessary and indispensable so that the energy efficiency can be increased and the energy saving can be promoted in near future.

A technology of heat transfer enhancement with the solid-gas two-phase flow and a technology of distant heat transportation with microcapsules are typical examples of high performance and enlargement of the nuclear heat utilization. A technology of coal gasification enables us to produce a clean energy and to make the transportation easier comparing with the transportation of the solid coal. Upgrading safety of nuclear reactor systems requires technologies of the multiphase flows.

This keynote lecture overviews the present status of nuclear heat utilization technology and expectation to multiphase-flow technology application for broadening the area of nuclear heat utilization and for upgrading the total efficiency of nuclear heat utilization systems. From this overview, then, it is preferable that importance of the nuclear heat utilization is much better recognized and that multiphase-flow researches can contribute more positively to this problem under the intensive international cooperation including the HTTR.

## Heat Transfer Augmentation by Gas-Particle Two-Phase Flow

Akihiko SHIMIZU

Kyushu University, Fukuoka, JAPAN

and

Zinovy R. GORBIS

University of California, Los Angeles, USA

### ABSTRACT

Most nuclear power is originally released as the kinetic energy of particles produced in respective nuclear reactions. The energy level of those particles is usually of MeV order or higher. An equilibrium gas temperature corresponding to molecular kinetic energy of only 1 eV is about  $10^4$  K, which is still much higher than 600 K at which that nuclear energy is converted to electricity in today's typical nuclear power plant. Raising the operating temperature of the energy conversion is, therefore, a due direction for more effective use of the nuclear energy, which can be achieved only by adopting gaseous coolant.

The helium-cooled HTGR (High Temperature Gas-cooled Reactor) will take an important position in the global energy strategy towards next century. It is expected to supply not only electricity but also high quality thermal energy for various industries and local utilities without exhausting any green house effect gas or acid rain gas. Of particular interest is the production of hydrogen and methanol that will be major liquid fuels for transportation after oil resource is exhausted out. The key R&D issue of the HTGR is economical competitiveness, particularly against light water reactors. Due to the poor heat transfer of the single phase helium, the HTGR's volumetric power density is restricted to tenth of corresponding PWR's value so that increasing the power density by improving heat transfer is strongly desired.

The situation is in a sense similar for fusion reactors. Although superiority of the helium-cooling is recognized from several aspects, cooling the plasma facing components by pure helium is quite difficult so that the key is again the heat transfer improvement.

The standstill can be broken through by adopting gas-solid suspension medium. Its heat transfer performance is quite excellent. Its heat capacity can be increased drastically without excessive pressurization. Although the thermal radiation is a dominant heat transfer mode in high temperature region, the helium which is always used in high temperature nuclear systems is monatomic so that is transparent to thermal radiation. Solid particles suspended there will emit or receive the radiation and exchange it easily with the ambient gas by conduction and convection. The suspension impinging jet is quite attractive for the divertor cooling of fusion reactors.

Erosion of the channel walls can be drastically reduced by using graphite powder as the suspended phase. Graphite is the major core material of HTGR and is steady from both chemical and nuclear viewpoints. Even the possibility of direct introduction of the suspension into gas turbine is examined.

A countermeasure against so-called thermophoresis force will be required. It acts on particles in the gas with temperature gradient and tends to push them towards lower temperature side, which makes them stick to the lower temperature walls of the heat exchanger. A possible countermeasure may be the use of swirling flow heat transfer tube.

Recent progress and status of the research activities for applying the suspension as the coolant of advanced nuclear systems are reviewed. Some authors' observations will also be presented.

## **Microencapsulated Phase Change Material for Heat Transfer Enhancement**

Subrata Sengupta  
School of Engineering  
University of Michigan

### **Abstract**

Microencapsulated phase change materials have proven to enhance heat transfer between surfaces and adjacent fluids. The significant mechanisms of enhancement are microconvection, increase in thermal capacity, and modification of the temperature gradient at the wall.

Results from a series of studies are presented as follows:

#### **Theoretical:**

##### **Forced Convection**

Flow in tubes

Flow between parallel plates

##### **Natural Convection**

Flow around a vertical heated flat plate

#### **Experimental:**

##### **Forced Convection**

Flow in tubes

##### **Natural Convection**

Flow in rectangular cavities

Both experimental and theoretical results indicate a 2- to 10-fold increase in Nusselt numbers. Comparison between theory and experiments are also presented.

## Application of Multiphase Flow to Improvement of Nuclear Power Plant Safety

T. TANAKA

Department of HTTR Project  
Japan Atomic Energy Research Institute

Application of multiphase flow technologies in High temperature gas-cooled reactors (HTGRs) system may lead to enhance the safety of reactor. This paper outlines following topics relating multiphase flow technologies which are applicable in the HTGR design.

### *(1) Heat Pipe Decay Heat Removal System*

The decay heat removal system is operated in case of the accident such as a depressurization accident in which the forced convection cooling by primary circuit is no longer available. Inherent and passive safety characteristics of HTGRs is apparently enhanced by adopting passive decay heat removal devices.

Heat pipe is one of the passive decay heat removal devices in the HTGR design. In a heat pipe decay heat removal system, decay heat of the irradiated fuel is transferred to the RPV mainly by conduction through graphite core components, then transferred to the heat pipe cooled steel membranes by means of radiation and natural convection. Heat pipe is a application of multiphase flow technology and has completely passive characteristics. It consists of a container vessel whose inside surfaces are lined with a porous capillary wick if necessary and working fluid. The heat pipe can continuously transport the latent heat of vaporization from the evaporator section to the condenser section irreversibly. This fact means heat pipes have a function like a thermal diode.

### *(2) Heat Pipe Cooled HTGR System*

The heat pipe cooled HTGR, or heat pipe cooled particle bed reactor (abbreviate to HPCPBR) is considered as one of passive and maintenance-free reactors, which is suitable to be used in the isolated islands or in a polar region to supply electricity in the region as well as nuclear heat for district heating. In this reactor system, the heat transport system and energy conversion device consist of the completely passive device like liquid metal heat pipes and thermionic and thermoelectric converter made of functionally gradient material. This fact leads that the HPCPBR has superior inherent safety characteristics. This reactor also has the possibility to expand its application area towards space use, for example, the energy source for deep space exploration and moon base use as well.

The reactor itself consists of a bed of coated fuel particles and a graphite funnel to form the active core. Reactivity of the reactor is also controlled by passive metallic poison injection system not only during normal operation but also accidents.

### *(3) Buoyancy Driven Exchange Flow*

Another topic relating HTGR safety is buoyancy-driven exchange flow in case of a stand pipe rupture accident in the HTTR. In the accident, after pressures inside and outside of reactor pressure vessel are balanced, relatively light gas of helium tends to flow upward through the breach. This behavior can be recognized as one of the mass transfer problems between gases with different bulk densities. Through experimental and analytical studies, it was found that the exchange flow rate was restricted by reduction of cross section of breach.

**Multiphase Flow Importance in  
Future Nuclear Process Heat Applications:  
ENERGY ALCOHOL BY BIOMASS GASIFICATION**

Heiko Barnert  
Research Centre Jülich GmbH, KFA and  
University of Aachen, Fed. Rep. of Germany

**ABSTRACT**

For future nuclear process heat applications multiphase phenomena are very important in a three-fold sense: For the ability to produce high temperature heat, for the realization of a catastrophe-free nuclear energy technology in case of the design event of the ingress of water droplets into the High Temperature Reactor HTR, and for the newly proposed carbondioxide-neutral energy system "energy alcohol from biomass plus HTR". Details are reported in the following:

The technology of the "Coated Particle" with the multi-coating of ceramic coatings on micro-particles on nuclear fuel for the HTR is the technological reason for the ability to produce high temperature heat from nuclear energy. This realizes a very good retention capability for radioactive material, including fission products. It is produced by chemical vapour deposition in a fluidized bed, this is a two-phase-fluidized-bed/gaseous-to-solid-states-change by pyrolysis/multi-component/phenomenon.

The new requirement of a catastrophe-free nuclear energy technology has led to the identification that the ingress of water droplets into the nuclear core of the HTR should be avoided by self-acting separation of droplets coming from the steam generator tube break before they can get into the core. The behaviour of the water/steam jet in the helium stream is a two-phase-flow/far-from-equilibrium-phase-change/two-component/phenomenon. It needs to be understood under the perspective of "self-acting-separation of droplets of water".

The biggest challenge to the energy industry in the industrialized countries is the carbondioxide-climate-change-problem. The solution requires the reduction of the application of fossil primary energy carriers by the factor of about 5 for the world, and e.g. by the factors of about 13 for FRG and about 10 for Japan. As a contribution to the solution a new proposal has been made recently: the production of energy alcohol, e.g. methanol, on the basis "biomass plus HTR". This proposal fulfills fundamental desirable feature of future energy systems: it is CO<sub>2</sub>-neutral (because of the biomass), it is environmentally benign (only C<sub>1</sub>-molecules), it is application-friendly (methanol is a staple commodity), and it reduces competition with food production (because of the HTR). The main part of the energy conversion process is the helium-heated fluidized bed steam gasification of biomass. This a a two-phase-flow/solid-to-gaseous states-change/pyrolysis and chemical reaction/multi-component/phenomenon.



## Status of the IAEA Coordinated Research Programme Design and Evaluation of Heat Utilization Systems for the HTTR

John Cleveland

and

Irene Lewkowicz

Division of Nuclear Power

Division of Physics and Chemistry

Department of Nuclear Energy and Safety

Department of Research and Isotopes

International Atomic Energy Agency

International Atomic Energy Agency

Vienna, Austria

Vienna, Austria

### ABSTRACT

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

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

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

In Japan an important milestone was reached in March 1991 with the start of construction of the High Temperature Engineering Test Reactor (HTTR) at the Oarai Research Establishment of the Japan Atomic Energy Research Institute (JAERI). This 30MW(t) reactor will produce core outlet temperatures of 850 °C at rated operation and 950 °C at high temperature test operation. It will be the first nuclear reactor in the world to be connected to a high temperature process heat utilization system. Criticality is expected to be attained in 1998. The timely completion and successful operation of the HTTR and its heat utilization system will be major milestones in gas-cooled reactor development and in development of nuclear process heat applications.

To foster international cooperation in HTGR applications, the IAEA's Division of Nuclear Power and the Division of Physics and Chemistry have established a Coordinated Research Programme (CRP) on Design and Evaluation of Heat Utilization Systems for the High Temperature Engineering Test Reactor (HTTR). The objective of this CRP is to identify the most promising heat utilization system(s) to be demonstrated at the HTTR.

Participating Member States are collaborating by exchanging existing technical information on the technology of heat utilization systems, by developing design concepts and by performing evaluations of candidate systems for potential demonstration with the HTTR. Countries participating in this CRP include China, Germany, Indonesia, Israel, Japan, Russia and the USA. The processes being assessed have been selected by CRP participants according to their own national interests depending on status of the technology, economic potential, safety and environmental considerations, and other factors.

The following systems are being examined:

- Steam reforming of methane for production of hydrogen and methanol
- CO<sub>2</sub> reforming of methane for production of hydrogen and methanol
- Combined coal liquefaction and steam generation
- Thermochemical water splitting for hydrogen production
- High temperature electrolysis of steam for hydrogen production
- Gas turbine for electricity generation
- Advanced intermediate heat exchangers

First priority candidates have been determined to be the steam (and/or CO<sub>2</sub>) reforming of methane and gas turbine systems. R&D is continuing for the other candidate systems towards the stage when they can be considered feasible for demonstration at the HTTR.

## 5. Keynote Lecture

### Present Status of Nuclear Heat Utilization Technology and Application of Multiphase Flow Researches

Mamoru AKIYAMA

Prof. The University of Tokyo

## 1. Preface

The worldwide population is around 5,600 millions at present, and it is said to reach 10,000 millions in the mid-twenty-first century. Figure 1 shows the increase in population and energy during our own century<sup>(1)</sup>. The increase in population requires us to enlarge the energy supply and the economy scale because a progress of civilization depends upon the energy and the economy scale as indexed by the GNP is said to be logarithmically proportional to the energy supply. However, the mass consumption of energy leads us to the depletion of energy resources and the destruction of the environment. The production of energy from the fossil fuels is pointed out to start declining until early the twenty-first century. The depletion of the fossil fuels endangers the continued welfare of society. Additional problem is also posed by geographically uneven distribution of the energy resources. When the emission of the pollutants such as ash, lead, SO<sub>x</sub>, NO<sub>x</sub>, and CO<sub>2</sub> exceeds the permissible level of the earth, for example, the excess emission of CO<sub>2</sub> causes the climate change due to the greenhouse effect as shown in Fig.1, and SO<sub>x</sub> and NO<sub>x</sub> results in the corrosive acid rain. Accordingly, how the economy growth i.e. the mass consumption of energy can be made consistent with the environmental preservation is a serious problem common to mankind. We must solve these problems by all means to keep the sustainable progress of mankind in future.

Political, technical, economical, and psychological (consciousness reform) programs are being discussed to solve the problems. Research and development (R&D) of clean, economical, stable, safe, and abundant energy should be promoted from the viewpoint of technologies for the energy supply and utilization. We have various options as the alternative energy against the fossil fuels: solar energy, geothermal energy, hydropower, nuclear energy and so on. Available renewable (natural) energy is limited by its stability, quality, quantity, and density. Table 1 shows available temperature conditions of typical industrial processes and nuclear reactors. As seen in the table, it is sure that the nuclear energy by high-temperature gas-cooled reactors (HTGRs) has potential to take a share in the energy supply and heat utilization.

The High Temperature Engineering Test Reactor (HTTR, a gas-cooled and graphite-moderated reactor) is being constructed at the Oarai Establishment of the Japan Atomic Energy Research Institute (JAERI), aiming at the first criticality in 1998. The thermal output and the outlet coolant temperature are 30MW and 950°C, respectively. Some of the R&D are being continued by the future advanced HTGR projects as new and innovative basic researches. The HTTR project aims at establishing and upgrading the HTGR technology basis, the innovative basic researches, and the enlargement of nuclear heat utilization. Most of nuclear power plants generate electricity in the world. The direct utilization of nuclear energy is necessary and indispensable so that the energy

efficiency can be increased and the energy saving can be promoted.

Many investigators of the multiphase flow have been engaged in reduction of energy consumption through conservation and more efficient use of the traditional fuels, and in development of the renewable energy and innovative technologies on energy conversion, transportation and storage. Table 2 lists the overview of nuclear-heat utilization technology and application of multiphase-flow researches discussed later in the field of the high temperature engineering associated with the environment and energy. A technology of heat transfer enhancement with a solid-gas two-phase flow and a technology of distant heat transportation with a microcapsule are typical examples of high performance and enlargement of the nuclear heat utilization. A technology of coal gasification enables us to produce a clean energy and to make the transportation easier comparing with the transportation of the solid coal. The upgrading safety of nuclear reactor systems uses technologies in the multiphase flows.

From the present overview, it is preferable that importance of the nuclear heat utilization is better recognized and that some possibility of international cooperation with the HTTR and some effective contribution to the future issues of multiphase-flow researches can be given to investigators. The present status of nuclear heat utilization technology and expectation to multiphase-flow technology application are described in the following sections. The panel discussion on utilization technology of nuclear heat and role of multiphase flow researches is expected to be a helpful and potential reference for investigators of various fields to find viable solutions to the most important problems of the environment and energy in future as well as at present.

## 2. Present Status of Nuclear Heat Utilization Technology

HTGR technologies have been developed through construction and operation of experimental and proto-type HTGRs in the United States and Germany as shown in Table 3. Nuclear heat utilization technology of the HTGR, however, was mainly limited in the field of an electric power generation. In this chapter, I would like to outline present status of nuclear heat utilization technology including R&D status of HTGRs.

### 2.1 R&D status of HTGRs with high temperature utilization<sup>(2)</sup>

There are several ongoing programs of R&D on HTGRs not only in Japan but also in foreign countries, such as the United States, Federal Republic of Germany, China and other countries. This section describes the outline of R&D status in these countries.

## The United States

The U.S. has accumulated extensive and excellent experiences on design, construction and operation of the experimental HTGR of Peach Bottom Reactor and the proto-type HTGR of Fort St. Vrain Reactor, which were constructed by General Atomics, Inc.. In 1978, the Gas Cooled Reactor Association (GCRA), which is mainly composed of utilities in the U.S. has been established to support the HTGR development program and to study the HTGR strategy.

Since 1985, the U.S. has been focussing its activities on the development of the modular HTGR (MHTGR) with steam-turbine system for electric generation. The MHTGR concept is expected to realize competitiveness against the light-water reactors (LWRs) by suppressing their construction and running costs by means of pre-fabrication in the works and high thermal efficiency as well as high fuel burnup, respectively. Rationalization of confinement structures in consequence of their intrinsic safety characteristics is also expected to suppress construction costs of the plant. Recent accomplishments include submittals to the U.S. Nuclear Regulatory Commission (NRC) in support of its Pre-application Safety Evaluation Report for the MHTGR and confirmation studies of a 450MWt up-sizing from the original 350MWt design. After that, the U.S. has changed its MHTGR program to the direct cycle gas-turbine modular helium reactor (GT-MHR) system as shown in Fig.2 to achieve further competitiveness against LWRs. In this system, approximately 50% of thermal efficiency is expected without degrading its inherent safety characteristics. It is believed that gas-turbine and heat-exchanger technologies in the U.S. have already matured through the development program in the U.S. aerospace industry.

## Germany

Germany also has extensive experiences on design, construction and operation of the experimental HTGR of AVR (Arbeitsgemeinschaft Versuchsreaktor) and the proto-type HTGR of THTR-300 (Thorium Hochtemperaturreaktor 300MWe). They employ a unique reactor configuration called as a pebble bed reactor; spherical fuel elements of 6cm in diameter are packed in a large graphite funnel and coolant of helium gas flows through voids in the core. The successors in Germany are also modular type reactors with spherical fuels: HTR-M (Module) of 200MWt and HTR-500 of rated 500MWt. The HTR-M shown in Fig.3 has small core dimension and rather low thermal output to enhance its inherent safety characteristics and to promote modularization. The reactor outlet coolant temperature of the HTR-M is 700°C in a standard plant design and is under design to be further increased to 950°C, aiming toward direct utilization of nuclear process heat. Targets of the HTR-M are the siting close to industrial zones and consumers on the basis of its inherent safety and modularization, while those of the

HTR-500 are weighted with an economical improvement.

Once, Germany had great interests on nuclear heat utilization for hydro- or steam-gasification of domestic brown coal or lignite. For these purposes, component and material development for steam reformer, heat exchanger, gasification furnace were carried out. Especially, Interatom GmbH has been performing a demonstration test of an intermediate heat exchanger (IHX) by its own high-temperature helium-gas loop (KVK) since the IHX is the most important interface between the reactor system and the gasification process. Furthermore, a pilot plant of distant heat transportation system using chemical heat pipe technologies, named as EVA-ADAM, was constructed and its performance was demonstrated<sup>(3)</sup>.

The development program on nuclear energy including the HTGR was almost terminated in Germany recently due to political as well as economical reasons.

### Japan

According to "Long-term Program for Development and Utilization of Nuclear Energy" determined by the Japanese Atomic Energy Commission, the HTTR is being constructed by the JAERI. The HTTR is the first HTGR in Japan and aims at establishing and upgrading the technology basis for HTGRs, serving at the same time as a potential tool for new and innovative basic researches.

Since 1969, the JAERI has carried out R&D which has covered all fields necessary for the reactor construction, that is, fields in (1) coated particle fuel, (2) materials such as graphite and heat-resistant alloys, (3) reactor engineering such as reactor physics, thermal-hydraulics and instrumentation & control, (4) high temperature helium technologies and also (5) nuclear heat utilization technologies represented by hydrogen production. The R&D works have been performed by using large scale test facilities such as the Oarai Gas Loop-1 (OGL-1) at the Japan Materials Testing Reactor for fuel and material irradiation, the Very High Temperature Reactor Critical Assembly for reactor physics experiments and the Helium Engineering Demonstration Loop (HENDEL) for demonstration tests of high temperature components, as well as small scale test facilities.

For utilization of the high temperature heat of HTGRs, several hydrogen production processes have been studied: thermo-chemical hydrogen production by Iodine-Sulfur (IS) process, steam reforming of methane and high-temperature electrolysis of steam. Details of them are described in the following section.

The JAERI now proceeds with the construction of the HTTR, focussing on the first criticality in FY 1998. Table 4 shows the construction schedule of the HTTR<sup>(4)</sup>. Fabrication of reactor components, such as a reactor pressure vessel (RPV), heat exchangers and others, and the construction of reactor building are almost finished and the RPV was installed in August, 1994. Facilities of the HTTR will be arranged as

shown in Fig.4. Photo 1 shows the reactor building under construction. The reactor building contains the RPV, a primary cooling system consisting of pressurized water coolers, a He/He intermediate heat exchanger (IHX) and others. Figure 5 shows a flow diagram of the HTTR cooling system. High-temperature heat of 950°C generated in the HTTR core is cooled by pressurized water coolers and the IHX. Figure 6 shows internal structures composed of helically coiled heat transfer tubes and a hot header for the IHX.

Future main R&D works of the HTTR are as follows;

- (1) Establishment of technology basis on HTGRs
- (2) Upgrading present HTGR technologies
  - (a) Basic technologies on fuel, materials and in-core instrumentations
  - (b) Improvement of core performance
  - (c) Safety demonstration tests
- (3) Establishment of nuclear heat application technologies
- (4) Innovative research on high temperature technologies
  - (a) R&D on nuclear fusion reactor
  - (b) R&D on radiation chemistry
  - (c) Development of new materials

The R&D schedule using the HTTR is shown in Table 5.

### People's Republic of China

The major concerns of the People's Republic of China (P.R.C.) are heavy oil recovery, steam reforming of methane, co-generation, district heating and others as the nuclear heat application. The P.R.C. plans to construct the 10MW HTR Test Module (HTR-10) employing pebble bed fuels, on the basis of cooperative works with Germany. The construction of HTR-10 started in October, 1994.

The P.R.C. started research works on fuel manufacturing technology as well as relevant inspection technology, fuel handling system, control rod driving system and others.

### Other countries

In the former USSR, design and research works on a co-generation system named as VGM whose thermal output is 200MWt at the reactor outlet coolant temperature of around 750°C has been carried out based on the HTR-M under the cooperation with Germany. It is planned to supply nuclear process heat from the VGM to the chemical industry and the coal gasification plants by increasing outlet temperature up to 950°C.

Switzerland has been proceeding the international cooperative program instead of domestic HTGR program. PROTEUS critical assembly in the Paul Scherrer Institute is delivered for evaluation of core neutronics with low-enriched uranium fuel through the



international project supported by the IAEA.

Indonesia and Venezuela also have interests on application of HTGR nuclear heat to heavy oil recovery. Preliminary study by Indonesia shows that nuclear heat utilization has economical competitiveness and technical advantages against conventional fossil fuel.

## 2.2 Present status of nuclear heat utilization

At present, about thirty percent of the world's primary energy consumption is used for electricity generation, and the rest is used for residential and industrial purpose. The whole heat market is almost supplied by burning fuels such as coal, oil, natural gas and so on. Then the nuclear energy has large potential for applications to the non-electric field. Currently a few nuclear plants are being used for non-electric applications: district heating, process steam supply, seawater desalination and so on. In these applications, a total capacity used to supply hot water and steam is less than 2GWt<sup>(5)</sup>.

### (1) District heating<sup>(6)</sup>

There have been some district heating projects with nuclear power plant in the world. One of the most famous system is a regional district heat supply system in the valley of the river Aare in Switzerland, called REFUNA (Regionales Fernwaermenetz im Unteren Aaretal) system. This system has been operated since 1983 and covers 8 municipalities with a total of about 18,000 inhabitants. The heat is supplied from Beznau I unit (PWR, 350MWe). The steam is extracted from two of four turbines between the high and the low pressure parts with a temperature of 128°C at 0.26MPa. The extracted steam is used to generate the hot water which is supplied to heat consumers. Annual saving of oil for heating would be amounted to about 20,000 ton. The maximum amount of heat supply is about 40MW in winter 1991: the availability of the system is nearly 100%. To meet popularity, the system is planned to increase heat supplying capacity up to 80MW.

### (2) Process steam supply<sup>(5)</sup>

Process steam supplied from nuclear power plants can be used as a source of heat energy in a wide variety of industrial applications such as distillation, curing, evaporation, washing, heating, cleaning and so on.

The most famous process-steam application system is the Bruce Energy Centre in Canada. Steam is supplied to The Bruce Energy Centre from the Bruce power plant consisting of four 740MWe CANDU reactors. Medium pressure steam (180°C, 1.03MPa) is generated at the steam transportation plants and is supplied to four heavy water production plants, site services and the Bruce energy centre. In the Bruce energy centre,

the steam is utilized at greenhouses, plastic forming factory, ethanol production from corn, alfalfa pelletizing factory and so on. The capacity of steam supply is about 110ton/h. The steam cost is about half or one-third of steam costs generated by fossil fuels.

### (3) Seawater desalination<sup>(7)</sup>

Currently only one reactor is used for the seawater desalination; a liquid metal cooled reactor, BN-350, has been operated since 1973 at Shevchenko in the former USSR. This plant can produce 125MW of electric power and 100,000m<sup>3</sup>/day of potable water. Steam from turbines (220°C, 0.5MPa) is transferred to the desalination plant. The thermal output of the reactor to the desalination plant is 75MW.

The prolonged operating experience of the BN-350 has proven the reliability of nuclear seawater desalination.

### (4) Greenhouse and fish farming

In the nuclear power plants, the temperature of the cooling water from condensers is less than 40°C. The low-temperature heat of the cooling water has been utilized at greenhouses or fish farmings in the world. Most of them are small or test facilities, not yet widely commercialized.

## 2.3 Present status of R&D of heat utilization technology

The nuclear energy is one of the promising options to meet a great amount of energy demands and to relax the problem of the global warming. It is very important to enlarge the nuclear heat utilization into the non-electric field. Especially, the heat utilization system in combination with the HTGR is expected to contribute to the future energy demands because of its capability of high-temperature energy supply. The various kinds of R&D works on the nuclear heat utilization technologies including power generation have been carried out.

### (1) Electric power generation

About forty percent of thermal efficiency has been achieved by the Fort St. Vrain in the U.S., and the THTR-300 in Germany with steam turbine cycle because of high temperature of generated steam. At the reactor outlet temperature of 900°C or above, the thermal efficiency could reach about 50% for a gas turbine or a gas turbine/steam turbine combined cycle. An overall heat utilizing efficiency could reach 70 to 80% for co-generation, heat cascading and others. Aiming at the high efficiency, helium gas turbine system with the HTGRs have been developed. In the U. S., the direct gas turbine system with the MHTGR have been developed. In Germany, the gas turbine system with pebble-bed type HTGRs and combined cycle have been developed.

## (2) Coal gasification<sup>(8)</sup>

Since it can be expected that today's major fossil energy sources, such as oil and natural gas, will run short and become even more expensive in the long run, coal gasification processes producing methane or synthesis gas have been developed in Germany with the aim of opening markets to coal in addition to power generation where oil and natural gas are the main suppliers now.

The two processes have been developed, namely hydro- and steam gasification of coal. Using both processes, it is possible to produce methane for the gas grid, methanol and synthesis gas for industrial processing and so on.

### 1) Hydrogasification of coal

The hydrogasification of coal is based on the conversion of coal with hydrogen into raw gas which has a high contents of methane. Since this reaction is an exothermic reaction, it proves to be most favorable to use a fluidized bed gasifier ensuring a reliable temperature control. The hydrogen required for this process is generated by utilizing the high-temperature heat from HTGR. Figure 7 shows the process flow sheet of methanol production system with hydrogasification of coal by the HTR-M. In the system, the heat from the HTGR is consumed at the steam reformer and the steam generator. The hydrogen generated at the steam reformer is utilized as a raw material of hydrogasification, also utilized for methanol synthesis.

To demonstrate the process, a semi-technical plant which was employed in a fluidized bed gasifier for processing max. 0.2 tones of carbon per hour was constructed and has been operated since 1975. The operational data have shown that coal hydrogasification is suitable as a component of an industrial-scale plant for coal gasification<sup>(9)</sup>.

### 2) Steam gasification of hard coal

The reaction of steam with coal to form synthesis gas, which takes place during the steam gasification of coal, requires higher temperature heat than the reaction in the hydrogasification process because the reaction of the steam gasification is an endothermic reaction. In the steam gasification reactor, the fluidized bed of crushed coal is heated by high-temperature helium gas flowing through heating coils submerged in the bed. Figure 8 shows the flow sheet of methane production system with steam gasification of hard coal by the HTR-M. As shown in the figure, the primary circuit is separated from the gasification plant by the IHX to ensure safety; the IHX works as a safety interface between the HTGR-M system and the gasification plant.

To demonstrate the process, a semi-technical plant which had a fluidized bed gasifier heated by high-temperature helium gas was installed and has been operated since 1976. The operational experience and the test results have confirmed that there

were no basic obstacles to the technical implementation of the steam gasification using heat from HTGRs<sup>(10)</sup>.

### (3) Heat transportation

The steam reformer, which is one of important components for nuclear heat applications in various kinds of chemical processes, can be applied to a heat transportation system with a combination of methanation reaction<sup>(11)</sup>. Figure 9 shows a concept of nuclear heat transportation system.

In the system, a mixture of methane and steam is reformed into synthesis gas in the steam reformer with the high-temperature heat from HTGRs. The synthesis gas is transported to the distant area, then the heat is generated by the methanation reaction of synthesis gas which is exothermic reaction. The produced methane is transported to the steam reformer. The heat generated by the methanation reaction, which is about 400 to 650°C, is utilized for heat source of district heating, process heat, power generation and so on.

To demonstrate the system, the EVA-ADAM system was constructed and has been operated since 1981 in Germany<sup>(3)</sup>.

### (4) Hydrogen production<sup>(12)</sup>

Hydrogen has a wide variety of applications to chemical industry and is an ideal substance as a clean fuel. Its typical production processes include steam reforming, thermo-chemical water splitting or high-temperature electrolysis of steam. The steam reforming process as a nuclear process heat utilization is thought to be established in a commercial stage through development of a nuclear steam reformer, and studies to connect the steam reforming system to the HTTR have been conducted. Innovative processes of thermo-chemical splitting have been developed; in Japan, typical ones are the UT-3 process using iron and halogen by the University of Tokyo and the IS process using iodine and sulfur by the JAERI. These processes have been studied in laboratory scale apparatus. High-temperature electrolysis of steam has been developed in private companies in Japan and the JAERI, aiming to reach a high level of industrial technologies.

### (5) Others

In a reduced steel-making system by which high-quality steel can be produced principally, the HTGR can be used as an energy source to generate high-temperature hydrogen and steam. If hydrogen is produced by the high-temperature electrolysis of steam, this system connected with the HTGR will be free from environmental problems caused by CO<sub>2</sub> emission. The Engineering Research Association of Nuclear Steelmaking, sponsored by the Ministry of International Trade and Industry of Japan, has carried out

R&D on relevant fundamental engineering technologies as a steelmaking system development.

### 3. Expectation to Multiphase Flow Technology Application

In the following, based on the present status of nuclear heat utilization technologies I just described now, I would like to present you my expectation to the application of multiphase-flow researches to nuclear heat utilization in some important and interest areas.

#### 3.1 High performance of heat utilization

It is one of most important subjects from the point of view of effective use of energy to attain as high heat utilization efficiency as possible in the nuclear heat utilization system with working fluid under as high temperature as possible.

As seen in Table 1, the HTGR can contribute to broaden the areas of nuclear heat utilization and to upgrade the total heat utilization efficiency of the applied system because of its working temperature as high as about 1000°C. To increase heat utilization efficiency of the HTGR, some application processes in the temperature range from 30 to 900°C are preferred to be combined to a cascade system of the HTGR, which also means enlargement of heat applications of the HTGR to the non-power-generation field. It is always important to make efforts to increase total thermal efficiency of systems consisting of various kinds of processes.

As an example, I will show you a conceptual design for the heat utilization system of the HTGR in Fig.10, which can achieve high heat utilization efficiency with outlet temperature of 950°C. Electric power is generated by a closed combined cycle of high-temperature helium gas and steam turbines. Electric power efficiency of the combined cycle is expected more than 50%<sup>(13)</sup>. High-temperature steam of about 550°C extracted from the steam turbine cycles and high-temperature helium gas of 900°C from the IHX are supplied to the heat utilization plants as process heats. Process heats are utilized so as to produce

- synthetic gas by steam reforming of natural gas,
- methane by coal gasification,
- synthesis of methanol, ethylene, ammonia etc.,
- hydrogen from water by thermo-chemical processes and high-temperature electrolysis of steam as well as pyrolysis materials of oil and by-products of its recovery and refinery.

Steam up to 200°C generated in the heat utilization plants can be supplied to a desalination facility, and then hot water below 100°C from the desalination facility can be supplied to green houses, fish farmings, district heating and so on. A part of electricity is supplied to a water electrolysis process to generate hydrogen as an electricity storage. Hydrogen generated is used as a fuel for fuel cells generating electricity in the daytime.

In realizing a heat utilizing system, the heat utilization efficiency is preferable as high as possible from the viewpoint of high performance of heat utilization and thus, the HTGR can achieve a heat utilization system as high as more than 80%. Besides, the heat utilization system of the HTGR shown in the figure is a clean energy system independent of fossil fuels though process heat are now supplied by fossil fuels to almost all of industrial processes except nuclear power generation.

Furthermore, to increase thermal efficiency of equipments and processes, multiphase-flow technologies can be applied and contributed to the HTGR systems actively for example, to heat exchangers up to 900°C such as recuperators and steam heaters in the combined cycle etc. and to waste heat recovery below 200°C in the heat utilization plants.

Multiphase-flow researches and technologies are also potentially contributed to enhance the heat transfer in the equipments and processes adopted in the system described above and at the same time to distant transportation of large amount of heat from the site where the heat is produced to the dense population sites where the large amount of heat is utilized most effectively.

### 3.2 Heat transfer enhancement

As the technology of heat transfer enhancement, a wide variety of multiphase-flow researches can be applied to the equipments and processes in the heat utilization system to increase potentially thermal efficiency.

A fluidized bed heat exchanger shown in Fig.11 can be used as the preheaters of water in the combined turbine cycle, the steam reforming process of natural gas etc.<sup>(14)</sup>. Process heat gas is injected through porous plate into fluidized bed in which small ceramic particles of about 1mm in diameter are packed, and water is supplied in finned metallic tubes installed in the bed. Fluidizing particles improve convective heat transfer of gas and several times higher heat transfer than conventional gas/liquid heat exchangers can be achieved. Because of the high heat transfer coefficients, tube wall temperature approaches to the fluid bed temperature. If ceramic tubes can be used, high-temperature gas/gas heat exchangers could be realized and convective heat transfer coefficients of internal tube surface can be enhanced by turbulence promoters such as twisted tapes.

In the high-temperature heat exchangers up to 950°C, it is preferable to enhance radiative and convective heat transfer by flowing small solid particles with gas in the heated side and by installation of high-porosity permeable bodies in a high-temperature process gas channel<sup>(15)</sup>. Then, the solid particles work as turbulence promoters and radiative absorber, and the high-porosity permeable bodies as effective radiative emitters. This type of heat transfer enhancement can be applied to chemical reactors for the steam reforming of natural gas, etc..

Heat pipes can be used for gas/gas or steam/gas heat exchangers of high-temperature process heat gas or steam and exhaust gas from the heat utilization processes since heat pipes have very high heat transfer performance by using phase change<sup>(16)</sup>. Working fluid is water, ammonia, methanol etc. in the range below 350°C and is liquid metal such as mercury, sodium, lithium etc. in the range over 350°C. Outer surfaces of heat pipes are spiral or plate finned surfaces to improve convective heat transfer performance. Dynamic performance of the heat pipe can be changed by inert gas concentration injected into container.

In the steam generators, boiling heat transfer can be improved by use of structured surface with restricted geometry called as reentrant cavities<sup>(17)</sup>. There are two types of reentrant cavity shown in Fig.12: thin porous film type and tunnel type. Boiling heat transfer performance is affected by reentrant cavity size, fluid and flow conditions.

Thus, much contribution is expected in the area of heat transfer enhancement.

### 3.3 Distant heat transportation technology

Technologies of the heat transportation between nuclear plants and heat consumers play an important role to utilize the large amount of energy most effectively. It is well recognized that heat transportation technologies using steam or pressurized hot water have some difficulties of applying because of its low density of heat transportation. Recently, the use of microencapsulated phase change suspensions has been suggested as heat transfer fluids for large amount and distant heat transportation technology. In the technology, heat is transported by a slurry suspended by encapsulated particles of phase change materials (PCM particles), whose diameter ranges from about 10 to 100  $\mu\text{m}$ <sup>(18)</sup>. This technology is also applicable for heat storage. Figure 13 shows a concept of heat transportation using the slurry and candidates of phase change materials.

The benefits from using the slurry suspended by PCM particles as follows<sup>(19)</sup>:

- a) a high energy storage density due to the absorption of latent heat during the phase change process,
- b) relatively low variations in operating temperatures of systems due to energy absorption at approximately constant temperature,

- c) the possibility of using the same medium for both energy transport and storage, thereby reducing losses during the heat exchange process,
- d) lower pumping power requirements due to the increased heat capacity,
- e) high heat transfer rates to the phase change material due to large surface area to volume ratio,
- f) the enhanced thermal conductivity of suspensions leading to increased heat transfer to the suspension, and
- g) the reduction/elimination of incongruent melting and phase separation.

In the heat transportation technology, it is also important to reduce friction loss between pipe surfaces and flowing fluid so as to reduce pumping power. It has been known for over forty years that one can reduce friction loss in turbulent flow by up to about 80% if one dissolves certain high molecular polymers into water. The amount of polymer needed is very small, being of the order of ten to a few hundred ppm. In an ideal case - and with small expense for most of the drag-reducing additives - the original pump driving the flow can therefore be replaced by a smaller one consuming one-fifth the original power. The implementation of polymeric drag-reducing additives has been limited in the case of recirculation systems, however, because of issues of polymer degradation.

Recently, it has also shown that dilute suspensions of some fibrous solid particles exhibit very appreciable drag reduction effects<sup>(20)</sup>. They have many advantages over polymers, especially with respect to degradation, and these drag-reducing additives may be very well-suited for applications involving recirculating loops. This technology is also expected to be so valuable for long distant heat transportation technology.

### 3.4 Safety upgrading of nuclear reactor systems<sup>(21)</sup>

The HTGRs have redundant heat removal system which is, for example, composed of the primary cooling system, a decay-heat removal system, namely, a vessel cooling system or a reactor-cavity cooling system, etc.. The decay-heat removal system is operated in case of the accident such as a depressurization accident in which forced convection cooling by a primary circuit is no longer available in the HTGRs. It is also operated to cool biological shielding concrete during normal operation as well.

Inherent and passive safety characteristics of the HTGRs is apparently enhanced by adopting passive decay-heat removal devices. The reactor-cavity cooling system (RCCS) of the MHTGR is one of the passive decay-heat removal system, in which the decay heat of the core is transferred by means of radiation and natural convection from the reactor pressure vessel surface to the passively air-cooled system. An option for the passive



decay-heat removal in the HTGR design is a heat pipe which is one of the applications of multiphase-flow technology and has completely passive characteristics.

Figure 14 shows a schematic diagram of the heat-pipe decay-heat removal system. The heat pipe has very simple configuration and high heat transfer capacity. It consists of a container vessel whose inside surfaces are lined with a porous capillary wick and working fluid. The heat pipe can continuously transport the latent heat of vaporization from the evaporator section to the condenser. Variable conductance heat pipes (VCHPs), whose heat transfer capacity is varied against operating conditions, are one of the promising heat transfer devices for the passive decay-heat removal system. The VCHP can be operated at minimum capacity during a normal operation and at maximum during accidental conditions. Variability in heat transfer capacity is realized by means of non-condensable gas injection, vapor or liquid reservoir tank, multi-component working fluid and others. In the non-condensable gas injection method, injected gas covers the surface of condenser section and degrades its performance. The position of gas front apparently moves in accordance with the pressure change which is triggered by temperature change. This means that heat transfer capacity is controllable to meet the requirements.

Another topic relating the HTGR safety is buoyancy-driven exchange flow in case of a stand pipe rupture accident in the HTGRs. In the accident, after pressures are balanced between inside and outside of reactor pressure vessel, relatively light gas of helium tends to flow upward through the breach. This behavior can be recognized as the mass transfer problem between gases with different bulk densities. If the air enters the core while the core temperature is high enough, graphite components will be oxidized seriously. Therefore, quantitative estimation of exchange flow rate becomes important. Through experimental and analytical studies, it was found that the exchange flow rate was greatly restricted by reduction of cross section area of opening.

#### 4. Concluding Remarks

I described my sincere expectation to the future positive application of multiphase-flow researches for broadening the area of nuclear heat utilization and for upgrading the total efficiency of nuclear heat utilization systems. More detailed presentation will follow my presentation by the today's panelists on each subject. I am looking forward to hearing the state-of-the-art on the subject from the prominent specialists from the world as well as you.

To end with my presentation, I would like to make one more emphasis on the importance of the role of international cooperation from the point of view of effective

utilization of R&D resources and human resources. I really believe that the HTTR, which is now being constructed on schedule on the site of Oarai Research Establishment, JAERI, can be effectively contributed to the international cooperation, in this sense, as the unique, worldwide center of high-temperature technology and nuclear heat utilization in very near future.

Wishing that further development and improvement of research and technology on nuclear heat utilization will be enthusiastically continued still from now on from the point of view of the worldwide welfare in both developed and developing countries, I would like to close my presentation.

It is my great pleasure if my presentation and the panel discussion on the present status of nuclear heat utilization and application of multiphase-flow research could give an opportunity to consider the importance of the subject to the specialists on multiphase flow gathering here from the world.

## References

- (1) "Energy '93", the Ministry of International Trade and Industry (JAPAN), Denryoku-Shinpou Corp., 10-134(1993).
- (2) "Proceedings of the 2nd JAERI Symposium on HTGR Technologies", JAERI-M 92-1115, 47-165(1992).
- (3) R. Harth et al., "A thermochemical pipeline system for distributing nuclear-generated heat", IAEA-TC-483/14, 285-289(1984).
- (4) "Present Status of HTGR Research & Development", JAERI(1992).
- (5) IAEA, "Nuclear applications for steam and hot water supply", 1991, IAEA-TECDOC-615.
- (6) IAEA, "Potential of low-temperature nuclear heat applications", 1986, IAEA-TECDOC-379.
- (7) IAEA, "Use of nuclear reactors for seawater desalination", 1986, IAEA-TECDOC-574.
- (8) W. Jaeger et al., "Nuclear process heat applications for modular HTR", Nucl. Eng. Des., 78, 137-145(1984).
- (9) H. J. Scharf et al., "Results from the operation of a semi-technical test plant for brown coal hydrogasification", Nucl. Eng. Des., 78, 223-231(1984).
- (10) R. Kirchhoff et al., "Operation of a semi-technical pilot plant for nuclear aided steam gasification of coal", Nucl. Eng. Des., 78, 233-239(1984).
- (11) J. Singh et al., "The nuclear heated steam reformer - design and semitechnical operating experiences", Nucl. Eng. Des., 78, 179-194(1984).

- (12) N. Wakayama et al., "Present status of R&D on heat utilization system in Japan", JAERI-M 92-215, 359-376(1993).
- (13) K. Sanokawa, "Highly efficient power generation by HTGRs, (II) Power generation by combined cycle with high-temperature helium-gas and steam turbines (written in Japanese)", J. Atomic Energy Soc. Japan, 35, 139-146(1993).
- (14) Y. Aoki, "Heat transfer augmentation by fluidized bed and application to heat exchangers (written in Japanese)", Sci. Machine, 40, 1321-1327(1988).
- (15) R. Echigo, "High temperature heat transfer augmentation", High Temperature Heat Exchangers, Hemisphere, 230-259(1986).
- (16) H. Muramoto, "Heat pipe (written in Japanese)", Refrigeration, 65, 1219-1227(1990).
- (17) Y. Fujita and K. Hijikata, "High performance heat exchange technique by boiling and condensation (written in Japanese)", Japan Soc. Energy Resources, 7, 334-341(1986).
- (18) N. Akino et al., "Microencapsulated PCM slurry for heat transfer media (2) Effect of particle diameter on phase behavior (written in Japanese)", 31st. Nat. Heat Transf. Sympo. Japan, Sapporo, 589-591(1994).
- (19) N. Goel et al., "Laminar forced convection heat transfer in micro-encapsulated phase change material suspension", Int. J. Heat Mass Transf., 37, 593-604(1994).
- (20) K. Gasljevic et al., "A feasibility study of the use of drag-reducing additives to reduce pumping power in hydronic thermal distribution systems", FED-vol.132, Industrial Applications of Fluid Mechanics, ASME, 57-65(1991).
- (21) K. Ohashi et al., "Evaluation on various passive decay heat removal systems of modular HTRs", Proc. ANP'92, AESJ, vol.2, 18.3-1 - 7(1992).

Table 1 Available temperature conditions of typical industrial processes and nuclear reactors

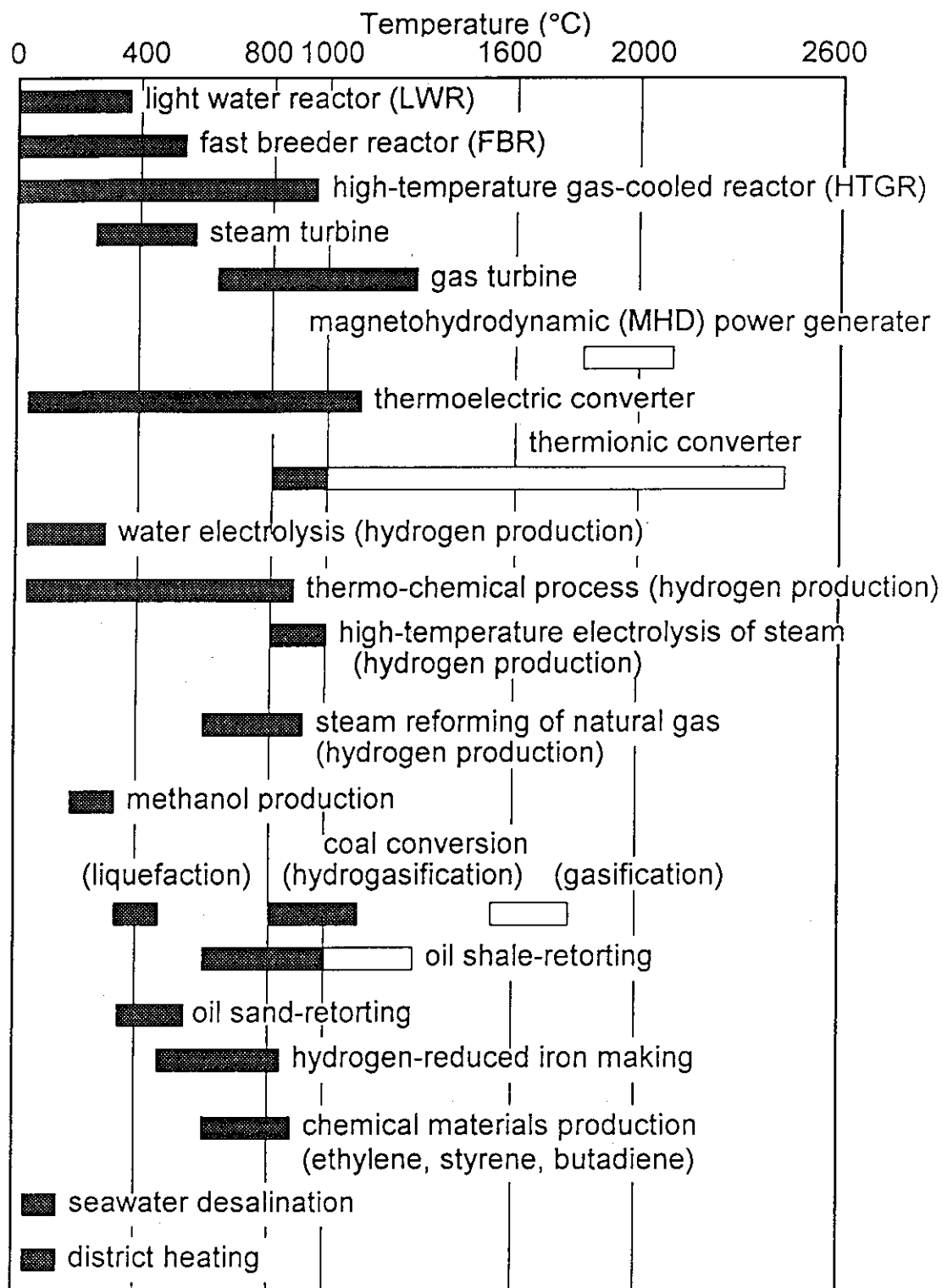


Table 2 Overview of nuclear-heat utilization technology and application of multiphase-flow researches

Multiphase flow		Nuclear heat utilization
Solid-gas multiphase flow	Dispersed flow	<u>Heat transfer enhancement</u> <u>Coal gasification</u> <u>Fluidized bed</u>
	Intermittent flow Impingement jet	
Solid-liquid multiphase flow	Deposit layer flow Partial deposit layer flow Sliding layer flow Suspended flow	<u>Heat transportation with microcapsule</u>
Gas-liquid multiphase flow	Bubbly flow Intermittent flow (Slug, Froth, Plug flows) Annular flow Stratified, wavy flows	Heat exchanger /Steam generator <u>Thermal transportation with heat-pipe</u>
Separate stratified flow (gas-gas, liquid-liquid)	Stable stratified flow Unstable stratified flow	<u>Air ingress accident</u> Properagation of fire
Solid-gas-liquid multiphase flow	Magnetic boiling flow	MHD electricity generation

Table 3 Development status of high-temperature gas-cooled reactors

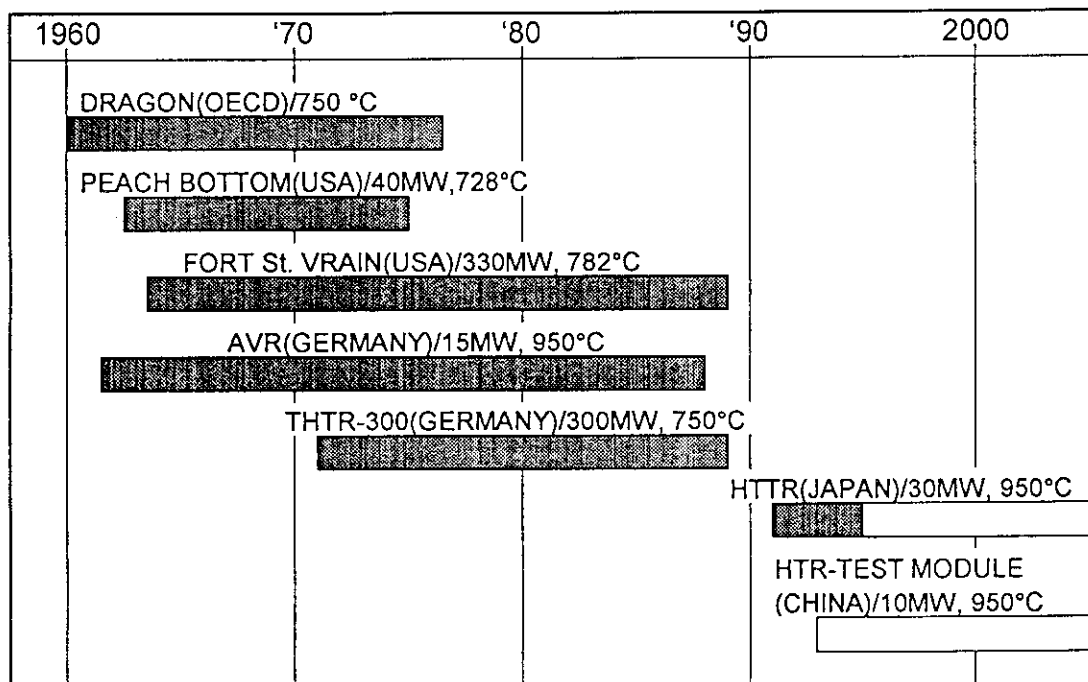


Table 4 Construction schedule of HTTR

Item \ FY	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Milestone	Permission Construction Start	Support Ground Inspection	CV Installation		RPV Installation				Criticality	Rated Operation
Reactor Building	Renovation	Excavation		Construction						
Components				Manufacturing · Installation						
Fuel			Uranium Procurement		Fabrication · Assembling					
Test						Pre-operational Test			Loading	
									Fuel Loading Test	
									Power Up Test	

Table 5 Operation and test plan of HTTR

Fiscal Year	1998	1999	2000	2001	2002	2003 ~
Items						
1. Operations and Tests	Initial Core					Advanced Core
2. Development of Advanced Technologies for HTGR	30MW / 850-950°C	30MW / 850°C			30MW / 950°C	30MW / 950°C
1) Development of Advanced Fuels/ Materials		Irradiation in Capsules or Full-sized Samples				Irradiation Tests
2) Safety Demonstration Tests		Demonstration Tests				
3) Process Heat Utilization Tests	Design, R&D (HENDEL)	Licensing		Construction		Demonstration Tests
3. Innovative Basic Technology			Development of Very High Temperature Heat-Resisting Material etc.			
			Tritium Production and Recovery Tests			

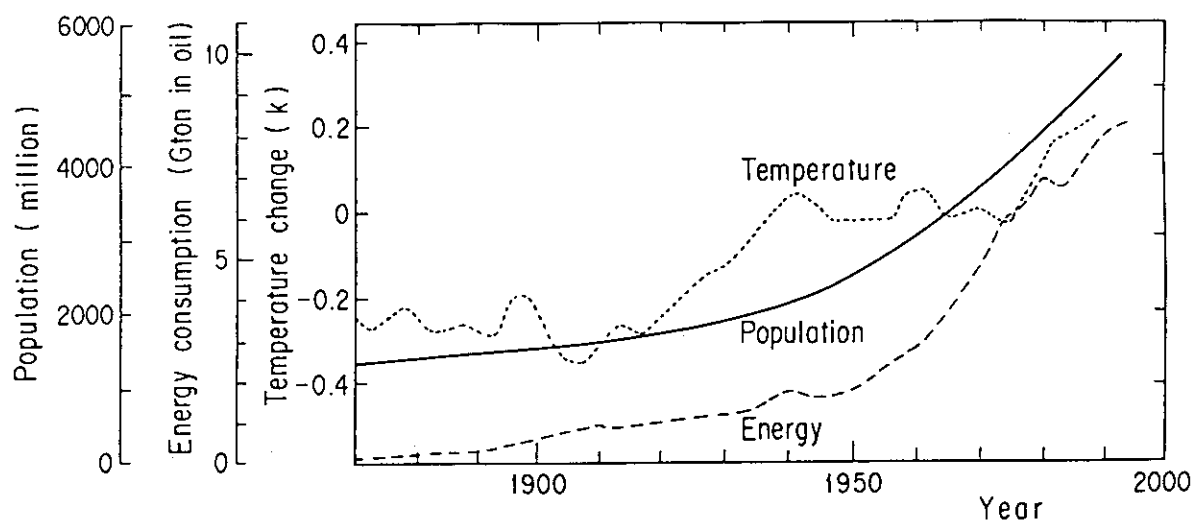


Figure 1 Increase in population, energy, and temperature change during our own century

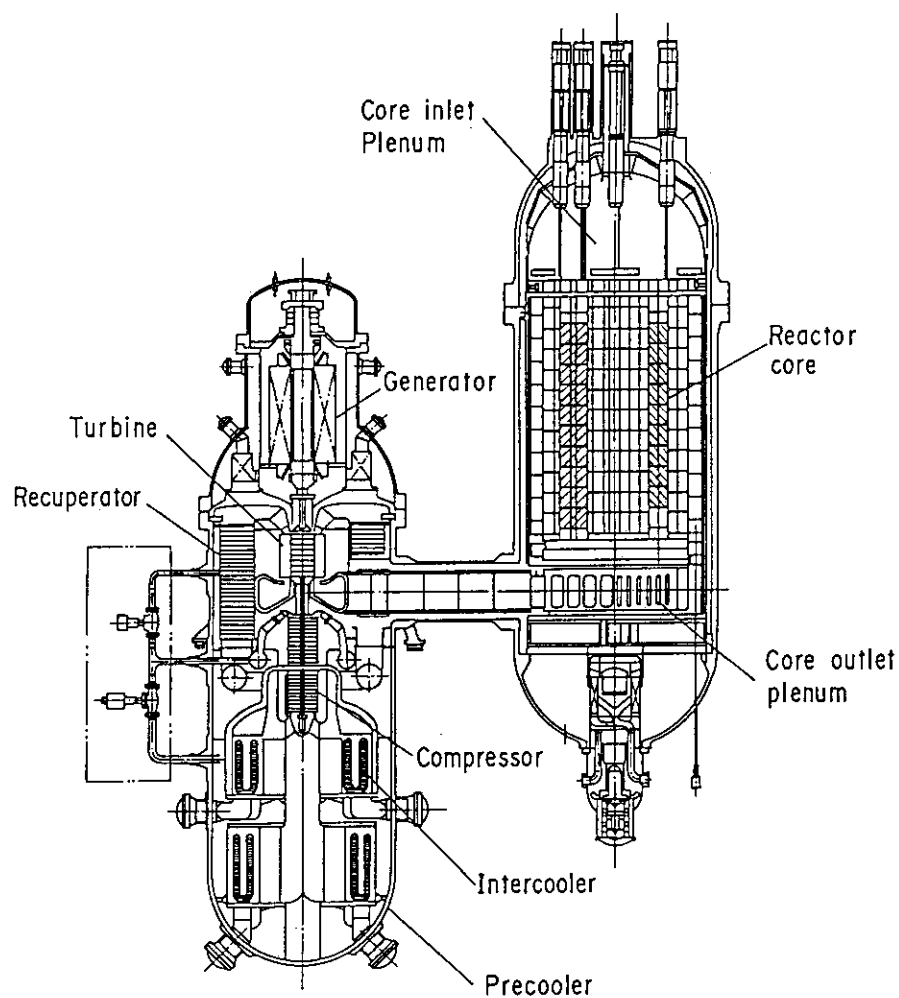


Figure 2 Schematic drawing of modular HTGR of the United States

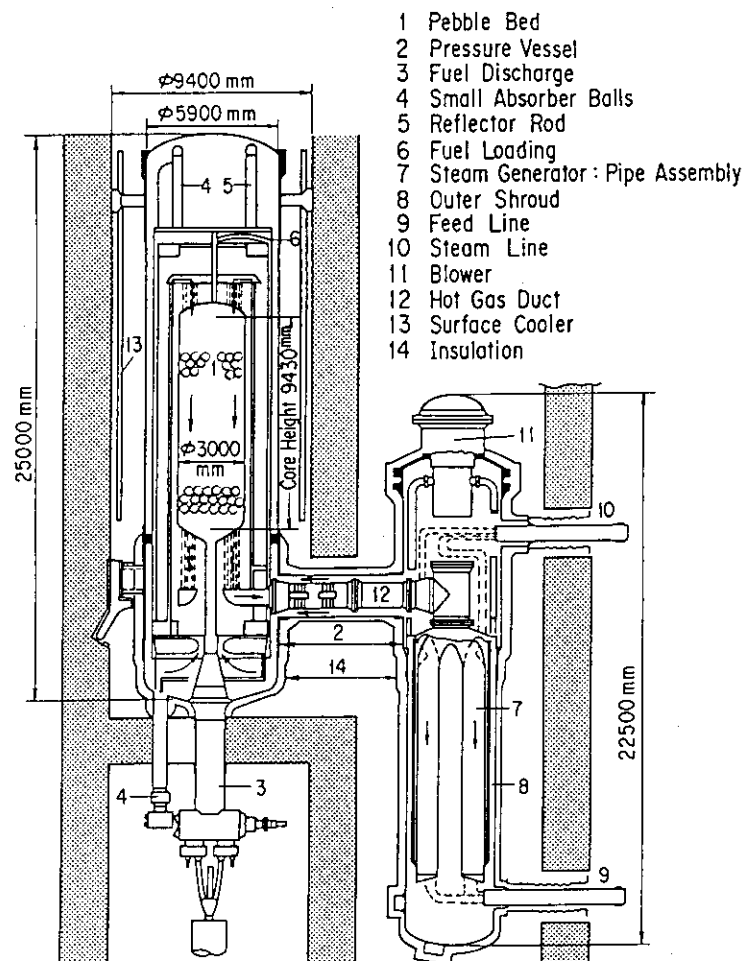


Figure 3 Schematic drawing of HTGR module of the Federal Republic of Germany

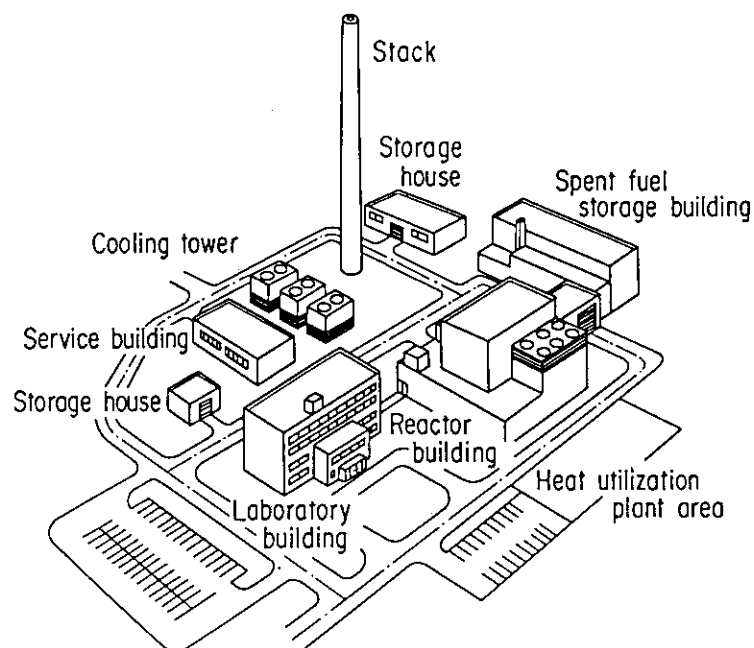


Figure 4 Facilities arrangement of HTTR



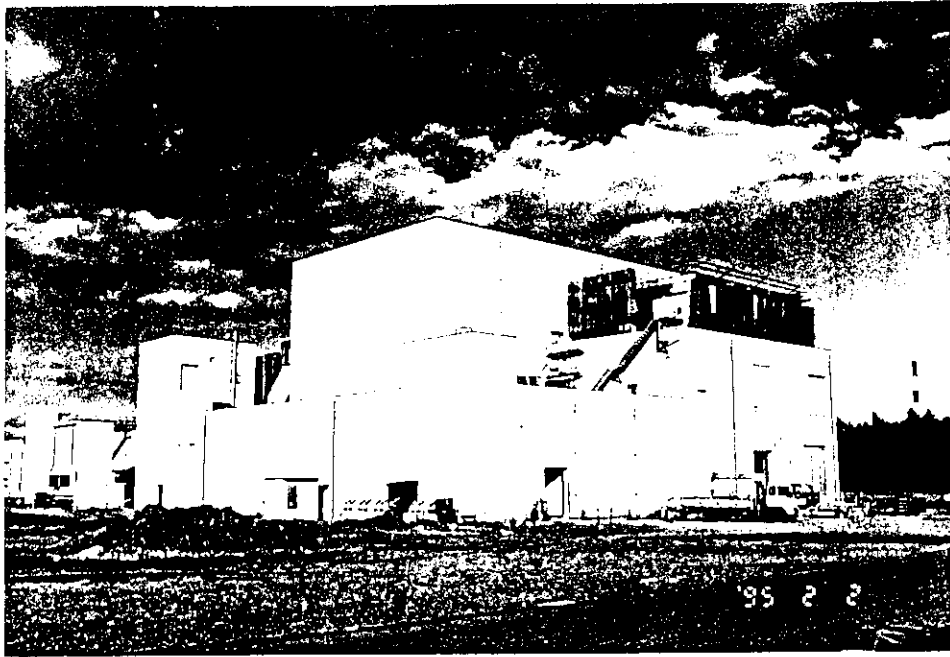


Photo 1 Overview of reactor building under construction

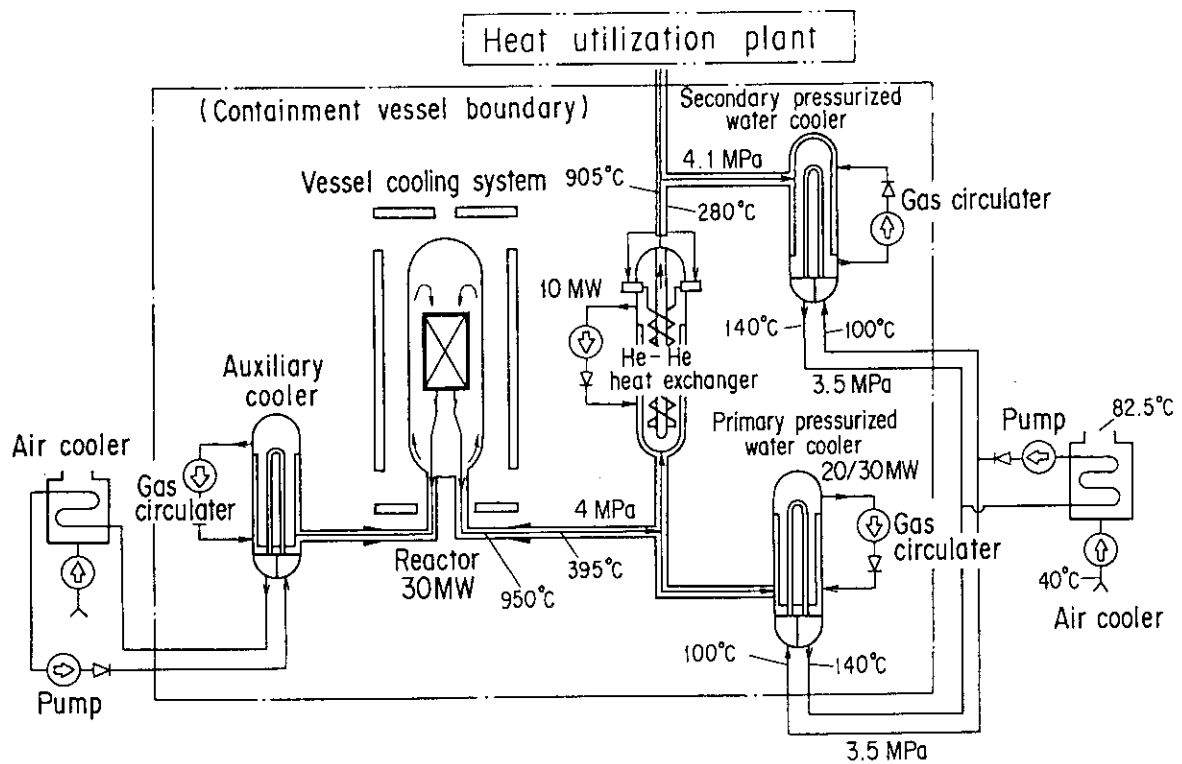


Figure 5 Flow sheet of HTTR cooling system

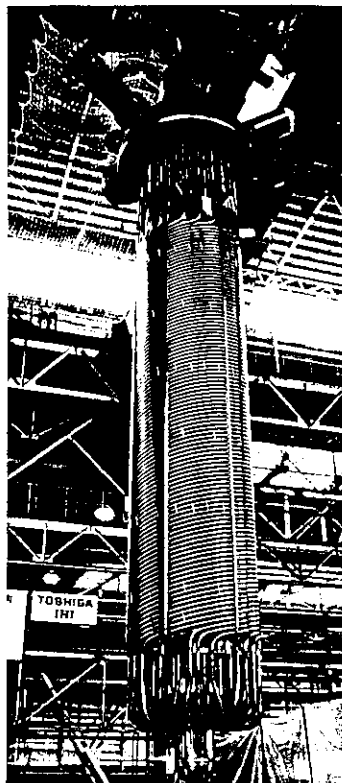
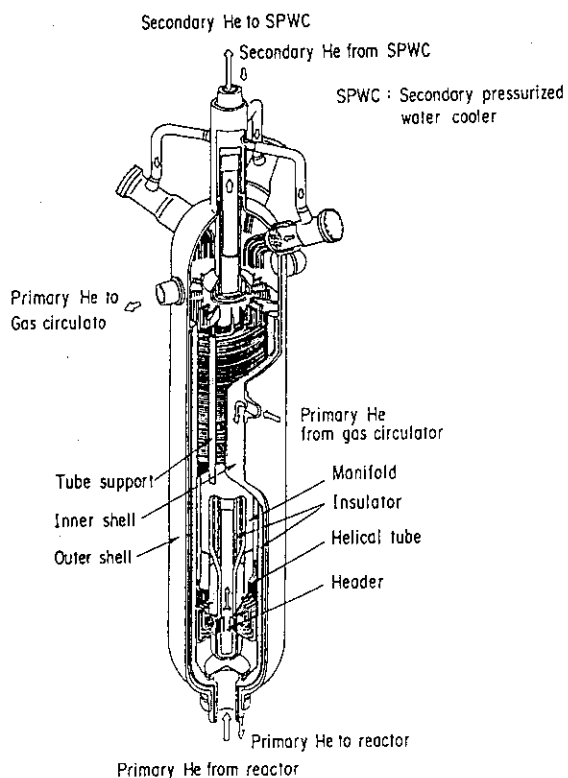


Figure 6 View of He/He intermediate heat exchanger of HTTR

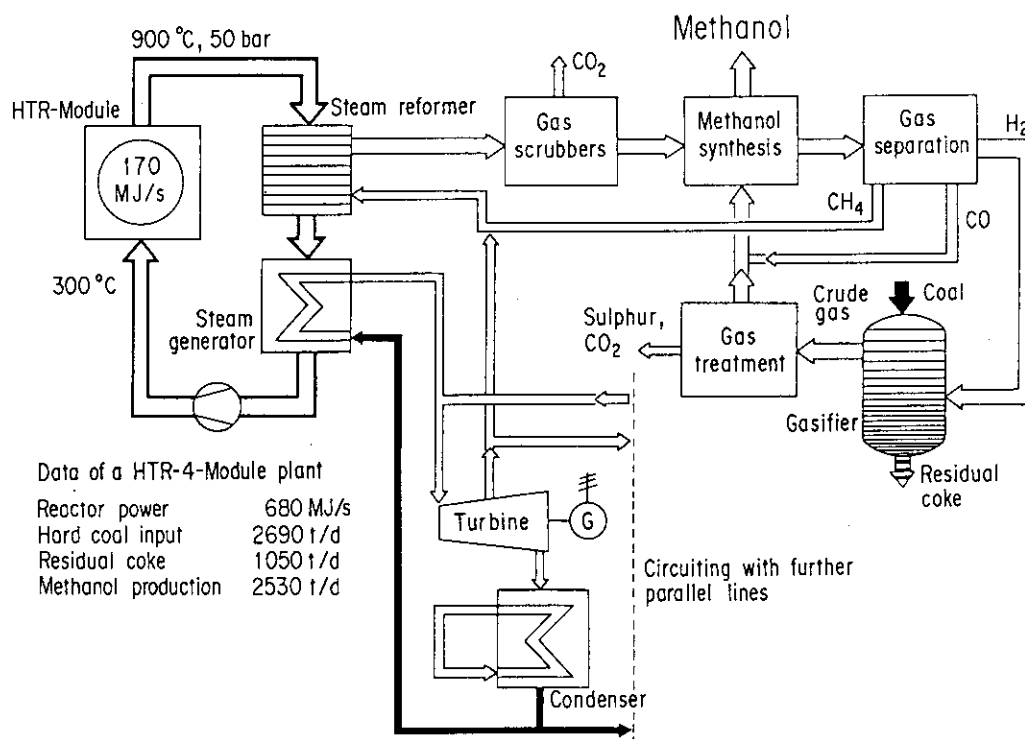


Figure 7 Flow sheet of hydrogasification of coal for methanol production with HTGR

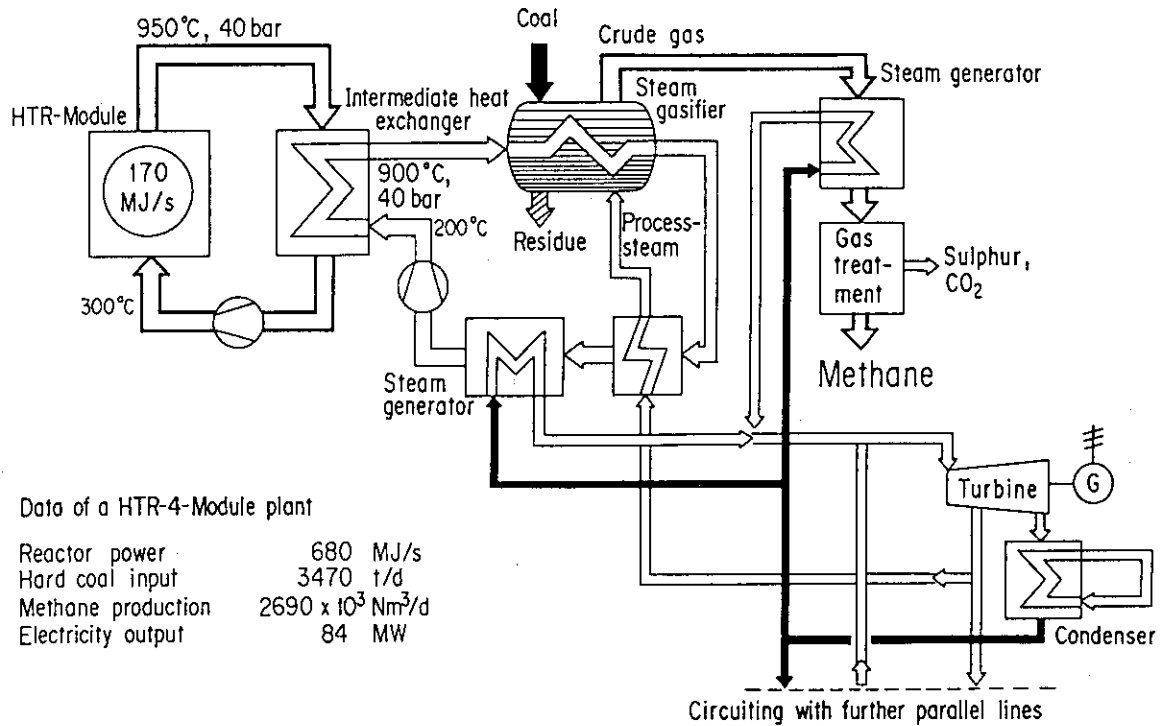


Figure 8 Flow sheet of steam gasification of coal for methane production with HTGR

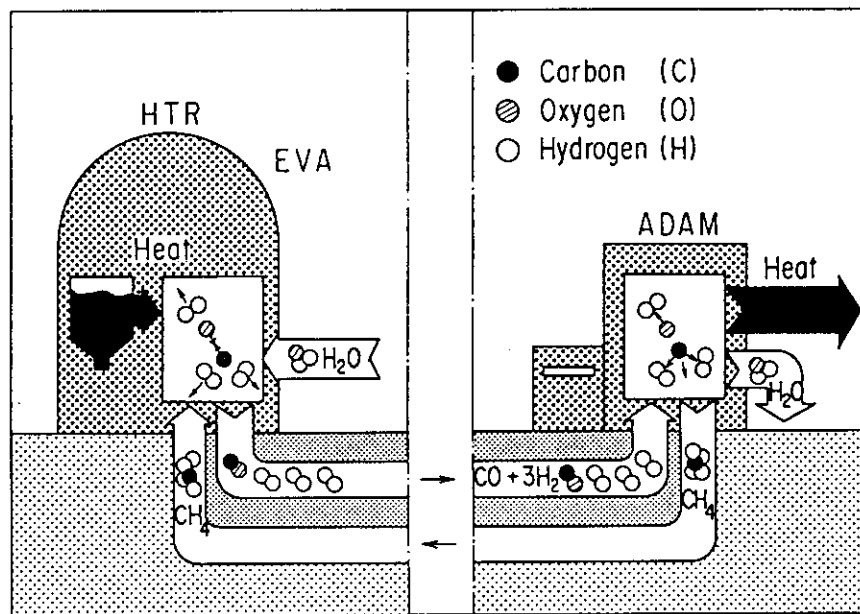
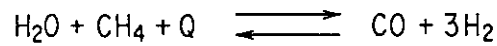


Figure 9 Concepts of nuclear heat transportation system

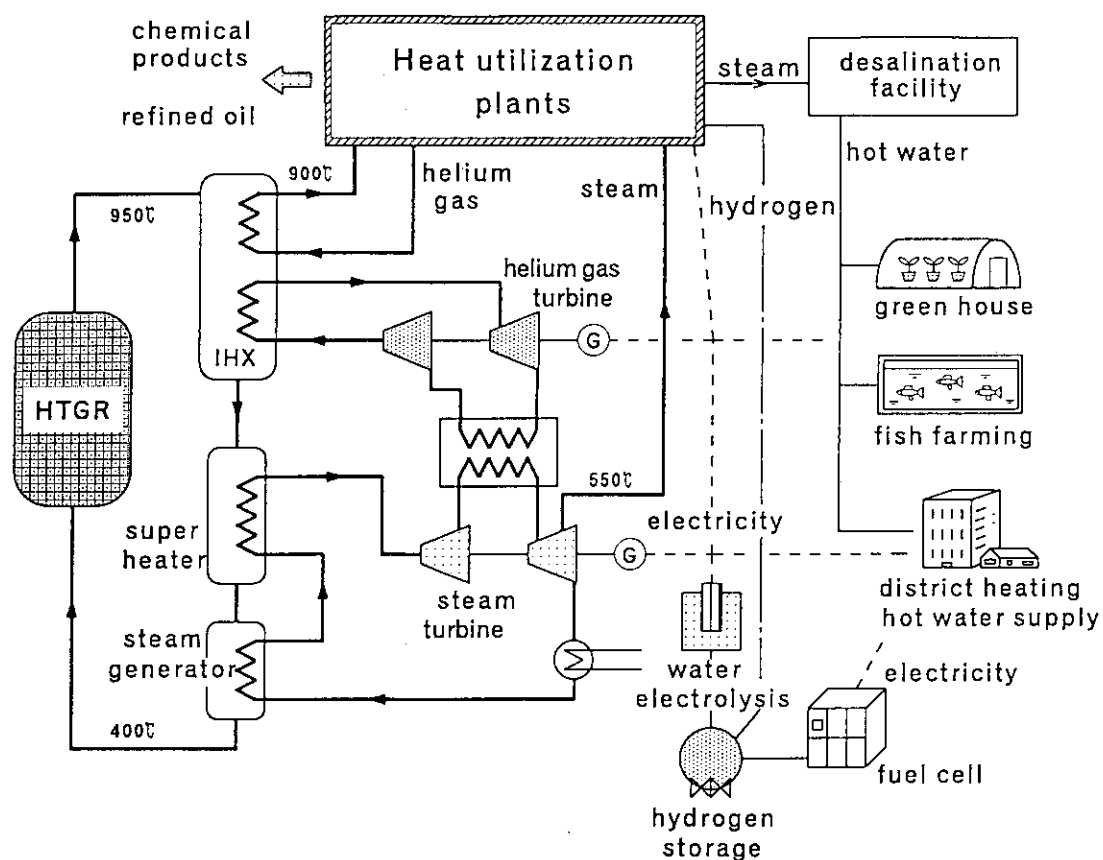


Figure 10 Conceptual plan of heat utilization system of HTGR

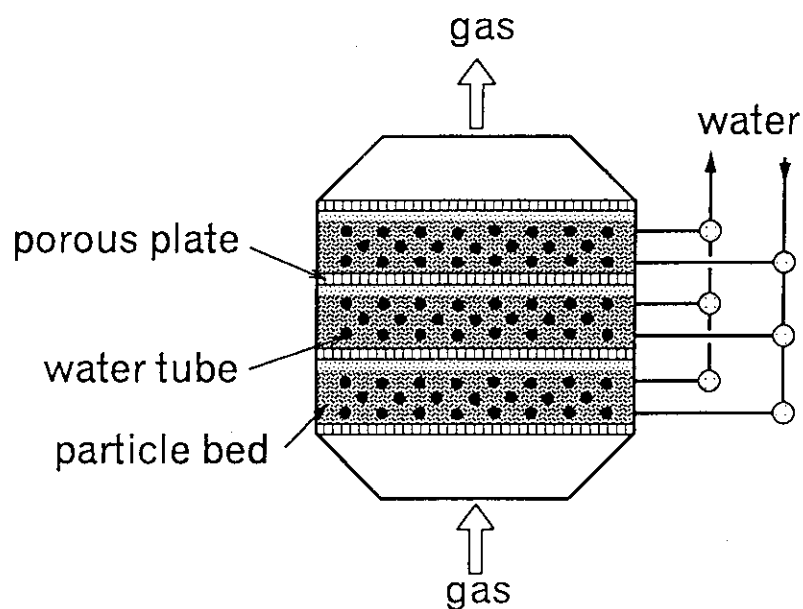


Figure 11 Schematic drawing of fluidized bed heat exchanger

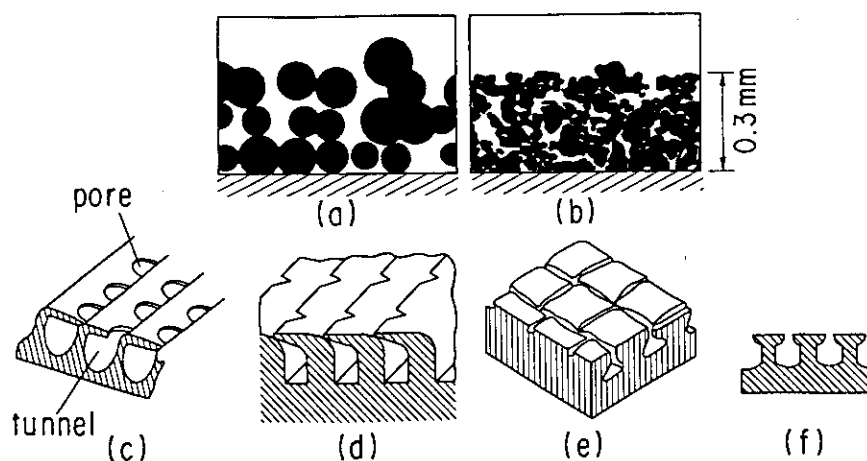
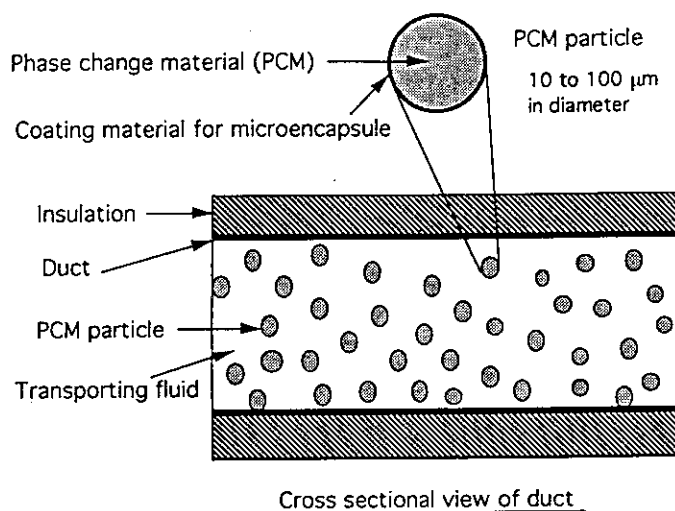


Figure 12 Reentrant cavity surface

(a), (b) thin porous layer (c)~(f) tunnel structure



Material	Melting point ( $^{\circ}\text{C}$ )	Latent heat (kJ/liter)
LiF	848	2761
$\text{Ca}(\text{OH})_2$	480	1965
$\text{FeCl}_3$	304	745
Pentaerythritol $\text{C}(\text{CH}_2\text{OH})_4$	188	269
$\text{Ba}(\text{OH})_2$	78	581
Fatty acids (for basic study)	10-70	130-190

cf. Steam (180  $^{\circ}\text{C}$ , 1MPa): 10 kJ/liter

Figure 13 Concepts of heat transportation using slurry and candidates of phase change materials

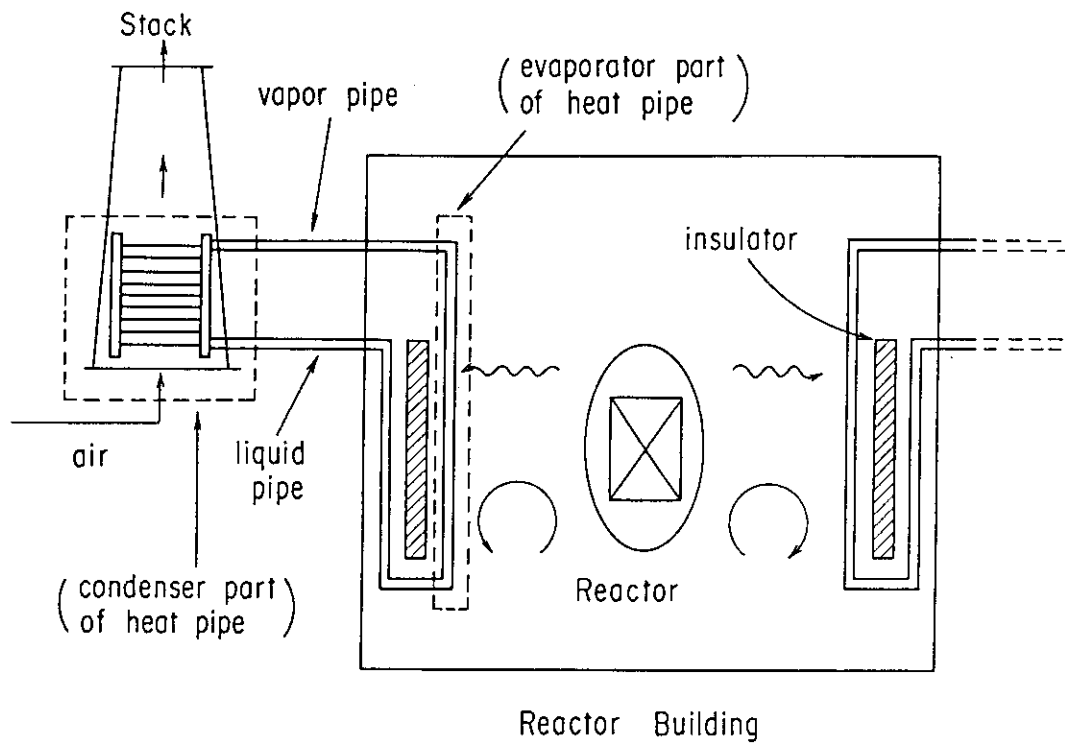


Figure 14 Diagram of heat-pipe decay-heat removal system for MHTGR

## 6. Papers presented by topic speakers

## 6.1 Heat transfer augmentation by gas-particle two-phase flow

Z. R. Gorbis

and

A. Shimizu

University of California, Los Angeles  
USA

Kyushu University  
JAPAN

### Introduction

Most nuclear power is originally released as the kinetic energy of particles produced in respective reactions. The energy level of those particles is of MeV order or higher. Meanwhile, an equilibrium gas temperature corresponding to molecular kinetic energy of only 1 eV is about  $10^4$  K which is still much higher than 600 K at which that nuclear energy is converted to electricity in today's typical nuclear power plants. Raising the operating temperature of the energy conversion is, therefore, a due direction for more effective use of the nuclear energy, which can be achieved only by the gaseous coolant.

The helium-cooled HTGR (High Temperature Gas-cooled Reactor) will take an important position in the global energy strategy towards next century. It is expected to supply not only electricity but also high quality thermal energy for various industries and local utilities without exhausting any green house effect gas or acid rain gas. Of particular interest is the production of hydrogen and methanol that will be major liquid fuels for transportation after oil resource is exhausted out. The key R&D issue of the HTGR is economical competitiveness, particularly against light water reactors. Due to the poor heat transfer of the single phase helium, the HTGR's volumetric power density is restricted to roughly tenth of corresponding PWR's value so that increasing the power density by improving heat transfer is strongly desired. The situation is in a sense similar for fusion reactors. Although superiority of the helium-cooling is recognized from several aspects, cooling the plasma facing components by pure helium is quite difficult so that the key is again the heat transfer improvement.

The standstill can be broken through by adopting gas-solid suspension medium. Its heat transfer performance is excellent. Its heat capacity can be increased drastically without excessive pressurization. Although the thermal radiation is a dominant heat transfer mode in high temperature region, the helium which is always used in high temperature nuclear systems is monatomic so that is transparent to thermal radiation. Solid particles suspended there will emit or receive the radiation and exchange it easily with the ambient gas by conduction and convection. The suspension impinging jet is quite attractive for the divertor cooling of fusion reactors.



The study of the gas-particle flow as promised coolant for gas-cooled reactor began in the USSR in the late fifties. They were concentrated on gas-graphite suspension turbulent flow as it was done in the USA and then in England. But, unlike the latter, they also included the following investigations:

- the dense flow and gravity driven packed bed, which covered all possible ranges of particulate volumetric concentration on the flows;
- the gas-particle interactions as an independent heat transfer process and as an important part of wall cooling by the suspension flows;
- the thermodynamic problems related to the use of the suspension flow as a possible working agent in gas turbines;

As usual, open studies were conducted in the USSR by some educational and research institute (such as Odessa Technology Institutes, Moscow Energetic Institute, Institute of Engineering Thermophysics, Ukrainian Academy of Sciences, Heat and Mass Transfer Institute of Byelorussian Academy of Sciences, Power Institute of USSR Academy of Sciences, etc.). The studies were provided under grants from the Ministry of Power, Kurchatov Atomic Institute, etc. The All-Union Coordinating Council on applying gas-particle flow as reactor coolant was established in the early seventies with Co-presidents from Kurchatov Atomic Institute and Odessa Technological Institute.

Because the knowledge of basic characteristics of particulate flow is very important for proper evaluation and design of reactors, the experimental and analytical studies were concentrated mainly on special fluid mechanics and heat transfer problems. Some main results of these studies will be briefly discussed later and are connected with use of the graphite particles as the prime candidate of solid components of these flows. The main characteristics of possible coolants of high temperature fission reactors with gas-particle flow are presented in Table 1 based on [1-3]. Some characteristics of particle flows as coolant for fusion nuclear reactors are in the Table 2 [5].

## **1. Special fluid mechanic problems**

### **1-1 Some characteristics of graphite particles**

The knowledge of friction factors of a bed of the graphite particles is important for design not only of reactors with a moving bed but also with suspension flow. Experimental data were obtained with bits of graphite electrodes with contents less than 0.5% ash and has a specific weight of  $2050 \text{ kg/m}^3$  [4]. The factor of external friction of rest (static friction) ranged from 0.33 to 0.62 with a decrease in the size of particulates from  $\sim 3.5 \text{ mm}$  to  $\sim 0.3 \text{ mm}$ . For a mixture of particulates, this factor was 0.62. The factor of external friction of motion was from 0.167 to 0.52 (material of the wall was

steel). It was found that the erosion rate of the wall surface could be neglected. The attrition rate is greater for coarse particles but it decrease with the size of graphite particulates, and it can be neglected for particles of several microns in size.

The slope of repose which characterizes the internal friction was from 39° and 48° for the same range of particulate size. The asphericity of the particles increases with decrease of their size; that is a special peculiarity of graphite as a material with a layered crystal lattice. According to [1,2], the shape factor of graphite particles increases from  $f=1.15$  to 1.5 (for a sphere it is 1).

The use of graphite particulate flow and some additional characteristics of these particles for the first wall coolant in fusion reactors was presented in [5,6]. The use of melted particles for divertor cooling (fusion nuclear reactors) was proposed and analyzed in [7]. Impinging jets with solid particles, including graphite particles, were studied in [8].

### 1-2 The drag coefficient, $C_f$

It was obtained experimentally as a function of Reynolds number for the particulate  $Re_s = u_s d_s / \nu$  and shape factor  $f$  [1,2]. If gas cross flow is in Newton's regime,  $C_f = 1.1$  for  $Re_s = 400-5000$  and  $f = 1.15-1.2$  and  $C_f = 1.8$  for  $Re_s = 300-5000$ , which is much higher than that for the equivalent sphere. For Stokes law ( $Re_s < 0.1-1$ ),  $C_f = 24 Re_s^{-1}$ . For intermediate regime ( $30 < Re_s < 400$ ),  $C_f = 37.8 Re_s^{-0.06}$  which is also different in comparison with spheres. The effect of particle volumetric concentration  $\beta$  on the drag coefficient was analyzed in [1,2]. It is more significant for Stokesian regime (fine particles) and can be neglected only at  $\beta$  less than  $\beta_{cr} = 0.5-1\%$ . If  $\beta > \beta_{cr}$  for Stokesian regime,

$$C_f^* / C_f = (1 - \beta)^{-9.6} \quad (1)$$

A general approximate expression was proposed in [2] for all types of cross-flow regimes:

$$\frac{C_f^*}{C_f} = \frac{18 + 0.61(1 - \beta)^{2.38} Ar_s^{0.5}}{(18 + 0.61 Ar_s^{0.5})(1 - \beta)^{4.75}} \quad (2)$$

where  $C_f^*$  and  $C_f$  are drag coefficients for multi-particle and single particle flows, respectively;  $Ar_s$  is the Archimedes number  $Ar_s = g(\rho_s - \rho)d_s^3 / \rho u^2$ .

### 1-3 Pressure Drops of gas-graphite longitudinal flow

It was analyzed in [2,3]. The correlation of different experimental data presented in [9-12] was obtained for stabilized vertical and horizontal flows with different carrier gases (helium, nitrogen, air and argon). The graphite loading ratio was  $\mu \leq 50$  kgs/kgs, Reynolds number of the gas flow:  $Re_f \geq 5 \times 10^3$  to  $5 \times 10^4$ , channel/particulate

diameter ratio:  $D/d_s = 38$  to  $3.2 \times 10^3$ , and the wall/flow temperature ratio:  $T_w/T_f \leq 1.25$ . According to Figure 1,

$$\xi_{fr} / \xi_o = A (D / d_s)^{0.08} K_f^{*n} \quad (3)$$

where  $\xi_{fr}$  is the coefficient of overall effect of friction, both of the moving particulates and gas flow which reflect all the shear stress transmitted to the channel walls and  $\xi_o$  is the friction coefficient of gas flow without particles. Notice that pressure  $\Delta P_f$  of the gas suspension flow is directly proportional to  $\xi_{fr}$ . This allows us to calculate the power needed for coolant circulation,  $N_c$ , properly. The main representative parameter,  $K_f^*$  in Equation 3, is the modified flow through number [1,2,3], which was proposed as a measure of the ratio of the inertia and friction forces for both solid and gas phases of the flow:

$$K_f^* = 64.2 (1 - \beta)^{3.8} (1 + \mu) Re_f^{0.125} \quad (4)$$

For equation 3,

$$\text{at } K_f^* = 800 \text{ to } 5200 \quad A = 2.3 \times 10^{-2}; n = 0.56$$

$$\text{at } K_f^* = 5200 \text{ to } 12000 \quad A = 1.27 \times 10^{-5}; n = 1.44$$

Some empirical and particular expressions for gas-graphite flows are given and discussed in [2]. They are simple functions of  $\mu$  or of  $\mu$  and  $Re_f$  and must be used only in some narrow range of experimental conditions, which limits the design requirements.

The distribution of the velocities of gases and particulates, peculiarity of turbulence, distribution of particle concentration in the gas flow, specifics of dilute suspension cross-flow, and other special fluid mechanics problems are analyzed in [2].

## 2. Special heat transfer problems

According to Table 1, the different heat transfer mechanisms may occur in different types of nuclear reactors with gas-solid particulate coolants. They are discussed shortly below.

### 2-1 Convective heat transfer interaction between gas and particulates (inter-component heat transfer)

This type of thermal process is the very special and the simplest one. It is only a part of a more complicated mechanism of heat transfer between channel walls and gas-particulate flow as a coolant. However, inter component heat transfer becomes a prime mechanism if the walls are adiabatic and heat exchange occurs only on the particles' surfaces. It can occur in fission nuclear reactors with dispersed fuel particles circulated through the core of the reactor by carrier gas flow. The main advantage of this system is a promised solution of problems of fuel elements designed for fission reactors and

problems of solid breeder design for fusion reactors. In the first case, the flowing fuel particles can be coated to decrease the radioactivity of the system. It is also used in some heat exchangers outside of reactor.

The experimental data, models, and analyses of this type of heat transfer are presented in [1-3]. Three main scenarios were studied:

- ☐ single-particle approximation
- ☐ inter component heat transfer under conditions of collective effects of particles in suspension flow
- ☐ inter component heat transfer under conditions of ventilated, stagnant, or moving packed bed [1,3].

The first two cases are discussed shortly next.

The solitary particle approximation can be applied to dilute suspensions[1,2] and was studied for moving and aspherical particles with very small volumetric concentration,  $\beta \rightarrow 0$ . In this instance, the case of connective inter component heat transfer in a free, unconstrained flow with  $\beta \leq \beta_{cr} = 3.5 \times 10^{-4}$  to  $4 \times 10^{-4}$  can be calculated from correlation of various experimental data obtained in [1]. According to Figure 2, at  $Re_s$  from 30 to 180:

$$Nu_{s,o} \equiv k h_o d_s / K_s = 0.186 Re_s^{0.8} \quad (5)$$

and at  $Re_s = 480$  to 2000:

$$Nu_{s,o} = 1.17 Re_s^{0.5} \quad (6)$$

where  $d_s$  is the diameter of a sphere with a surface equivalent to that of the particle. Eqs. (5) and (6) are valid for particles with the Biot number  $Bi_s \leq 0.1$  and the asphericity factor  $f=1$  to 1.5. The main difference between heat transfer of a freely moving particle and an equivalent non-moving sphere (lines I, II and III in Fig. 2) is associated with rotation of the moving particle. According to hydrodynamic theory of intercomponent heat transfer[1], at  $Re_s = idem$ :

$$\frac{Nu_{s,o}}{Nu_{sph,o}} = \frac{C_{f,s,o}}{C_{f,sph,o}} \times \frac{1}{f} \quad (7)$$

where "sph,o" and "s,o" are subscripts related to stagnant sphere and to flow particle with given asphericity factor  $f$ ; and  $C_f$  is the drag coefficient. The ratio expressed by Eq. (7) can be either smaller or greater than unity depending on  $f$  factor and the velocity shape factor  $C_f/C_{f,sph}$ . Hence, according to Fig. 2 and eqs. (5), (6) and (7), calculations, based on the usual recommendations, which are valid for a stagnant sphere, will be incorrect. It will overestimate the actual situation at  $Re_s < 30$ , especially at  $Re_s \rightarrow 0$  (fine particulate) for the lower limit of the Nusselt number. Because small graphite particles are not

spherical, it gives  $Nu_{s,min}$  a smaller value than usual  $Nu_{sph,min} = 2$ , for the higher value of the particle asphericity factor  $f$ . For  $Re_s > 30$  to 50, the heat transfer with moving particles increases compared to the equivalent non-moving sphere because of earlier turbulization of the particle boundary layer.

Collective effects of particles on intercomponent heat transfer usually arise with an increase of volumetric particle concentration  $\beta$  and was analyzed by the ratio  $Nu_s(\beta)/Nu_{s,o}$  in [1-3]. It was found that this ratio becomes smaller than unity when the motions of individual particles become constrained and their distribution in the gas flow is no longer uniform. This is why the values of  $Nu_s(\beta)$  became an averaged, effective quantity  $Nu_s$ , which also depends on design factor (phases entry and exit conditions, etc.).

According to Fig. 3 at  $Re_s = idem$ ,  $\beta \leq \beta_{cr} = 3.5 \times 10^{-4}$  to  $4.5 \times 10^{-4}$  and chambers without decelerating inserts  $\overline{Nu_s}/Nu_{s,o} = 1$ . When  $\beta < \beta_{cr} < 2 \times 10^{-3}$  at  $Re_s = 40$  to 330,

$$\overline{Nu_s} / Nu_{s,o} = 0.033\beta^{-0.43} \quad (8).$$

For chamber with helical mesh-type inserts at  $\beta < 0.25$ ,  $\overline{Nu_s}/Nu_{s,o} = 1$  (notice that  $\beta_{cr}$  in this case increased very much), but at  $\beta < 0.25$

$$\overline{Nu_s} / Nu_{s,o} = 0.017\beta^{-0.69} \quad (9).$$

If cascade arranged mesh-type inserts are used in chamber with counter flow of particulates,

$$\overline{Nu_s} / Nu_{s,o} = 0.00505\beta^{-0.66} \quad (10).$$

It must be stressed, that often ignored phenomena of collective effects on heat transfer should be taken into account for design of coolant systems.

In all cases at  $\beta < \beta_{cr}$ ,  $Nu_s < Nu_{s,o}$ , i.e., the effective rate of intercomponent heat transfer becomes smaller than otherwise, and the greater the degree of non uniformity in the interactions between components in the chamber channels, etc., the smaller it becomes. The use of mechanical inserts, especially helical types, can greatly improve intercomponent heat transfer in counterflow of phases of gas suspension flows. The uniformity of phase (both gaseous and solid) distribution into the channels of coolant and between channels is a very important design task both for fission and fusion nuclear reactors with gas-solid particulate coolants.

## 2-2 Radiative heat transfer with particulates

Radiative transfer is controlled, in many cases, by the optical properties of the particles because helium is diathermal. For the ensemble of them, the effective absorptivity  $\alpha_s$  also depends on the volumetric concentration of particles  $\beta$ :

$$\alpha_s = 3K_s\beta / 2d_s \quad (11)$$

where  $K_s$  is the relative effective attenuation cross-section that depends on particle

diameter ( $d_s$ ) distribution, its material and the spectral characteristics of the radiation source. The emissivity of particulate suspension flows  $\epsilon_f$  depends on  $\alpha_s$ . According to Fig. 4, the emissivity of helium-graphite coolant for high temperature fission reactors can be raised appreciably at very small values of  $\mu D$  ( $\mu$  is the flow solids loading ratio;  $D$  is the diameter of reactor channel). For example, if  $d_s \sim 1 \mu\text{m}$  and  $D = 0.021 \text{m}$  (FTGR "Dragon"), the emissivity  $\epsilon_f$  may be equal to 0.9 as early as at  $\mu \sim 0.05$ , i.e., at dilute suspension (look at Table 1). In this case (optically thin layer approximation without particles radiative interaction) the radiant heat flux density  $q_R$  can be analyzed by the formula:

$$q_R = \epsilon_{red} \sigma (T_w^4 - T_f^4) \quad (12)$$

Here  $\epsilon_{red}$  is the reduced emissivity,  $\epsilon_{red} = (1 + \epsilon_f) \epsilon_w / 2$ ;  $\epsilon_w$  and  $T_w$  are the emissivity and average temperature of the channel wall;  $\sigma$  is the Stefan-Boltzmann constant.

If gas suspensions are used at an elevated concentration of fine particulates, the radiative heat transfer between the particles is the controlling mechanism. In this second limiting case - optically thick layer approximation - the radiation thermal conductivity  $\kappa_R$  is an important part of total, combined (convective and radiative) heat transfer with suspension flow  $Nu_R$ :

$$Nu_{f,s} / Nu_{f,o} \cong 1 + \kappa_R / \kappa_{gas} \quad (13)$$

Using the experimental relationship obtained in [11], the expression (13) for standard flow can be replaced by

$$Nu_{f,s} / Nu_{f,o} = 1 + 0.15(\nu - 1) \quad (14)$$

and in this case:

$$q_R = 0.15(\nu - 1) h_f (T_w - T_f) = 0.15(\nu - 1) q_R \quad (15)$$

where  $\nu = T_w / T_f$  is the temperature factor and  $h_f$  is convective heat transfer coefficient with suspension flow.

In some cases, the optical thickness of suspension flow may be between these two limiting approximations, expressions (12) and (13), which are modeled and discussed in [2].

### 2-3 Convective heat transfer with channel walls

The physical model, mathematical description and analysis of experimental data, and empirical expressions are given in the book [2]. It was found that most reliable correlations are possible only for experimental data of convective heat transfer of gas suspension flow, in which the component temperature and velocity slips can be assumed zero (gas-particle equilibrium). In this case the intercomponent thermal resistance can be neglected. The data given in [11-14] are close to these conditions and are in good

agreement. All of them were obtained for fine graphite particulates flow, which is important for this analysis. The results given in [11] and [12] are in good mutual agreement and can be accomplished for calculating the local convective heat transfer. At  $d_s=5\text{ }\mu\text{m}$ ,  $Z=\mu c/c \leq 50$ ;  $v=T_w/T_f \leq 2.1$  and  $Re_f = idem \geq 10^4$  [11]:

$$Nu_x / Nu_{ox} = \left[ 1 + 0.6 \exp(-0.084x/D) \right] \left[ 1 + 0.15(v-1)(0.71 + 0.125Z - 0.001Z^2) \right] \quad (16),$$

where subscript "o" means gas flow without particulates.

The results, given in [12] and [13] are recommended for calculating the average heat transfer coefficient. According to the correlation obtained in [10] at  $d_s=1$  to  $5\text{ }\mu\text{m}$ ,  $Z=2$  to  $50$ ,  $v>1$  (heating), pressure to  $0.9\text{MPa}$ ,  $Re_f = idem \geq 10^4$ , for different carrier gases, including helium, it can be suggested that,

$$Nu_f / Nu_o = 0.83 Pr^{0.4} (1 + Z)^{0.45} \quad (17)$$

Values of the heat transfer coefficient somewhat higher than those in [11] were obtained in [15] and [16], who employed sub-micron ( $0.03$  to  $0.3\text{ }\mu\text{m}$ ) particles of acetylene soot. According to [11,14,15,16] the thermal entry length is about  $30$  channel diameters  $D$ . The principal mechanism of possible high enhancement of convective heat transfer with turbulent, heated gas flow by the particles is their disturbing effect on wall region, especially on viscous sublayer [1,2].

If suspension flow is cooled ( $v<1$ ) the mechanism of heat transfer is usually changed because of particle deposition on the wall under the thermophoresis force. It can occur only outside of the nuclear reactor core with  $v$  always higher than  $1$ . According to experimental data obtained with fine graphite particles in [11] and [17] at  $\mu=30$  the ratio  $Nu_f/Nu_o$  in cooling of the suspension flow was half its value in heating. These problems are discussed in [2]. A detailed study of convective heat transfer with cylinder in cross flow of dilute graphite fine particle flow was performed at  $Re_f=2 \times 10^3$  to  $9 \times 10^3$ ,  $\mu < 2 \times 10^{-3}$  and  $v$  to  $0.5$  under grant from Kurchatov Atomic Institute [18,19]. The graphite dust can naturally occur in the high temperature gas cooled fission reactors, especially with spherical fuel elements bed in the core, because of erosion of graphite coating fuel elements. The fouling of heat surfaces of the steam generator by this dust may cause up to  $40\%$  reduction in the rate of heat transfer. This and some other problems were discussed shortly in [20]. Some cleaning methods must be employed. It was stressed that, for example, periodic blowoff of the steam generator surfaces can help because it was found that fine graphite particulate deposits are loose and highly coherent.

Convective heat transfer at high heat fluxes may lead to abrupt reduction of

cooling in the case of a particle-free fluid. This is caused by the laminarizing effect on turbulent transfer by the thermal acceleration. It must be taken into account especially for high-temperature elements of fission and fusion reactors. The situation can be improved by use of dilute gas suspension. It was first experimentally detected at  $Re_f$  to  $1.2 \times 10^4$ ,  $\nu=1.1$  to  $1.9$ ,  $\mu$  to  $2$ ,  $T_w$  to  $1100$  K with nickel particles  $d_s=2$  to  $6$   $\mu\text{m}$  [21,2]. If without particulates,  $\mu=0$ , the ratio  $Nu_f/Nu_0$  becomes less than  $0.6$  at acceleration parameter more than  $10^6$ , the ratio increases more than  $1$  with solids loading ratio  $\mu=0.9$  to  $2$ . For the suspension flow a general expression of acceleration criteria was proposed and used [2]. It must be stressed that maybe only for this purpose the gas-solid flow may be used: to overcome the laminarization phenomena that are especially dangerous under transient or LOCA regimes in channel type high-temperature fission reactors, or in gas-cooled divertors of fusion reactors. But, as it was mentioned before, these types of coolants can be attractive also because of the enhancing effect of solids on radiative, convective and combined processes.

#### 2-4 Radiative-Convective heat transfer with flow

As it was shown before (Table 1), the dominant contributor to the combined heat transfer varies with the concentration factor  $\beta$ : for the dilute suspension it is the radiative transfer which increases very much with temperature factor  $\nu=T_w/T_f$ ; for non-dilute suspension, the convection becomes the prime heat transfer mechanism that increases with the increase in the solid loading  $\mu$ . But in all cases, the use of gas-solid flow as a coolant of high temperature nuclear reactors is the only way to make the thermal radiation participate in heat transfer and, consequently, to enhance the overall heat transfer, increase the outlet temperature of the gas, or decrease the temperature of fuel elements under smaller helium pressure, and achieve higher power density of the reactor. According to Fig.5 [16], the temperature factor - at  $\nu=T_w/T_f=1$  to  $3$ ,  $T_w=1300\text{K}$ ,  $Re=1.3 \times 10^4$ ,  $q_w=10$  to  $500$   $\text{kW/m}^2$  - has a perceptible effect on the increase in the rate of heat transfer when  $\mu=6.8$  and  $\nu=2.25$ .

As is shown by Fig.6[21], the radiative contribution on total heat transfer is the higher the wall temperature, the higher the emissivity of the dusty coolant, and the larger the channel diameter  $D$ . According to Fig.7, the possibility of marked reduction of maximum temperature of the surface of the fuel elements results from radiative heat transfer and increase in  $D$ . Specially designed dilute suspension coolants will be the more promising, the higher the permissible reactor's channel wall temperature.

### 3. Helium-graphite coolant as a promising way to increase power density of high temperature gas cooled fission reactors

The power density of the core of the fission reactor  $P_v, \text{W/m}^3$  for the same core volume and fuel geometrical factors depends on heat removed by coolant  $q_f$ . If



suspension flow is used as the coolant,  $q_f$  can be higher than for pure helium flow  $q_{f,0}$  and then  $P_v > P_{v,0}$ . Next three scenarios are used for calculation of  $P_v/P_{v,0} = q_f/q_{f,0}$ :

- dilute suspension in comparison with pure helium flow (Fig.8);
- suspension in comparison with helium flow (Fig.9);
- dilute suspension in comparison with suspension flow (Fig.10 & 11).

In all cases, the helium-graphite particles were taken into calculation and it was assumed that  $T_f = 1000^\circ\text{C} = \text{idem}$ . Combined heat transfer was evaluated as a function of temperature of the wall  $T_w$ , heat transfer coefficient and  $Z \equiv \mu c_s / c_{he}$ . According to Fig.8 the power density may increase by dilute suspension coolant by  $\sim 2.7$  folds (notice that for pure helium flow  $q_R = 0$ ). Power density can increase by  $\sim 3.9$  folds under the same temperature and velocity conditions for helium and dilute suspension but with much higher particulate loading and  $Z$  factor = 10 (Fig.9). If comparison with helium flow is made not for  $Re_f = \text{idem}$ , but for the same power of coolant circulation  $N_c = \text{idem}$  the ratio  $P_{v,s}/P_{v,0}$  is still higher than one, but  $\sim 2.2$  folds at  $Z = 10$ . Notice that this ratio,  $P_{v,s}/P_{v,0}$ , can be increased more with particulate loading and  $Z > 10$ . Comparison between two types of particulate flows can be made by Fig.10 and Fig.11.

It is important during the design of the coolant system to take into account that dilute suspension flow may provide increased power density of high temperature fission reactors thousands times smaller solids loading ratio  $\mu$  and without decreased effect on  $N_c = \text{idem}$  on  $P_v/P_{v,0}$  than suspension flow. On the other hand the advantages of suspension flow with high  $\mu$  depends much less on the increase of wall temperature than dilute suspension and may reach a higher maximum of heat transfer coefficient  $h_f$  by increased graphite particles volumetric concentration more than 3% (close to the beginning of dense suspension area) [1,2,5,14].

#### **4. Increase of nuclear power plants efficiency by use of suspension coolant.**

Some possible schemes of nuclear power plants with flowing helium-graphite particulates mixture are in Fig.12. Theoretically, the higher thermal efficiency can be achieved by direct cycle (scheme c, d, e) in comparison with indirect cycle (scheme b) and Rankine cycle (scheme a). According to [22] the nuclear power plant with pure helium cooled GT-MHTGR may achieve efficiencies of 37%, 43.8%, and 47.6% if Rankine, indirect or direct cycle are used, respectively. DOE decided to adopt the direct cycle because of better efficiency, less cost and advances in high temperature machinery and heat exchangers by the USA aerospace industry [22], but utilization of suspension flow in the direct cycle is not the same as for working pure gas because of principal differences in fluid mechanics and thermodynamics[2]. Because of the heterogeneous structure of suspension flowing through the gas turbine, the particles may serve as dispersed internal heat sources in the course of expansion of the gas. This positive phenomena bring

thermodynamic processes closer to the isothermal and to the Carnot's cycle, which improves the efficiency. The polytropic index was obtained under only pure thermodynamic point of view in [23]. It depends on Z-factor and increases with the solid loading rate  $\mu$ . To avoid difficulties of operating compressors in schemes c & d of Fig.12, the scheme e of Fig.12 can be chosen. Calculations performed for this arrangement [7, 23, 24] showed that the ideal cycle efficiency can be raised by 11.5% to 20%, by increasing  $\mu$  up to 20. The more realistic overall efficiency, including effects of Ne etc. on efficiency and the characteristics of heat transfer equipment of the single-loop plant under study (scheme Fig.12 e), were analyzed in [25]. It was done at  $T_f=973\text{K}$ ,  $T_{w,\max}=1073\text{K}$ ,  $P=3.3\text{MPa}$  and  $\mu=\text{var}$  in comparison with similar arrangements employing particle-free helium flow. According to Fig.13, there is optimal  $\mu_{\text{He}}=10$ ; the reactor's core power density increases 2.5 folds and absolute cycle efficiency raised by 3.5 to 4.5%.

Some problems associated with the use of helium-graphite flow as a working fluid may be negative [2] but it can be overcome because of favorable graphite characteristics. Experimental investigations with gaseous suspension performed in Kazan' Aircraft Institute [26] are important, though they did not include thermodynamic nor fluid-mechanical analysis. However, the experiments could characterize the real conditions of gas turbine that works with gas suspension flow. Very important data about the behaviors of particles and of gas in the course of expansion in nozzles were accumulated in the field of rocket engines operated with solid fuel seeded by particles of light metals. These experience and data may be helpful for the problems under study.

## References

1. Gorbis, Z.R., "Heat transfer and fluid mechanics of through disperse flows", Energiya Publishing House (in Russian), Moscow (1970) pp.427; "Heat transfer of through disperse flows", Energiya Publishing House (in Russian), Moscow-Leningrad (1964)
2. Gorbis, Z. R. and Spokoyny, P. E., "Momentum and heat transfer in turbulent gas-solid flows", Begill House, Inc., New York - Wallingford (U.K.) (1975) pp.372
3. Gorbis, Z. R. and Kalendyan, V. A., "Heat exchangers with flowing disperse heat carriers", Energiya Publishing House (in Russian), Moscow (1975)
4. Gorbis, Z. R. and Kalendyan, V. A., "Investigation of certain physical properties of a layer of particles of synthetic graphite", Atomnaya Energiya (in Russian), Vol.11, No.5 (1961)
5. Gorbis, Z. R. and Abdou, M. A., "On first wall cooling by helium-graphite particulate flow", UCLA-FNT-89, UCLA-ENG-94-39, December (1994)
6. Raszmerov, A., Epimatjev, A. and Pereverzencev, V., "Helium suspension of solid in F.W. cooling", Abstracts of ISFNT-3, Los Angeles (1994)
7. Gorbis, Z. R., Raffray, A. R. and Abdou, M. A., "High-heat flux removal by phase

change fluid and particulate flow", Fusion Technology, Vol.23 (1993)

8. Shimizu, A. and Echigo, R., Hasegawa, S., "Impinging jet heat transfer with gas-solid suspension medium", Proc. 18th National Heat Transfer Conference, San Diego (1979); Shimizu, A. Fukamichi, K. and Hasegawa, S., "Impinging jet heat transfer of gaseous suspension on concaved surface", Trans. JSME, Ser.B (in Japanese), Vol.51 (1985)
9. Sukomel, A. S., Tsevetkov, F. F. and Kerimov, R. A., "Heat transfer and hydraulic resistance in pipe flows of gas suspensions", Energiya Publishing House (in Russian), Moscow (1977)
10. Tsevetkov, F. F., "Investigation of local heat transfer from the wall of a pipe to a turbulent flow of gas conveying suspended solid particles", Candidate Thesis (in Russian), Moscow Energetics Institute, Moscow (1967)
11. Haves, R. I., Holling, E., Kirly, G. J. and Walter, P.R., "An experimental investigation into heat transfer and pressure drop properties of gaseous suspensions of solids", U.K. Atomic Authority, Reactor Group NAEW-R, 24.2 (1964)
12. Schulderberg, D. C., Whitelaw, R. L. and Carlson, R. W., "Gaseous suspensions - A new reactor coolant", Nucleonics, Vol.19 (1961)
13. Reizing, G. F. S., "Dust suspension - A novel heat transfer medium", Chemical and Process Engineering, August Vol.46 (1965)
14. Curievichi, I. et al., "Experimental investigation of local heat transfer from a tube wall to a turbulently flowing gas-graphite suspension", Buletinal Institute Poleteknic, Vol.16, No.3-4 (1970)
15. Sukomel, A. S., Rozkho, V. A., Kerimov, R. V. and Isvetkov, F. F., "Experimental investigation of heat transfer in pipe flow of an aerosol", Heat Transfer - Soviet Research, Vol.8, No.5 (1976)
16. Koryukin, S. I., "An experimental study of local heat transfer in pipe flows of an aerosol at high and moderate wall temperature", Candidate Thesis (in Russian), Moscow Energetics Institute (1977)
17. Nosov, V. S., "Investigation of heat transfer in logitudinal pipe flow of an air-graphite suspension", Candidate Thesis (in Russian), Ural Polytechnic Institute, Sverdlovsk (1965)
18. Spokoyny, F. E. and Molin, O. V., "Measurement of local thermal resistances on heat transfer syrfaces with particle deposits", Physics of Aerodisperse System (in Russian) (1983)
19. Molin, O. V., "Experimental study of heat transfer in cross-flow of dilute gas suspensions over the surface with forming layer of particulate deposits", Candidate Thesis (in Russian), OTN, Odessa (1984)
20. Gorbis, Z. R. and Spokoyny, F. E., "Problems of fluid mechanics and heat transfer of gas suspension flows with low dust concentration for nuclear power plant applications",

Problems in Nuclear Science and Technology, Nuclear and Hydrogen Energetics (in Russian), No.1(4) (1978)

21. Gorbis, Z. R., Spokoyny, F. E. and Svyatetsky, N. V., "On effect of adding small quantities of solids to the gas on radiative-convective heat transfer in channels of high temperature gas cooled reactors", Problems in Nuclear Science and Technology, Nuclear and Hydrogen Energetics (in Russian), No.3(4) (1981)

22. Williams, P. M., "MHTGR development on the United States", Progress in Nuclear Technology, Nuclear, Vol.28 (1991)

23. El'perin, I. T. and Minkov, V. A., "Concerning the utilization of the two-phase systems as a thermodynamic working fluid", Inzh.-fiz. zh. (in Russian), Vol.7, No.9 (1964)

24. Sapozhnikov, V. V. et al., "Analysis of the cycle of a nuclear gas turbine plant with gas-solids working fluid",

25. Gorbis, Z. R., Tetel'baum, S. D. and Geibovsky, V. P., "Evaluation of the use of gas suspensions as the working fluid in single-loop gas turbine plants", Izv. Vuzov. Energetika (in Russian) No.7 (1974)

26. Schchukih et al., "Heat transfer from gas-suspension flows with inertial separation of solids wall", Heat Transfer-Soviet Research, Vol.8, No.5 (1976), "Heat transfer of gas suspension flowing a short curved channel", Inzh.-fiz. zh. (in Russian) Vol.32, No.2 (1977)

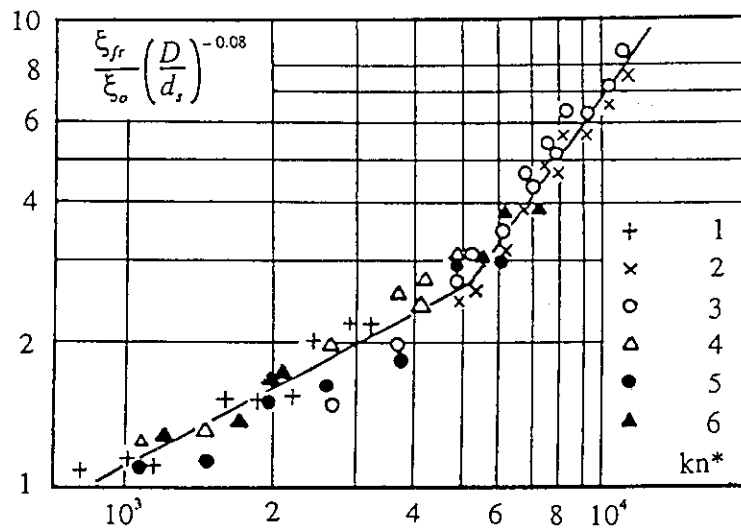


Fig.1 Correlation of experimental data for friction coefficient of gas-graphite particulates flows

1- [12] N<sub>2</sub>, He  $\mu < 12$ ,  $Re = 10^4 \sim 10^5$ ; 2- [11] N<sub>2</sub>  $\mu < 50$ ,  $Re = 5 \times 10^3 \sim 5 \times 10^4$ ; 3- [14] Ar  $\mu < 50$ ,  $Re = 5 \times 10^3 \sim 5 \times 10^4$ ; 4- [9] Air  $D = 8.16 \text{ mm}$ ,  $\mu < 25$ ,  $Re = 5 \times 10^3 \sim 5 \times 10^4$ ; 5- [10] Air  $D = 8.16 \text{ mm}$ ,  $\mu < 25$ ,  $Re = 5 \times 10^3 \sim 5 \times 10^4$ ; 6- [6] Air  $D = 5.33 \text{ mm}$ ,  $\mu < 25$ ,  $Re = 5 \times 10^3 \sim 5 \times 10^4$ .

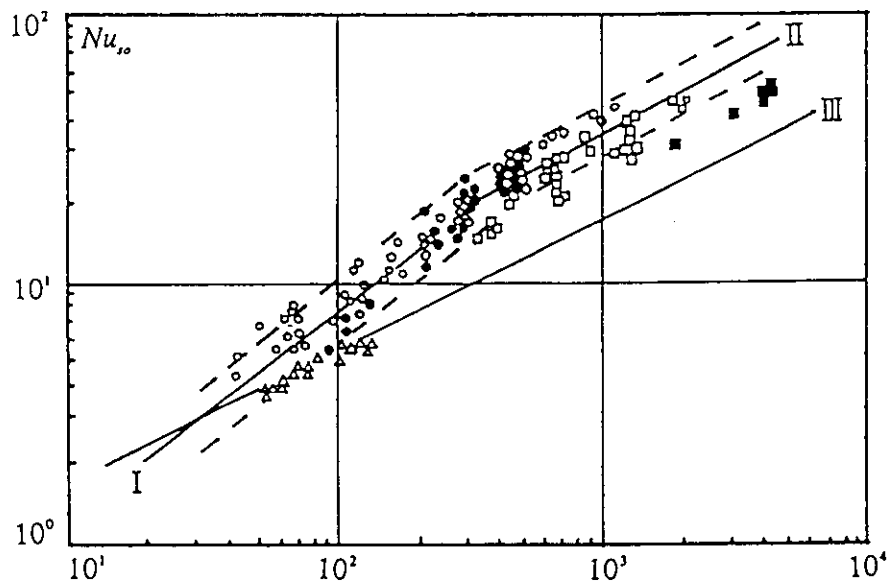


Fig.2 Correlation on experimental data on convective intercomponent heat transfer in a free unconstrained gas suspension

I) Eq.(5) II) Eq.(6) III) from the equation for a non-moving sphere, the symbols represent experimental data of different investigators.

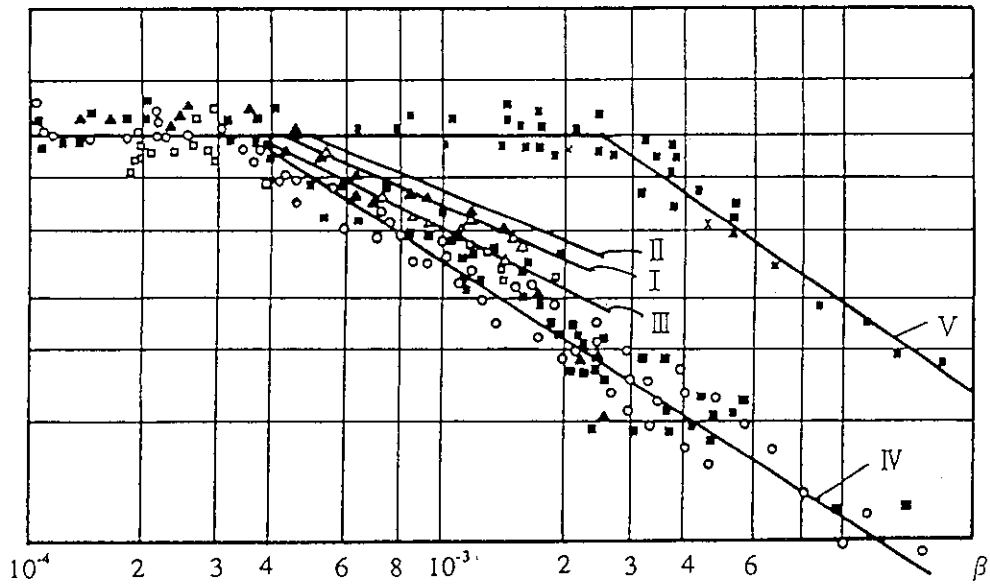
$\overline{Nu}_{s,s} / \overline{Nu}_{s,o}$ 

Fig.3 Effect of volumetric particle concentration on the relative rate of intercomponent heat transfer in a gas suspension flow ; the symbols designate data points of various investigators, I to V are attempts at approximating experimental data.

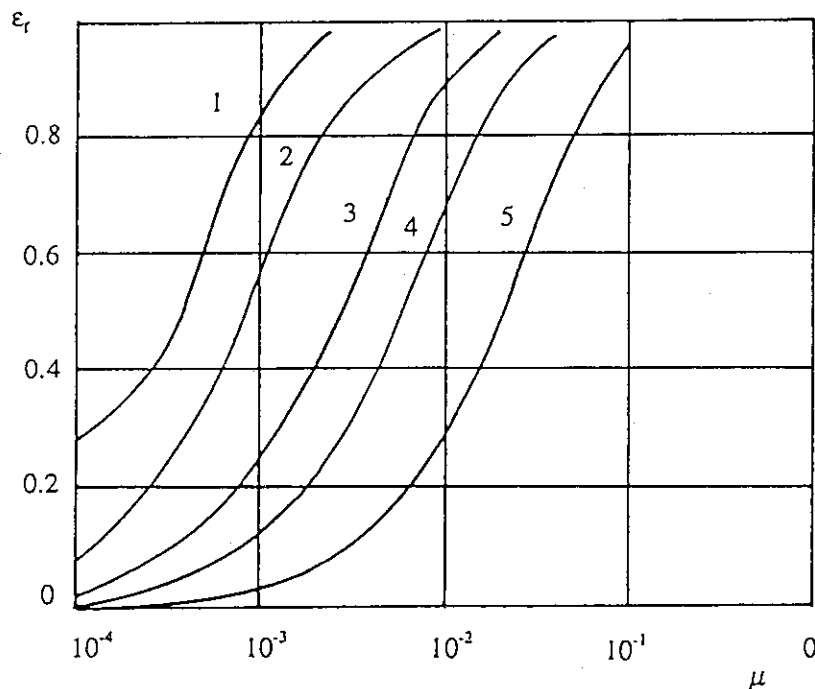


Fig.4 Emissivity of a gas suspension flowing in a cylindrical channel as a function of the product of the flow solids loading ratio ( $\mu$ ) and the channel diameter ( $D$ ) at  $T_w=1800$  [K],  $\rho=1.93$  [kg/m<sup>3</sup>],  $\rho_s=1700$  [kg/m<sup>3</sup>],  $ds, \mu m$ : 1) 1; 2) 3; 3) 5; 4) 10; 5) 30.

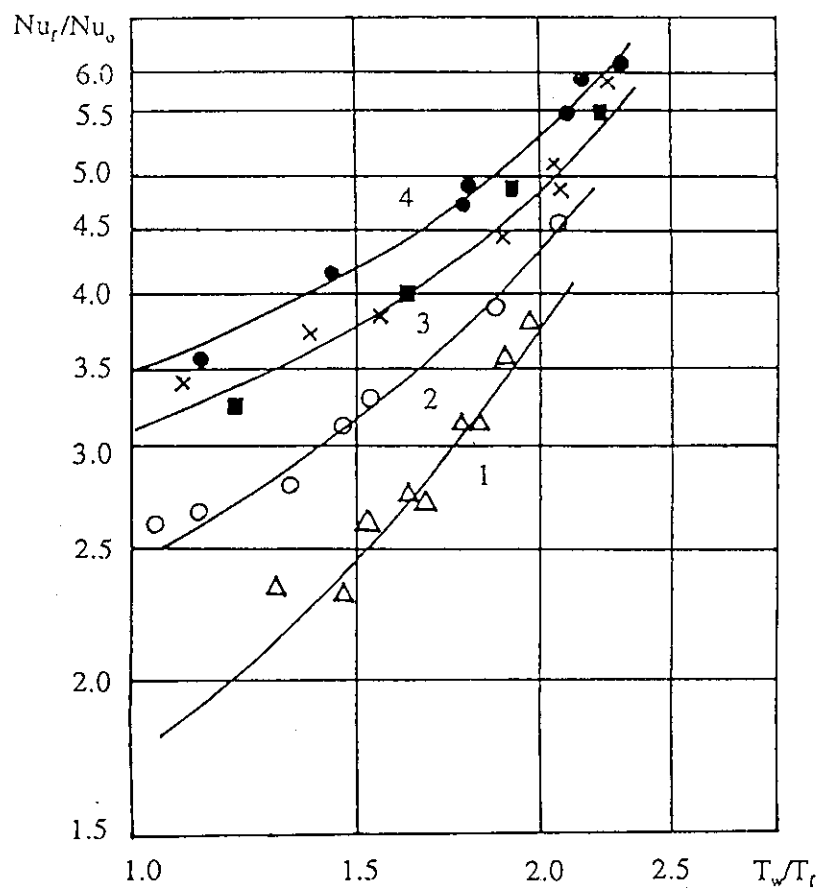


Fig.5 Effect of temperature factor and solids loading ratio on the relative coefficients of radiative-convective heat transfer with a flowing suspension of soot particulates in argon [16]  
 $\mu\text{m}$ : 1) 2; 2) 4.3; 3) 5.7; 4) 6.8

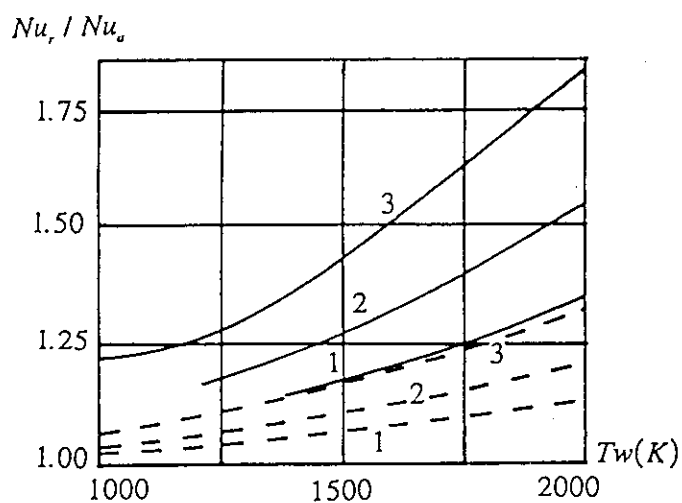


Fig.6 Effect of principal factors on the rate of radiative-convective heat transfer with a flow of a gas suspension in the channel of a high-temperature gas-cooled reactor

$$D=8\text{mm}, \text{Re}=2 \times 10^4, q_w=2.9 \times 10^5 \text{W/m}^2$$

$$D=21\text{mm}, \text{Re}=2 \times 10^4, q_w=2 \times 10^5 \text{W/m}^2$$

$$\epsilon_f: 1) 0.3; 2) 0.5; 3) 0.9$$

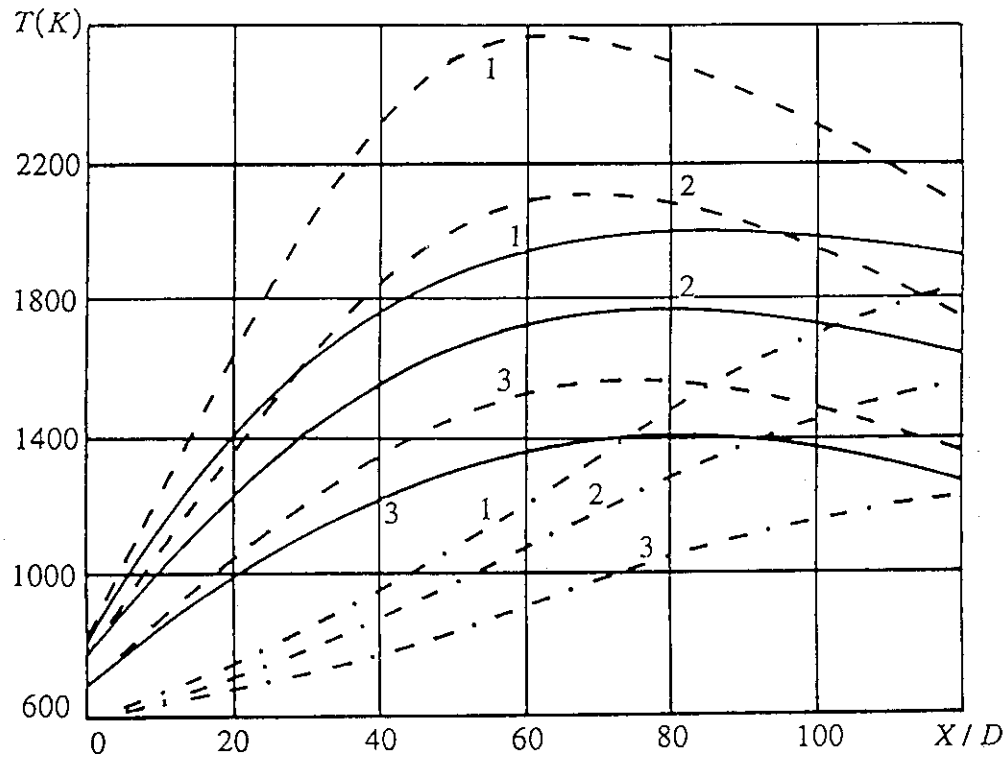


Fig.7 Variation in the temperature of a wall cooled by a gas ( $\mu=0$ , dashed curves) flowing along a channel ( $D=21\text{mm}$ ,  $Re=3.7 \times 10^4$ ); by a gas-graphite suspension flow ( $\mu=0.2$ ,  $d_p=5\mu\text{m}$ , solid curves); flow temperatures (dash-dotted curves);  $q_w = \frac{1}{L} \int_0^L q_w dx \cdot 10^3 \text{ W/m}^2$ ; 1) 10; 2) 7.5; 3) 5



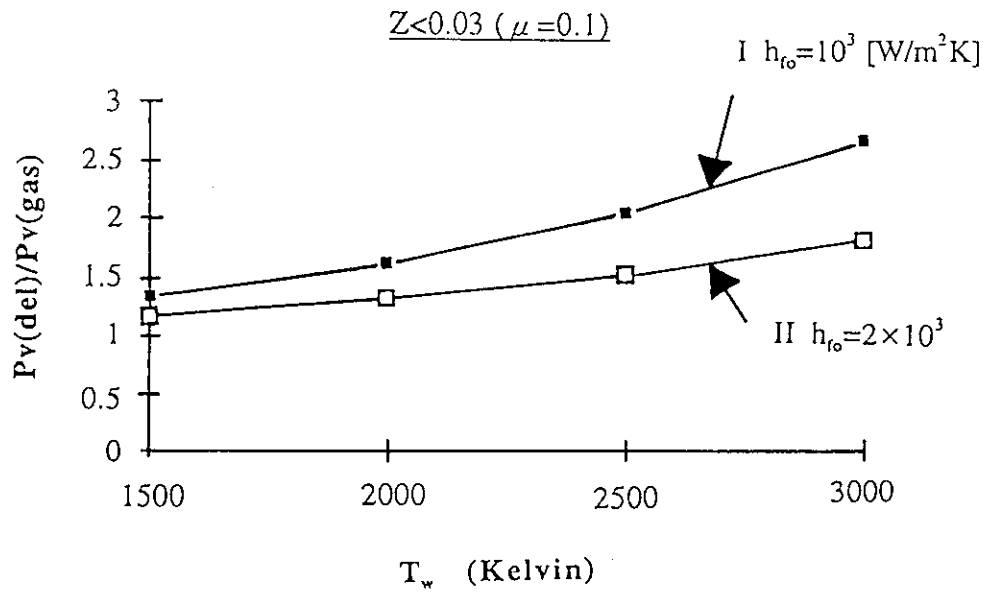


Fig.8 Power density increase as a function of wall temperature and heat transfer coefficient of helium flow  $h_{fo}$  by dilute suspension.

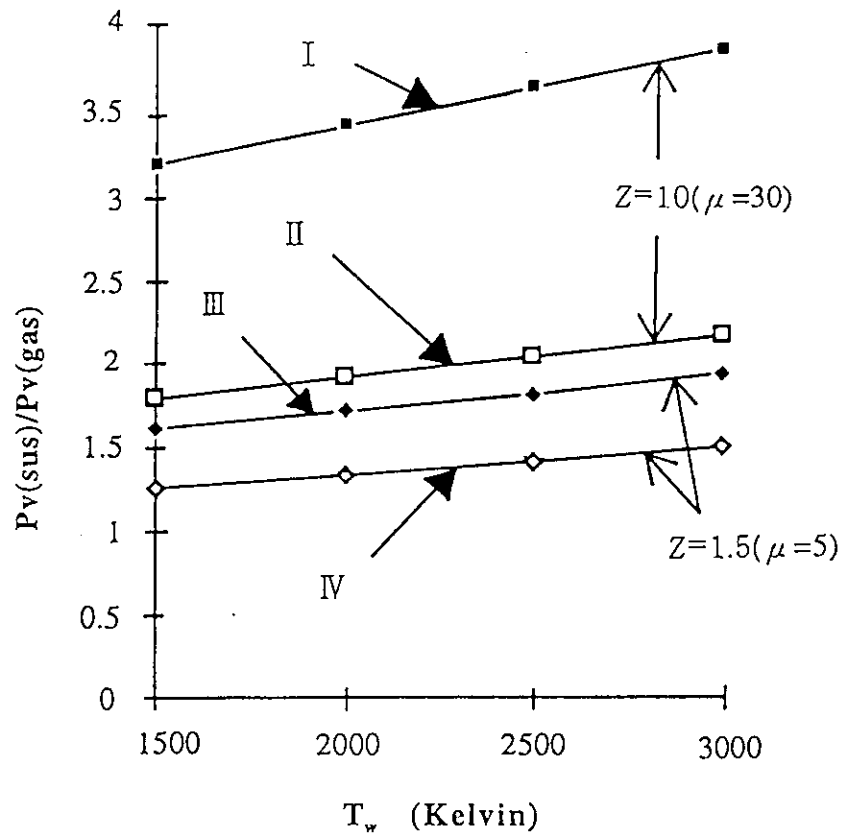
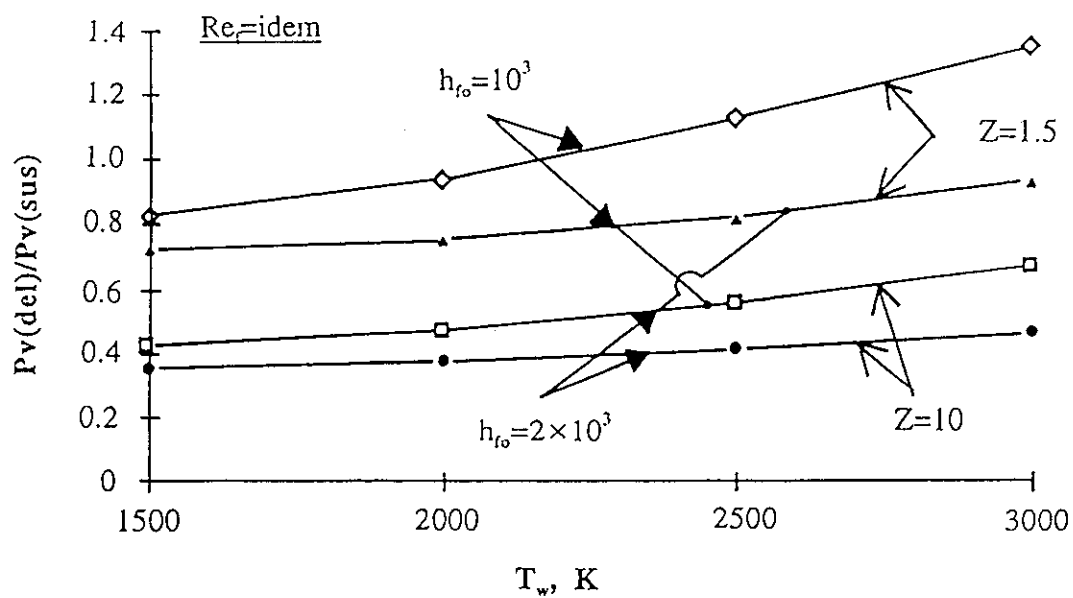
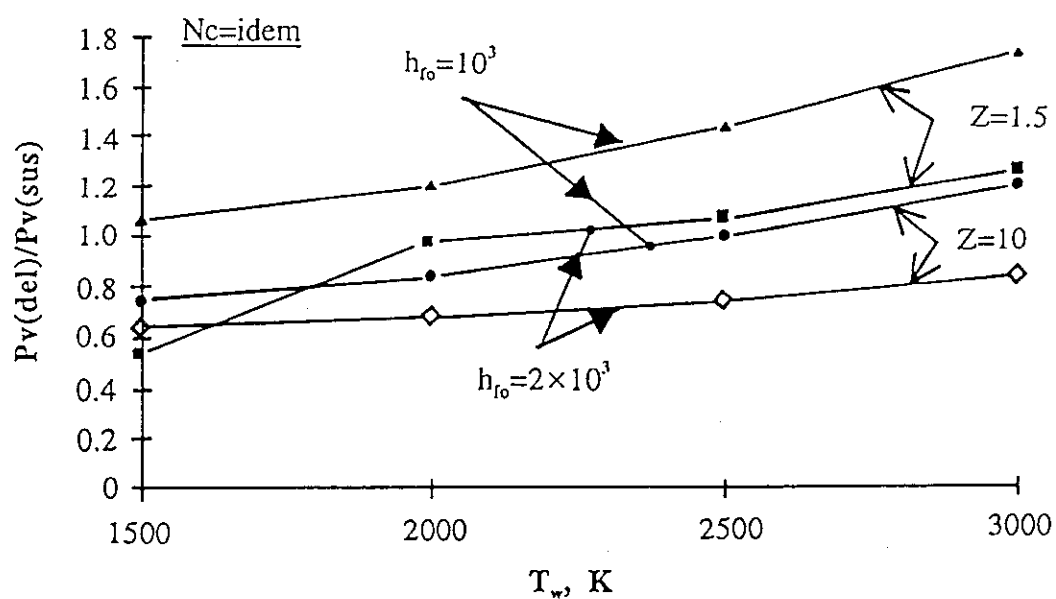


Fig.9 Increase of power density independence of wall temperature  $T_w$  and Z-factor (solid loading ratio  $\mu$ ) for suspension flow with  $h_{fo} = 10^3 \text{ [W/m}^2\text{K]}$  and  $Re = idem$  (lines I and III) or  $Nc = idem$  (lines II and IV).

Fig.10 Comparison of dilute suspension and suspension flows if  $Re=idem$ Fig.11 Comparison of dilute suspension and suspension flows if  $Nc=const$ .

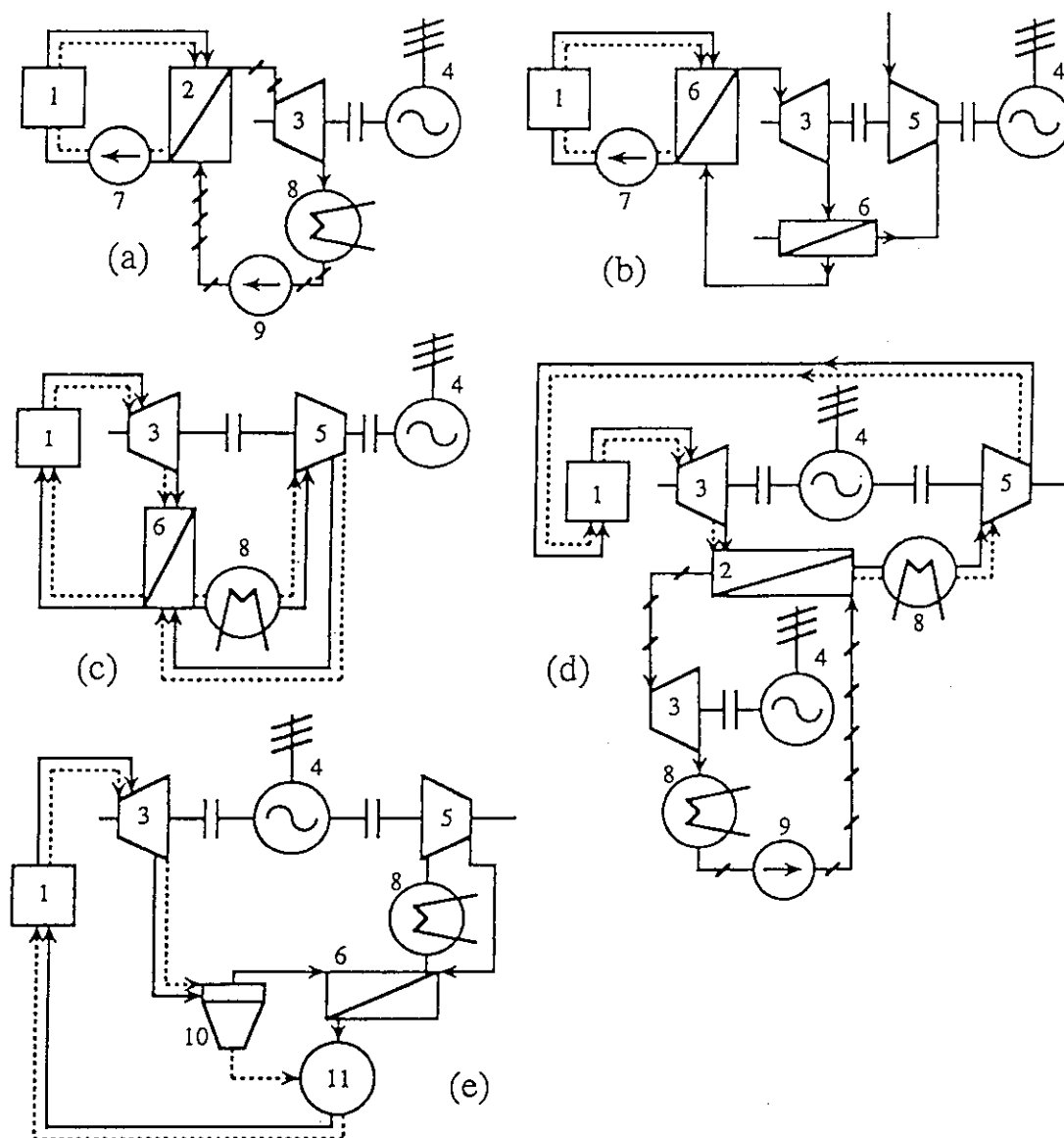
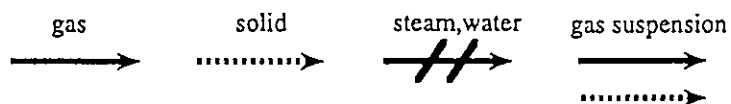


Fig.12 Examples of possible arrangement for utilizing flowing gas suspensions in nuclear plants as a coolant (scheme a and b) and as a coolant and working fluid (scheme c,d,e)



1) Reactor ; 2) Steam Generator ; 3) Turbine ; 4) Electric Generator ; 5) Compressor ;  
6) Heat Exchanger ; 7) Gas Pump ; 8) Condenser ; 9) Water Pump ; 10) Separator ;  
11) Mixer

(Rankine, Brayton and combined cycles) [12]

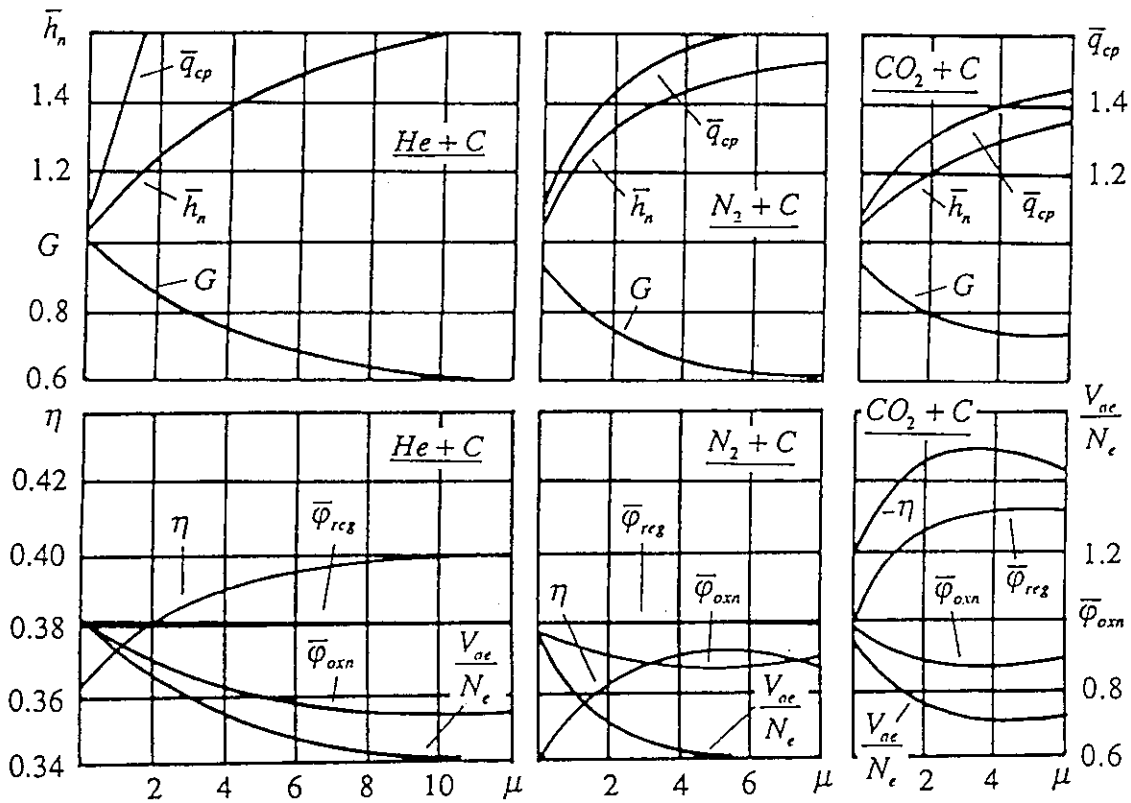


Fig.13 Thermodynamic efficiency ( $\eta$ ) and relative values of the specific net work of the Brayton cycle (scheme e) ( $\bar{h}_n$ ), gas flow rate ( $G$ ), average heat flux density in the reactor core ( $\bar{q}_{cp}$ ), regenerator surface area ( $\bar{\phi}_{reg}$ ), cooler surface area ( $\bar{\phi}_{oxn}$ ), volume of reactor core ( $V_{ac}/N_e$ ) as functions of the flow solids loading ratio  $\mu$  for He-graphite, N<sub>2</sub>-graphite and CO<sub>2</sub>-graphite flows through the reactor and gas turbine ( $T \cong 1000K, P = 3.3MPa$ ). [2.22]

Table1

Type of gas-cooled reactors	Recommended subclass of gas-solid flow	Approximate critical particle volumetric fraction $\beta$	Material of particulates	Main mechanism of heat transfer	Main factors which allow increase of heat transfer and power density
Heterogeneous high temperature reactors	Dilute suspension	$4 \times 10^{-4}$	Graphite	Capital combined heat transfer with increased contribution of thermal radiative mechanism	Rise of emissivity of Helium from 0 to about 0.9 and increase in the heat flux
	Suspension	$10^{-2} \sim 6 \times 10^{-2}$	Graphite	Capital combined heat transfer with main role of convective mechanism	Improvement of situation in the channel wall region and increase of $h_f$ and specific heat several times depends on mass loading
	Moving bed	0.3~0.65	Graphite	Conductive heat transfer through particulates, gas and solid contact zones	Increase of effective conductivity with $\beta$ especially for binary size beds
Quasi-homogeneous high temperature reactors	Suspension of fuel particulates	$10^{-2} \sim 3 \times 10^{-2}$	Uranium carbide or oxide	Thermal intercomponent interactions, particle-particle radiation	Very small "conductive" and "convective" size of transfer elements, i.e. particles
	Moving ventilated bed of fuel spheres	$\sim 0.6$	Uranium fuel coated with graphite	Intercomponent heat transfer, conduction in spheres	Increase specific heat and uniformity of gas and solid flow distribution
Super high temperature gaseous nuclear rocket engine	Hydrogen-tungsten dilute suspension flow as a coolant and working fluid	$< 4 \times 10^{-4}$	Tungsten, etc.	Thermal radiation from plasma core to the suspension flow	Artificially increase emissivity of the gas by adding solid-then vaporized-particles

Main Characteristics of Gas-Solid Flows as Possible Coolants for Fission Reactors [1,2,3,]

Table2. Characteristics of Gas-Solid Particulate Cooled  
Fusion Reactors

Type of design	Material and size of particulates	Solid to gas flow rate $\mu$ , or particulate volume fraction, $\beta$ %	Outlet temperature of blanket, $^{\circ}\text{C}$	Type and Pressure of gas, MPa	Maximum first-wall temperature, $^{\circ}\text{C}$
Tokamak (moving bed) UWMAK-III (1976)	$\text{Li}_2\text{O}$	60%	600	He, $\sim 0.01$	300
ITER-relevant 3 variant (1991)	$\text{Li}_2\text{O}$ , 500 $\mu\text{m}$	55%	450	He, $\sim 0.01$	400
ICF (moving bed) SOLASE-H (1977)	$\text{Li}_2\text{O}$ , 100-200 $\mu\text{m}$	60%	600	He, $\sim 0.01$	1800
SOMBERO (1991)	$\text{Li}_2\text{O}$	60%	740	He, $\sim 0.01$	1485
Tokamak (suspension flow) HERCULES 1,2,3 (1988)	$\text{SiC}$ , $\text{Li}_4\text{SiO}_4$ , 5-10 $\mu\text{m}$	1.5%	700 1000 550	$\text{CO}_2$ , 0.5 $\text{CO}_2$ , 0.5 $\text{CO}_2$ , 1.5	1035 1150 593
ITER-related variant (1989)	$\text{Li}_4\text{SiO}_4$ , 5-10 $\mu\text{m}$	1.5% (10.6 kg-s/kg-s)	200	He, 3	354
ITER-relevant variant (1989)	$\text{Li}_2\text{O}$ , $\text{LiAlO}_2$ , $\text{Li}_4\text{SiO}_4$	1~5%	--	He, 2~3	--
ARIES-I relevant variant (1989)	$\text{SiC}$ , 5-10 $\mu\text{m}$	41kg-s/kg-s	700	$\text{CO}_2$ , 0.5	946
SSTR-2 (1992,1994)	$\text{SiC}$ , 50 $\mu\text{m}$	13kg-s/kg-s	700	He, 5	800

## 6.2 Microencapsulated Phase Change Material for Heat Transfer Enhancement

Subrate Sengupta  
University of Michigan-Dearborn

- **Forced Convection**

- Tubes

- Numerical (Charunyakorn)

- Experimental (Goel, Roy)

- Parallel Plates

- Numerical (Charunyakorn)

- **Natural Convection**

- Vertical Flat Plate

- Numerical (Harhira, Roy)

- Enclosure

- Experimental (Datta, Roy)

## Basis For Heat Transfer Enhancement

- Change in thermophysical properties of the fluid due to the addition of microcapsules: thermal conductivity, specific heat, viscosity

- Microconvective effects due to microcapsules enhance heat transfer

- Temperature of suspension changes very slowly as long as the phase change material melts, thus enhancing heat transfer



No.	Core material	Encapsulating material	Diameter( $\mu\text{m}$ )	Wall thickness $\mu\text{m}$
1.	n-eicosane	Cross-linked PVA	50	30
2.	n-eicosane	----- " " -----	100	30
3.	n-eicosane	----- " " -----	250	30
4.	Stearic acid	----- " " -----	50	15
5.	Stearic acid	----- " " -----	100	15
6.	Stearic acid	----- " " -----	250	15

Particle sizing of the samples have been done at Coulter Electronics, Inc. The sizes and size distribution are given in Appendix I. Statistical results also include the mean and median diameters of the particles, the variance, standard deviation and skewness of the samples. Particle sizing for all the samples have also been done using an Unitron Series-N optical microscope at the Department of Mechanical Engineering, University of Miami. Photographs of the different samples are shown in Fig. 1. Further work is currently being done on the following:

1. Technology for the manufacture of microcapsules is being developed at the Epics Division of Coulter Electronics, Inc., Hialeah. Manufacturing equipment has already been assembled and is currently being debugged. Production of microcapsules are expected to begin in the near future.
2. Thermal cycling tests of the microcapsules manufactured by Ronald T. Dodge Co. are currently underway at the Department of Mechanical Engineering, University of Miami. Each of the samples are being cycled through the melting point of the core material in a constant temperature bath. Differential calorimetry will be used to investigate any possible hysteresis or degradation of the material due to repeated cycling.

## TASK II: NUMERICAL MODELLING

A mathematical model for heat transfer of phase-change suspension flow in a circular duct has been formulated. This model takes the heat transfer enhancement due to particle generated fluid motion and the phase change process inside the capsules into account. With a slight modification, it can be applied to a flow between flat plates as well.

The flow is assumed to be incompressible with a parabolic velocity profile given by:

$$u = 2u_m(1 - r^2/R^2) \text{ for circular ducts}$$

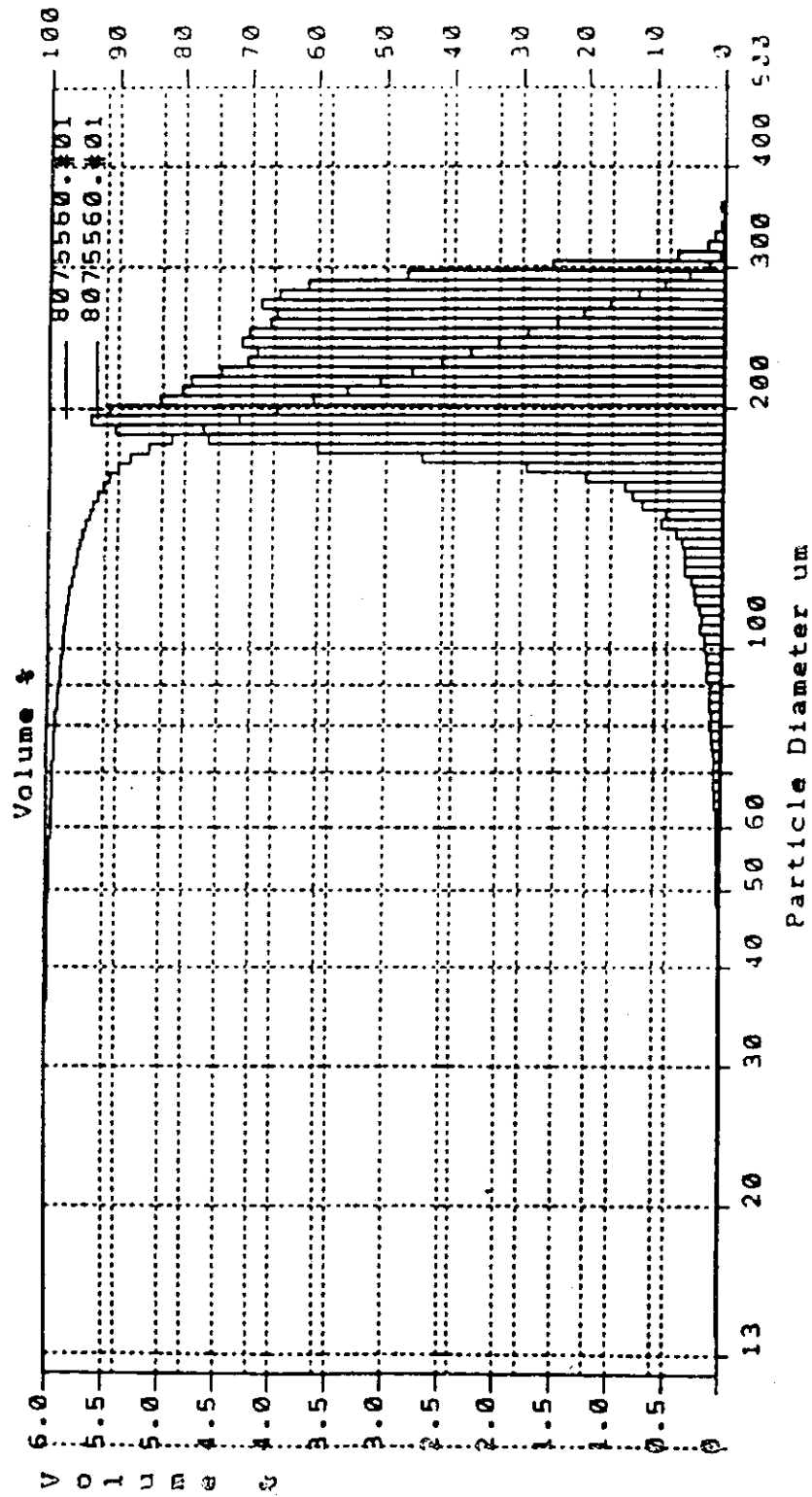
$$u = 1.5u_m(1 - y^2/Y^2) \text{ for parallel plates}$$

For low and moderate velocities, the energy dissipation is negligibly small and the energy equation can be written as:

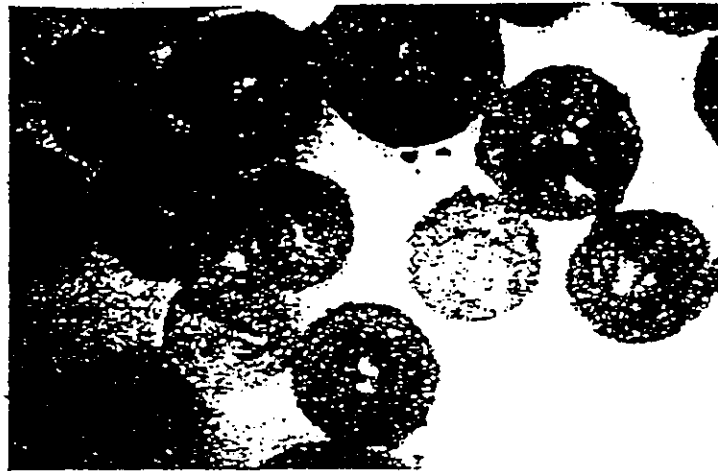
$$\rho c u \frac{\partial T}{\partial x} = \frac{\partial}{\partial r} \left[ k \frac{\partial T}{\partial r} \right] + \frac{k}{r} \frac{\partial T}{\partial r} + k \frac{\partial^2 T}{\partial x^2} + S$$

All properties except for the thermal conductivity  $k$  are those of the bulk fluid. The thermal conductivity  $k$  is the effective bulk conductivity which accounts for the heat transfer enhancement due to the presence of particles. The general form of the conductivity relation is:

$$k_e = k_b(1 + BcPe_p^m)$$

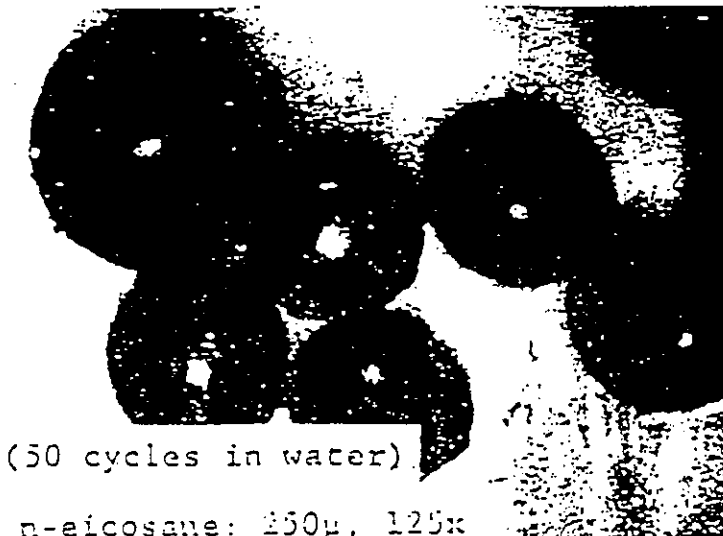


Particle sizing results, n-Eicosane, 250u: After 10 cycles



n-eicosane: 250 $\mu$ , 100x

Fig. 2a : n-Eicosane Phase Change Slurry Before Thermal Cycling  
(Sengupta, 1990)



(50 cycles in water)

n-eicosane: 250 $\mu$ , 125x

Fig. 2b : n-Eicosane Phase Change Slurry After Thermal Cycling  
(Sengupta, 1990)

## Model Description

- Governing equations include conservation equations for mass, momentum and energy
- Energy absorbed during melting is modelled as a source term in energy equation
- Non-dimensional parameters are:
  - Microcapsule volumetric concentration
  - Microcapsule to fluid thermal conductivity ratio
  - Fluid Peclet number
  - Microcapsule to duct radius ratio
  - Bulk Stefan number

## MATHEMATICAL MODEL

- Fully Developed velocity profile :

$$u = 2u_m(1 - r^2/R^2) \text{ for circular ducts}$$

$$u = 1.5u_m(1 - y^2/Y^2) \text{ for parallel plates}$$

- Energy Equation :

$$\rho c u \frac{\partial T}{\partial x} = \frac{\partial}{\partial r} \left[ k \frac{\partial T}{\partial r} \right] + \frac{k}{r} \frac{\partial T}{\partial r} + k \frac{\partial^2 T}{\partial x^2} + S$$

- Effective Thermal conductivity is given by

$$k_e = k_b (1 + B c Pe_p^m)$$

where

$k_e$  effective thermal conductivity

$k_b$  bulk thermal conductivity

$c$  volumetric particle concentration

$Pe_p$  particle Peclet number

$B, m$  constants

$S$  term accounting for energy released / absorbed  
( depending on freezing / melting model)

where  $k_e$  is the effective conductivity,

$k_b$  is the bulk fluid conductivity,

$c$  is the volumetric particle concentration

$Pe_p$  is the particle Peclet number ( $= ed^2/\alpha_f$ )

$e$  is the flow velocity gradient,

$\alpha_f$  is the suspending fluid diffusivity, and

$B, m$  are constants whose values depend on the value of Peclet number.

The source or sink term  $S$  is the energy released or absorbed by the phase change process inside the microcapsule. It can be related to the phase change process once an appropriate freezing or melting model of a sphere is chosen. For small spheres, the conduction model is adequate, and we obtain:

$$S = 3ck_p(T_m - T) \frac{1}{R_p^2} \frac{1}{1 - (1 - \beta)r_p/R_p}$$

where  $k_p$  is the particle conductivity,

$T_m$  is the melting point of the phase change material,

$\beta = k_p/U R_p$

and the subscript  $p$  refers to the particle.

The case of heat transfer in a circular duct subject to an uniform wall temperature has been solved numerically, and preliminary results are shown in Fig. 2. The change in temperature of the suspension is seen to be reduced substantially. Thus, the temperature difference is maintained at a relatively high level and a heat flux of two to four higher than that of the pure fluid flow can be achieved. Wider parameter ranges and different boundary conditions are being investigated. These include heat transfer with constant wall heat flux and flow between flat plates.

### TASK III: RESEARCH PROGRAM DEVELOPMENT

#### A. Industrial Collaboration

- Coulter Electronics, Inc.: The Epics Division of Coulter Electronics, Inc., Hialeah is developing technology for the manufacture of microcapsules. An investment of approximately \$50,000 has been made to procure the necessary equipment which is now being debugged. On completion, the manufacturing capability is expected to be about 100g per week. Coulter Electronics, Inc. is also providing its expertise in particle sizing as discussed in an earlier section.

- Harris Corporation: Three meetings have been held with the thermal management engineering group at Harris Corporation, Melbourne. They have provided a needs list and have proposed the development of a passive heat sink using microencapsulated phase change suspensions. An earlier heat sink using phase change materials developed at Harris Corporation used an aluminum honeycomb sandwiched between two aluminum plates as the heat sink. However, this concept was not very successful due to the poor conductivity of the phase change material solidifying at the plates. The use of a suspension of phase change particles is expected to overcome this problem. Harris Corporation is also developing an internal R&D effort. Further details are given in Appendix II.

- Martin Marietta, Inc.: Two discussions have been held with Martin Marietta, Inc., Orlando. Mr. Jack Fennimore is currently compiling a needs list at Martin Marietta Inc. to identify a specific task to be incorporated in next years proposal. They are also developing an internal R&D effort.

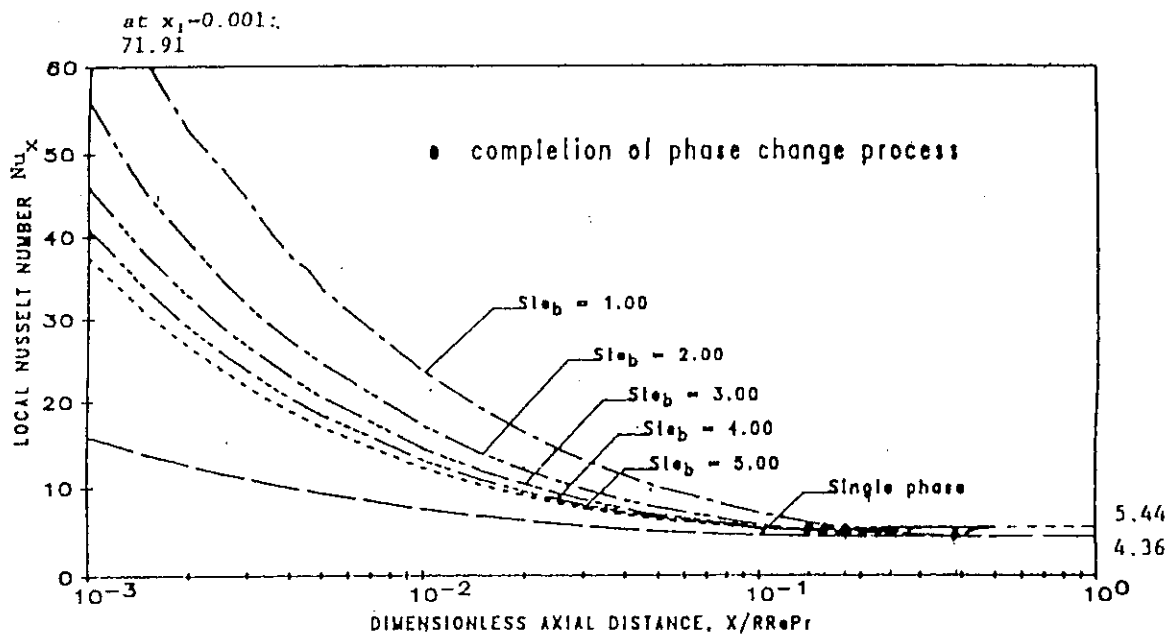


Fig. 1a : Heat Transfer Characteristics of Microencapsulated Phase Change Material Slurries in Circular Ducts Compared to Single Phase Flow. Constant Wall Heat Flux. Effect of "Stefan Number" on Local Nusselt Number. Concentration of Slurry = 0.10 (Charunyakorn, 1989)

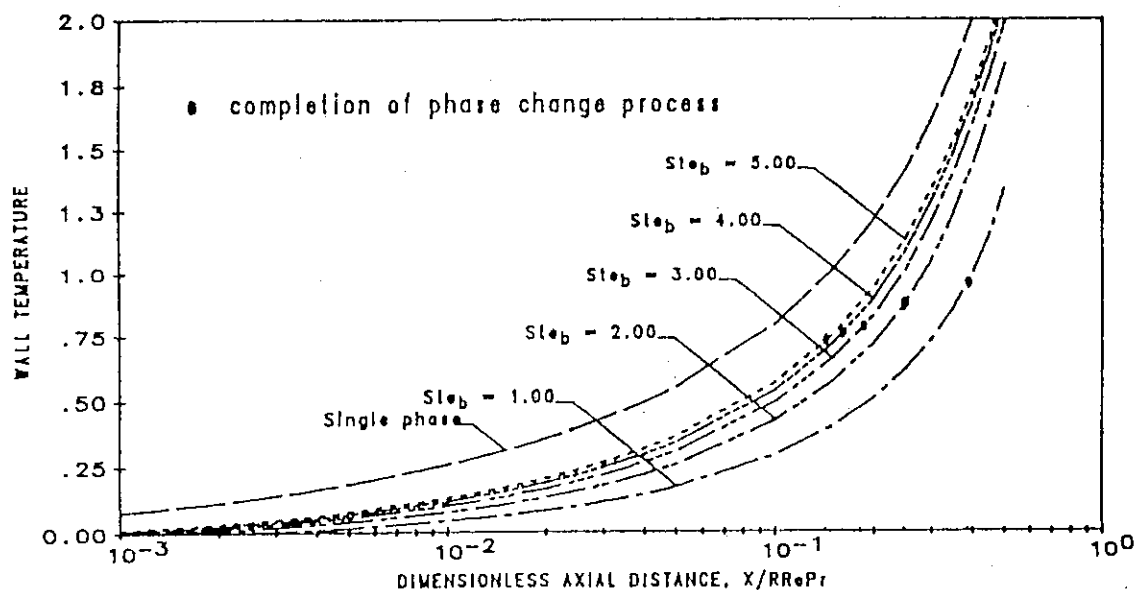


Fig. 1b : Heat Transfer Characteristics of Microencapsulated Phase Change Material Slurries in Circular Ducts Compared to Single Phase Flow. Constant Wall Heat Flux. Effect of "Stefan Number" on Wall Temperature. Concentration of Slurry = 0.10 (Charunyakorn, 1989)

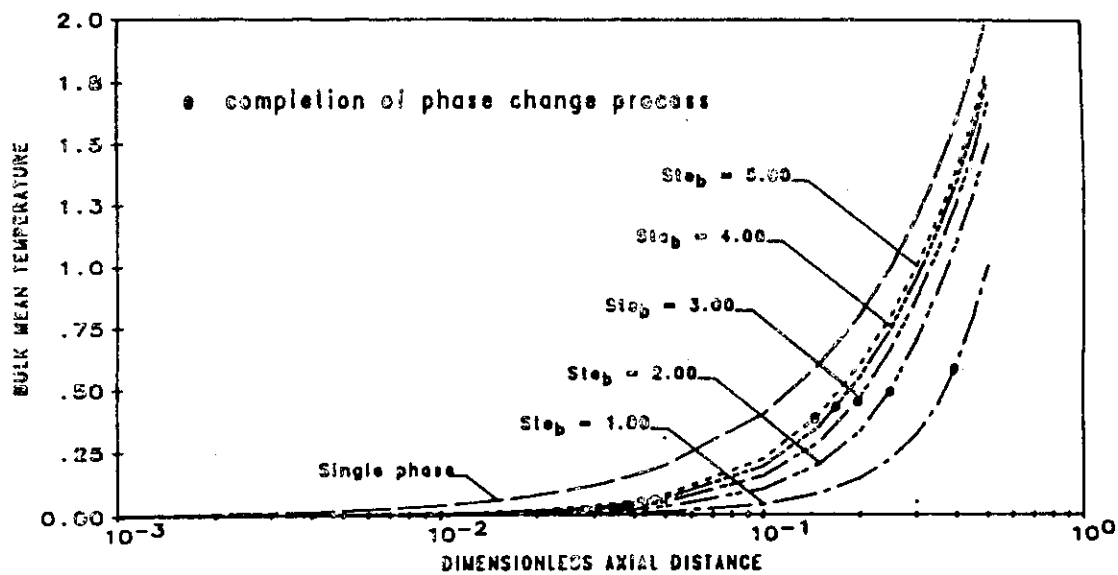


Fig. 7a Heat transfer characteristics of microencapsulated phase change material slurries in circular ducts compared to single phase flow. Constant wall heat flux. Effect of Stefan number on bulk mean temperature.

$c = .150$ ,  $k_p/k_f = 4.00$ ,  $Pe_f(R_p/R_d)^2 = 1.00$ ,  $R_d/R_p = 100$ .

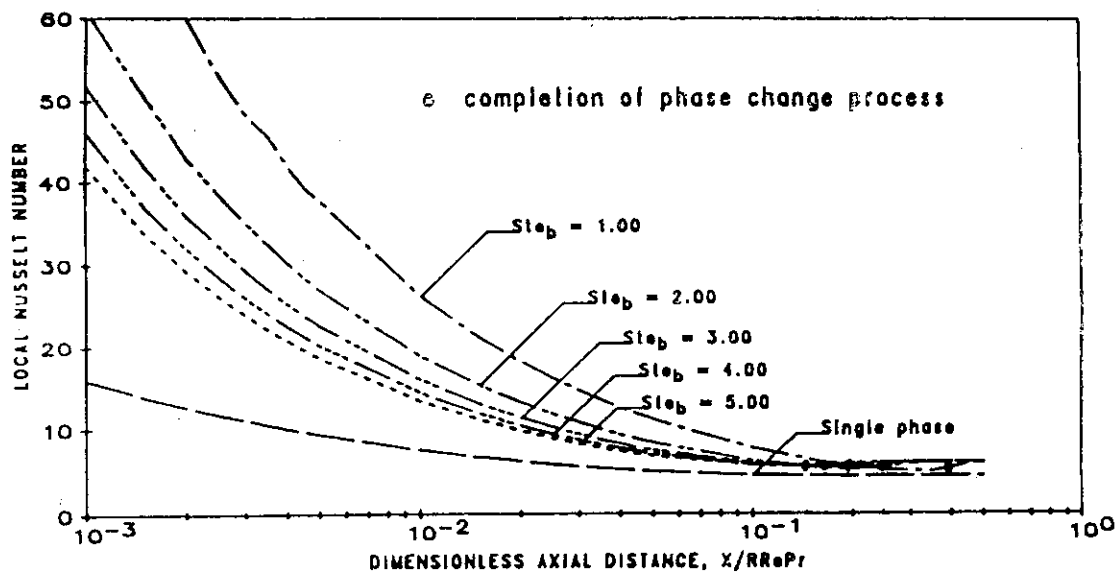


Fig. 7b Heat transfer characteristics of microencapsulated phase change material slurries in circular ducts compared to single phase flow. Constant wall heat flux. Effect of Stefan number on local Nusselt number.

$c = .150$ ,  $k_p/k_f = 4.00$ ,  $Pe_f(R_p/R_d)^2 = 1.00$ ,  $R_d/R_p = 100$ .



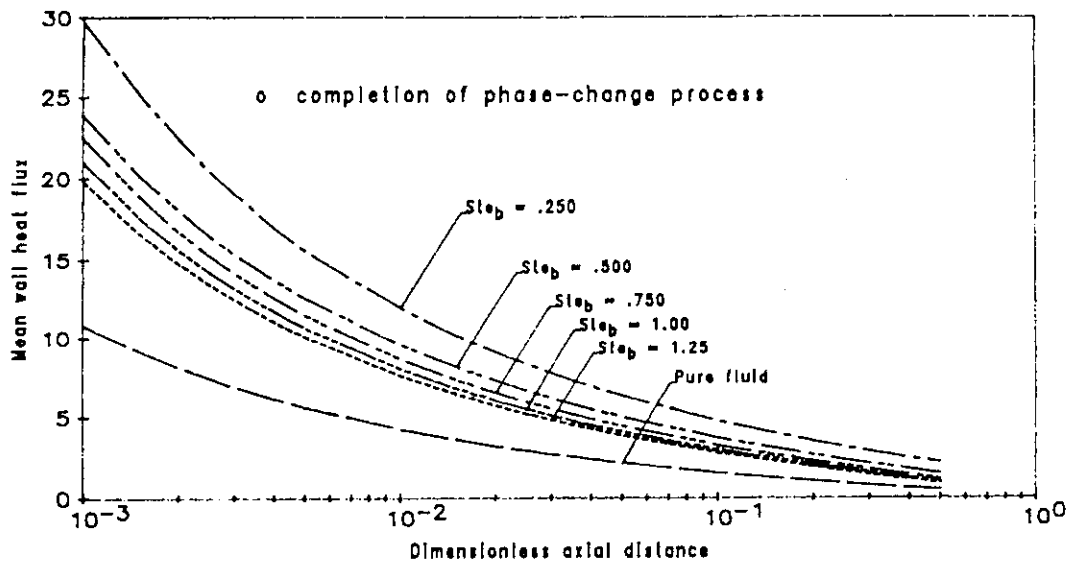


Fig.2 Heat transfer characteristics of microencapsulated phase-change material slurries in circular ducts compared to pure fluid flow. Constant wall temperature. Effect of Stefan number on mean wall heat flux.

$c = .150$ ,  $k_p/k_f = .750$ ,  $Pe_f = .100E+05$ ,  $R_p/R_d = .010$

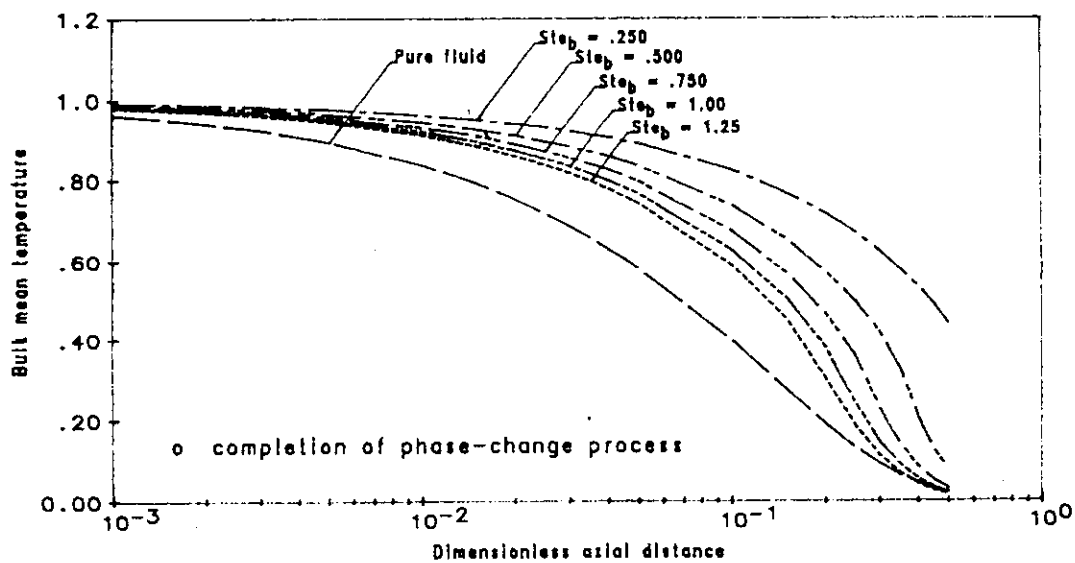


Fig.3 Heat transfer characteristics of microencapsulated phase-change material slurries in circular ducts compared to pure fluid flow. Constant wall temperature. Effect of Stefan number on bulk mean temperature.

$c = .150$ ,  $k_p/k_f = .750$ ,  $Pe_f = .100E+05$ ,  $R_p/R_d = .010$

Table C.1 Summary of the comparisons

	Heat Flux (W/cm <sup>2</sup> )	Fluid Flow Rate (m/s)	$\Delta T$ °C
(1) Circular ducts, constant wall temperature			
Single Phase	0.191	0.19	2.2 <sup>1</sup>
Slurry	0.191	0.022	2.4
Slurry	0.449	0.19	1.6
(2) Circular ducts, constant wall heat flux			
Single Phase	0.214	0.27	20 <sup>2</sup>
Slurry	0.214	0.026	20
Slurry	0.214	0.27	5.4
(3) Parallel plates, symm. constant wall temperature			
Single Phase	0.214	0.15	0.92 <sup>1</sup>
Slurry	0.213	0.0106	1.68
Slurry	0.619	0.15	0.41
(4) Parallel plates, symm. constant wall heat flux			
Single Phase	0.214	0.14	24.8 <sup>2</sup>
Slurry	0.214	0.0145	24.8
Slurry	0.214	0.14	9.1
(5) Parallel plates, boundary condition of the 1st kind			
Single Phase	0.213	0.165	0.42 <sup>1</sup>
Slurry	0.214	0.0116	0.82
Slurry	0.582	0.165	0.14
(6) Parallel plates, boundary condition of the 2nd kind			
Single Phase	0.214	0.135	25.2 <sup>2</sup>
Slurry	0.214	0.0145	24.9
Slurry	0.214	0.135	7.5

<sup>1</sup> Fluid temperature rise,  $T_{f,out} - T_{f,in}$

<sup>2</sup>  $T_{w,out} - T_{f,in}$

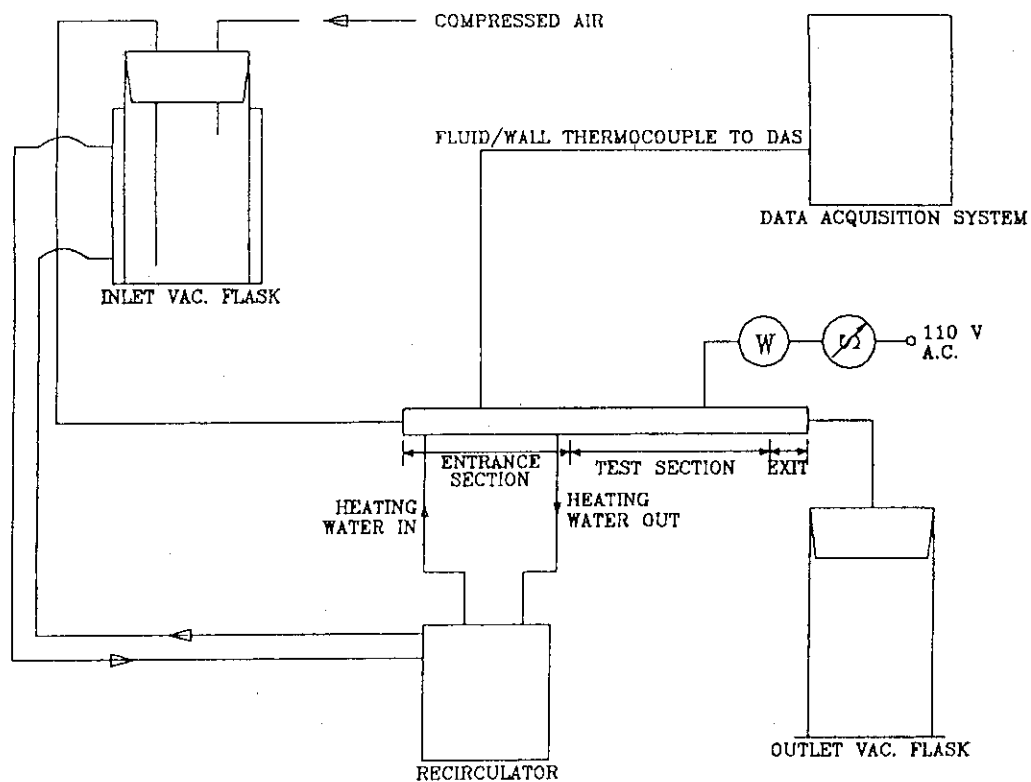


Fig. 3 : SCHEMATIC DIAGRAM - EXPERIMENTAL SET UP

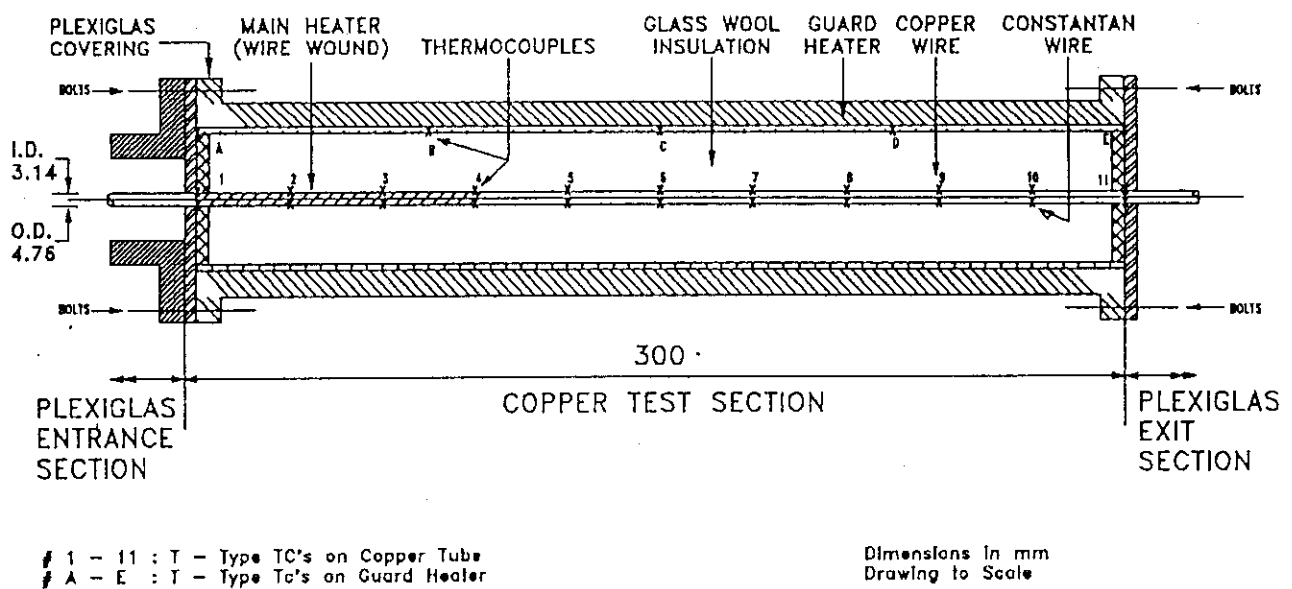


Fig. 4 : THE TEST SECTION

A1, B1 : HEATING WATER INLETS  
A2, B2 : HEATING WATER OUTLETS

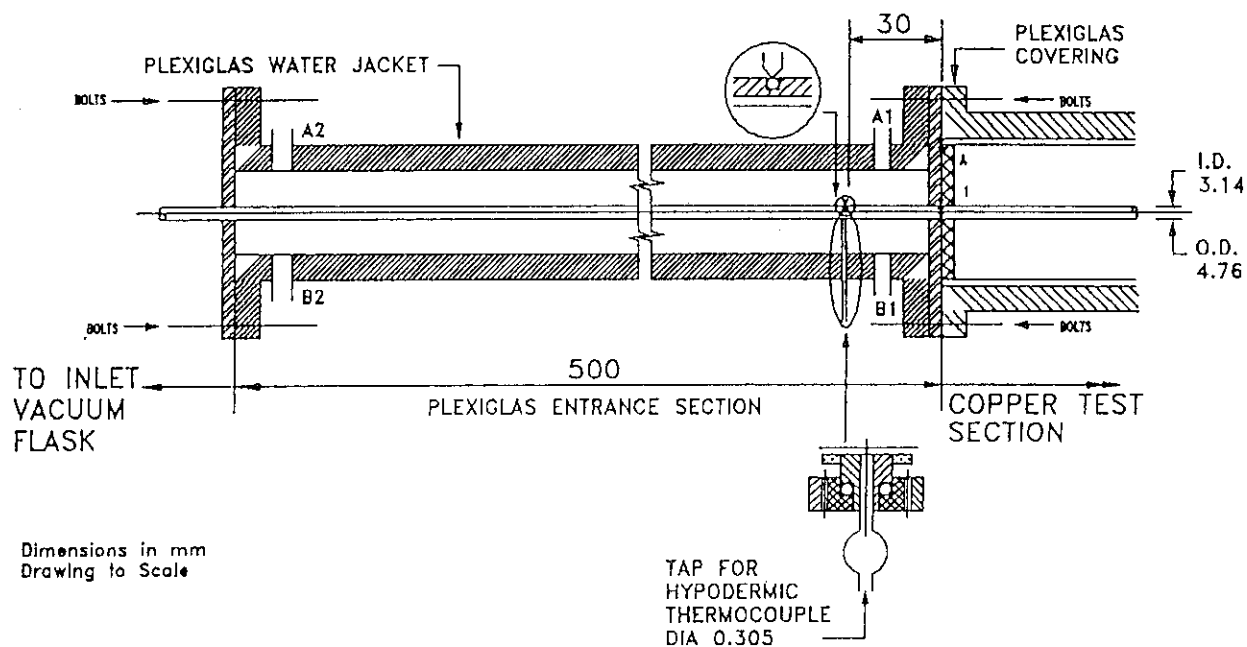


Fig. 5 : ENTRANCE SECTION AND WATER JACKET

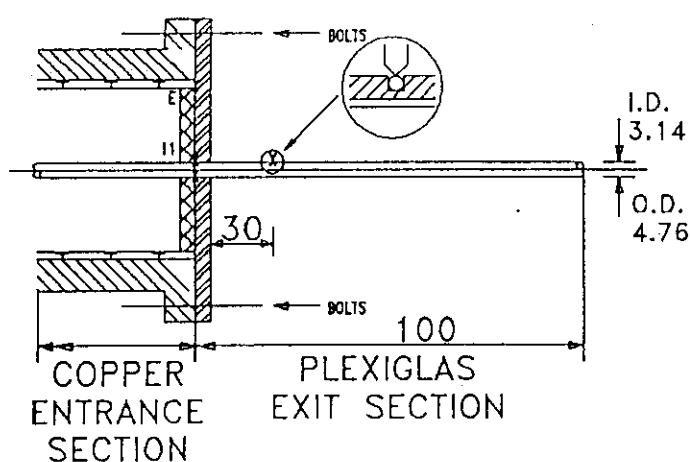


Fig. 6 : THE EXIT SECTION

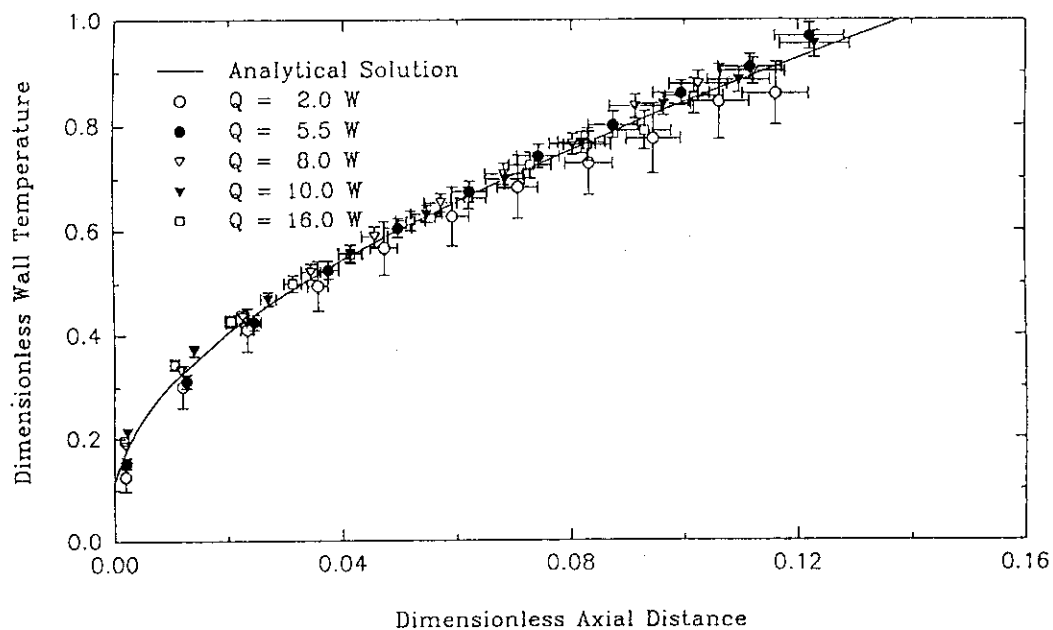


Fig. 17 Verification Results for the Experimental Apparatus  
(Runs conducted with water as the heat transfer fluid,  
Experimental data compared to the analytical solution  
after correcting for systematic errors)

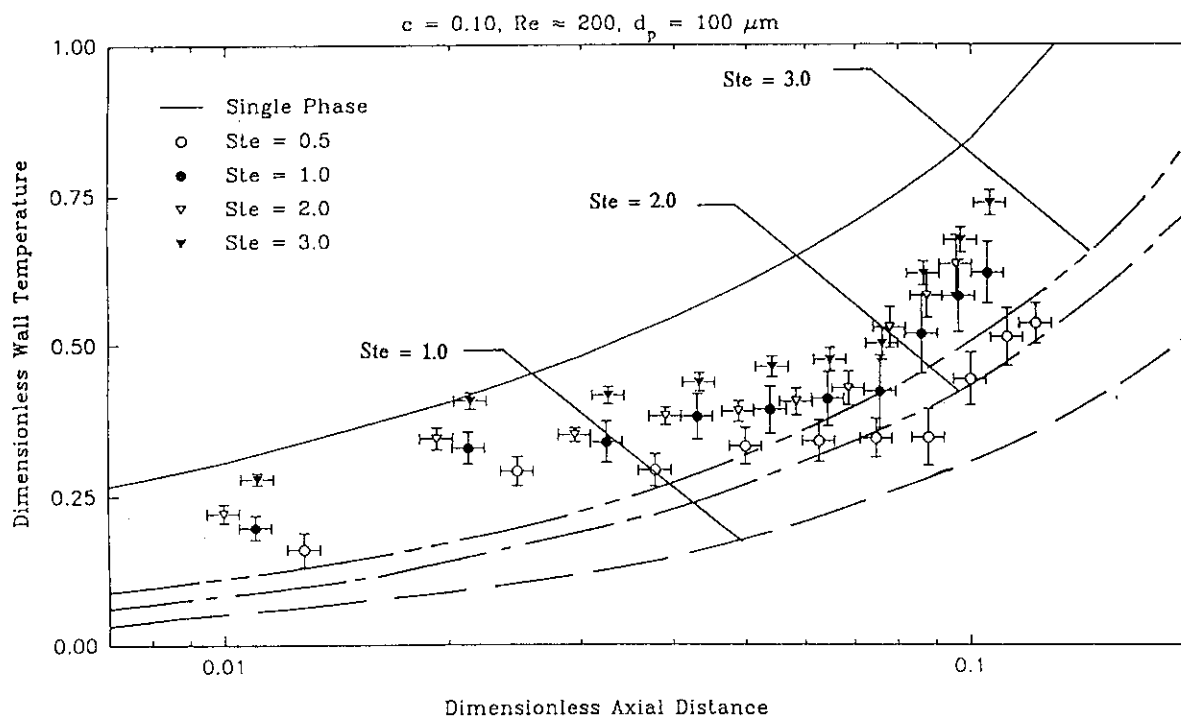


Fig. 34 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated  
Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared  
to Charunyakorn's Results for 10% Concentration of the Suspension.

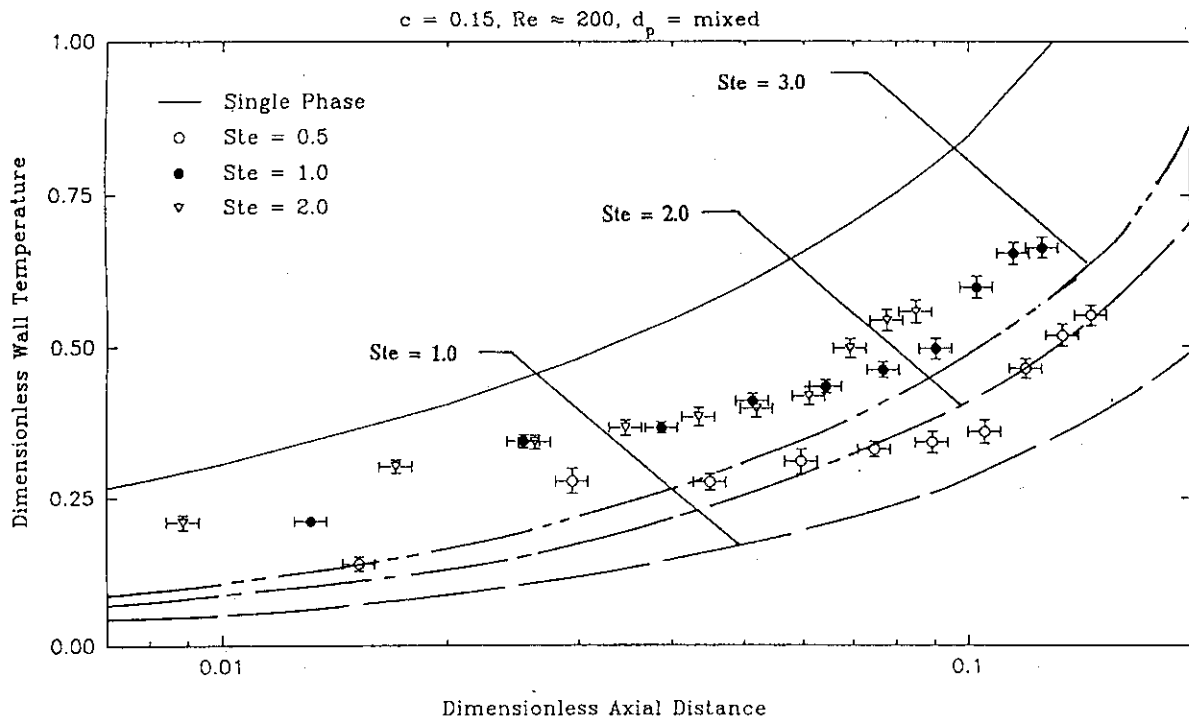


Fig. 35 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Charunyakorn's Results for 15% Concentration of the Suspension.

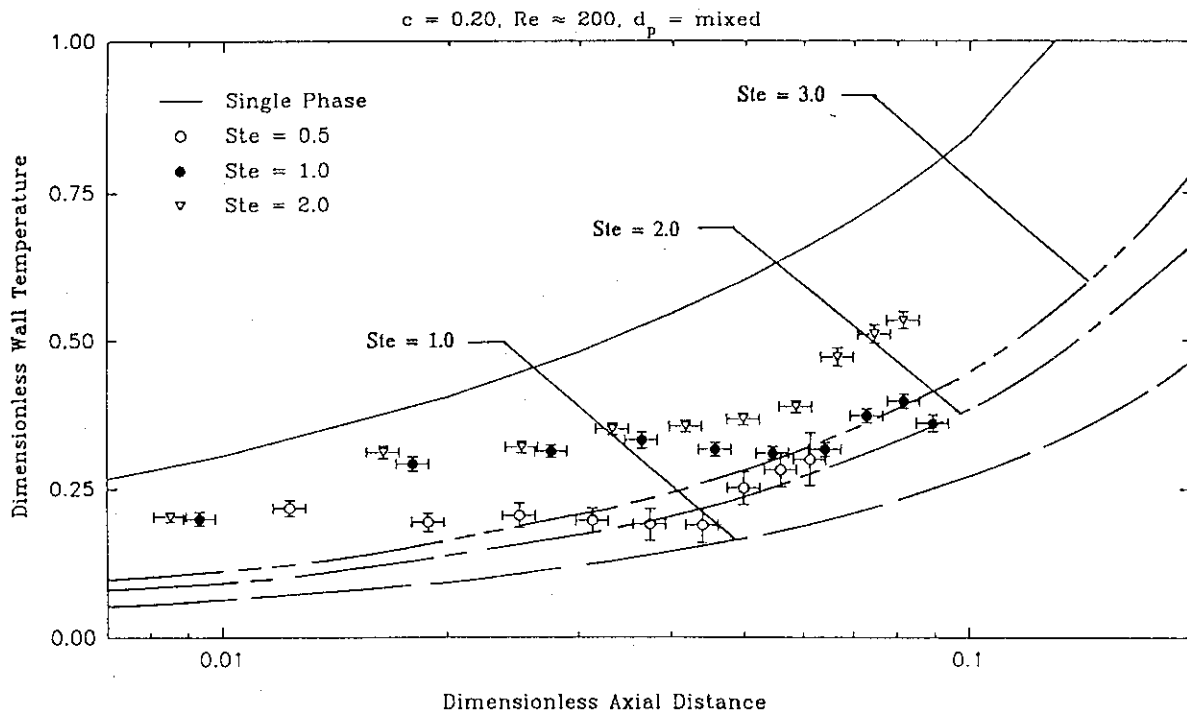


Fig. 36 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Charunyakorn's Results for 20% Concentration of the Suspension.

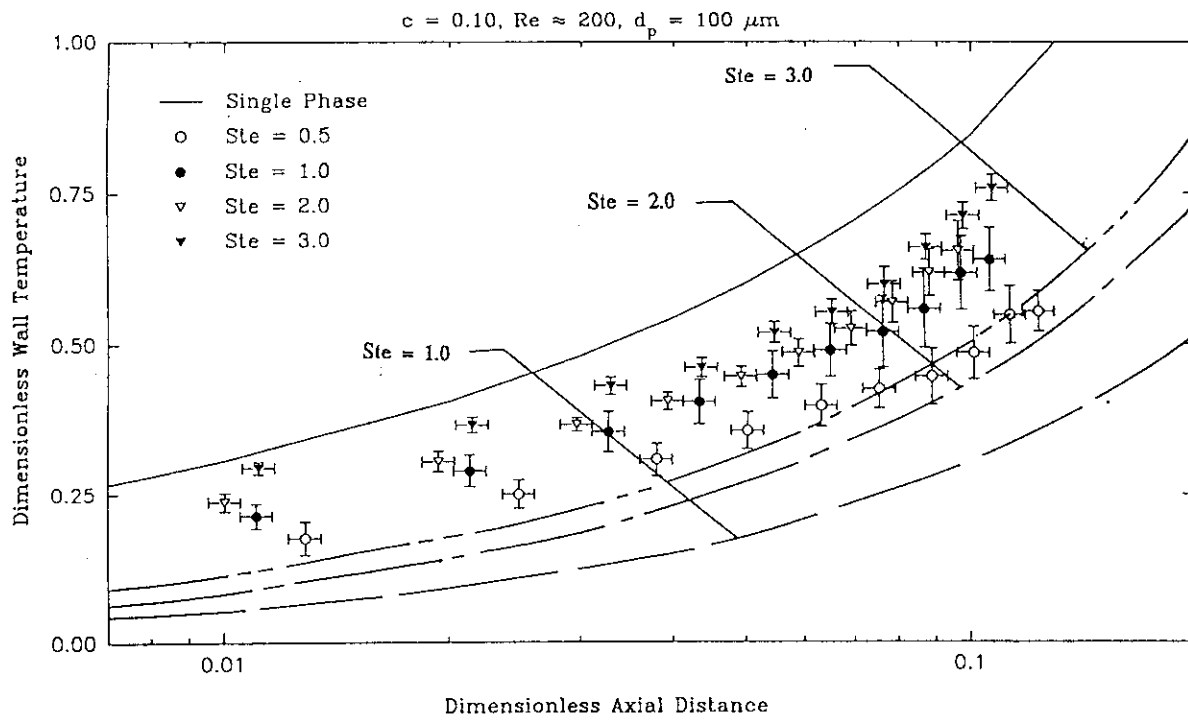


Fig. 37 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Charunyakorn's Results for 10% Concentration of the Suspension. (Experimental data corrected for systematic errors)

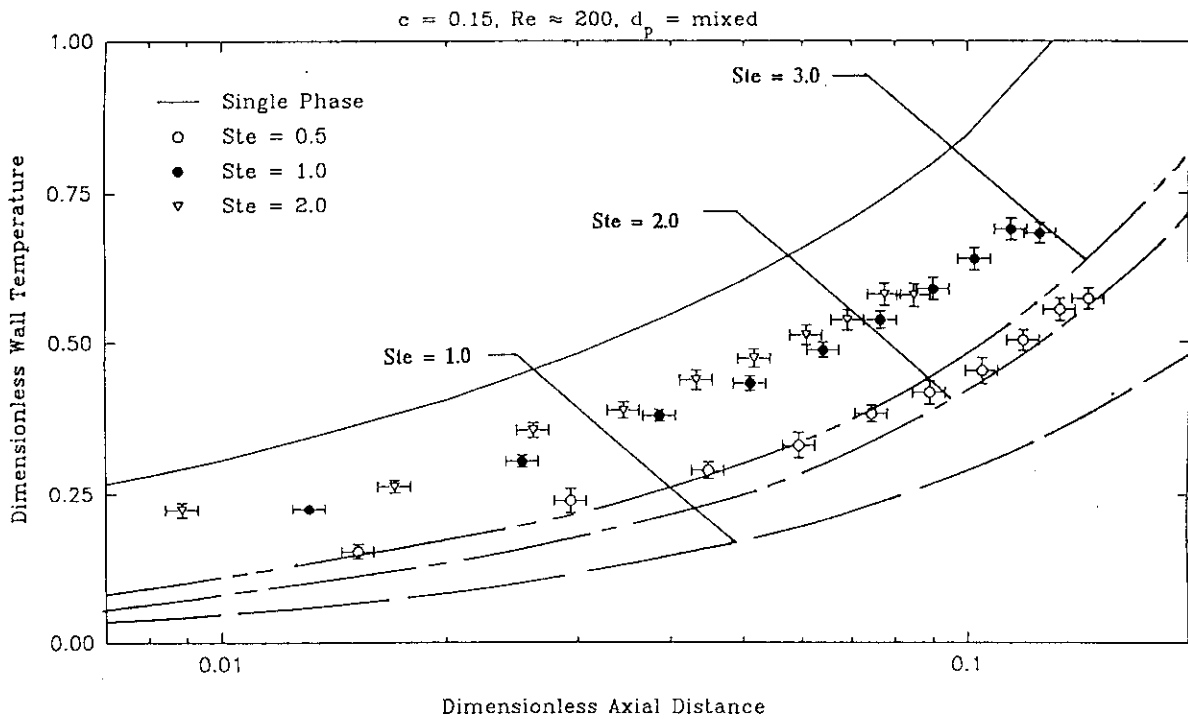


Fig. 38 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Charunyakorn's Results for 15% Concentration of the Suspension. (Experimental data corrected for systematic errors)

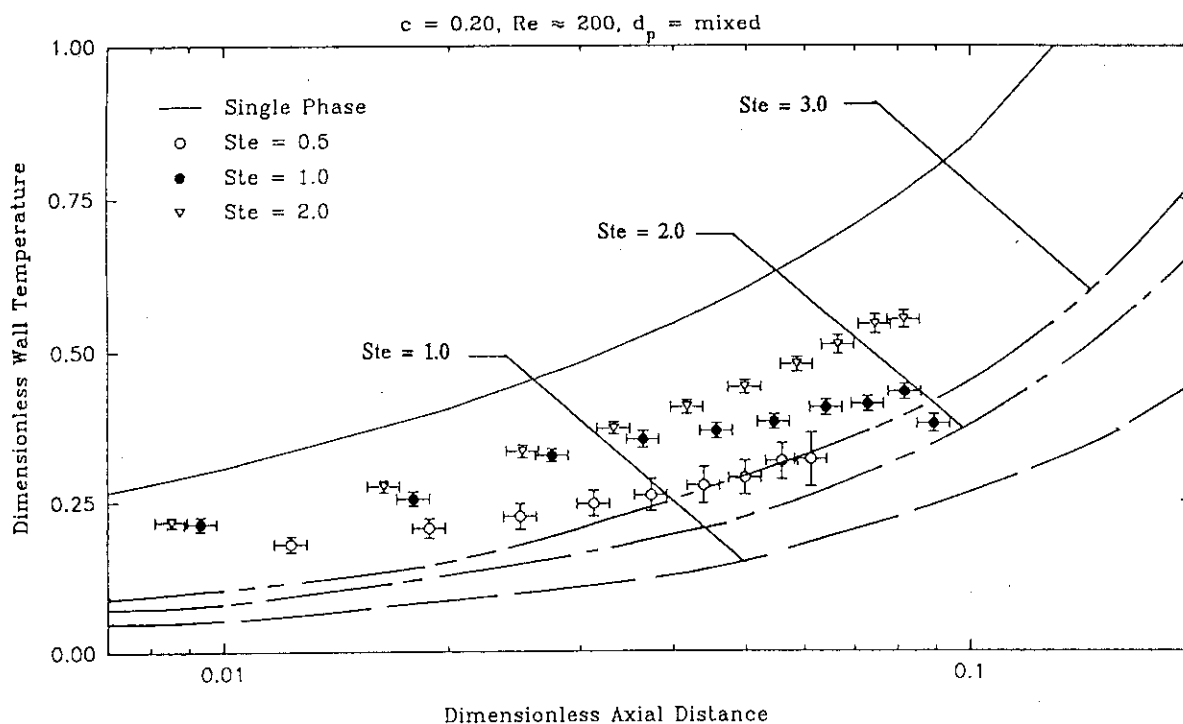


Fig. 39 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Charunyakorn's Results for 20% Concentration of the Suspension. (Experimental data corrected for systematic errors)

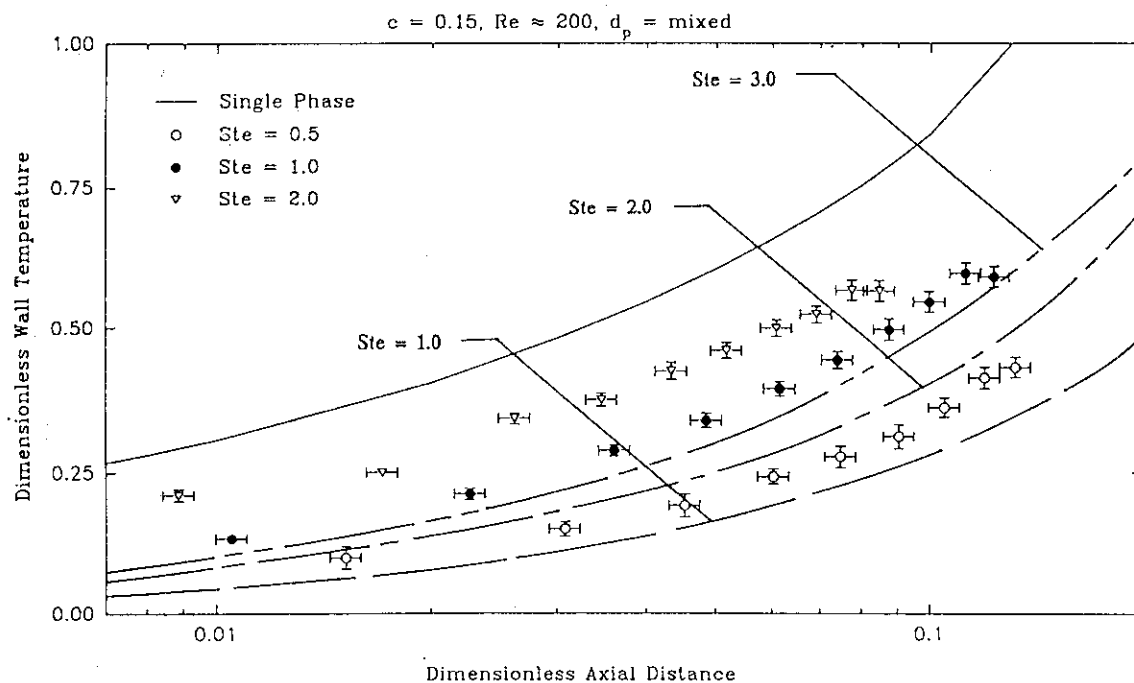


Fig. 40 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Charunyakorn's Results for 15% Concentration of the Suspension. (Experimental data corrected for systematic errors and Inlet condition shifted to eliminate initial sensible heating in the test section)



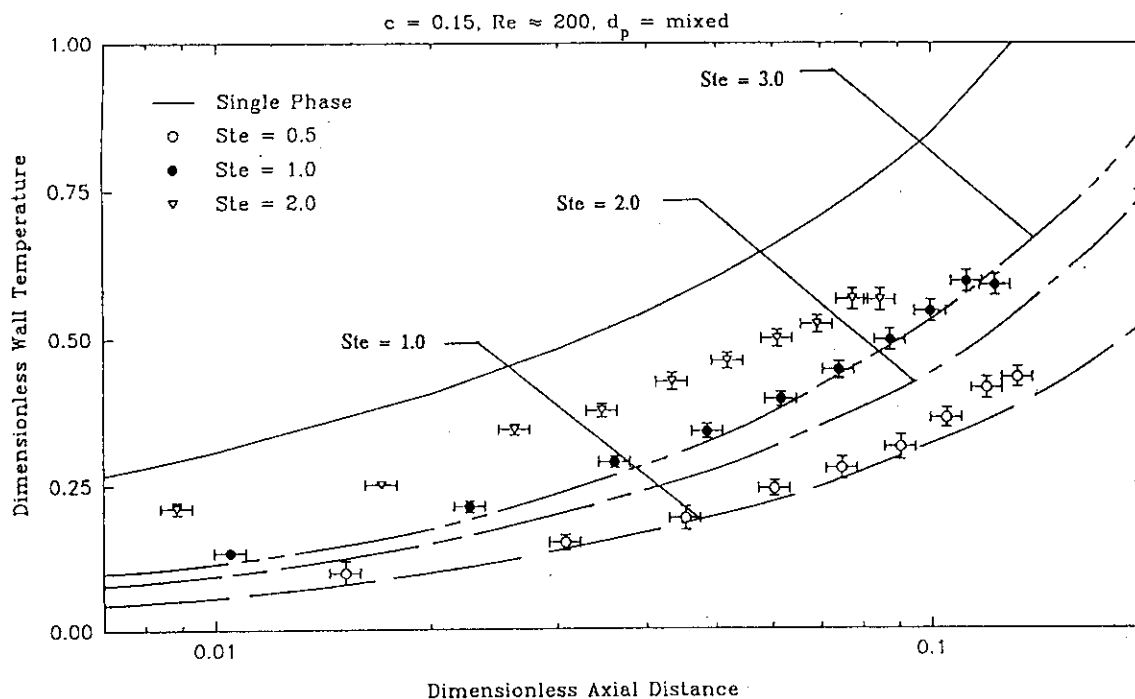


Fig. 41 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Charunyakorn's Results for 10% Concentration of the Suspension. (Experimental data corrected for systematic errors and Inlet condition shifted to eliminate initial sensible heating in the test section)

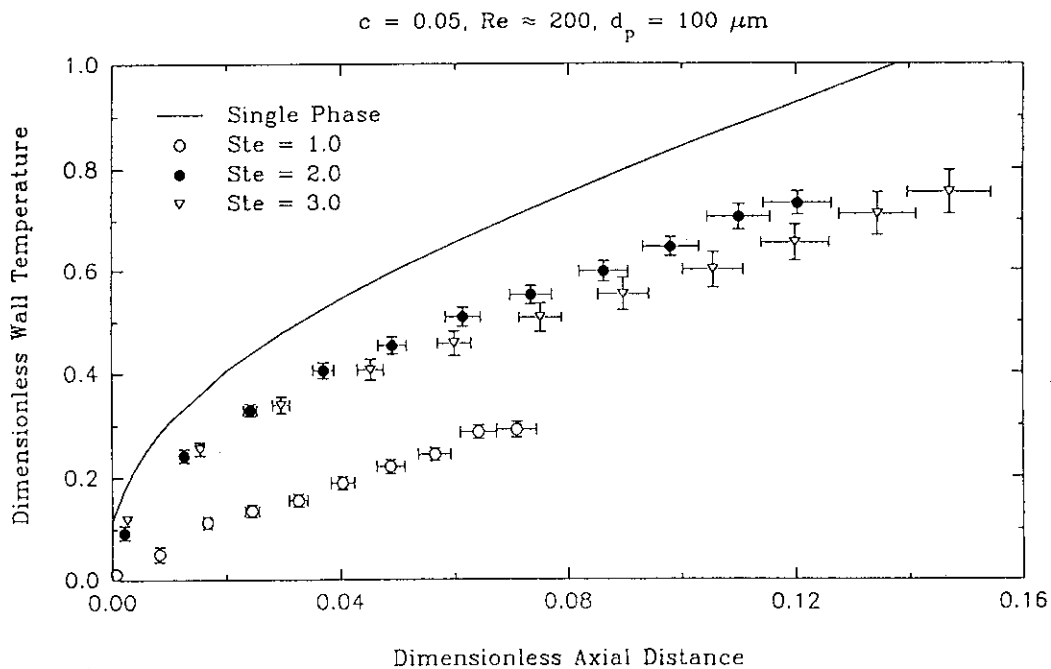


Fig. 42 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors and Inlet condition shifted to eliminate initial sensible heating in the test section)

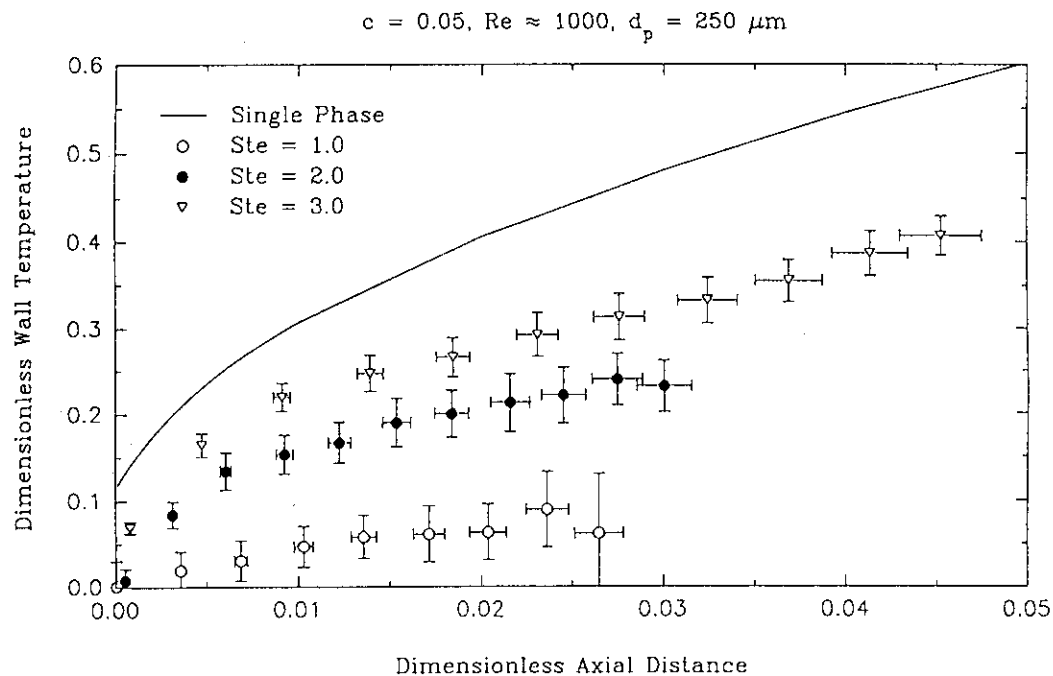


Fig 45 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors and Inlet condition shifted to eliminate initial sensible heating in the test section)

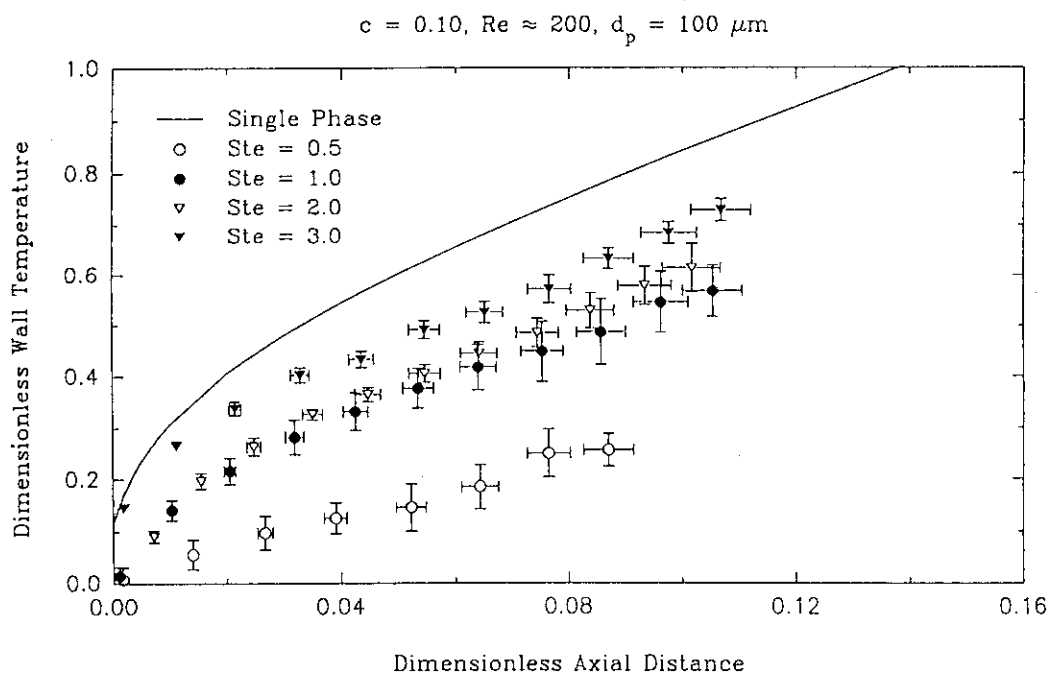


Fig 46 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors and Inlet condition shifted to eliminate initial sensible heating in the test section)

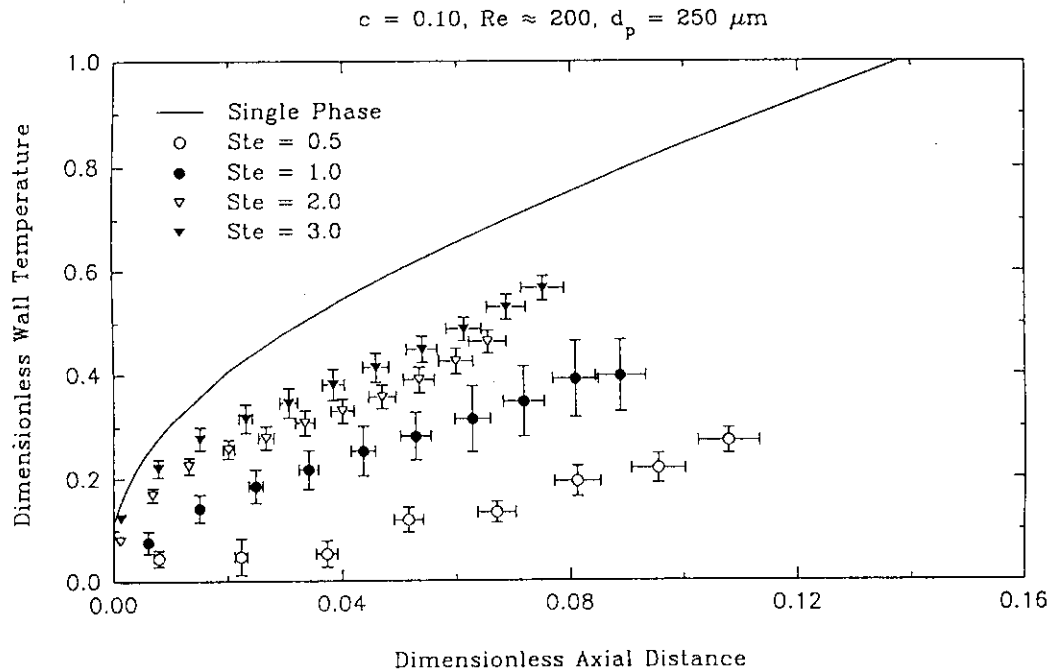


Fig 47 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors and Inlet condition shifted to eliminate initial sensible heating in the test section)

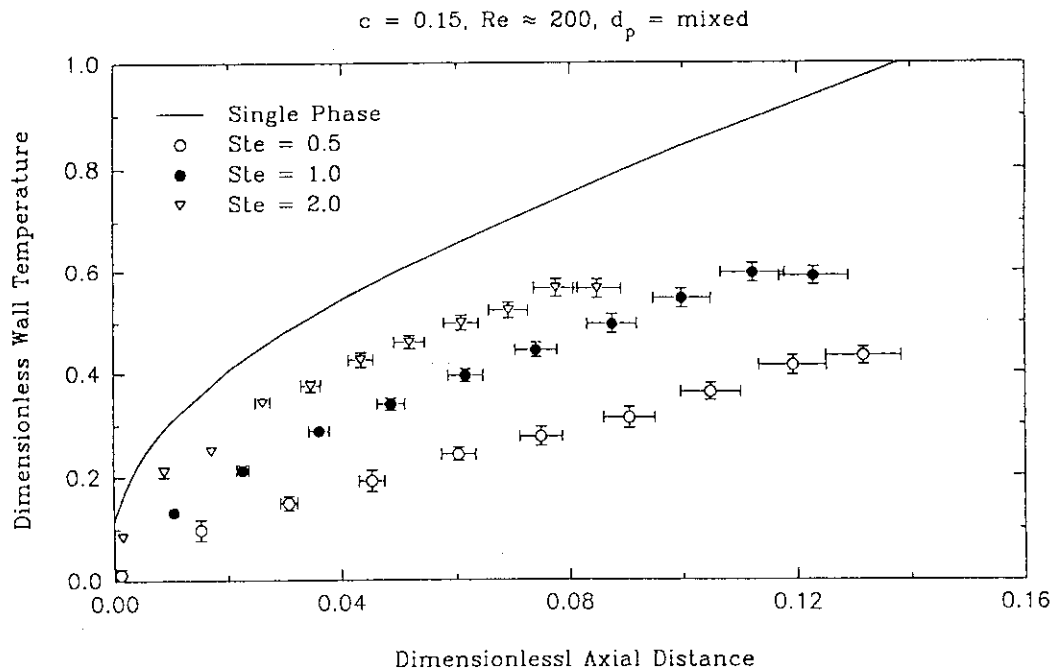


Fig 48 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors and Initial condition shifted to eliminate initial sensible heating in the test section)

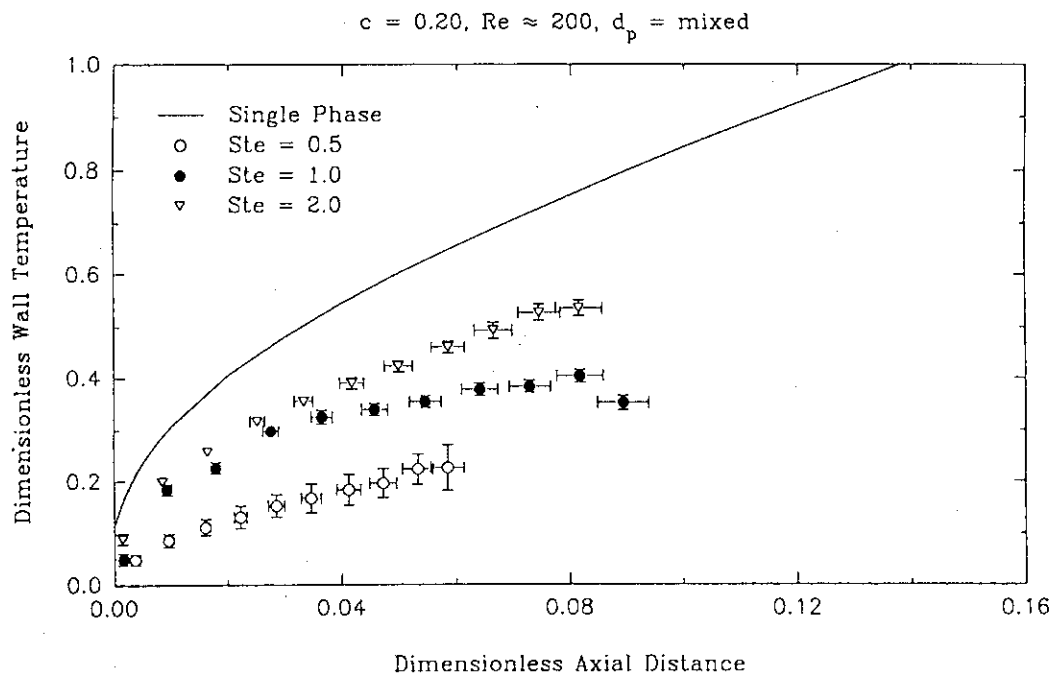


Fig 49 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors and Inlet condition shifted to eliminate initial sensible heating in the test section)

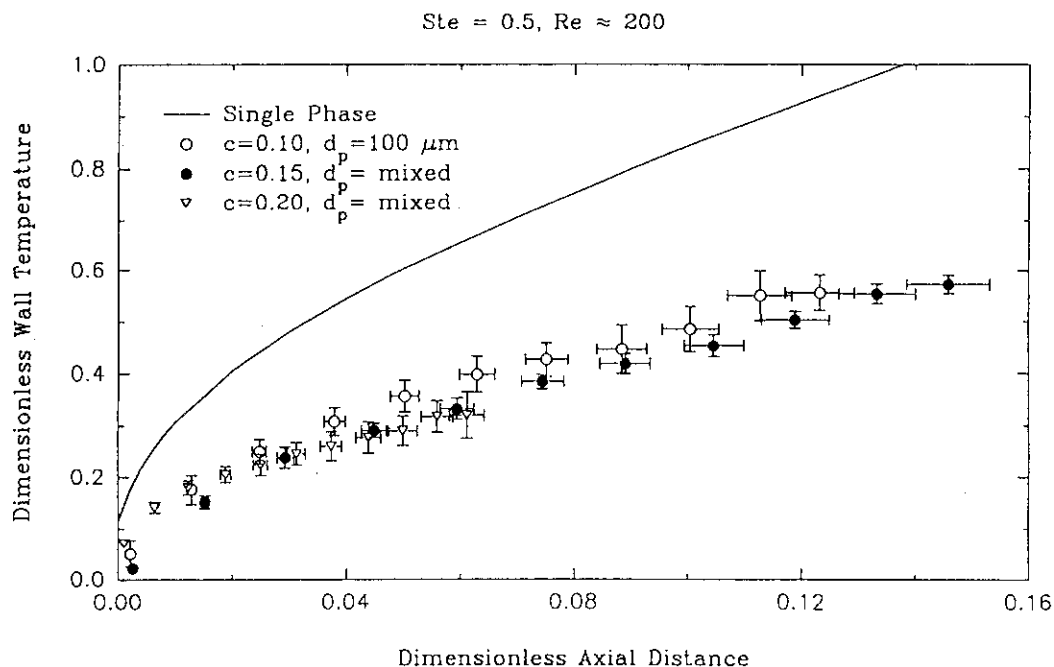


Fig 54 Effect of Bulk Volumetric Concentration on the Wall Temperature for Microencapsulated Phase Change Suspension Flow through a Circular Tube with Constant Wall Heat Flux. (Experimental data corrected for systematic errors)

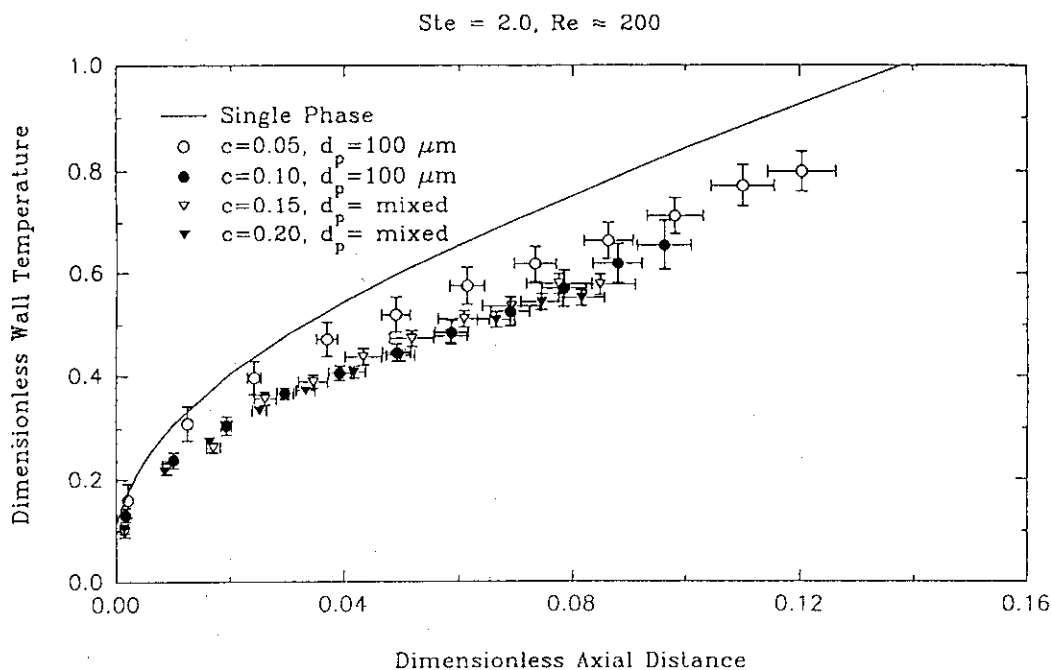


Fig 56 Effect of Bulk Volumetric Concentration on the Wall Temperature for Microencapsulated Phase Change Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors)

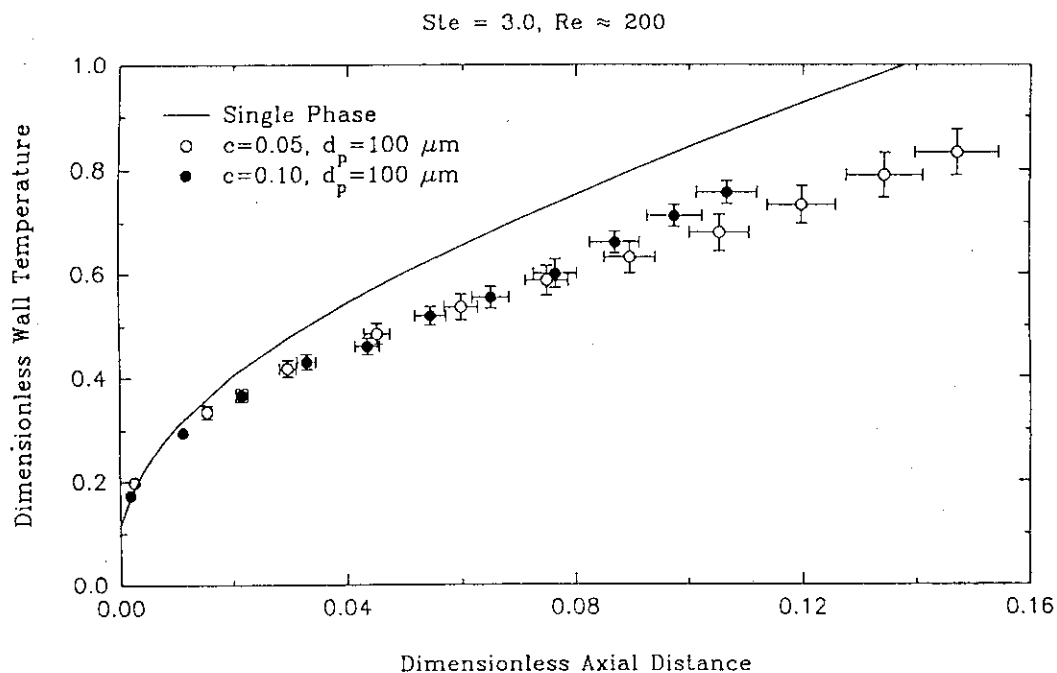


Fig 57 Effect of Bulk Volumetric Concentration on the Wall Temperature for Microencapsulated Phase Change Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors)

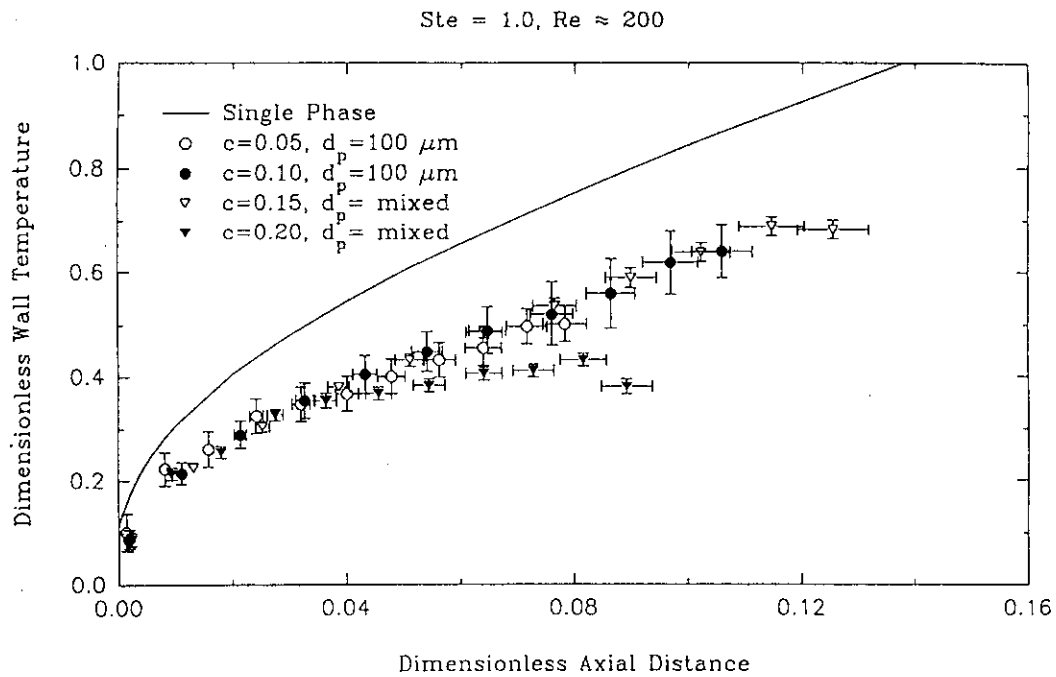


Fig. 55 Effect of Bulk Volumetric Concentration on the Wall Temperature for Microencapsulated Phase Change Suspension Flow With Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors)

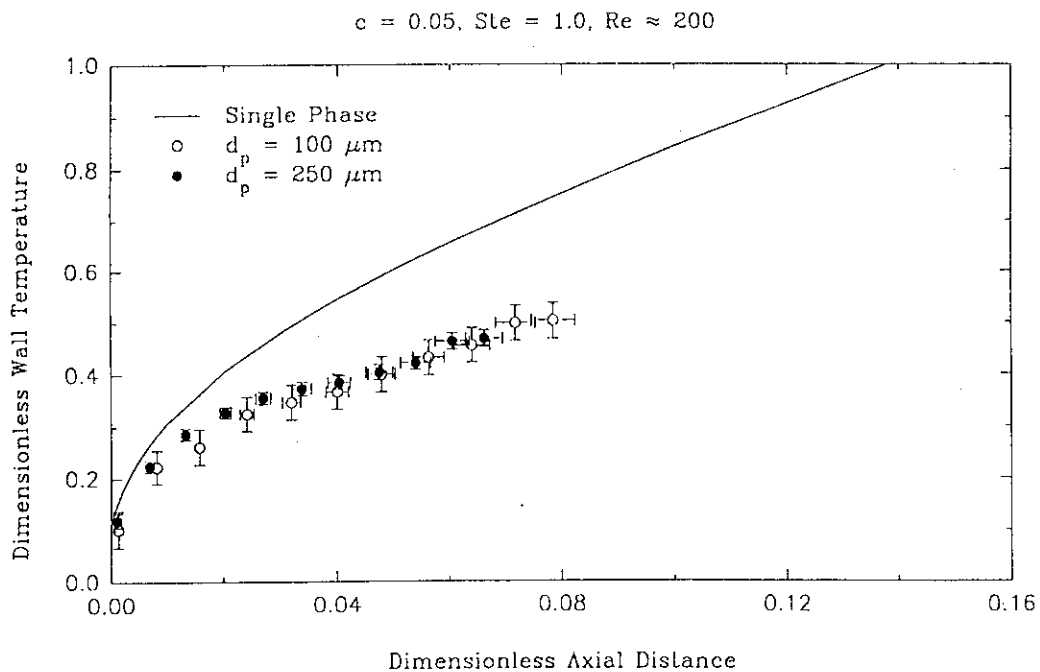


Fig. 72 Effect of Microcapsule Diameter on the Wall Temperature for Microencapsulated Phase Change Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors)

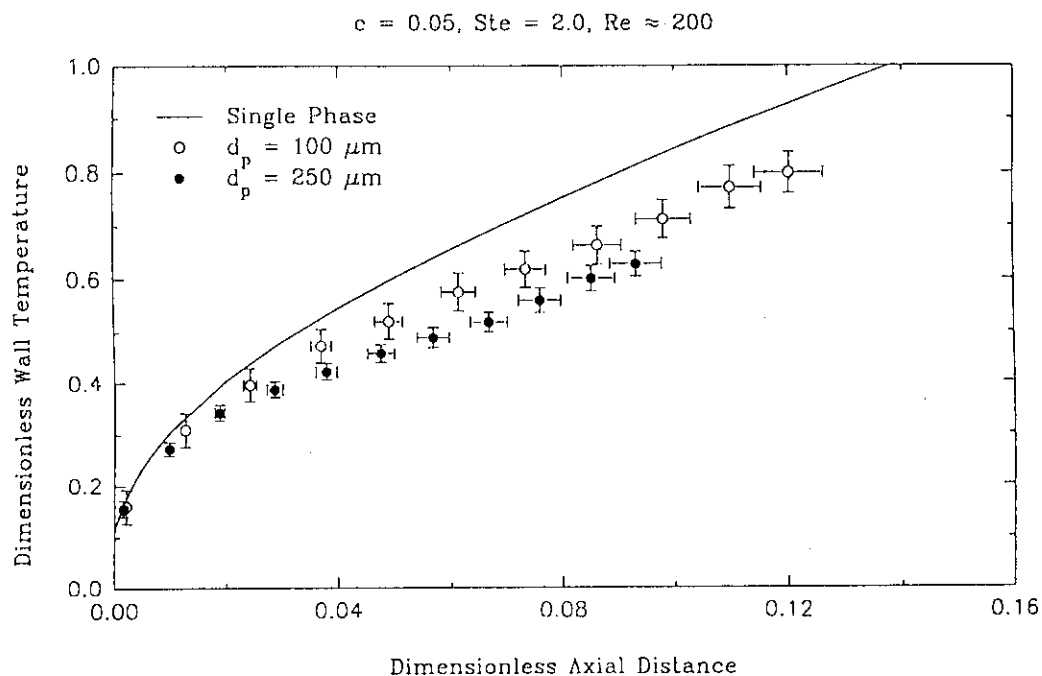


Fig 73 Effect of Microcapsule Diameter on the Wall Temperature for Microencapsulated Phase Change Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors)

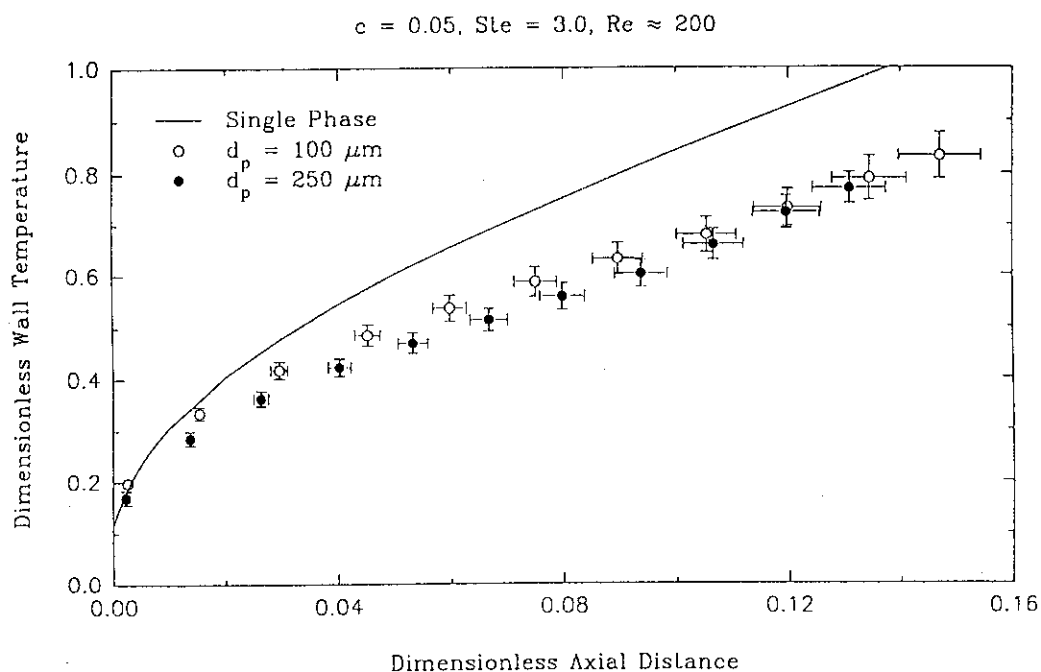


Fig 74 Effect of Microcapsule Diameter on the Wall Temperature for Microencapsulated Phase Change Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors)

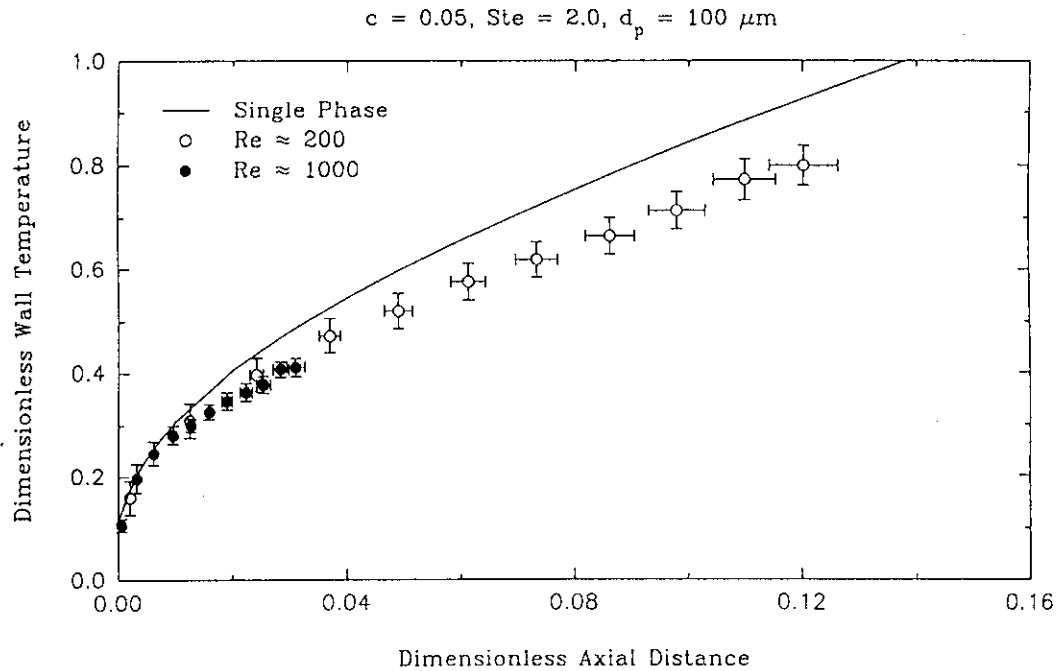


Fig 99 Effect of Flow Rate on the Wall Temperature for Microencapsulated Phase Change Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors)

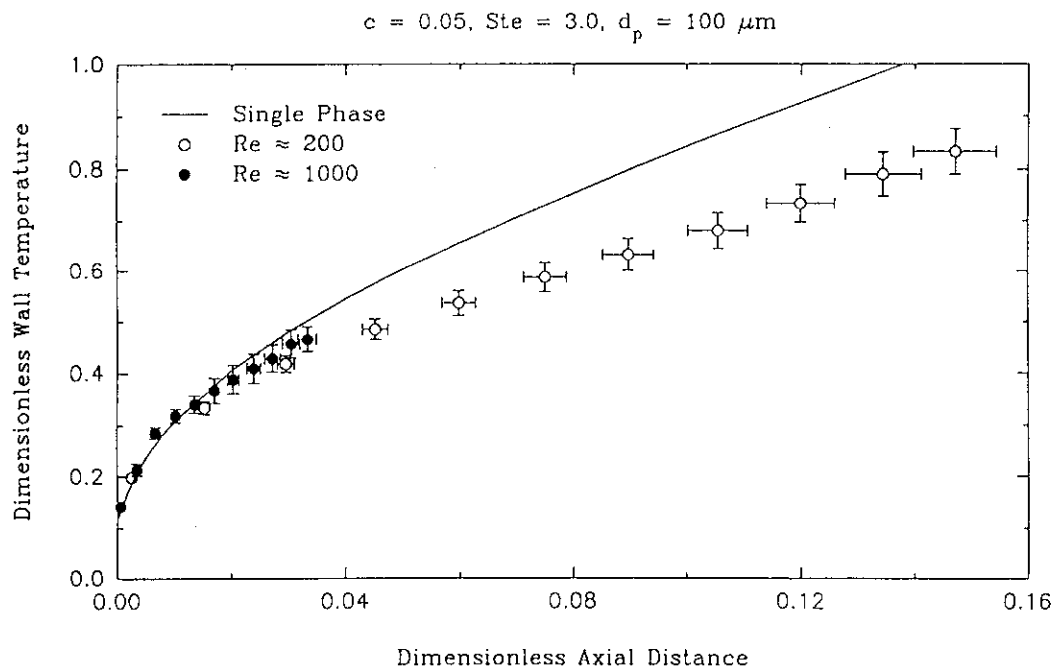


Fig 100 Effect of Flow Rate on the Wall Temperature for Microencapsulated Phase Change Suspension Flow through a Circular tube with Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors)



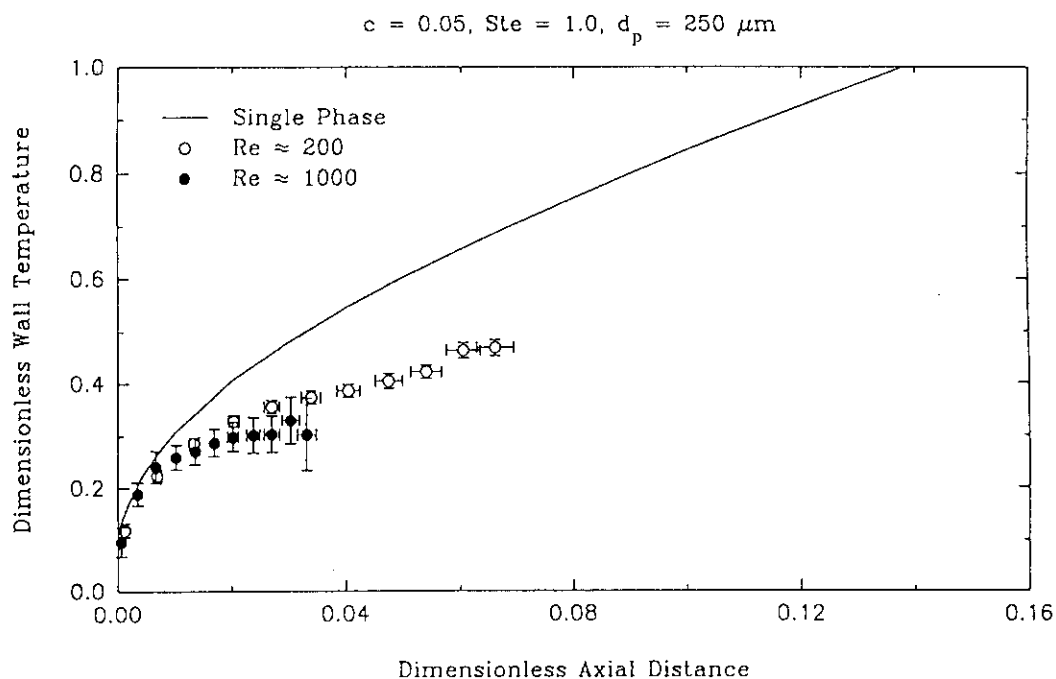


Fig 101 Effect of Flow Rate on the Wall Temperature for Microencapsulated Phase Change Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors)

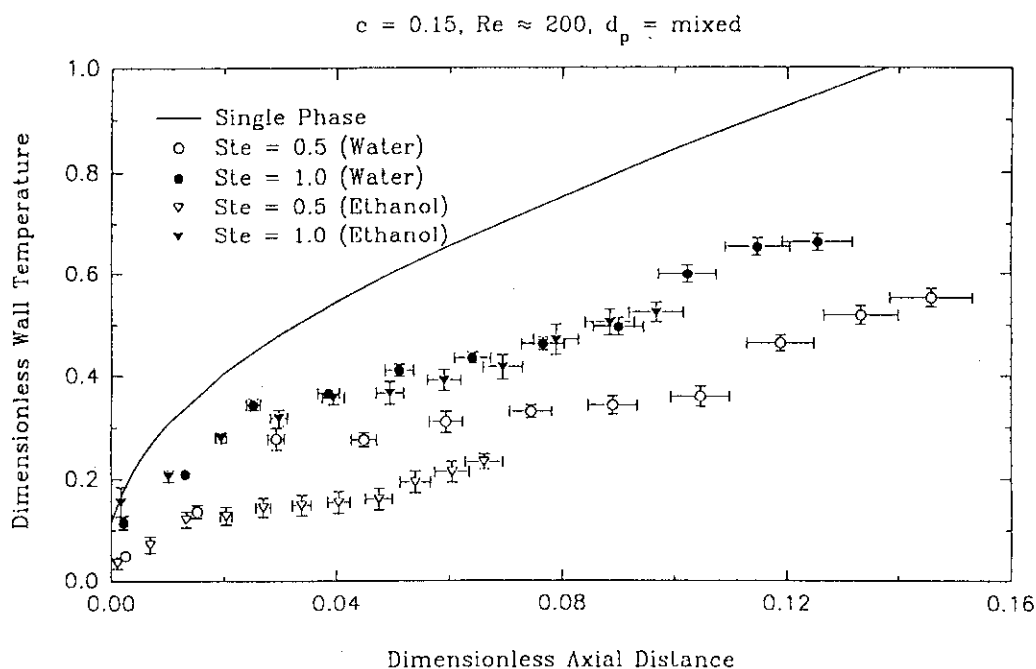


Fig 110 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Single Phase Flow.

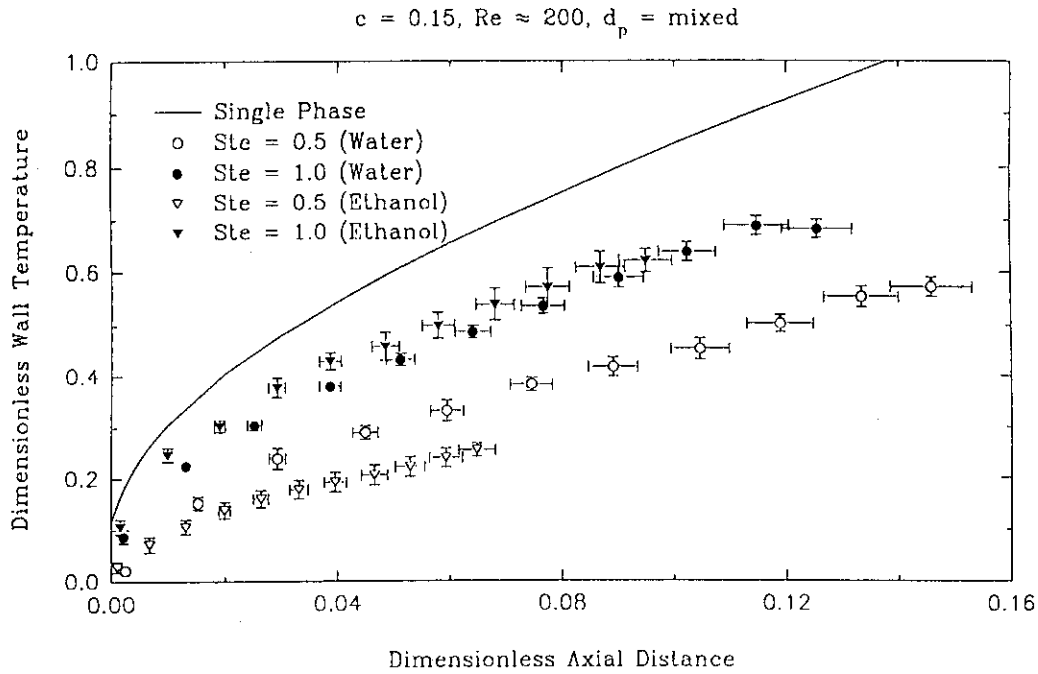


Fig 111 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Single Phase Flow. (Experimental data corrected for systematic errors)

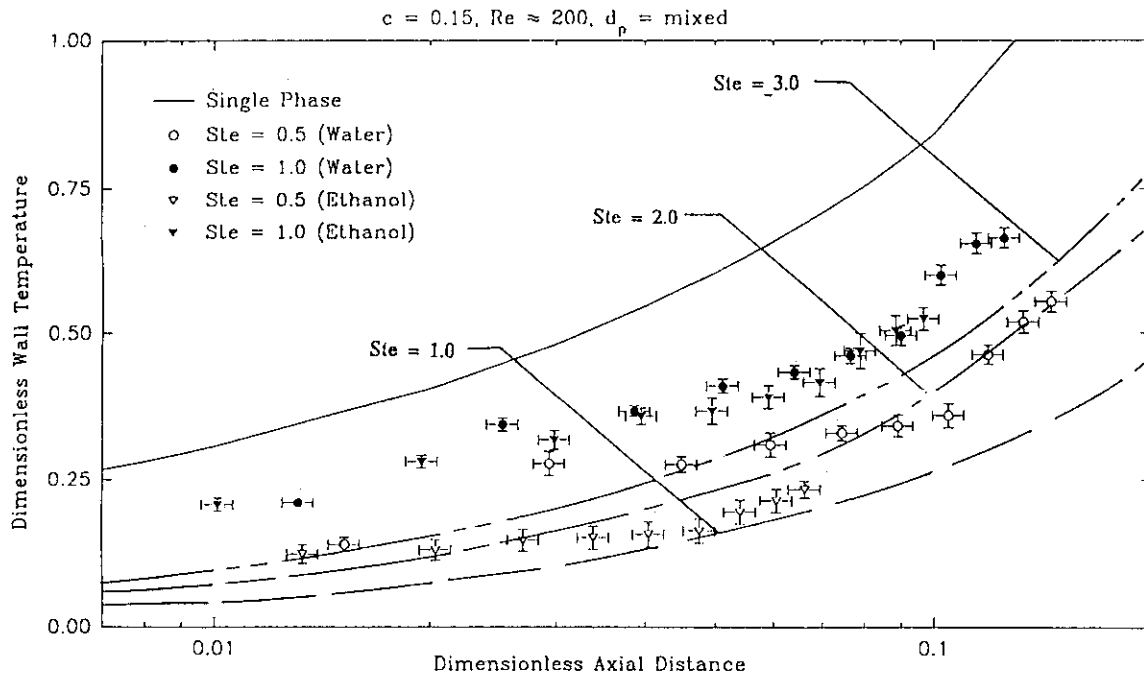


Fig 113 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Phase Change Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Charunyakorn's Results for 10% Concentration of the Suspension

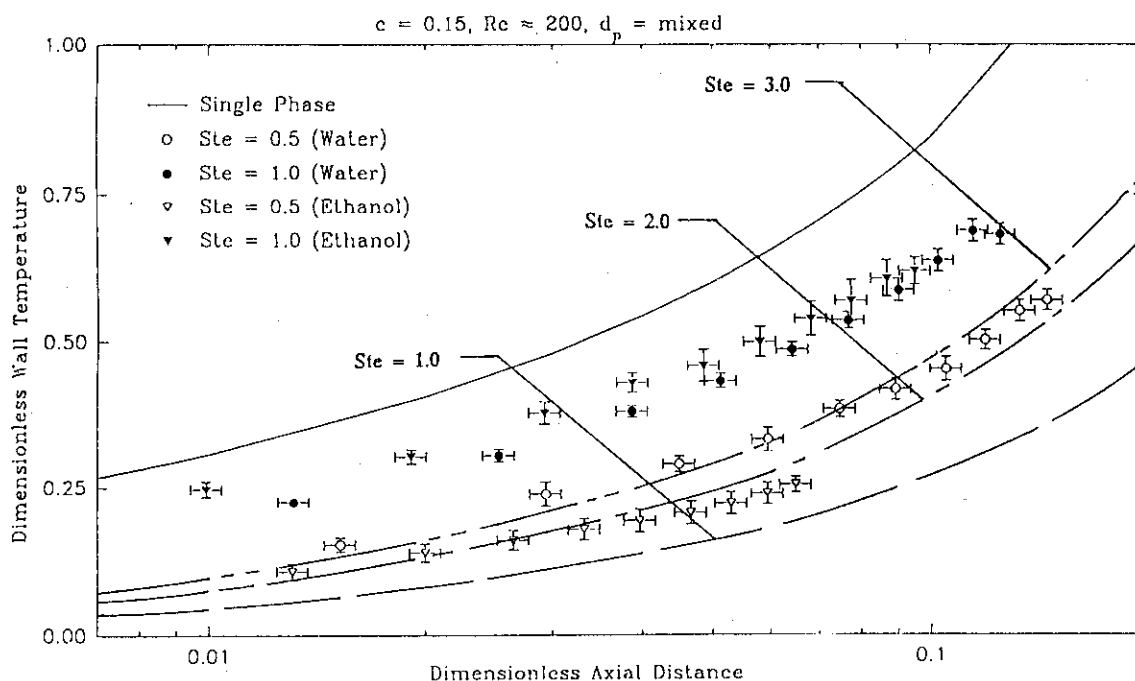


Fig 114 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Phase Change Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Charunyakorn's Results for 10% Concentration of the Suspension. (Experimental data corrected for systematic errors.)

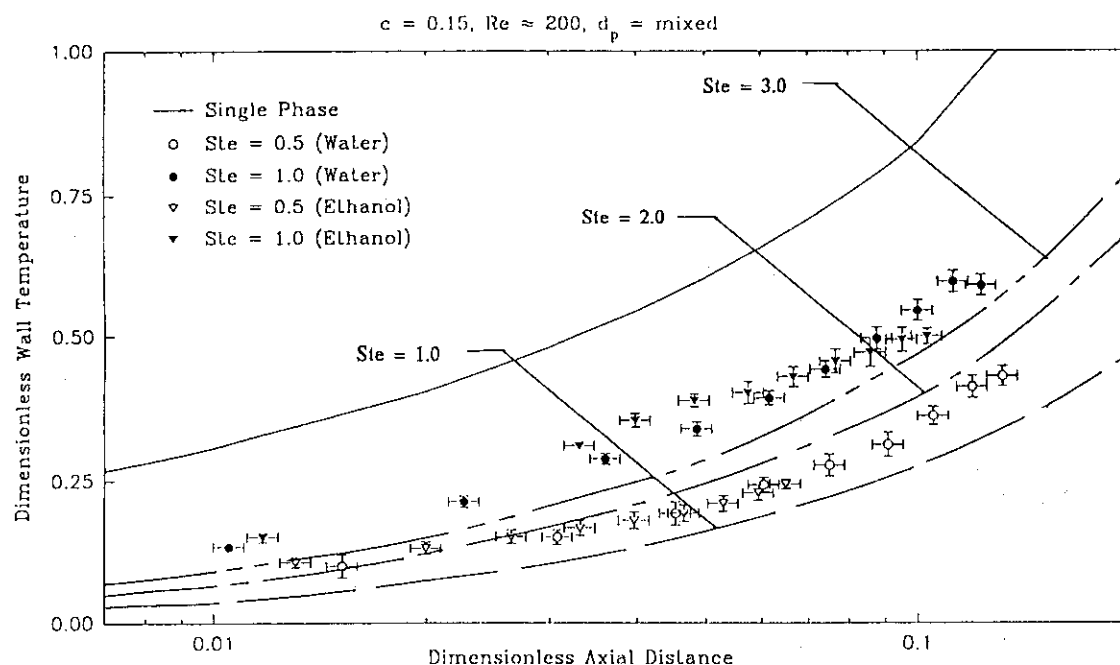


Fig 115 Effect of Bulk Stefan Number on the Wall Temperature for Microencapsulated Phase Change Suspension Flow through a Circular Tube with Constant Wall Heat Flux compared to Charunyakorn's Results for 10% concentration of the suspension. (Experimental data corrected for systematic errors and inlet condition shifted to eliminate initial sensible heating in the test section)

## 6.3 Application of multiphase flow to improvement of nuclear power plant safety

T.TANAKA and S.MARUYAMA

Department of HTTR Project  
*Japan Atomic Energy Research Institute*  
*Oarai-machi, Higashiibaraki-gun, Ibaraki-ken, Japan*

### 1.Introduction

High temperature gas-cooled reactors (HTGRs), such as the HTR-Module in Germany, the GT-MHR in the US and the HTTR in Japan, have been designed to have salient safety characteristics of no core melt in the accidents with relatively low power density in the core, which leads to the large volume of the core with the same power and imposes penalties on economics of the HTGR. Application of multiphase flow technologies in the HTGR actually manages to enhance the safety and economics of the reactor. This paper outlines following topics relating multiphase flow technologies which have been contemplated, through the design works of the HTTR, to be applicable in the advanced HTGR design and safety relating topics.

- Heat pipe decay heat removal system,
- Heat pipe cooled HTGR system, and
- Buoyancy driven exchange flow.

### 2.Heat Pipe Decay Heat Removal System

The HTGRs have redundant heat removal system which is, for example, composed of primary and secondary cooling systems (PCS and SCS), a decay heat removal system (DHRS), etc. The PCS transports the heat from the core to heat exchangers during normal operation. The DHRS is operated in case of the accident such as a depressurization accident in which the forced convection cooling by the PCS is no longer available. Of course, it is operated after the normal reactor shutdown to remove the residual heat of the core.

Inherent and passive safety characteristics of HTGRs are apparently enhanced by adopting passive decay heat removal devices. The reactor cavity cooling system (RCCS) of the MHTGR<sup>(1)</sup>, shown in **Fig.1**, is one of the passive DHRS, in which the decay heat of the core is transferred by means of radiation and natural convection from the surface of reactor pressure vessel (RPV) to the passively driven air-cooled system.

A heat pipe can be another design option for the passive DHRS in the advanced HTGR. **Figure 2** shows a schematic diagram of heat pipe decay heat removal system (HPDHRS), called a temperature initiated passive cooling system (TIPACS), which is studied at the ORNL<sup>(2)</sup>. In this system, decay heat of the irradiated fuel is transferred to the RPV wall mainly by conduction through graphite core components, then transferred to the heat pipe cooled steel membranes by means of radiation and natural convection. The TIPACS is also required to protect concrete wall facing the RPV wall due to its high exterior temperature ( $>220^{\circ}\text{C}$ ) during normal operation.

Heat pipe is one of the applications of multiphase flow technology and has completely passive characteristics. It consists of a container vessel, or container tube, whose inside surface is lined with a porous capillary wick if necessary, and working fluid. The heat pipe can continuously transport the latent heat of vaporization from the evaporator section to the condenser section irreversibly. Carbon dioxide ( $\text{CO}_2$ ) is selected as a working fluid for the system because of its critical point of  $31.1^{\circ}\text{C}$ .

The JAERI is to start research and development program on heat removal performance of the HPDHRS for the HTGR application to improve safety performance. Variable conductance heat pipes (VCHPs), whose heat transfer capacity is varied against an operating condition, are one of the promising heat transfer devices for the HPDHRS. The VCHP can be operated at minimum capacity during normal operation and at maximum during accidental conditions. Variability is realized by means of non-condensable gas injection, vapor or liquid reservoir tank, multi-component working fluid and others.

### 3.Heat Pipe Cooled HTGR System

The JAERI proposes a heat pipe cooled HTGR system as a super safe reactor system<sup>(3)</sup> which has completely passive characteristics. The heat pipe cooled HTGR, or heat pipe cooled particle bed reactor (abbreviated to HPCPBR) shown in **Fig.3**, is considered as one of passive and maintenance-free reactors which is suitable to be used in the isolated islands or in a polar region to supply electricity in the region as well as process heat for district heating. In this reactor system, the heat transport system and energy conversion device consist of the completely passive device like a

heat pipe and a thermoelectric converter, for example. This fact leads that the HPCPBR has superior inherent safety characteristics. This reactor also has the possibility to expand its application for a space use, for example, the energy source for deep space exploration and moon base use as well.

The reactor itself consists of a bed of coated fuel particles and a graphite funnel to form the active core. The reactor has the passive cooling device of liquid metal heat pipes for heat transportation from the core to the energy conversion device like thermoelectric and thermionic converters.

The Science and Technology Agency of Japan started the development program on a functionally gradient material (FGM) for energy conversion system. In this program, the development of FGM thermoelectric and thermionic converter is a key issue pursuing higher efficiency of 50%<sup>(4)</sup>. In these converters, micro structure and content of the material will be functionally gradient so as to achieve maximum performance at their operating condition. These accomplishments should be taken into account for this reactor system.

Lithium is selected as working fluid for the heat pipe because of its good thermal properties in high temperature application to achieve higher performance.

Reactivity of the core is also controlled by passive metallic poison injection system not only during normal operation but also accidents. In this system, metallic poison of Li-6 is inserted in the active core following the temperature change. In case of core heat-up accident, metallic fuse will be melted so as to eject Li-6 into the core region by pressurized gas in the system.

Due to aforementioned design features, the HPCPBR could be a promising passive safe reactor system. The JAERI started a preliminary experimental study on T/H characteristics of the HPCPBR, such as transient response of heat pipes and a particle bed, interaction among heat pipes and other facilities.

#### 4. Buoyancy Driven Exchange Flow

The last topic relating HTGR safety is a buoyancy driven exchange flow in case of a stand pipe rupture accident in the HTTR, which is one of the critical design based accidents. In this accident, after pressures of inside and outside of the RPV are balanced, relatively light gas of helium tends to flow upward through the breach. **Figure 4** shows schematic process of air ingress after a stand pipe rupture in HTTR. This behavior can be recognized as one of the mass transfer problems between gases with different bulk densities. If the air enters the core while the core temperature is high enough, graphite components might be oxidized seriously. Therefore, quantitative estimation of exchange flow rate becomes important.

For the understanding of the fundamental phenomena, experimental studies have been carried out using the simplified apparatus, shown in **Fig.5**, with nitrogen gas as a working fluid. The velocity profile in the vertical pipe, measured by a laser Doppler velocimeter, fluctuates irregularly with time and space. In the course of experiments, it was found that Rayleigh number is not a key factor to the scaling law for the exchange flow but length-to-radius ratio<sup>(5)</sup>.

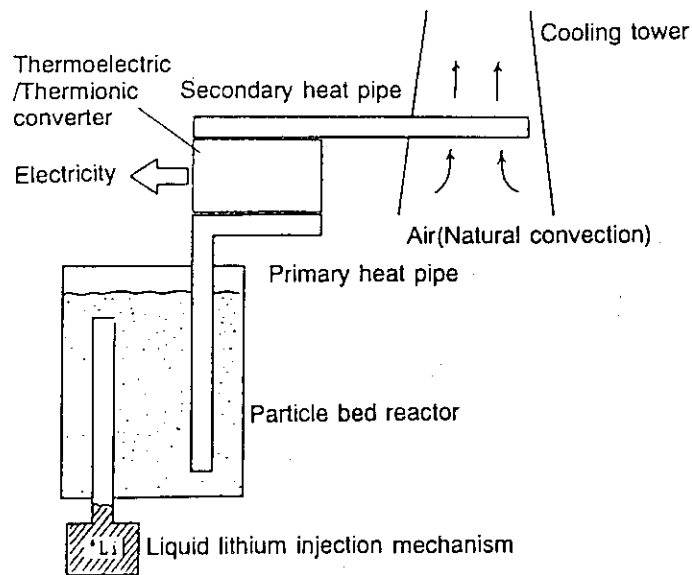
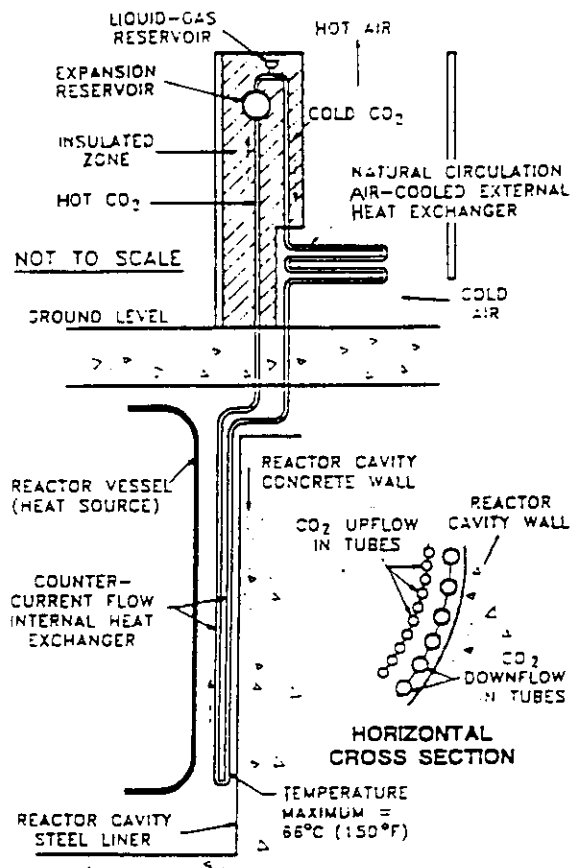
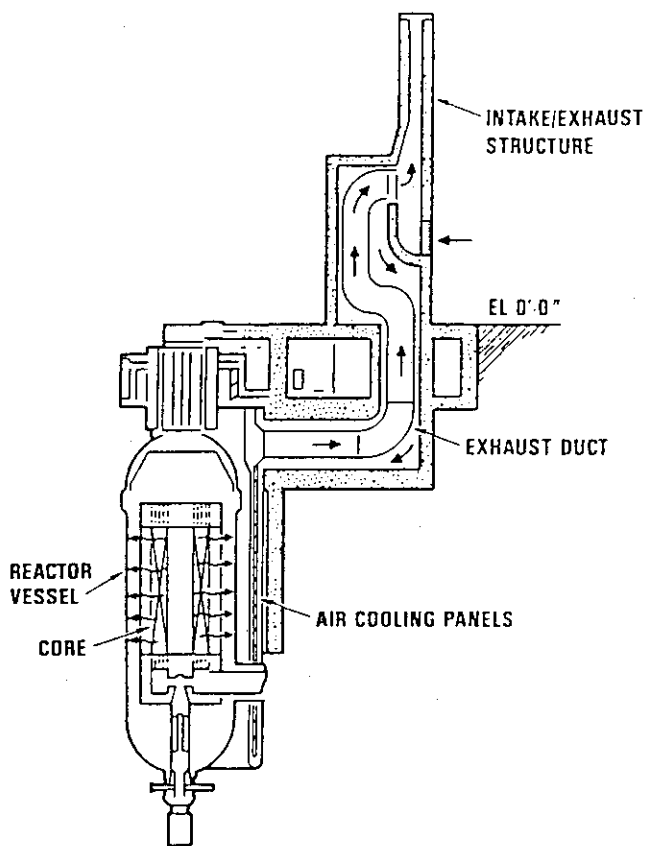
In addition, it is revealed through the flow visualization by a smoke method that a hot finger of exchange flow moves upward one side and a cold finger downward the other side, simultaneously. From this result, it can be said that the exchange flow is strongly affected by the interaction between upward and downward flow at the opening. This means that a vertical partition in the channel may decrease the interaction between upward and downward flow. In the case of the HTTR, as the breach of a stand pipe has an annular cross section, the exchange flow rate is restricted by the interaction of the flow.

## 5. Concluding Remarks

This report summarizes the application of multiphase flow technologies to enhance safety characteristics of HTGRs and fundamental phenomena on the buoyancy driven exchange flow. It is apparent that the passive heat transport device of heat pipe improve the safety performance of the HTGRs. Buoyancy driven exchange flow through the breach of the stand pipe may not lead to significant effect upon graphite oxidation during the stand pipe rupture accident.

## Reference

- (1) Conklin, J.C., ORNL/TM-5159(1976).
- (2) Forsberg, C.W. et al., ORNL-6767(1994).
- (3) Kunitomi, K. et al., to be published as the Proceedings of IAEA Technical Committee Meeting, Petten(1994).
- (4) Niino, M. et al., IAF-93-R.1.428, Austria, (1993).
- (5) Fumizawa, M and Hishida, M., Proc. NURETH-5, pp.369-376, Salt Lake City(1992).
- (6) Tae-il Kang et al., Proc. ISTP-6, pp.325-330, Seoul(1993).





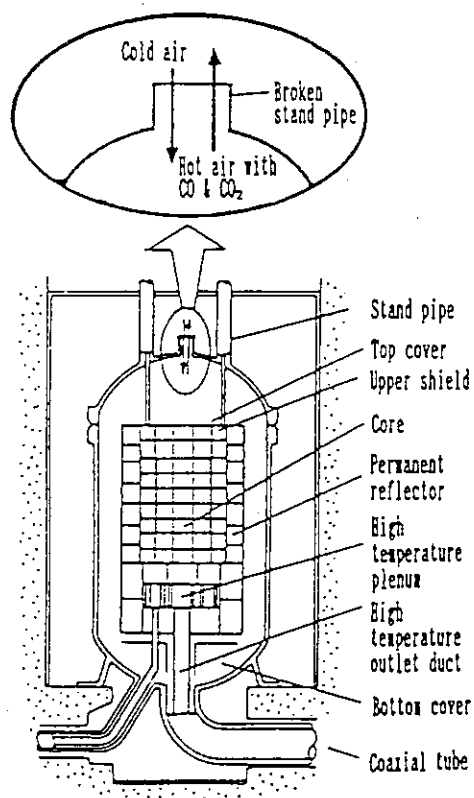


Fig.4 Schematic drawing of air ingress process

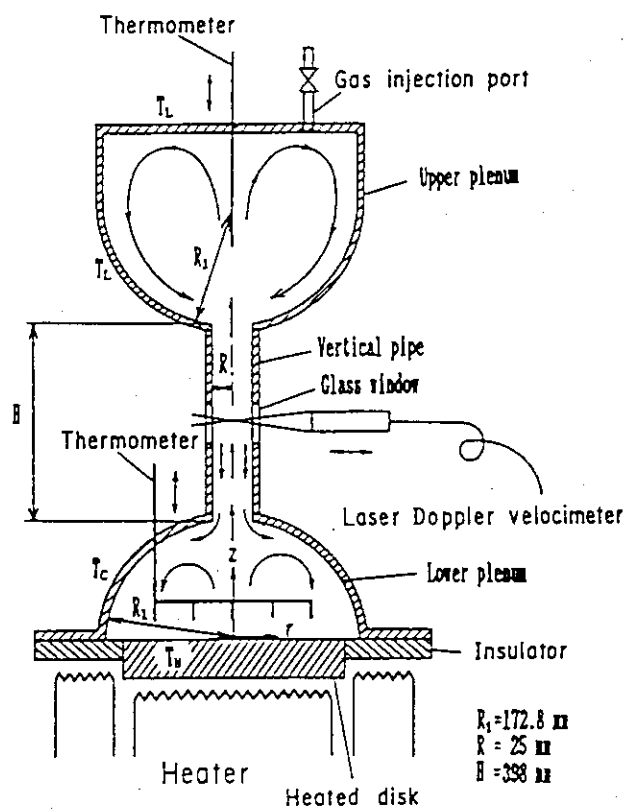


Fig.5 Side view of test apparatus

## 6.4 Multiphase flow importance in future nuclear process

### heat applications : energy alcohol by biomass gasification with HTR

Heiko Barnert  
Research Centre Jülich GmbH, KFA and  
University of Aachen, Fed. Rep. of Germany

#### ABSTRACT

For future nuclear process heat applications multiphase phenomena are very important in a three-fold sense: For the ability to produce high temperature heat, for the realization of a catastrophe-free nuclear energy technology in case of the design event of the ingress of water droplets into the High Temperature Reactor HTR, and for the newly proposed carbondioxide-neutral energy system "energy alcohol from biomass plus HTR". Details are reported in the following:

The technology of the "Coated Particle" with the multi-coating of ceramic coatings on micro-particles on nuclear fuel for the HTR is the technological reason for the ability to produce high temperature heat from nuclear energy. This realizes a very good retention capability for radioactive material, including fission products. It is produced by chemical vapour deposition in a fluidized bed, this is a two-phase-fluidized-bed/gaseous-to-solid-states-change by pyrolysis/multi-component/phenomenon.

The new requirement of a catastrophe-free nuclear energy technology has led to the identification that the ingress of water droplets into the nuclear core of the HTR should be avoided by self-acting separation of droplets coming from the steam generator tube break before they can get into the core. The behaviour of the water/steam jet in the helium stream is a two-phase-flow/far-from-equilibrium-phase-change/two-component/phenomenon. It needs to be understood under the perspective of "self-acting-separation of droplets of water".

The biggest challenge to the energy industry in the industrialized countries is the carbondioxide-climate-change-problem. The solution requires the reduction of the application of fossil primary energy carriers by the factor of about 5 for the world, and e.g. by the factors of about 13 for FRG and about 10 for Japan. As a contribution to the solution a new proposal has been made recently: the production of energy alcohol, e.g. methanol, on the basis "biomass plus HTR". This proposal fulfills fundamental desirable feature of future energy systems: it is CO<sub>2</sub>-neutral (because of the biomass), it is environmentally benign (only C<sub>1</sub>-molecules), it is application-friendly (methanol is a staple commodity), and it reduces competition with food production (because of the HTR). The main part of the energy conversion process is the helium-heated fluidized bed steam gasification of biomass. This a a two-phase-flow/solid-to-gaseous states-change/pyrolysis and chemical reaction/multi-component/phenomenon.

## Multiphase Flow Importance in Future Nuclear Process Heat Applications: Energy Alcohol by Biomass Gasification

### 1. Multiphase Flow Phenomena in Modern Technology

1.1. In summary: Phenomena of multiphase flow are very important in industrial technologies, and in particular in the energy industry. Additional importance arises from nuclear energy conversion processes, because of the relevance of phase change to safety. For the future of nuclear energy with extended function and new applications the three identified examples of importance of multiphase phenomena are multi-coating on micro-particles of nuclear fuel, self-acting separation of droplets outside of the core, and fluidized bed steam gasification of biomass.

1.2. In detail on multiphase flow phenomena in conventional energy and established nuclear energy conversion processes:

1.2.1. Multiphase flow phenomena are very important in industrial technology; many industrial processes include phase changes in any combination of solid, liquid and gaseous states, often also in multi-component systems. The scientific description of these phenomena is sometimes decisive for the application in the market.

1.2.2. In energy industry multiphase phenomena became important, because the phase change of water in liquid/steam-states is the main reason for the success of the steam turbine cycle in comparison to other proposed cycles, e.g. gas turbine cycle for the production of electricity from heat. Additionally the stimulating effect of phase change on heat transfer in liquid/steam-states is the reason for the many applications in energy conversion processes.

1.2.3. In the nuclear energy conversion technology multiphase flow phenomena are important because of the above mentioned reasons, but have also importance because of the relevance of phase changing processes to the safety. Liquid water (light water and heavy water, with the light hydrogen atoms and the heavy hydrogen atoms, called deuterium-atoms) is used as the moderator (to slow down fast neutrons into thermal equilibrium) and as the coolant, and phase changes therefore have an effect on the reactivity of the neutron-chain-reaction. The phase change from liquid to steam states is called the "void-effect of reactivity", it is a feed back-effect and may be positive or negative. The most important one of the many reasons of the catastrophic accident of the Chernobyl reactor is that it has a positive void-effect of reactivity, which - under the conditions of the accident - did cause the nuclear explosion.

1.3 In extension on multiphase phenomena in future nuclear energy conversion processes:

1.3.1. For the future of nuclear energy multiphase flow phenomena are important for reasons of extended function by production and application of high temperature heat, also for process heat application, and of improved safety.

1.3.2. The three selected examples are:

- multi-coating on micro-particles of nuclear fuel in "Coated Particles"
- self-acting separation of droplets outside of the core of the HTR, and
- fluidized bed steam gasification of biomass in a helium-heated gas generator for the newly proposed energy system "energy alcohol from biomass plus high temperature heat".

## 2. Multi-Coating on Micro-Particles of Nuclear Fuel for the High Temperature Reactor HTR

2.1. In summary: The technology of the "Coated Particles" with the multi-coating of ceramic coatings on micro-particles of nuclear fuel produced by chemical vapour deposition in a fluidized bed is the technological reason for the ability to produce high temperature heat because the multi-coating realizes a very good retention capability for radioactive material, including fission products. The good retention capability is achieved by ceramic material being deposited in phase change from gaseous to solid state forming the coatings, as a two-phase-fluidized flow/gaseous-to-solid-states-change by pyrolysis/multi-component phenomenon.

2.2. In detail on the High Temperature Reactor HTR, its fuel with coated particles, the production process and the possibilities to improve it:

2.2.1. The High Temperature Reactor HTR is a graphite moderated helium-cooled thermal reactor. In its historical development three types of fuel elements have been developed, the "Pin-in-Block" design in Japan, the block-type in USA and the pebble-type fuel element in FRG, fig. 1. But, irrespective of the type of fuel element, the important technological feature is that the nuclear fuel is used in the form of "Coated Particles", fig. 1, lower part and fig. 2.

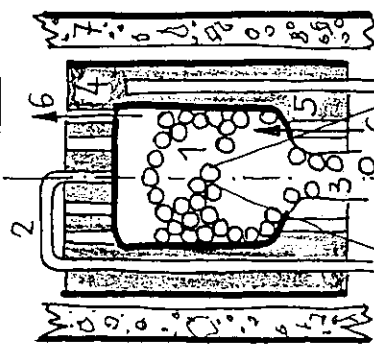
2.2.2. The Coated Particle in its advanced form with the TRISO-coating, fig. 2, consists of the kernel with the nuclear fuel uranium dioxide  $UO_2$  with a diameter of about 0.5 mm, and of the coating, which consists of 4 different layers of coatings, forming the multi-coating on the micro-particle. The total diameter of the Coated Particle is about 0.9 mm. The inner layer is the "buffer"-layer, consists of carbon, and serves as buffer for gaseous fission products. The following three layers are the a) inner PyC-layer (PyC = Pyrolytic Carbon), b) the SiC-layer (SiC = Silicon Carbide), and c) the outer PyC-layer. Typical values for the thickness of the 4 layers, from inside to outside, are: 95, 40, 35 and 40  $\mu m$ .

2.2.3. The coating of the Coated Particle is a multi-coating on a micro-particle being produced by Chemical Vapour Deposition in a fluidized bed, fig. 3, lit. BARNERT-E-1977. The fluidized gas, coming from the bottom of the cone of the coater, containing (in mixture) the chemical deposition gas. The pyrolytic reaction in that gas, type: hydrocarbons  $C_nH_m$  and  $C_nH_mSi$ , at temperatures of about 1 800 °C produces by phase change from gaseous to solid state the solid material of the ceramic layers of the coating. The technology has been developed and demonstrated, and it is in industrial application with good success.

2.2.4. The technological purpose of the coating of the Coated Particle is the retention of radioactive material, including fission products inside of the coating, at conditions of normal operation, and of deviations from normal operation as well as in intermediate and final storage. The retention acts against the driving force of mobility of the various isotopes of radioactive

# High Temperature Reactor HTR

Coated Particle, Pebble (SiC), MODUL, Pre-stressed

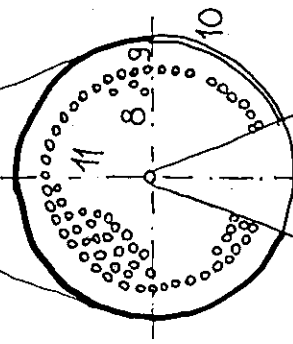


## Reactor Core

- 1 pebble bed, e.g. 3m  $\phi$   
e.g. 100 000 pebbles
- 2 fueling, continuously
- 3 discharge, continuously
- 4 graphite structure
- 5 shut down system
- 6 cooling: helium
- 7 shielding

## Fuel Pebble 6cm $\phi$

- 8 coated particle matrix  
e.g. 30 000 coated particles  
in mixture with graphite
- 9 outer shell, 5mm
- 10 SiC coating, e.g. 100  $\mu$ m
- 11 pebble of graphite



## Coated Particle 1mm $\phi$

- 12 kernel of nucl. fuel  
e.g.  $UO_2$ , 0.5mm  $\phi$
- 13 coating, e.g. 4 layers
- 14 buffer PyC pyrolytic carbon
- 15 PyC
- 16 SiC silicon Carbide
- 17 PyC

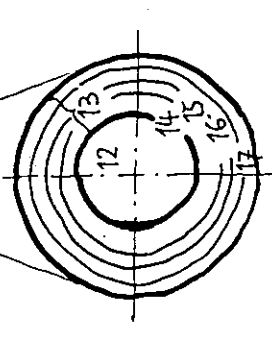
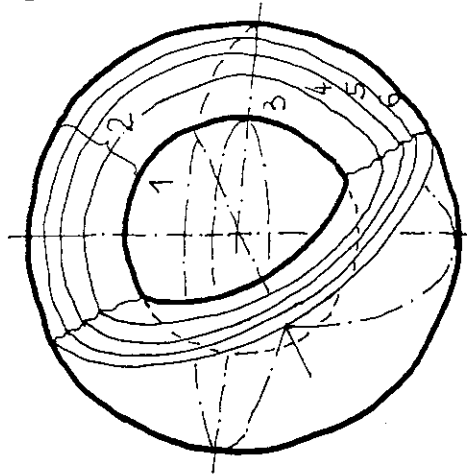


Fig. 1

# High Temperature Reactor HTR HTR Fuel in Coated Particles

## Coated Particle

TRISO Coating



coating cut open

- 1 kernel of nuclear fuel, e.g.  $UO_2$ , 0.5mm  $\phi$
- 2 coating, e.g. 4 layers
- 3 buffer layer, low density pyrolytic carbon, 95  $\mu$ m
- 4 inner PyC layer (PyC = Pyrolytic Carbon) high dens. 40  $\mu$ m
- 5 SiC layer (SiC = Silicon Carbide) 35  $\mu$ m
- 6 outer PyC layer, 40  $\mu$ m

Fig. 2

# Coater : Conical Fluidized Bed

## Production of Coated Particles, HTR

---

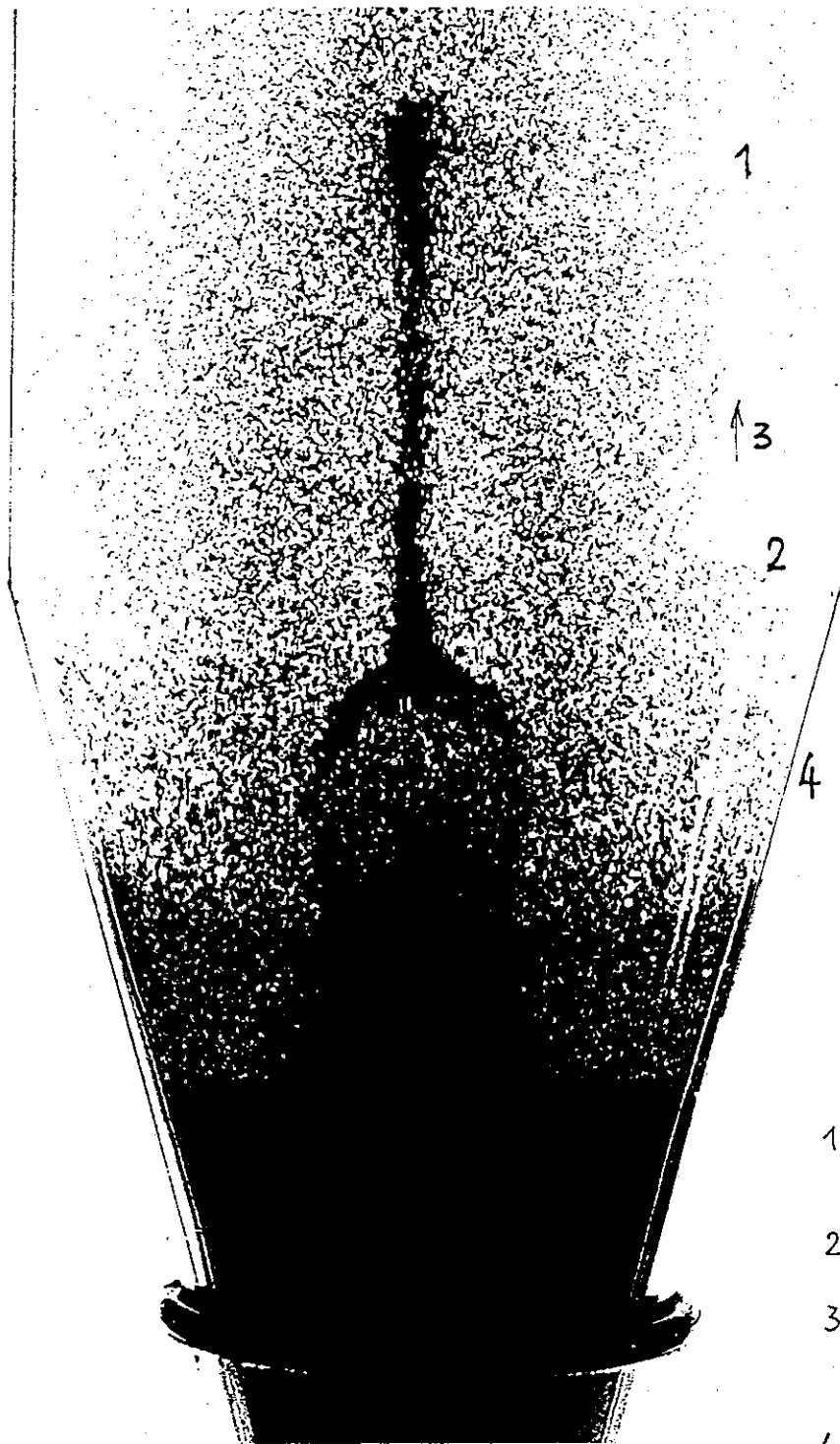


Fig. 3

- 1 Fluidized Bed of Particles
- 2 Conical Structure
- 3 Flow of Gases  
Carrier Gas  
Coating Gas
- 4 Glas structure for Foto Making

Lit.: BARNERT-E-1977

material, which is increasing with temperature. The good retention capability is the technological reason for the ability to produce high temperature heat from nuclear energy.

2.2.5 The retention of radioactive material, measured as "Release/Birth, R/B" is e.g.  $R/B = 2 \times 10^{-7}$  for Kr 85 m (radioactive fission product: isotope Krypton 85 m, noble gas) after 359 days of irradiation with the central temperature of 1 200 °C and a burnup of 7.5 % in FIMA (= fissions per initial heavy metal atom) with a fluens of  $4 \times 10^{21} \text{ cm}^{-2}$  ( $E > 0.1 \text{ MeV}$ ) for the probe HFR-K3/1; another typical value for the retention is e.g.  $R/B = 7 \times 10^{-9}$  (Kr 85 m), 396 days, central temperature 1 120 °C, 7.6 % FIMA at  $0.2 \times 10^{21} \text{ cm}^{-2}$  for the probe FRJ 2 -K 13/4, lit. SCHENK-1993, table 2, for both probes.

2.2.6. For the conditions of the design basis event "loss of active afterheat removal" the "design-margin" of 1 600 °C has been introduced, meaning that in a modular design of an HTR core the fuel temperature should due to afterheat only rise up to values below that margin. The retention capability at that design-margin temperature of 1 600 °C is still very excellent with e.g.  $R/B = \text{below } 1 \times 10^{-6}$  (for Kr 85 m) for more than 300 hours, lit. SCHENK-1993, Abb. 4. Only for higher temperatures the retention is degrading.

2.2.7. The retention capability of the coating is produced by the three outer layers, that is: PyC-layer, SiC-layer, and PyC-layer (therefore TRISO: 3 zones), with most contributions from the SiC-layer (which historically was later added to the BISO: 2 zones-concept). The most important barrier against release, the SiC-layer, does not show damages due to irradiation and due to temperature up to about 2 000 °C, only for temperature of about 2 100 °C decomposition starts, lit. SCHENK-1993.

2.2.8. Due to the fabrication process of the Coated Particle the fraction of the so called "free uranium" is about 10 ppm, lit. NABIELEK-1993. In that description of the state of art, see also lit. KASTEN-1994, it is explained that an improvement in the quality has been achieved and that "measurements have shown that practically all measured free uranium comes from defect particles".

2.2.9. The R & D work on Coated Particles will be continued and does have the objective to reduce e.g. the fraction of defect Coated Particles in the production process. The results show that this obviously is possible, lit. FUKUDA-1993, first table. The goal is a further reduction of that fraction and a high standard of quality assurance, as well as generally a further overall improvement of the retention, e.g. by introduction of isotope-class-specific barriers, against e.g. noble metal fission product migration, e.g. by an additional layer.

2.2.10. The operation of the experimental high temperature reactor AVR in Jülich has demonstrated for years - in the first time with fuel elements with BISO-Coated Particles and than with fuel elements with TRISO-Coated Particles - that the production of high temperature heat with temperatures up to 1000 °C is a reality.

### 3. Self-Acting Separation of Droplets outside the Nuclear Core of the HTR

3.1. In summary: The requirement of catastrophe-free nuclear energy technology led to the identification that the ingress of water droplets into the nuclear core of the HTR should be avoided by a self-acting separation of droplets coming from the steam generator tube break before they can get into the core. The behaviour of the water/steam jet in the helium stream as a two-phase-flow far from equilibrium phase change/two component-phenomenon-flow needs to be understood under the perspective of "self-acting separation of droplets of water". R & D work has been started recently.

3.2. In detail on catastrophe-free nuclear energy technology, on the positive effect on reactivity caused by water/steam ingress into the core of the HTR and design problems:

3.2.1. Recently the fundamental future requirement of catastrophe-free nuclear energy technology has been introduced, lit. THEENHAUS-1992. Meanwhile in the Federal Republic of Germany the Atomic Law has got amendments of revolutionary character, lit. ATOMIC-LAW-1994: The new requirement is "that also events which are .... practically excluded, would not make necessary decisive countermeasures off-site of the fence of the plant". In the explanation of the text from the discussions in the German Parliament those events are described as "core-melts" and those decisive countermeasures as "evacuation of the people".

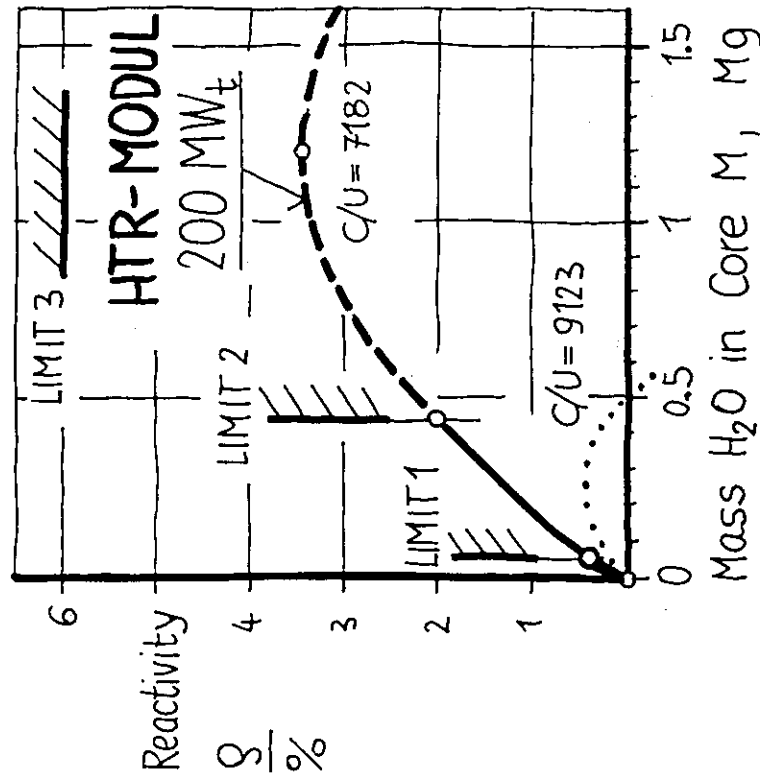
3.2.2. The formulation of the requirement of catastrophe-free nuclear energy technology means the following: self-acting stabilization of the operational processes under operational and accidental conditions leading to neutron physical, thermal, chemical, and mechanical stability, lit. KUGELER-1994.

3.2.3. From the process of neutron moderation in graphite it is known that additional water, e.g. from the ingress of steam and or water, may lead to the positive effect on reactivity, fig. 4, lit.: SIEMENS-1988, SCHERER-1994, TEUCHERT-1992. This effect depends from the moderation ratio C/U (carbon/fissile atoms) and from the additional amount of H-atoms in the form of H<sub>2</sub>O in the core, it needs to be controlled, and - possibly - be minimized, or - even better - be avoided to the utmost extent. Further details are explained in point 3.3.

3.2.4. The ingress of water into the primary circuit is a design basis event; the water comes from the break of a tube in the steam generator and forms a water/steam-jet, fig. 5. The usual assumption "filling of the empty space of the core by high pressure steam with limited pressure by the safety valves", lit. SIEMENS-1988, needs to be approved and possibly corrected, because H<sub>2</sub>O of high density may reach the core in the form of droplets increasing the mass of water without a corresponding increase of the pressure and thereby led to higher values of positive reactivity.



# HTR Core + Steam Generator Reactivity vs. Water in Core



LIMIT 1 : 60 kg H<sub>2</sub>O , 606 He + 106 steam  
 LIMIT 2 : 450 kg H<sub>2</sub>O , 706 steam  
 LIMIT 3 :  $\rho_3 = -\Gamma_f \cdot \Delta T = -(-6 \cdot 10^{-5} \text{K}^{-1}) \cdot 1000 \text{ K} = 6 \%$   
 design - margin - T = 1600 °C

Lit.: SIEMENS-1988 , SCHERER-1994 , TEUCHERT-1992

# HTR Core + Steam Generator Self-acting Separation of Droplets

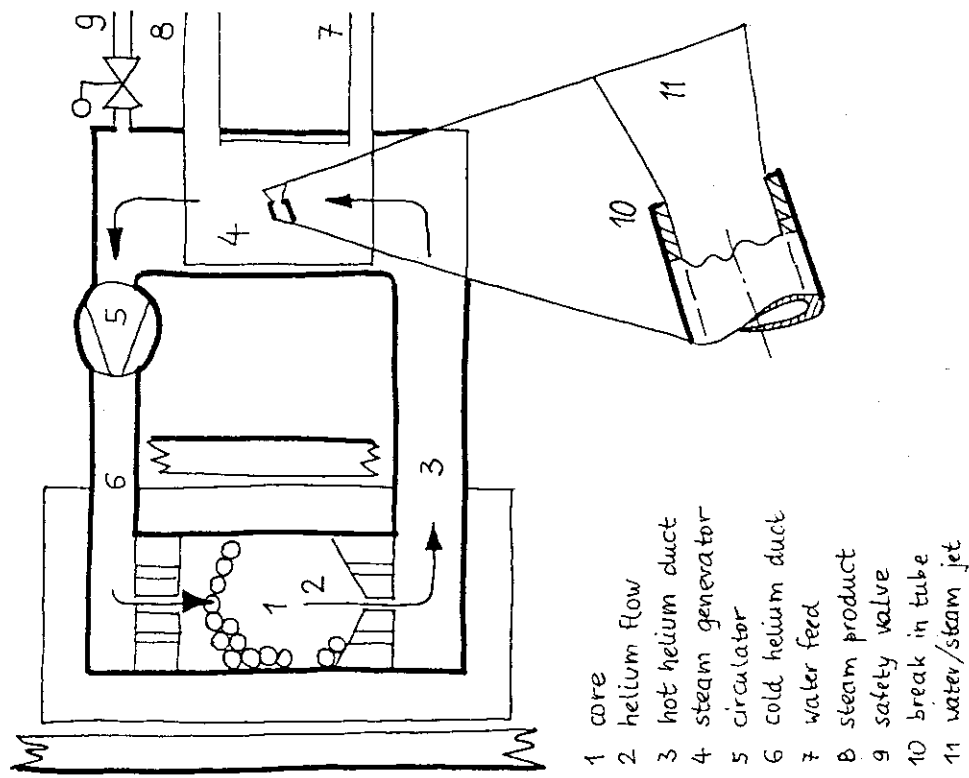


Fig. 4  
 Fig. 5

3.2.5. The behaviour of the water/steam-jet in the helium stream as "a two-phase phase-change two component-phenomenon" needs to be understood under the perspective of "self-acting separation of droplets of water" from the helium stream before they can reach the nuclear core of the HTR. The solution has to consider a large variety of forms of breaks, locations, and of conditions of water/steam and jets; R and D work has been started recently with an experimental facility simulating the primary circuit of the HTR.

### 3.3. In extension on the effect of water on the reactivity of the core of the HTR:

3.3.1. The reactivity of the core of the HTR - as a graphite moderated reactor - is mainly determined by the so-called moderation ratio  $C/U$  (carbon/fissile atoms), but shows also a dependence from additional water because the H-atoms are rather effective moderator-atoms. For the HTR-Modul, 200 MWt, the recent product of the vendor industry in the Federal Republic of Germany, lit. SIEMENS-1988, the reactivity versus mass of  $H_2O$  in the core, lit. SIEMENS-1988, SCHERER-1994, TEUCHERT-1992, fig. 4, shows an increase of reactivity up to a maximum of 3,5 % from 0 to about 1.2 Mg of  $H_2O$ , and then a decline, which crosses the zero reactivity abscissa at about 3 Mg of  $H_2O$ .

3.3.2. In the considerations of the safety of the HTR-Modul the following 3 limits have been discussed and can be identified as follows, fig. 4:

LIMIT 1:  $M = 60$  kg  $H_2O$  makes  $P = 60$  bar helium + 10 bar steam, safety valves opens,  $\rho_1 = 0.4$  %, that is a small value, it is compensated by a slight temperature increase of about 100 K if the control-system fails, design basis event, lit. SIEMENS-1988, TEUCHERT-1992.

LIMIT 2:  $M = 450$  kg  $H_2O$  at  $P = 70$  bar steam at open safety valves makes  $\rho_2 = + 2$  %, hypothetical design basis event, can also be compensated by temperature increase, lit. TEUCHERT-1992, SCHERER-1994.

LIMIT 3: With the temperature difference between the design margin temperature of 1 600 °C and the operational temperature (550 °C) of about 1 000 K and with an integrated mean temperature coefficient of  $\Gamma_T = - 6 \cdot 10^{-5} K^{-1}$  the maximum compensation limit is  $\rho_3 = + 6$  %, which is well above the maximum reactivity of the water ingress.

3.3.3. A more fundamental solution of the positive reactivity effect of water is the increase of the moderation ratio from  $C/U = 7182$  in the HTR-Modul to e.g.  $C/U = 9123$ , which reduces the maximum reactivity  $\rho_{max}$  from about 3.4 to only 0.4, fig. 4 dotted line, lit. TEUCHERT-1992. An imperceptible change of the normal operational point from the left slop side to the right could be avoided by the control system.

3.3.4. All these conceptual efforts are in R + D because of the fundamental desirable feature "to avoid self-acting de-stabilizing qualities in the fundamental conceptual design choices", lit. BARNERT-1991, p. 39.

#### 4. Energy Alcohol from Biomass plus High Temperature Heat

4.1. In summary: The proposed energy system "energy alcohol from plant biomass plus high temperature heat", e.g. from the High Temperature Reactor HTR, has the following advantages: it is CO<sub>2</sub>-neutral, environmentally benign and application friendly, and it realizes a reduced competition with food stuff production. The main part of the energy conversion process is the helium heated fluidized bed steam gasification of biomass, e.g. wood, as a two-phase-fluidized-flow/solid-to-gaseous-states-change by pyrolysis and chemical reaction/multi-component/phenomenon. R and D work can rely on know how developed for steam gasification of coal.

4.2. In detail on the CO<sub>2</sub>-problem, the proposed CO<sub>2</sub>-neutral energy system and the main part of the energy conversion process, the steam gasification of plant biomass, e.g. wood:

4.2.1. The biggest challenge to the energy industry in the industrialized countries is the CO<sub>2</sub>-climate change problem, to a main part caused by the application of fossile energy carriers in the world. The solution requires the reduction of the application of fossile primary energy carriers by the factor of about 5 for the world and e.g. by the factors of about 13 for FRG, and about 10 for JAPAN (as calculated with energy market figures of today for the future with an increased population if 8 billion people), lit. BARNERT-1992, p. 83.

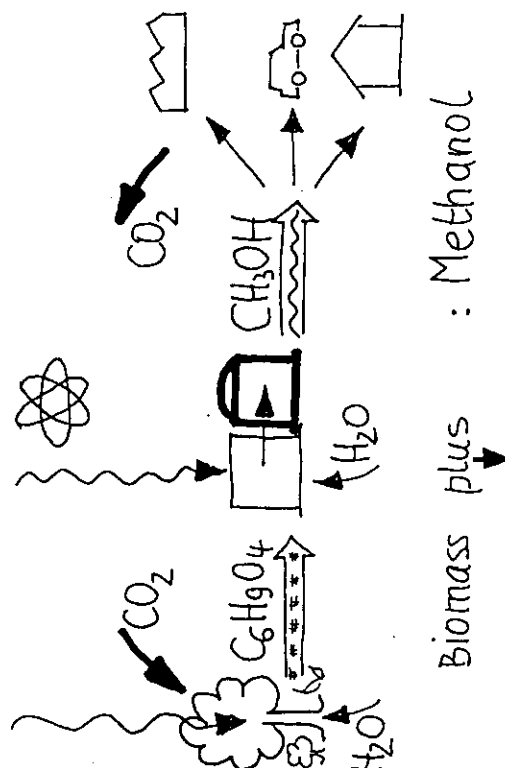
4.2.2. As a contribution to the solution of the problem a new proposal has been made recently; it is: "Switch into the Carbon-Cycle of the Biosphere, but with High Yield", lit. BARNERT-1995.

4.2.3. That headline summarizes the following new secondary energy production system on the basis of new primary energy carriers: the production of energy alcohol, e.g. methanol, on the basis "biomass plus exogeneous, CO<sub>2</sub>-free primary energy", e.g. nuclear energy from the High Temperature Reactor HTR or solar energy, fulfils fundamental desirable feature of future energy systems: it is CO<sub>2</sub>-neutral (because of the biomass), it is environmentally benign (only C<sub>1</sub>-molecules), it is application friendly (methanol is a liquid) and it reduces competition with food production (because of the exogeneous CO<sub>2</sub>-free primary energy). The product methanol is a staple commodity, it can easily be stored, and it serves as an oil substitute for fueling motors and heating rooms, fig. 6, lit. BARNERT-1995.

4.2.4. Methanol is a liquid and has the highest C<sub>1</sub>-mol specific heating value, fig. 7. This is important from the view point of secondary energy carriers being produced from nuclear energy, because up to now nuclear energy is only used for the production of electricity, which is a grid commodity. The perspective is that by the production of a staple commodity e.g. methanol, the real requirements of the energy market can be met in an easier and more application friendly way, with improved conditions for economical competitiveness.

**G-Cycle : Biomass plus : Methanol**

CO<sub>2</sub> - neutral : C-Cycle  
environmentally benign : C<sub>1</sub>  
application friendly : liquid  
reduced competition with food prod.: exogenous



exogenous  
CO<sub>2</sub> free  
energy, e.g.  
solar energy  
nuclear energy

wood  
grass

oil substitut  
motor fuel  
room heating

Methanol: Highest  $H_{1c}$  Liquid

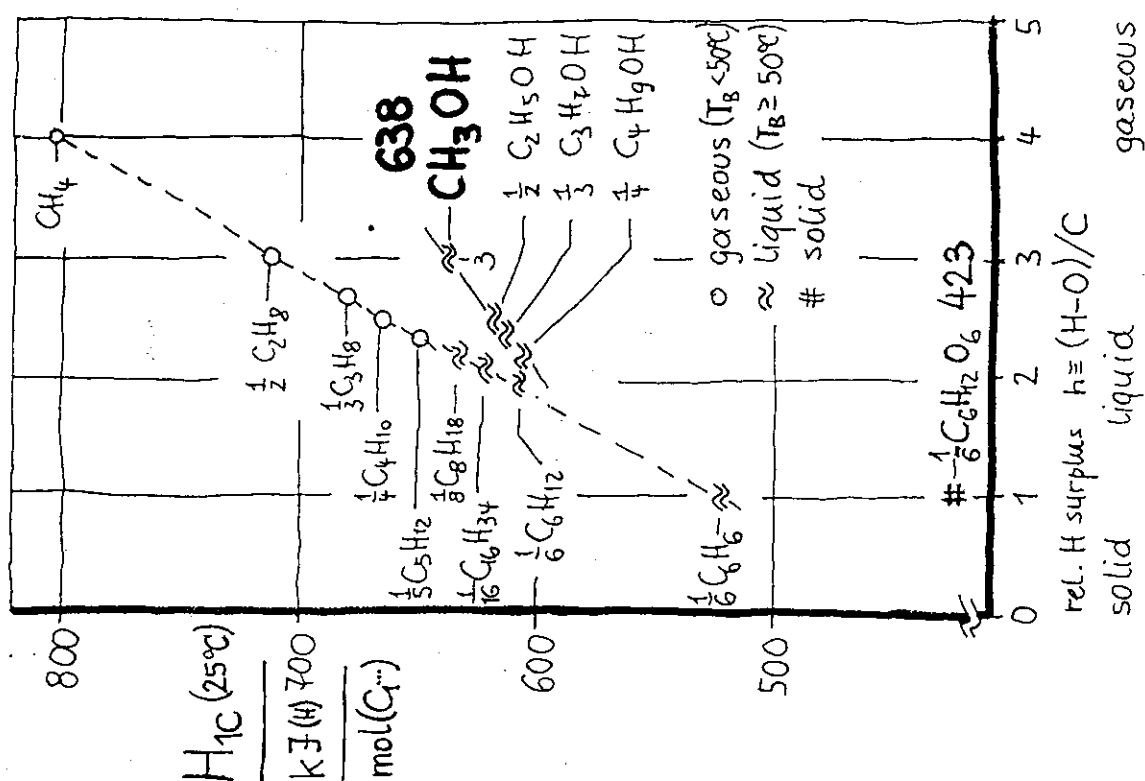


Fig. 6      Fig. 7

4.2.5. From chemical point of view the proposal means the following: the solid carbohydrates of plant biomass, as produced by photosynthesis in the form of glucose  $C_6H_{12}O_6$  (the most synthesized substance on earth), respectively in the polymerized form, e.g. cellulosis of wood,  $C_6H_8.63 O_{3.7} \times 2 H_2O$  (wood, air dry), are under "energy increasement" with high yield converted into the hydrocarbon methanol  $CH_3OH$ , which is optimized to the application. The energy increasement is possible because of the  $C_1$ -mol specific hydrogen deficit of plant biomass in comparison to methanol. The for the energy increasement necessary energy should be taken from other energy than plant biomass, that is called "exogenous", to produce a high yield with respect to the C-atoms in plant biomass: All C-atoms from plant biomass should be converted into the product methanol.

4.2.6. The exogenous energy should be taken from  $CO_2$ -free primary energy carriers, that means from other than fossil fuels (coal, oil, natural gas and others more), e.g. nuclear energy or solar energy, to provide a contribution to the solution of the  $CO_2$ -climate change problem. The result is than a " $CO_2$ -neutral" energy system, because the from the burning of methanol produced emissions of  $CO_2$  are "recycled" by photosynthesis in sustainable plant biomass production.

4.2.7. The exogenous energy is partly coupled into the production process in the form of high temperature heat (which usually is advantageous), because carbohydrates can be used for the production of hydrogen by the reduction of water in the same manner as coal; the remaining amount needs to be provided hydrogen, being produced by the electrolysis of water.

4.2.8. The production process for methanol from biomass plus High Temperature Reactor HTR consists mainly of the process of gasification of biomass, e.g. Steam Gasification of Wood, SGW, in a gas generator, being heated by helium with a temperature of 1 000 °C from the HTR, fig. 8. The required steam is taken from the steam turbine cycle (back pressure), partly mixed to the feed biomass and partly via the steam Super Heater, SSH, fed into the gas generator for the fluidization of the biomass. The required temperature of the superheated steam is about 800 °C. The required additional hydrogen is produced by electrolysis of water, ELY; with electricity being produced in the steam turbine cycle, STG-T-G (Steam Generator, Turbine, Generator), applying the lower temperature heat from the primary circuit of the HTR. The product gas of the SGW and the hydrogen  $H_2$  from ELY form the synthesis gas for the methanol synthesis MES.

4.2.9. An overview on the chemical reactions and on the energy balance of the production process for methanol from biomass plus HTR, fig. 9, indicates that the efficiency  $e$  and the product yield  $c$  are about  $e = 52 \%$  and  $c = 150 \%$ . The product yield  $c$  is defined as the energy content of the product methanol relative to that one of the feed biomass, and it describes thereby the energy increasement.

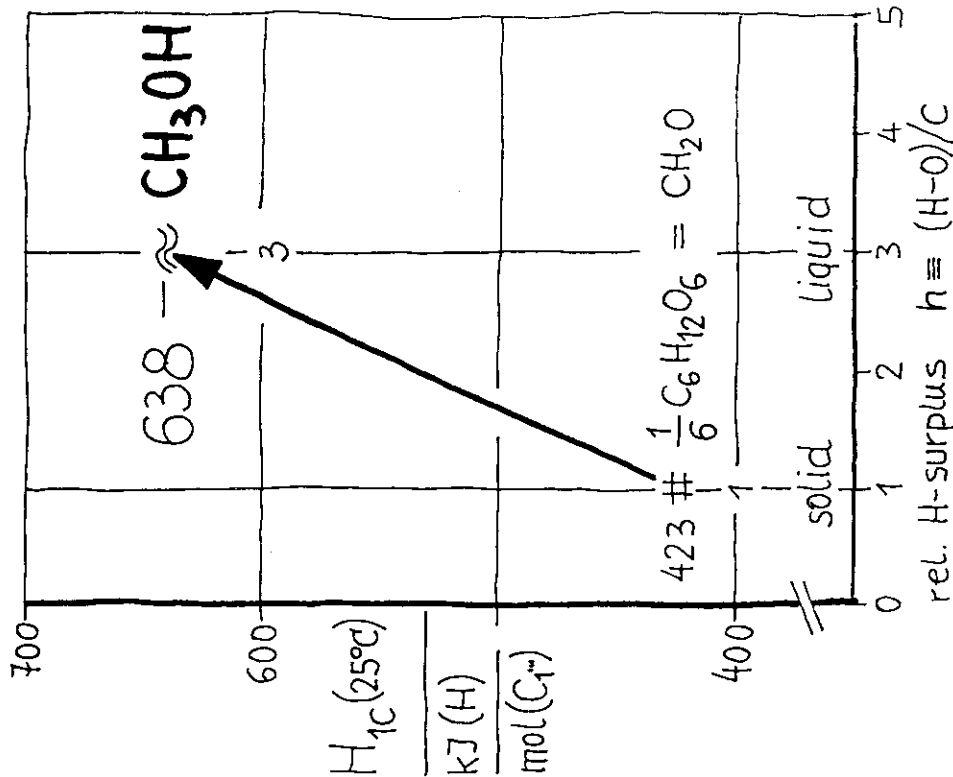


4.2.10. The emergy increasement for the production process for methanol from biomass plus HTR, is graphically represented in the H-h-diagram (H for  $H_1C$  = lower heating value,  $C_1$ -mol specific; and  $h = (H - O)/C$  = relative H-atoms surplus), in overview (on the basis of glucose  $C_6H_{12}O_6$ ) in fig. 10 and in detail (for Steam Gasification of Wood, SGW,  $C_6H_{8.63}O_{3.7} \times 2H_2O$ , wood, air dry) in fig. 11, including the various production steps SWG, ELY and MES. The exogenous energy for the energy increasement is provided by the HTR in the form of high temperature heat (high temperature helium in the gas generator, SWG, and superheated steam, SSH and STG, and of hydrogen  $H_2$  from the electrolysis, ELY, together with the unavoidable energy losses of the overall production process. Nuclear energy (from the HTR) is  $CO_2$ -free and exogenous (non-biomass).

4.2.11. The comparison of the proposed new process with an established process, e.g. "ethanol from sugar cane", lit. HEINRICH-HERGT-1990, S. 238, as systems (including biomass production) shows, that the new process has a much higher production yield c. It is by the factor of 3.5 higher, fig. 12. The reason is simply that the new process uses a high amount of exogenous,  $CO_2$ -free primary energy, and that it avoids residues from biomass to the utmost extend. This factor of 3.5 is decisive with respect to economical competitiveness and with respect to the competition between energetic applications of biomass and food stuff production of biomass.

4.2.12. The main part of the production process, the steam gasification of biomass, e.g. wood, SWG, needs to be developed, all other steps are existing technologies or technologies in development, as e.g. the HTR with e.g. the project of the High Temperature Engineering Test Reactor HTTR in JAPAN, lit. JAERI-1994. A helium-heated fluidized-bed gas generator is proposed, being based on a two-phase-flow/solid-to-gaseous-states-change/pyrolysis and chemical reaction/multi-component/phenomenon. Old designs of gas generators, lit. DUBBEL-1956, Bd. 2, S. 86, fig. 13, indicate feasibility; know how is provided from designs for the helium-heated fluidized bed gas generator for steam gasification of hard coal, lit. SINGH-1992, fig. 14. The difference of biomass to hard coal is mainly that the volatile fraction of biomass is larger, indicating that the two phase flow phenomenon needs to be studied with respect to fluidization of biomass of different kind, behaviour of the various contents of water in biomass, the methods of feeding and of product gas cleaning, mainly from dust, the heat transfer from the helium-heated bundles to the fluidized bed, and others more.

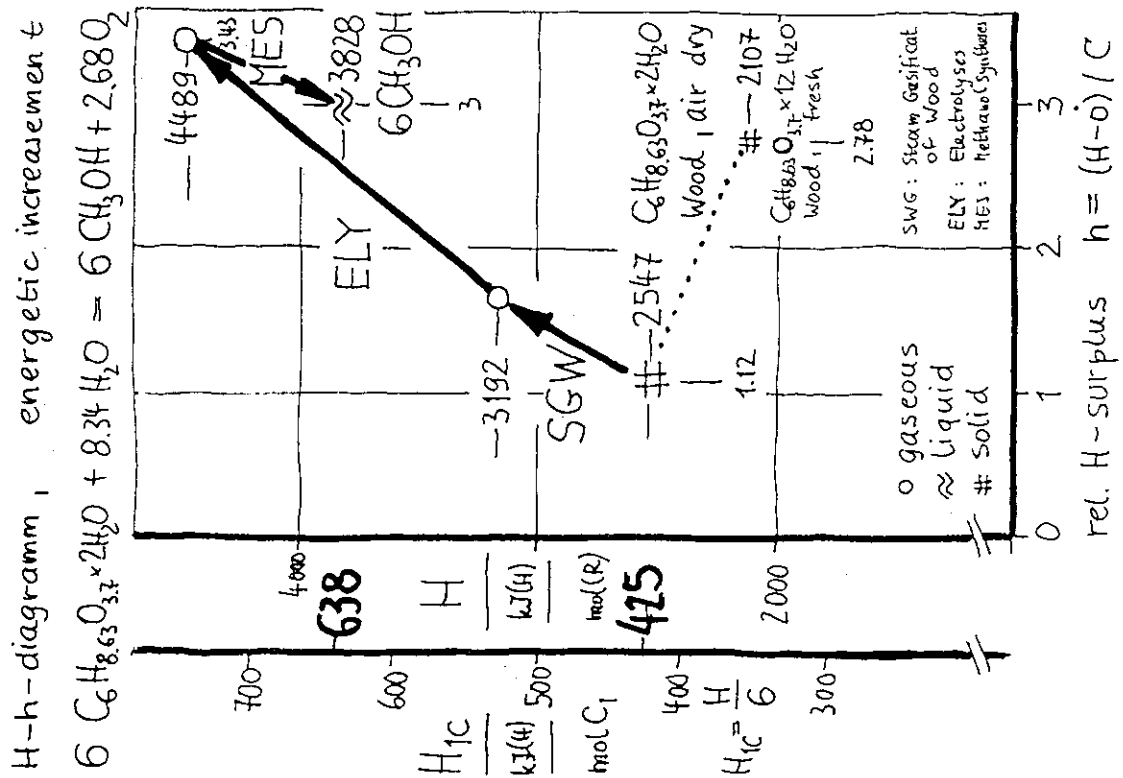
# Energy Increase: Biomass plus



$C_6H_{12}O_6$  : biomass, e.g. Glucose  
 $CH_3OH$  : methanol

Fig. 10  
11

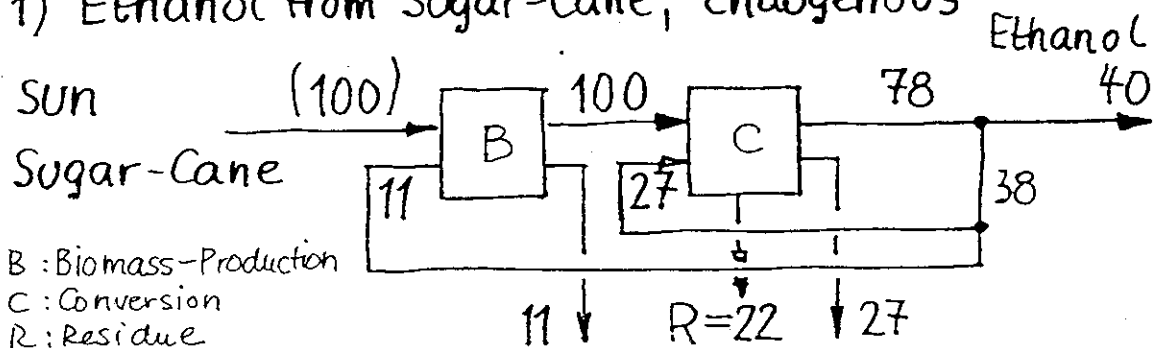
# Methanol from Wood, exogenous





# CO<sub>2</sub>-neutral alcohol, comp. systems

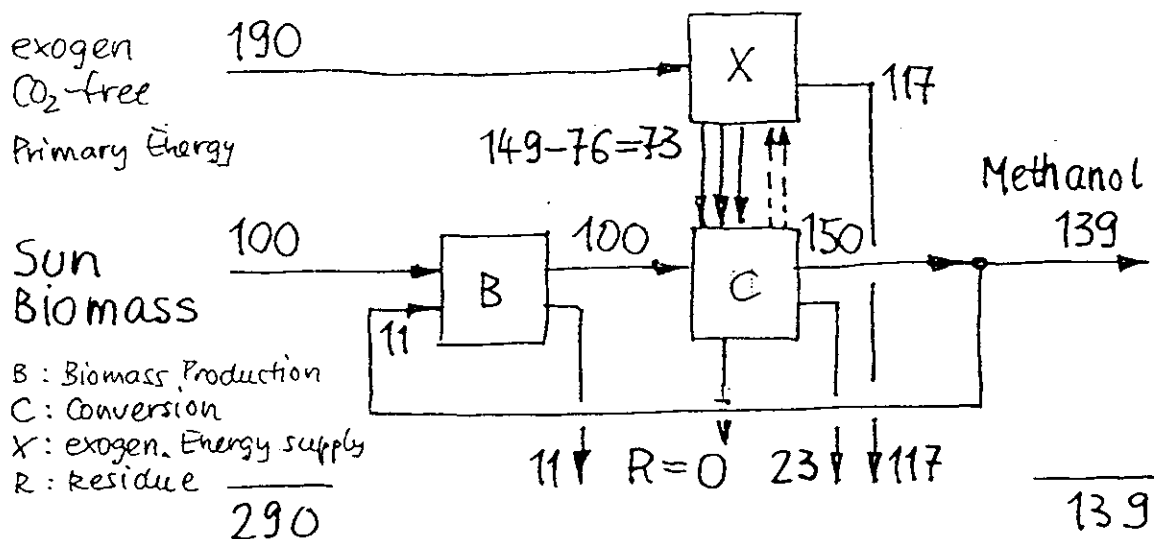
## 1) Ethanol from Sugar-Cane, endogenous



$$e = c = \frac{40}{100} = 0.4 = 40\%$$

Lit.: HEINRICH-HERGT-1990, S.238

## 2) Methanol from Sugar-Cane or Wood, exogenous



$$e = \frac{139}{290} = 0,4793 \approx 48\%$$

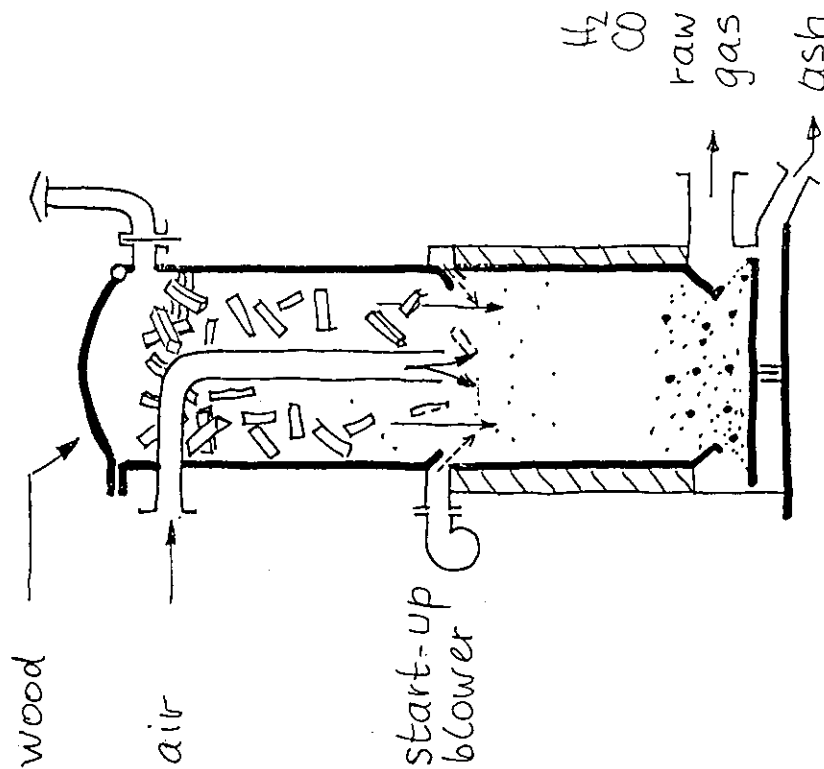
$$c = \frac{139}{100} = 1,39 = 139\%$$

Fig.12

## 3) Comparison

$$\text{Ratio} \equiv \frac{C_2}{C_1} = \frac{1,39}{0,40} = 3,475 \approx 3,5$$

## Gasgenerator, conventional



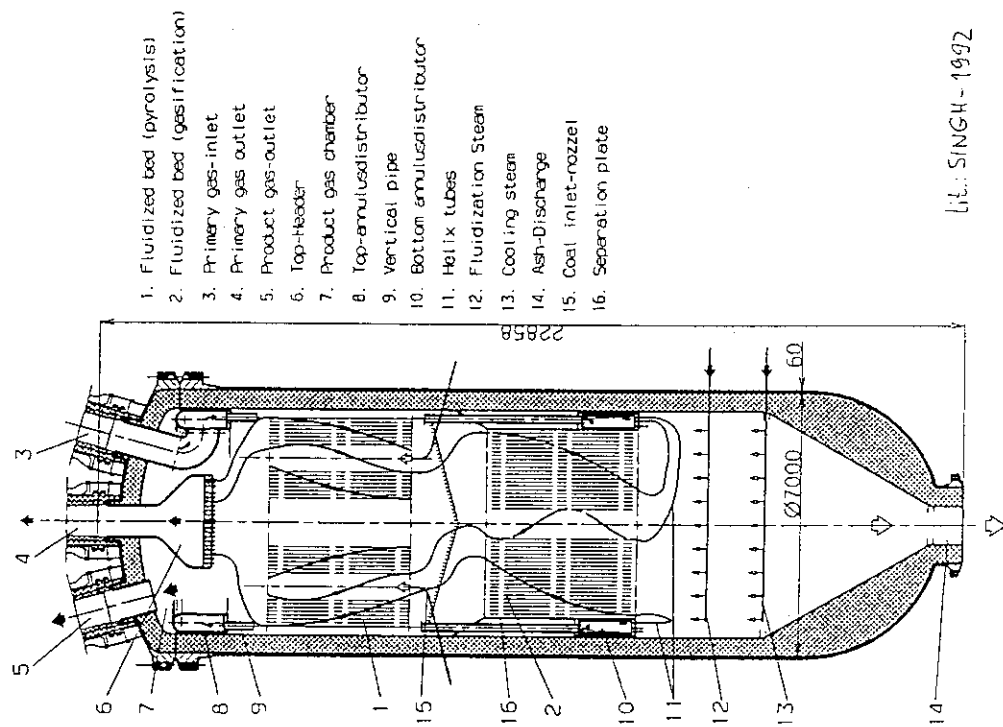
co-current  
down draught

Lit.: DUBBEL-1956, II, 86

Fig. 13

## Gas Generator, Steam Gasification

Helium-heated, for hard coal, vertical



Lit.: SINGH-1992

Fig. 14

## 5. Summary and Background of the Three Identified Examples of Importance

5.1. Phenomena of multiphase flow are very important in industrial technologies, and in particular in the energy industry. Additional importance arises from nuclear energy conversion processes, because of the relevance of phase change to safety of nuclear energy. For the future of nuclear energy with extended function and new applications the three identified examples of importance of multiphase phenomena are

- multi-coating on micro-particles of nuclear fuel in "Coated Particles",
- self-acting separation of droplets outside of the core of the HTR, and
- fluidized bed steam gasification of biomass in a helium-heated gas generator for the newly proposed energy system "energy alcohol from biomass plus high temperature heat".

5.2. The three identified examples of importance:

5.2.1 The technology of the "Coated Particles" with the multi-coating of ceramic coatings on micro-particles of nuclear fuel produced by chemical vapour deposition in a fluidized bed is the technological reason for the ability to produce high temperature heat because the multi-coating realizes a very good retention capability for radioactive material, including fission products. The good retention capability is achieved by ceramic material being deposited in phase change from gaseous to solid state forming the coatings as a two-phase-fluidized-bed/gaseous-to-solid-states-change by pyrolysis/multi-component/phenomenon.

5.2.2. The requirement of catastrophe-free nuclear energy technology led to the identification that the ingress of water droplets into the nuclear of the HTR core should be avoided by a self-acting separation of droplets coming from the steam generator tube break before they can get into the core. The behaviour of the water/steam-jet in the helium stream as a two-phase-flow/far-from-equilibrium-phase-change/two-component/phenomenon needs to be understood under the perspective of "self-acting separation of droplets of water". R and D work has been started recently

5.2.3. The proposed energy system "energy alcohol from plant biomass plus high temperature heat", e.g. from the High Temperature Reactor HTR, has the following advantages: it is CO<sub>2</sub>-neutral, environmentally benign and application friendly, and it realizes a reduced competition with food stuff production. The main part of the energy conversion process is the helium heated fluidized bed steam gasification of biomass, e.g. wood, as a two phase-flow/solid to gaseous states change/pyrolysis and chemical reaction/multi-component/phenomenon. R and D work can rely on know how developed for steam gasification of coal.

## LITERATURE

### ATOMIC-LAW-1994

Bundesgesetzblatt: Gesetz zur Sicherung des Einsatzes von Steinkohle in der Verstromung und zur Änderung des Atomgesetzes und des Stromeinspeisungsgesetzes, Bundesgesetzblatt, Teil I, Z5702 A, Nr. 46, S. 1618-1624, ausgegeben zu Bonn am 28. Juli 1994; sowie Deutscher Bundestag (12. Wahlperiode): Gesetzentwurf der Bundesregierung, Drucksache 12/6908, Kapitel: C. Kernenergie, Einzelbegründung zu Artikel 4 (Gesetz zur Änderung des Atomgesetzes), 25. Februar 1994; in English: Federal Bulletin of Law: Law for Securing the Application of Bituminous Coal for Electricity Production and for the Change of the Atomic Law and the Law for Electricity Feed into the Grid, delivered at Bonn, 28. July 1994, as well as Federal Parliament (12th period): Proposal for a Law from the Federal Government, Document 12/6908, Chapter: C. Nuclear Energy, Reasoning in Detail to Article 4 (Seventh Law for the Change of the Atomic Law), 25. Februar 1994.

### BARNERT-1995

Barnert, H.: Energy alcohol from plant biomass plus high temperature heat, the CO<sub>2</sub>-neutral, environmentally benign, and consumer friendly future alternative, report from the Research Centre Jülich GmbH, KFA, Jül- , in preparation 1995.

### BARNERT-1992

Barnert, H.: The Reduction of the Global CO<sub>2</sub> Emission to One fifth, the BADEN-Approach and the CROCUS-Formulation, Jül-2653, July 1992.

### BARNERT-1991

Barnert, H.: Working Material on Nuclear Reactor Safety, the "Defence by Design"-Concept, Internal Report KFA-ISR-IB-23/91.

### BARNERT-E-1977

Barnert, Eike: Entwicklung einer Anströmeinheit für einen Wirbelschichtofen zur Beschichtung von HTR-Brennstoffkernen, in English: Development of a gas injector for HTR-particle coating in fluidized beds, Jül-1457, Sept. 1977.

### DUBBEL-1956

Sass, F., Bouché, Ch.: Dubbel, Taschenbuch für den Maschinenbau, 2 Bände, Springer Verlag, Berlin-Göttingen-Heidelberg, 1956, in English: Dubbel's Handbook of Mechanical Engineering, Springer Publication Company, Berlin, Göttingen, Heidelberg, 1956.

### FUKUDA-1993

Fukuda, K.: Recent progress in fuel research, JAERI, fuel irradiation and analysis laboratory, 21, October 1993, in NABIELEK-1993.

### HEINRICH-HERGT-1990

Heinrich, D., Herget, M.: dtv Atlas zur Ökologie, Tafeln und Texte, Deutscher Taschenbuchverlag dtv, 1990, in English: dtv Atlas on Ecology, Tables and Texts, 1990.

### JAERI-1994

Japan Atomic Energy Research Institute, JAERI: Design of High Temperature Engineering Test Reactor (HTTR), JAERI-1332, Sept. 1994.

**KASTEN-1994**

Kasten, P.R., Smith, D.A., Lichtenwalter, J.J., Nabielek, H., Verfondern, K.: Fuel performance in modular high temperature gas-cooled reactors, Forschungszentrum Jülich GmbH, KFA, Interner Bericht, KFA-ISR-IB-12/94, Oct. 1994.

**KUGELER-1993**

Kugeler, K., Neis, H., Ballensiefen, G. (Hrsg.): Fortschritte in der Energietechnik für eine wirtschaftliche, umweltschonende und schadenbegrenzende Energieversorgung, Prof. Dr. Rudolf Schulten zum 70. Geburtstag, Monografien des Forschungszentrums Jülich, Band 8, 1993, in English: Progress in the Energy Technology for an Economically Competitive, Environmentally Benign and Damages Limiting Energy Supply, Reports dedicated to Prof. Dr. Rudolf Schultens 70th Birthday, Monographs of the Research Center Jülich, Volume 8, 1993.

**KUGELER-1994**

Kugeler, K.: Innovative Techniken für eine langfristige Nutzung der Kernenergie, Jahresbericht Forschungszentrum Jülich GmbH, KFA, in English: Innovative Technologies for a Long-Term Use of Nuclear Energy, Annual Report of the Research Center Jülich GmbH, KFA, 1994.

**NABIELEK-1993**

Nabielek, H., Baba, O.: KFA-JAERI 1993 Annual Co-ordination Meeting, Forschungszentrum Jülich GmbH, KFA, Interner Bericht, KFA-ISR-IB-18/93, Oct. 1993.

**SIEMENS-1988**

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

**SCHENK-1993**

Schenk, W., Nabielek, H., Pott, G., Nickel, H.: Die Spaltproduktrückhaltung im Kugelbrennelement, in English: The retention of fission products in the pebble type fuel element, in KUGELER-1993, p. 321-328.

**SCHERER-1994**

Scherer, W., Brockmann, H., Drecker, S., Gerwin, H., Haas, K.A., Kugeler, K., Ohlig, U., Rütten, H.-J., Teuchert, E., Werner, H., Wolf, L.: Zur selbsttätig sicheren Begrenzung von nuklearer Leistung und Brennstofftemperatur in innovativen Kernreaktoren, in English: On self-acting safe limitation of fission power and fuel temperature in innovative nuclear reactors, Forschungszentrum Jülich GmbH, Jül-2960, Aug. 1994.

**SINGH-1992**

Singh, J., Barnert, H.: New Prospectives and Pre-feasibility results of the process heat HTR work, Nucl. Eng. & Design 136, p. 51-56, 1992.

**TEUCHERT-1992**

Teuchert, E., Haas, K.A., Rütten, H.J., Yulian Sun: Reduction of the reactivity of water ingress to modular pebble-bed High Temperature Reactors, ANS reprint, Nuclear Technology, Vol. 122, p. 192-195, May 1992.

**THEENHAUS-1992**

Theenhaus, R., Kugeler, K., presentation by H. Barnert: New requirements and recent work in safety questions, the 2nd JAERI symposium on HTGR technologies, Proceedings, Oarai, Japan, 21.-23. Oct. 1992.

## 6.5 Status of IAEA coordinated research program design and evaluation of heat utilization systems for the HTTR

John Cleveland  
Division of Nuclear Power  
Department of Nuclear Energy and Safety  
International Atomic Energy Agency  
Vienna, Austria

and

Irene Lewkowicz  
Division of Physics and Chemistry  
Department of Research and Isotopes  
International Atomic Energy Agency  
Vienna, Austria

Presented to the  
Panel Discussion on Nuclear Heat Utilization Technology  
and Role of Multiphase Flow Researches  
at the  
2nd International Conference on Multiphase Flow  
Kyoto, Japan, April 1995

### 1. Introduction

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

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

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

In Japan an important milestone was reached in March 1991 with the start of construction of the High Temperature Engineering Test Reactor (HTTR) at the Oarai Research Establishment of the Japan Atomic Energy Research Institute (JAERI). This 30 MW(t) reactor will produce core outlet temperatures of up to 950°C. It is anticipated that the HTTR will be the first nuclear reactor in the world to be connected to a high temperature process heat utilization system. Criticality is expected in 1998. The timely completion and successful operation of the HTTR and its heat utilization system will be major milestones in gas-cooled reactor development and in development of nuclear process heat applications.

## 2. Coordinated Research Programme framework and goals

The early development of nuclear power was conducted to a large extent on a national basis. However, for advanced reactors, international co-operation is playing an increasingly greater role. The IAEA promotes international co-operation in advanced reactor development and application. Especially for designs incorporating innovative features, international co-operation allows a pooling of resources and expertise in areas of common interest to help to meet the high costs of developing the technology.

The IAEA is advised on its activities in development and application of gas-cooled reactors by the International Working Group on Gas-Cooled Reactors (IWGGCR) which is a committee of leaders in national programmes in this technology. The IWGGCR meets periodically to serve as a global forum for information exchange and progress reports on the national programmes, to identify areas for collaboration and to advise the IAEA on its programme. This regular review is conducted in an open forum in which operating experience and development programmes are frankly discussed. Countries participating in the IWGGCR include Austria, China, France, Germany, Italy, Japan, the Netherlands, Poland, the Russian Federation, Switzerland, the United Kingdom and the United States of America.

The activities carried out by the IAEA within the frame of the IWGGCR include technical information exchange meetings and co-operative Co-ordinated Research Programmes (CRPs).

Co-ordinated Research Programmes are typically 3 to 6 years in duration, and often involve experimental activities in selected technology areas of mutual interest to the participating countries. Such CRPs allow a sharing of efforts on an international basis and benefit from the experience and expertise of researchers from the participating institutes.

The IAEA's Co-ordinated Research Programmes in gas-cooled reactor development focus on technical areas which are predicted to provide advanced HTGRs with a high degree of safety, but which must be proven. These technical areas are:

- a) the safe neutron physics behaviour of the reactor core;
- b) reliance on ceramic coated fuel particles to retain fission products even under extreme accident conditions, and
- c) the ability of the designs to dissipate decay heat by natural heat transport mechanisms.

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

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

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

The participating institutes are:

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

The systems being assessed for potential demonstration have been selected by CRP participants according to their own national interests depending on status of the technology, economic potential, safety and environmental considerations, and other factors.

The following systems are being examined:

- steam reforming of methane for production of hydrogen and methanol
- CO<sub>2</sub> reforming of methane for production of hydrogen and methanol
- combined coal conversion and steam generation
- thermochemical water splitting for hydrogen production
- high temperature electrolysis of steam for hydrogen production
- gas turbine for electricity generation

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

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

- a) define the R&D needs remaining prior to coupling to the HTTR
- b) define the goal of the demonstration with the HTTR
- c) prepare design concepts for coupling selected systems to the HTTR and perform



- d) preliminary safety evaluations
- d) check licensability of selected systems under Japanese conditions

### 3. The HTTR and its heat utilization system

According to the revision of the Long-term Programme for Development and Utilization of Nuclear Energy, issued by the Atomic Energy Commission of Japan in 1987, the High Temperature Engineering Test Reactor (HTTR), which is the first HTGR in Japan, is constructed by JAERI at the Oarai Research Establishment [1]. Supporting R&D for the HTTR has been conducted by JAERI since 1969. The HTTR will be utilized for establishing and upgrading the technology bases for HTGRs including irradiation tests for fuels and materials, safety demonstration tests and nuclear heat application, and for carrying out various kinds of innovative basic researches on high temperature technologies.

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

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

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

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

As an energy source, nuclear energy provides a means to produce not only electricity but also other clean energy carriers. Hydrogen is a convenient medium for storing and transporting energy in chemical form and has a high energy density. Methanol is attractive as automobile fuel, is easy to transport and store, and is less CO<sub>2</sub> emissive than gasoline. Hydrogen and/or methanol production with nuclear energy could play a key role in resolving global warming and conserving fossil fuels. At the same time, it is important to bear in mind that the large scale use of hydrogen as an energy carrier would require changes in the energy infrastructure.

Hydrogen can be produced by several methods. The most important process used on an industrial scale is steam reforming of methane. Produced in this way it serves as

feedstock for the ammonia and the fertilizer industries, for oil refining and for the synthesis of methanol. Another small scale industrial process is the electrolysis of water, which produces much purer but more expensive product. Integration of coal hydrogasification to produce methane together with steam reforming of methane leads to production of methanol from coal.

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

#### 4.1 Hydrogen and Methanol Production by Steam Reforming

Steam reforming of methane is a well known industrial process, often combined with hydrogasification of coal. The basic reactions involved in these processes are shown in Figure 4. The coal to methanol reaction requires substantial quantities of heat. For efficient reaction rates, the reformer requires heat at temperatures of 790°C and above. If the heat were supplied by coal about 80% more coal feedstock would be required along with oxygen for combustion and would produce 1 to 1.4 moles of CO<sub>2</sub> per mole of methanol produced.

In order to produce methanol from coal without CO<sub>2</sub>, two process inputs in addition to coal and steam are required: a supplemental hydrocarbon feed with a H/C ratio higher than two, and a non-combustion source of high temperature heat. The ideal supplemental feed would be H<sub>2</sub>. Although small quantities of inexpensive H<sub>2</sub> are available as process by-products, a large scale methanol economy would require enormous quantities of H<sub>2</sub>. In lieu of a cheap H<sub>2</sub> source, CH<sub>4</sub> from natural gas can be an interim feedstock.

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

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

- steam reforming for production of hydrogen and methanol is an endothermic reaction
- it is a well-experienced production process in non-nuclear industrial applications
- at present and in the near future, the most economical process to produce

- hydrogen is considered to be steam reforming of natural gas
- hydrogen and methanol are co-produced from the syngas. Hydrogen, as shown in Figure 4, can be used further for coal hydrogasification or liquefaction.

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

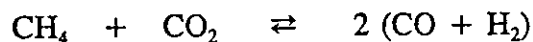
Test module helium heated steam reformers have been successfully tested at the 10 MW(t) level in Germany in the 1980s, using 40 bar helium heated by electric heaters to 950°C and steam reforming temperature of ~820°C. Total operation included 13,000 hrs, of which 7,750 hr were above 900°C verifying the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

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

#### 4.2 CO<sub>2</sub> reforming of methane for production of hydrogen and methanol

While CO<sub>2</sub> reforming of methane is not commercially performed, it is currently experimentally investigated at the solar energy research facilities of the Weizmann Institute of Science, Rehovot, Israel. The system investigated involves a "solar chemical heat pipe". The CO<sub>2</sub> reformer could potentially be adapted for demonstration at the HTTR to produce syngas as feed for a methanol synthesis plant.

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



The reforming reaction is conducted in a solar furnace by passing methane and CO<sub>2</sub> through a catalyst (1% Ru on alumina) at 800 to 1000°C. In the chemical heat pipe process the stored solar energy is released in a methanator plant that reacts hydrogen and carbon monoxide to recover methane and release high temperature heat to generate steam, electric power or both. The methane is returned to the solar site, completing the cycle. CO<sub>2</sub> reforming is preferred to steam reforming for solar application because its gaseous phase simplifies the start up - shutdown cycle which occurs daily.

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

#### 4.3 Combined coal conversion and steam generation

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

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

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

#### 4.4 Thermochemical water splitting for hydrogen production

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

- (i)  $2\text{H}_2\text{O} + \text{I}_2 + \text{SO}_2 \rightarrow \text{H}_2\text{SO}_4 + 2\text{HI}$       ambient temperature
- (ii)  $\text{H}_2\text{SO}_4 \rightarrow \text{SO}_2 + \text{H}_2\text{O} + \frac{1}{2}\text{O}_2$       950°C and above (endothermic)
- (iii)  $2\text{HI} \rightarrow \text{H}_2 + \text{I}_2$       ~ 300°C - 370°C

Preliminary studies showed the process thermal efficiency of ~ 40-50% can be expected under optimum operating conditions. Since the process utilizes corrosive chemicals the structural materials impose a serious problem and their proper selection constitutes an important part of the R&D.

Experimental results reported by JRC Ispra in 1983 [4] point out that thermochemical production of hydrogen is feasible on a pilot plant scale (10Nm<sup>3</sup>/h) using the above mentioned technology. The overall efficiency of the process has been assessed to be around 36-40%. However many difficulties remain in establishing the gaps in optimal engineering design including materials corrosion resistivity, coupling of the chemical plant to the nuclear heat source and safety problems. As a result JAERI has developed an improved process on the laboratory scale of 1-10 liter H<sub>2</sub>/h in glass, quartz and teflon apparatus. The main achievements are the demonstration of thermal efficiency higher than 40% and selection of better structural materials.

Further R&D will focus on optimization of the hydrogen iodide decomposition step with respect to structural materials and efficiency, and on the sulphuric acid decomposition step. The optimal engineering design is in progress including coupling

to the helium loop. Mechanical properties of the selected structural materials will be investigated. The planned demonstrations are:

- (i) laboratory scale to show continuous production of hydrogen in more efficient operation mode
- (ii) process demonstration using metallic reactors to produce  $1\text{Nm}^3\text{H}_2/\text{h}$
- (iii) scale-up process  $100\text{ m}^3\text{H}_2/\text{h}$  coupled to the 10 MW non nuclear HENDEL facility of JAERI.

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

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

#### 4.5 High temperature electrolysis of steam for hydrogen production

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

For further development the following tasks are planned by JAERI in cooperation with Fuji Electric Co.

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

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

#### 4.6 Gas turbine for electricity generation

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

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

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

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

In both facilities negative and positive experiences were gained. At initial com-

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

At the HHV some start-up problems also occurred, but were corrected. The HHV achieved 1100 hrs of operation, of which 325 hrs were at 850°C [5].

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

Activities within the CRP will examine the potential goals and benefits of a demonstration involving the coupling of a small helium turbine to the HTTR.

#### 4.7 Advanced intermediate heat exchangers

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

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

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

### 5. Status and plans for CRP

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

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

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

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

## 6. Summary

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

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

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

First priority candidate systems for demonstration with the HTTR have been determined to be the steam (and/or CO<sub>2</sub>) reforming of methane and gas turbine systems. R&D is continuing for the other candidate systems towards the stage when they can be considered feasible for demonstration at the HTTR.

## References

- [1] S. Shiozawa, S. Maruyama and K. Sawa, The HTGR Programme in Japan and the HTTR Project, presented at the IAEA Technical Committee Meeting on Development Status of Modular High Temperature Reactors and their Future Role, Petten, the Netherlands, 28-30 November 1994 (Proceedings in preparation).
- [2] R. Harth, et. al, Experience Gained from the EVA II and KVK Operation, *Nuclear Engineering and Design*, 121 (1990) 173-182.
- [3] High Temperature Application of Nuclear Energy, Proceedings of a Technical Committee Meeting held in Oarai, Japan, 19-20 October 1992 (IAEA-TECDOC-761).
- [4] Nuclear Heat Application, Proceedings of a Technical Committee Meeting and Workshop, Cracow, 5-9 December 1983 (IAEA, Vienna).
- [5] Summary Report on Technical Experiences from High Temperature Helium Turbomachinery Testing in Germany (IAEA report, in publication).

statcrph.ttr  
pvg/17 March



**Table 1 Major technical parameters of HTTR**

Thermal power	30 MW
Core outlet coolant temperature	850°C / 950°C <sup>a</sup>
Core inlet coolant temperature	395°C
Primary coolant pressure	4 MPa
Fuel	Low enriched UO <sub>2</sub>
Fuel element type	Prismatic block
Pressure vessel	Steel
Number of main cooling system	1
Heat removal	Pressurized water cooler and IHX, parallel loaded
Hot helium temperature (secondary side of IHX)	905°C <sup>a</sup>
Intermediate loop helium flow rate	9.07 t/h
Intermediate loop pressure	4.1 MPa
Targeted temperature at inlet/outlet of heat utilization plant	880 <sup>a</sup> / 144°C
Plant lifetime	20 years (load factor = 60%)

<sup>a</sup> at high temperature test operation

Table 2 Construction schedule of HTTR

ITEM	FY <sup>*1</sup>	1990	1991	1992	1993	1994	1995	1996	1997	1998
MILESTONE		Construction start ▽				Electricity receive ▽			Fuelling ▽	Criticality ▽
Safety review										
Approval of design and construction method										
Site renovation										
Excavation of reactor building										
Reactor building										
Containment vessel										
Cooling system										
Reactor pressure vessel and core internals										
Fuel fabrication										

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

Table 3 Operation schedule and test plan of the HTTR

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

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

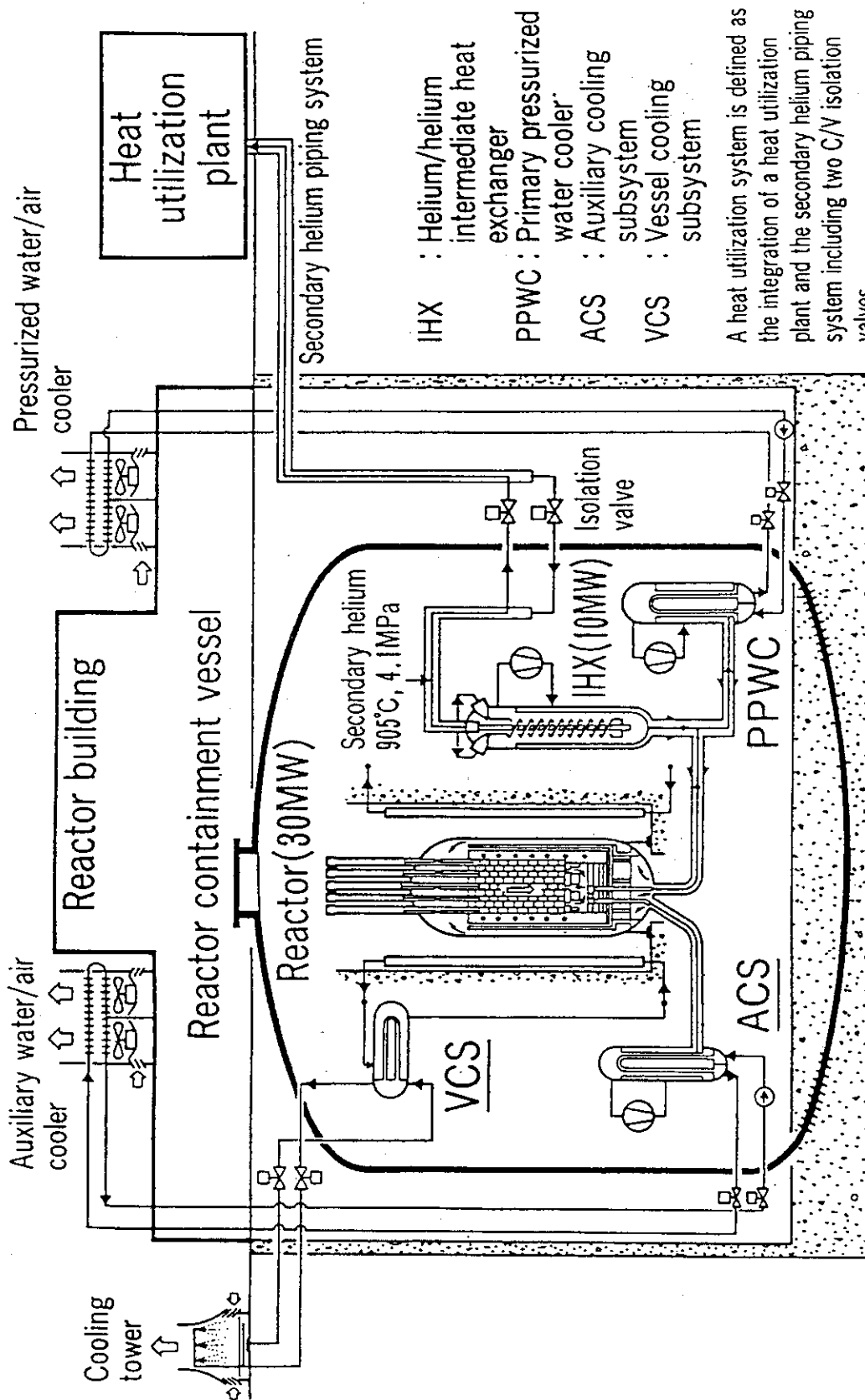


Fig. 1 Simplified diagram of the HTTR plant with a heat utilization system

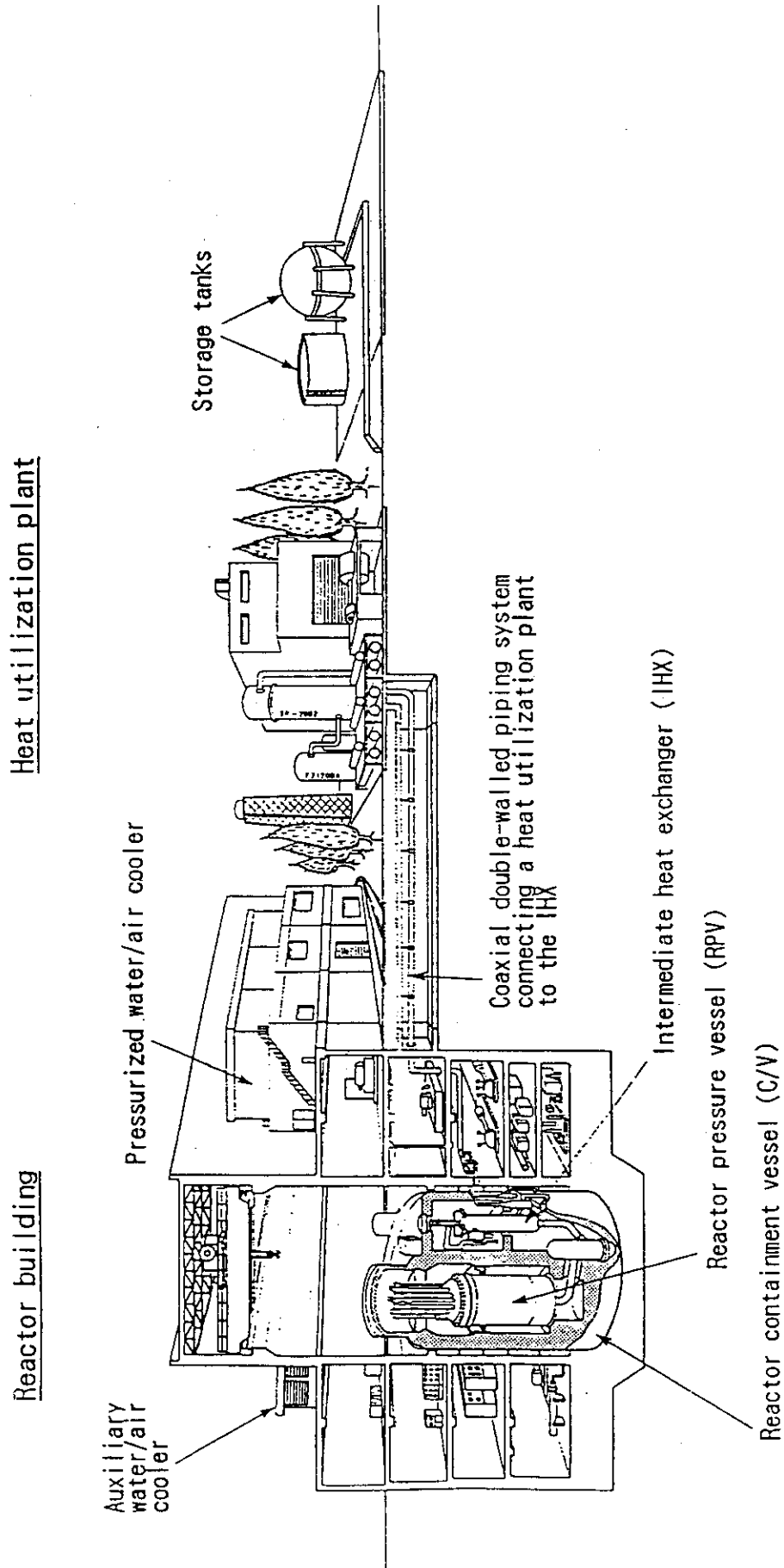
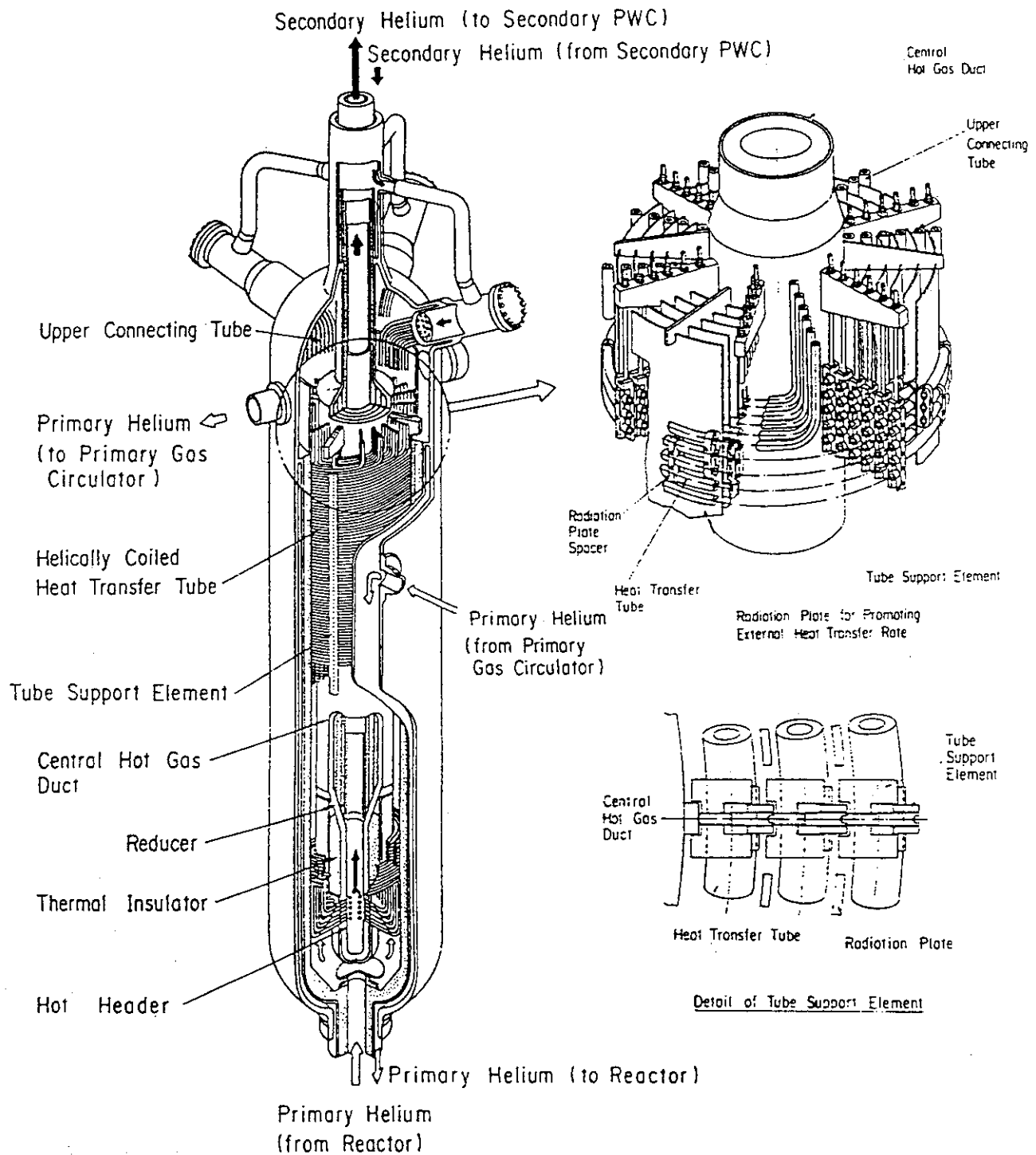


Fig. 2 Cutaway drawing of the HTTR plant with a heat utilization system



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

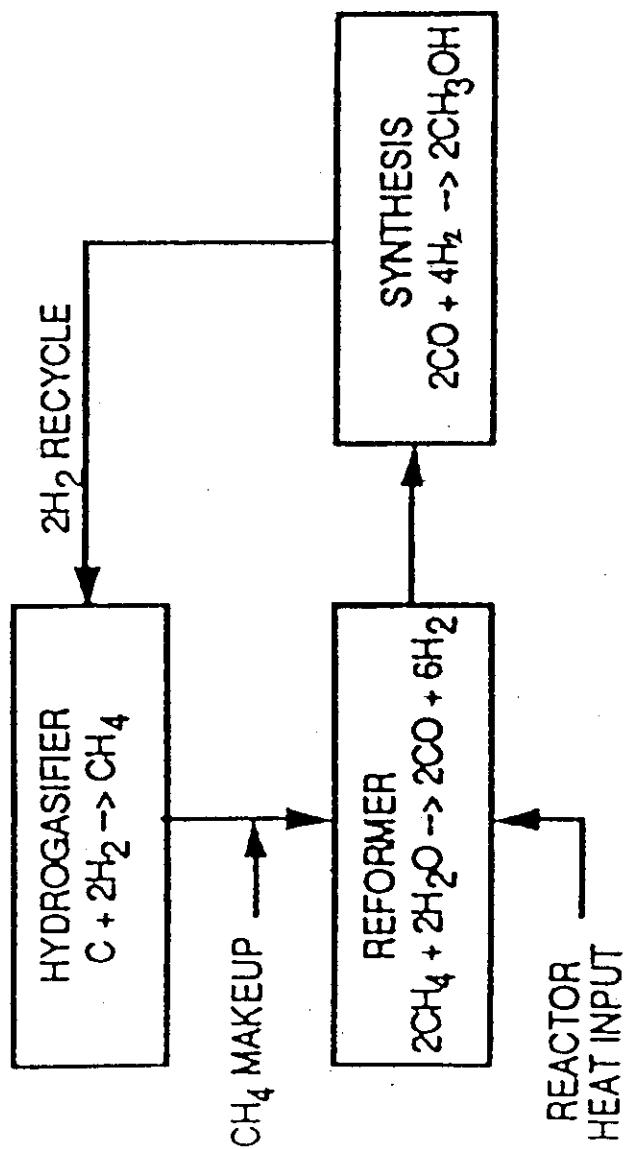


Fig. 4 Reactions for coal to methanol by hydrogasification

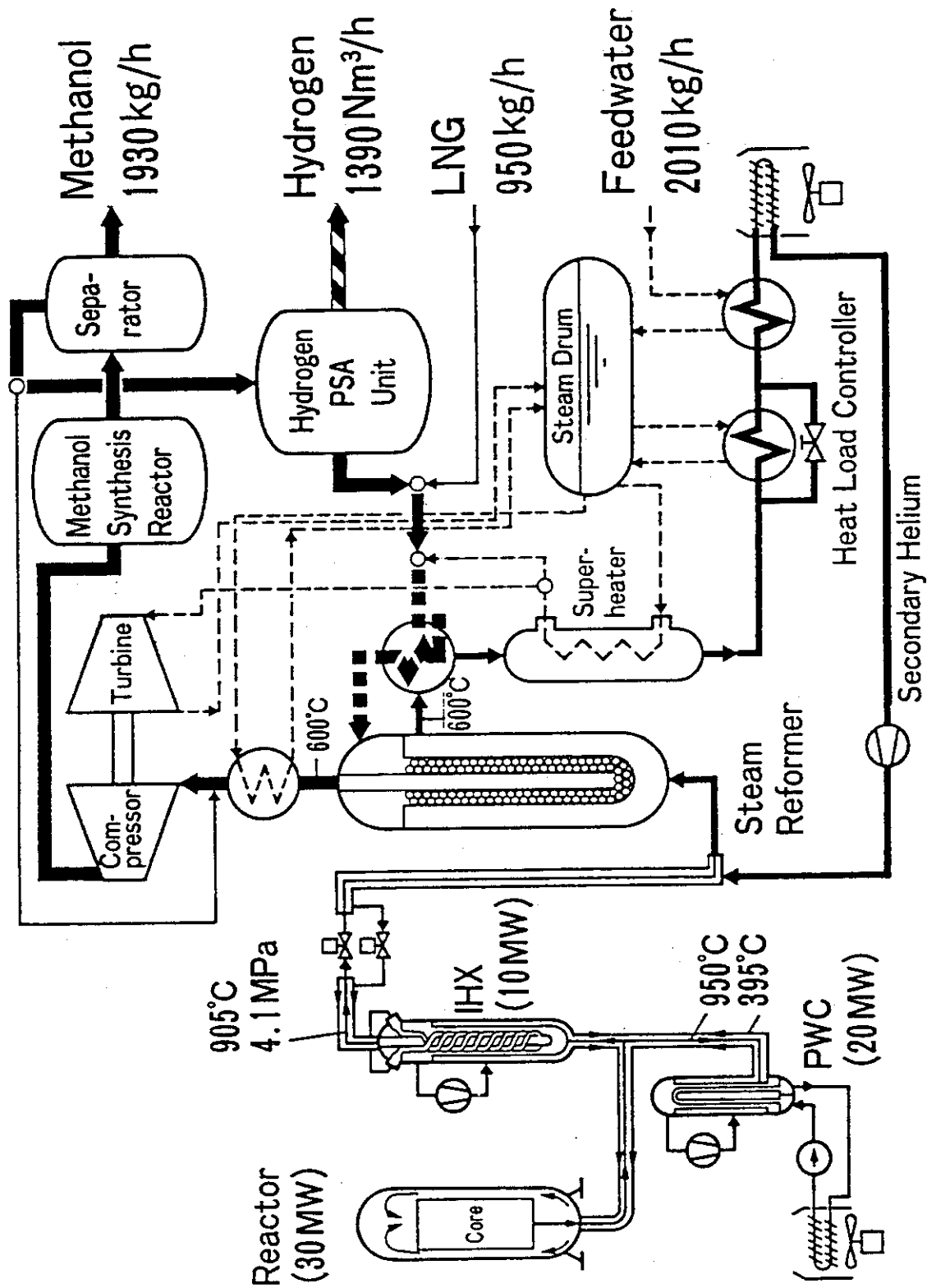


Fig. 5 Schematic Illustration of HTTR steam reforming hydrogen/methanol co-production system



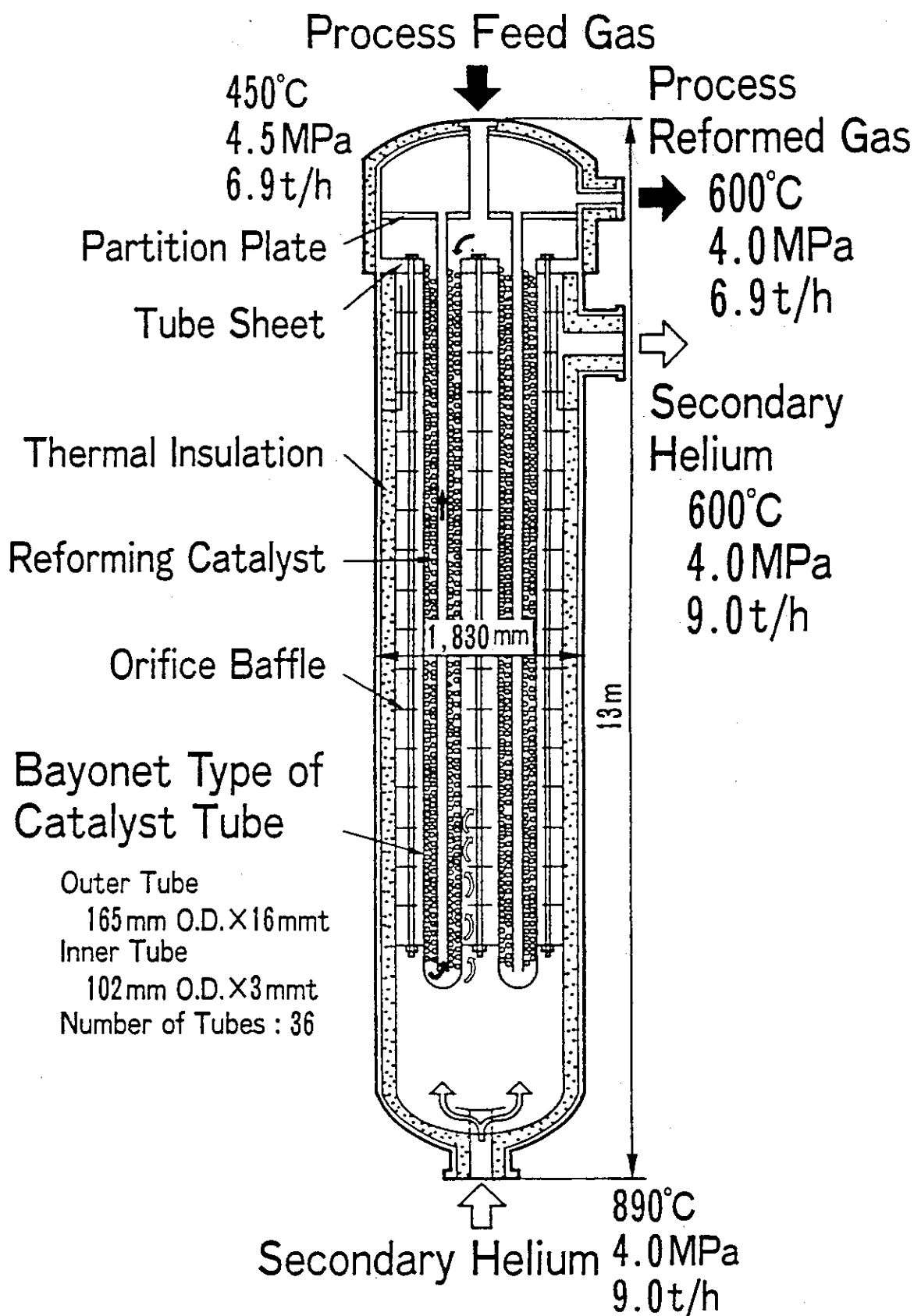


Fig. 6 Sectional view of steam reformer

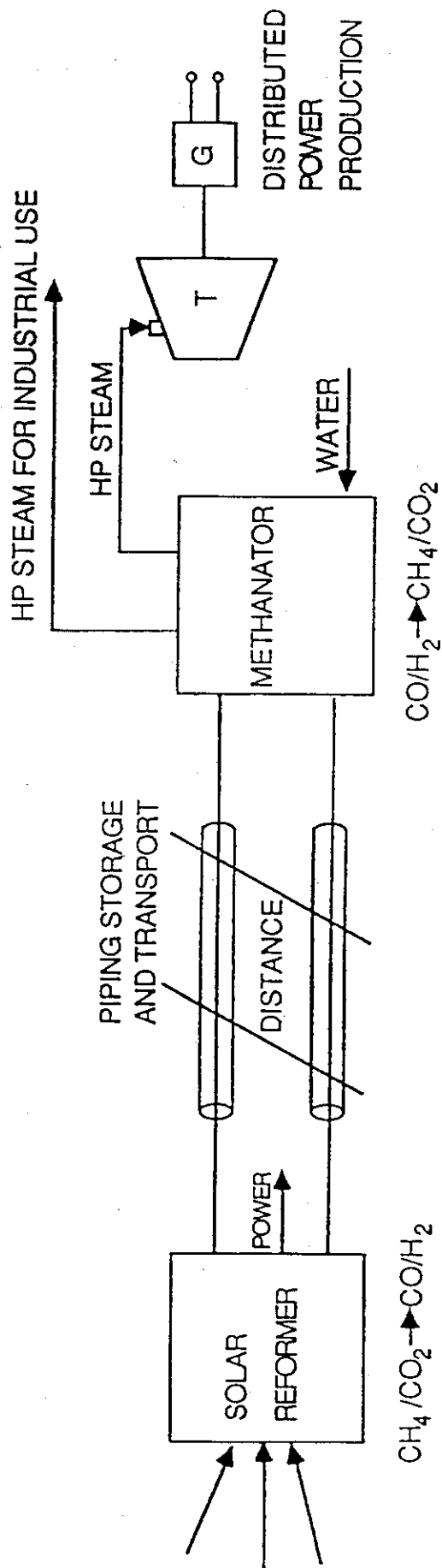


Fig. 7 Solar thermochemical concept reference system

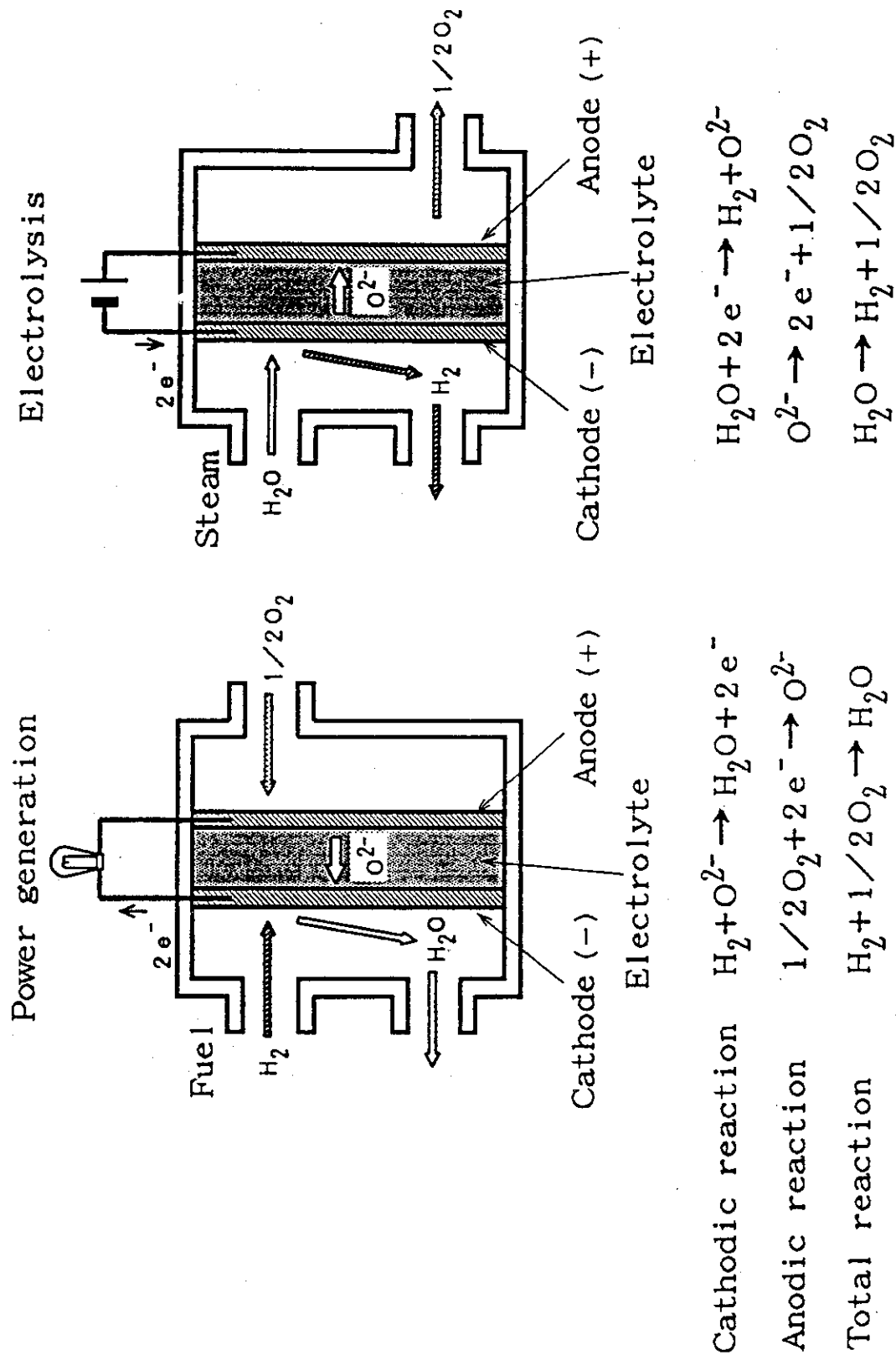


Fig. 8 Principle of high-temperature electrolysis of steam  
(Reverse reaction of solid oxide fuel cell)

## 6.6 Application of the heat pipe to the passive decay heat removal system of the modular HTR

Kazutaka OHASHI, Hitoshi HAYAKAWA, Maso YAMADA  
Nuclear Power Promotion Division, Fuji Electric Co., Ltd.

Takao HAYASHI, Kazuhiko IIGAKI  
Nuclear Engineering Department, Tokai University

## ABSTRACT

To investigate the applicability of heat pipe to the decay heat removal (DHR) system of the modular HTRs, preliminary study of the Heat Pipe DHR System was performed. The results show that the Heat Pipe DHR System is applicable to the modular HTRs and its heat removal capability is sufficient. Especially, by applying the variable conductance heat pipe, possibility of a fully passive DHR system with lower heat loss during normal operation is suggested.

The experiments to obtain the fundamental characteristics data of the variable conductance heat pipe were carried out and the experimental results are also shown.

## 1. INTRODUCTION

Two types of the modular high-temperature gas-cooled reactors have been developed in Germany and U.S., which are called "HTR-module (HTR-M)" and "MHTGR" respectively. Both reactors have excellent inherent and passive safety features. One of the most important features is the ability of passive decay heat removal under the primary system depressurization accident or the loss of forced circulation accident.

Passive decay heat removal is performed by the cooling system installed outside the reactor pressure vessel. Decay heat of the core is transferred to the reactor pressure vessel and then to the decay heat removal system passively by radiation and convection.

The authors are examining the application of the heat pipe (or thermosiphon) system to the DHR system expecting to have comparatively high heat removal capacity and low pressure vessel temperature without any active components.

This paper provides the outline of preliminary study of the Heat Pipe DHR system. The result of the study to introduce the variable conductance heat pipe (VCHP) is also provided.

The experiments to obtain the fundamental characteristics data of the variable conductance heat pipe were carried out and the experimental results are also shown.

## 2. PRELIMINARY STUDY OF HEAT PIPE DHR SYSTEM

### 2-1. System Concept

The concept of the Heat-Pipe DHR System is shown in Fig. 1.

The separated type of heat pipe (or separated thermo-syphon) is suitable for DHR system because of its large heat removal capacity. It consists of four parts, i.e., pipe for vapor, pipe for liquid, the evaporator part and the condenser part. The evaporator part is installed on the reactor cavity wall. Decay heat of the core is transferred from the reactor pressure vessel to the evaporator part by radiation and natural convection in the reactor cavity. In the evaporator part, the heat from the reactor pressure vessel is changed into the latent heat of the working fluid and flow to the condenser part outside of the reactor building. The condenser part comprises heat exchanging pipes cooled by the atmospheric air through natural convection strengthened by the stack. Decay heat of the core is transferred to the atmosphere in this condenser part and condensed working fluid returns to the evaporator part by the gravity.

No active components is used in the system and the core decay heat is removed by fully passive measures.

### 2-2. Design process of Heat Pipe DHR System

Fundamental equations for the Heat Pipe DHR System is expressed as follows.

$$T_1 - T_w = QR_1 \quad (1)$$

$$T_w - T_2 = QR_2 \quad (2)$$

where

$T_1$  : Temperature of the heat source  
(reactor vessel)

$T_2$  : Temperature of the heat sink  
(atmospheric air)

$T_w$  : Working temperature of the heat pipe

$R_1$  : Thermal resistance of the evaporator part

$R_2$  : Thermal resistance of the condenser part

Since the key parameters for the heat transfer at the evaporator side are almost determined by the dimensions of the reactor pressure vessel and the reactor cavity, the thermal resistance  $R_1$ , determined by the radiation and natural convection, does not depend on the design detail of the decay heat removal system. On the other hand,  $R_2$  is determined by the design of the condenser side.

Hence the heat removal characteristics of the total system are determined almost by the thermal resistance  $R_2$ , and the following steps were adopted in this preliminary study. 350MWth MHTGR was taken as a reference reactor in this study.

#### A. Selection of the maximum heat removal rate

The system should be designed so that the maximum heat removal rate necessary under the accident conditions can be achieved. Because the fuel temperature in the accident conditions depends mainly on the heat capacity of the core and the reflectors, the maximum heat removal rate should be determined so that the temperature of the reactor pressure vessel does not exceed the safety limit during the accidents. Since the reference reactor design for this study is MHTGR, the maximum heat removal rate was selected as 1.5MW, which is the design capacity of the DHR system.

#### B. Selection of the maximum working temperature and the working fluid of the heat pipe

Higher working temperature of the heat pipe results in a smaller size of the condenser part, but causes higher reactor vessel temperature. The maximum working temperature of the heat pipe during accident was selected as around 80°C in this study in order to make the size of condenser not so large. The water was selected as working fluid because it is suitable to the working temperature of around 80 °C and its characteristics are well-known.

#### C. Sizing of the condenser part (heat exchanger and stack)

Heat exchanging pipe configuration, dimensions and stack height etc. were selected to satisfy the maximum heat removal rate at the specified maximum working temperature.

### 3. TEMPERATURE DISTRIBUTION ANALYSIS UNDER DEPRESSURIZATION ACCIDENT

Temperature distribution analyses of the reactor with heat pipe DHR system under the normal operating condition and the depressurization accident were performed. 350MWth MHTGR is taken as a reference reactor here.

#### 3-1. Computer program and analytical model

Computer program used in the analysis is TAC-2D which is a two dimensional heat transfer calculation program using the finite difference method.<sup>1</sup> The reactor and the decay heat removal system outside of the reactor vessel were

modeled in a r-z cylindrical configuration as shown in Fig. 2. The structures above the upper reflector and below the lower reflector were neglected and the top of the upper reflector and the bottom of the lower reflector were modeled as adiabatic boundaries for simplicity. This simplification does not have much effect on the estimation of the maximum core temperature and the maximum reactor vessel temperature.

The active core was modeled into one homogeneous material which has an equivalent thermal conductivity and heat capacity of the fuel block. The decay heat was calculated with Sure's equation.

### 3-2. Analytical model for Heat Pipe DHR System

The heat removal characteristics of the Heat Pipe DHR System previously derived as a function of the reactor vessel temperature were modeled as a boundary condition outside the reactor vessel.

### 3-3. Initial condition

The core temperature distribution under the normal operation were previously calculated with an adiabatic single channel model for each radial region of the core. Then the temperature of the reactor vessel and the other reactor internals were calculated with the reactor model shown in Fig. 2 under the boundary condition of the core temperature distribution derived above.

### 3-4. The results of the transient temperature calculation

The calculation results of the transient temperature under the depressurization accident are shown in Fig.3.

After loss of primary system pressure and forced cooling from full power operation, the core temperature begins to increase. The temperature of RPV and DHR system under normal operating condition are 203°C and 61°C, respectively, and the heat loss is 600 kW. The maximum core temperature during accident reaches to 1397°C at about 81 hr. The maximum reactor vessel temperature of 414 °C occurred at about 106 hr. The heat removal rate of the Heat Pipe DHR System exceeds the decay heat at about 95 hr and begins to decrease at about 108 hr.

## 4. INTRODUCTION OF VARIABLE CONDUCTANCE HEAT PIPE

To improve the advantages of the Heat Pipe DHR System, an introduction of Variable Conductance Heat Pipe (VCHP) was investigated.



Basic principle of Variable Conductance Heat Pipe (VCHP) is adding a quantity of non-condensable gas into the system for controlling the system working temperature at the intended temperature level. Fig. 4 shows a concept to apply VCHP to DHR system. By adjusting the amount of the non-condensable gas in the system, the volume of the surge tank connected to the condenser, as shown in Fig.4, or the gas pressure initially enclosed into the system, it can be designed that the heat loss during the normal operation can be reduced with maintaining the maximum heat removal rate under accident.

Brief design procedures of the VCHP DHR System are as follows.

The sizing procedure for the VCHP DHR System to achieve the maximum heat removal rate and the working temperature during accidents are same as that for the ordinary heat pipe. The heat pipe working temperature during normal operation is determined from the viewpoint of the reduction of the heat loss during normal operation. Finally the amount of the non-condensable gas is determined by the volume of the gas surge tank or by the initial pressure enclosed, based on the working temperatures of the heat pipe under the normal and the accident condition.

The advantages of the proposed system is to be capable of selecting the preferable working temperature with consideration on both the normal condition and accident condition. In this study, the working temperature at 100°C, for example, is selected. The heat removal characteristics is shown in Fig.5.

The results of the accident analysis are shown in Fig.6. The maximum core temperature and the maximum reactor vessel temperature are 1399 °C and 415°C, respectively, which are almost same as those of the ordinary heat pipe case. The heat loss during the normal operation is 560 kW, which is lower than the case of the ordinary heat pipe system.

## 5. EXPERIMENTS

### 5-1. Experimental Apparatus

Experiments have been done on the apparatus shown in Fig.7.

Nitrogen gas was fed from N<sub>2</sub> gas bomb through a reducing valve at an intended pressure level. The system was also capable of being vacuums by a rotary pump. The heat was supplied by a sheathed heater fixed around the evaporator covered with thermal insulation and was controlled by the voltage regulator.

## 5-2. Experiments

Nitrogen gas and water were used for the non-condensable gas and working fluid respectively. The temperature distributions in the condenser tubes were recorded by travelling a sheath thermo-couple through a thin tube enclosed in the condenser tubes. Experiments and analysis showed it would show the steam and nitrogen boundary.

Experiments have been done under the various conditions and parametric changes in combination of the following parameters ;

- o With and without nitrogen gas
- o Air flow rate on the cross-flow fan  
(including fan stoppage)
- o Initial  $N_2$  gas pressure  $P_o$  (including vacuum)
- o Heat input  $Q$

Fig.8 shows temperature distribution behaviors when the heat input is varied from 300 W to 500 W and 700W on the condition with no non-condensable gas initially enclosed. The temperature levels are seen to be stepped up in accordance with the increase of the heat input.

If non-condensable gas is enclosed initially, however, the temperature behaviors drastically changes. In Fig.9 are shown the temperature distributions when the heat input  $Q = 500$  W was given, with the conditions of initially enclosed  $N_2$  gas pressure  $P_o = 0.2$  MPa at full power rate of air cooling. There seems to be clearly a boundary between the steam region and gas region which restrains the cooling area smaller to invite higher system (steam) temperature.

Fig.10 shows the temperature distribution behaviors in the condenser tube in response to the heat input increase. The heat input was varied from  $Q = 300$  W by three steps to 500W and 700W. The steam boundary seems to automatically expand in accordance with the increase of the heat input, resulting in moderate system temperature rise.

The same self-regulation characteristics are also shown in extreme case of applications as shown in Fig.11, when the cooling fan was stopped and natural convective cooling was kept after forced air cooling of fan operation with a heat input of  $Q = 300$  W in the same condition of the initial enclosed gas pressure of 0.1 MPa as in Fig.10.

The system temperature behaviors in response to the various heat input  $Q$  at the parametric values of the initial  $N_2$  gas pressure enclosed are shown in Fig.12. With no  $N_2$  gas enclosed, the system temperature crawls low but the slope is steep. If non-condensable gas is enclosed, the system temperature goes up and becomes flat. Furthermore, if the enclosed pressure is increased the system pressure steps up in accordance with the pressure values of gas initially

enclosed. It means that by designing the gas pressure initially enclosed the intended temperature can be achieved and the system temperature can be controlled in such a system of the separated thermo-siphon (or variable conductance heat pipe) systems.

## 7. Conclusion

The Heat Pipe DHR system, which is fully passive up to the final heat sink, has a sufficient capability to maintain the reactor vessel temperature under its safety limit during accidents. Especially, by adoption of the variable conductance heat pipe, it is possible to design a fully passive DHR system which can minimize the heat loss during normal operation and can achieve a lower reactor vessel temperature during accidents.

The experiment was carried out and the fundamental characteristics on the variable conductance heat pipe DHR system was demonstrated.

## REFERENCES

- (1) S.S.Clark and J.F.Petersen, GA-9269 (1969).
- (2) K.OHASHI et al., "Evaluation on Various Passive Decay Heat Removal System of Modular HTR", ANP '92, Oct.25 ~29, 1992.
- (3) T.HAYASHI et al., "Studies on the characteristics of the separated thermo-siphon system with non-condensable gas for the use of the passive decay heat removal in reactor system", ICONE-3, to be published.

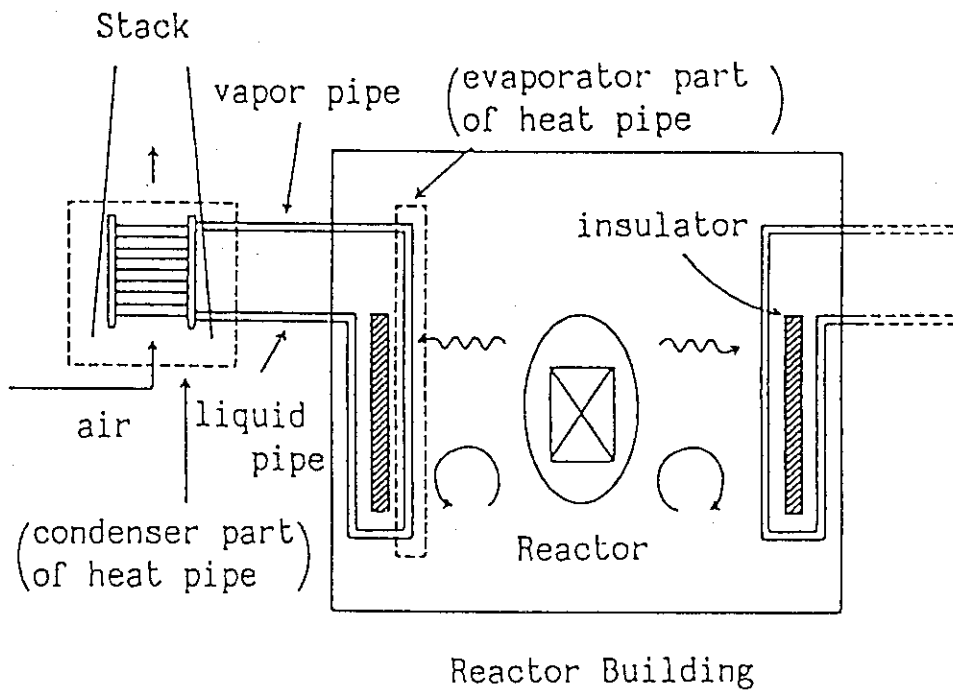


Fig.1. Diagram of Heat Pipe DHR System

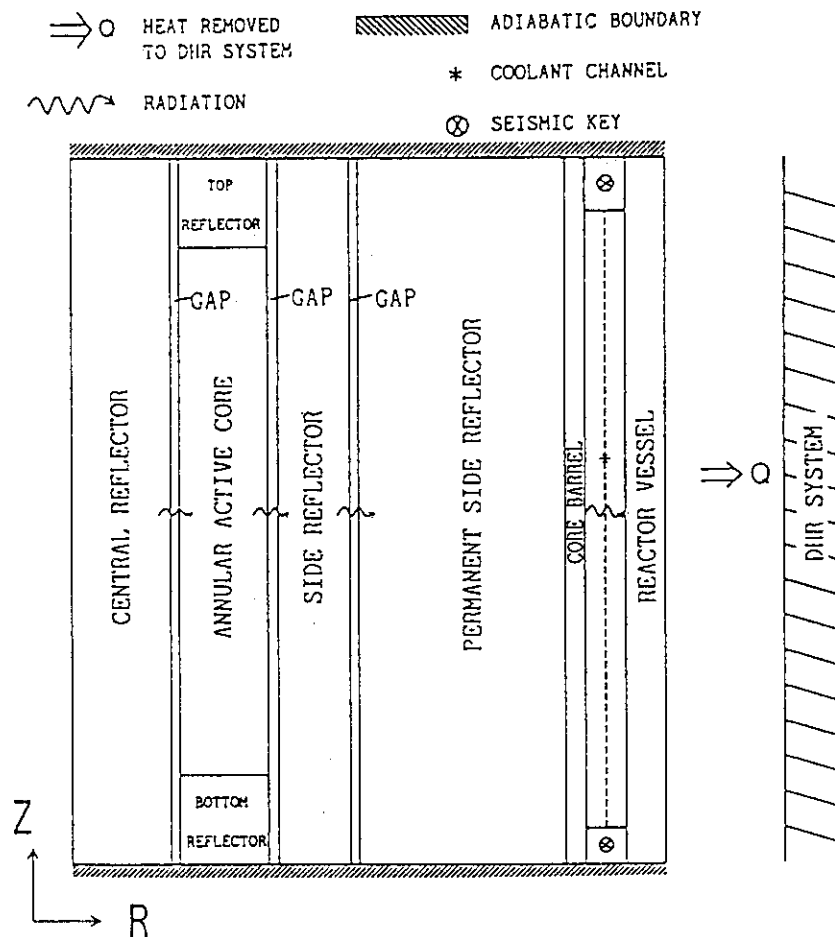


Fig.2. Analytical model for the temperature distribution calculation

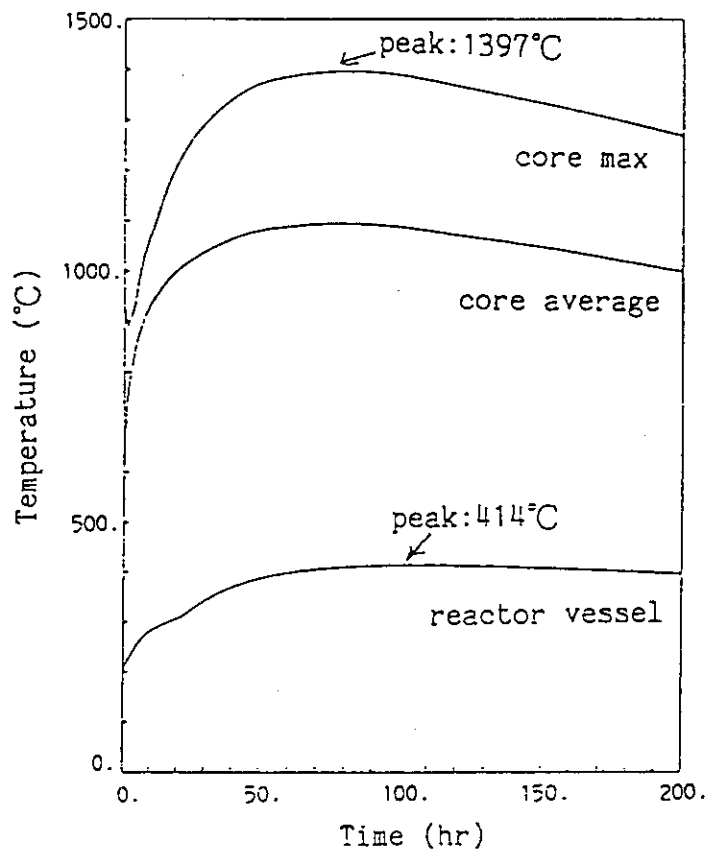


Fig.3. Temperature behavior under depressurization accident

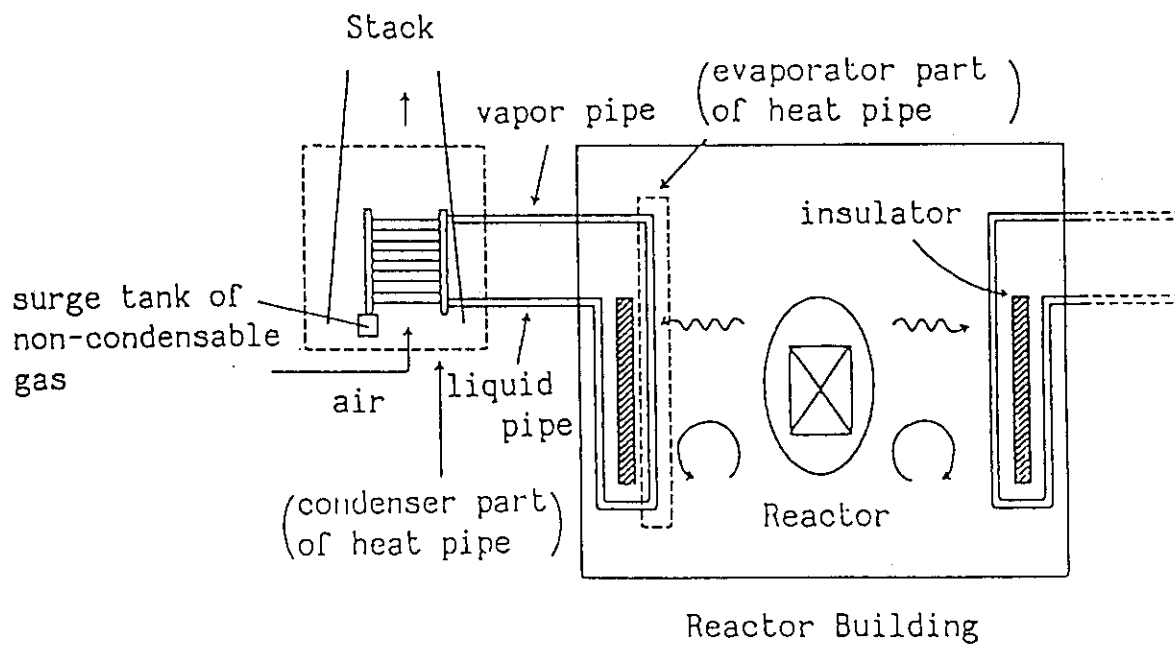


Fig.4. Diagram of Variable Conductance Heat Pipe (VCHP) DHR System

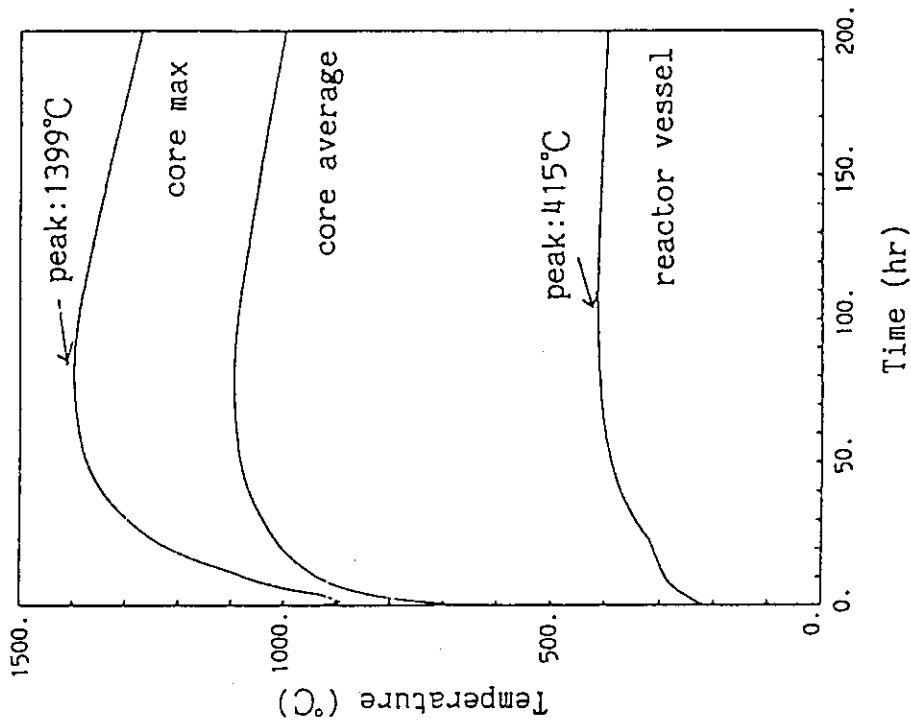


Fig.6. Temperature behavior under depressurization accident (VCHP)

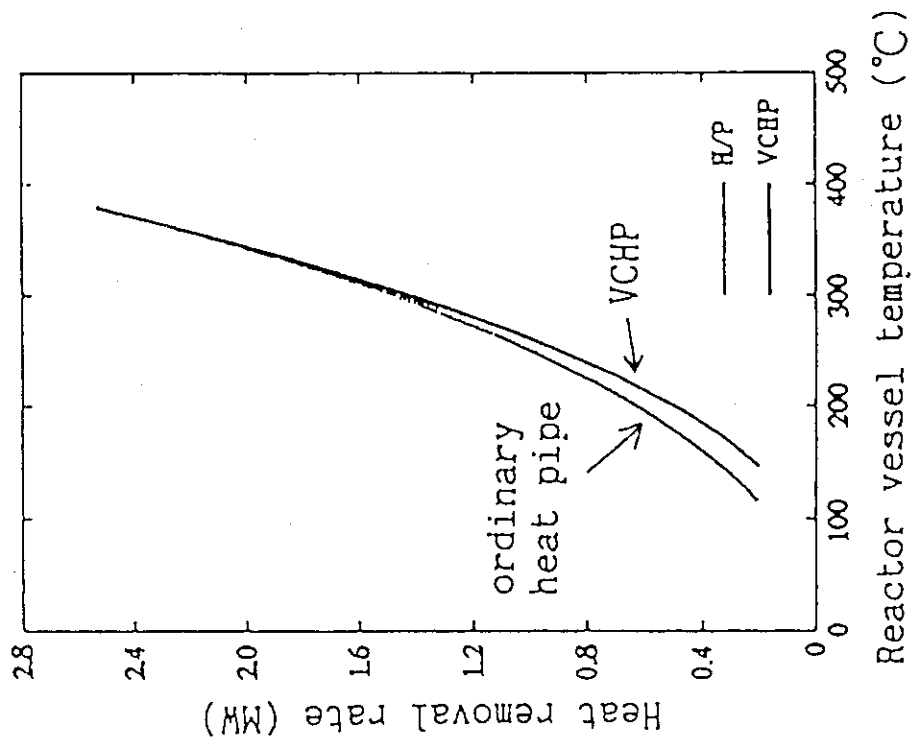


Fig.5. Heat removal rate of the VCHP DHR System

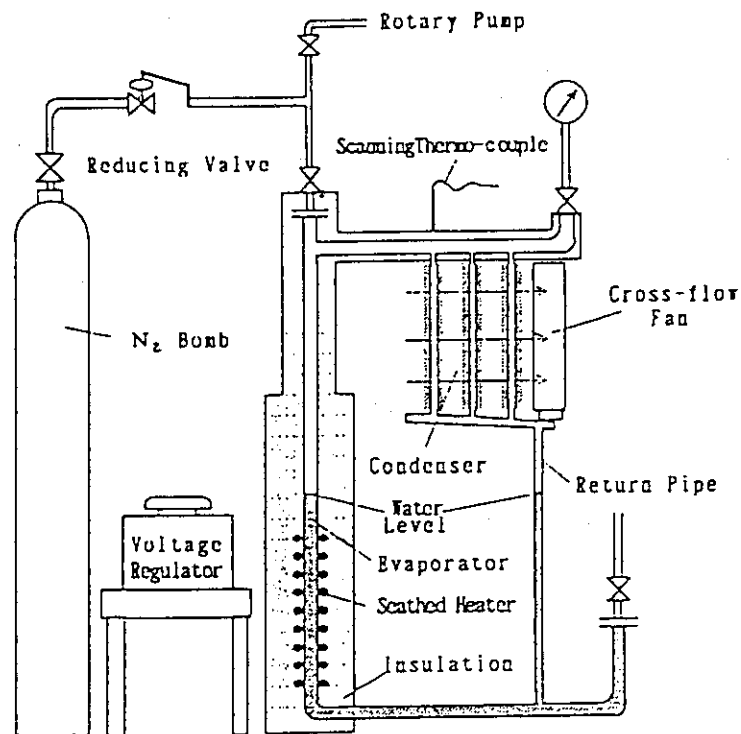


Fig.7. Vertical Condenser Type Apparatus  
with Forced Air Cooling

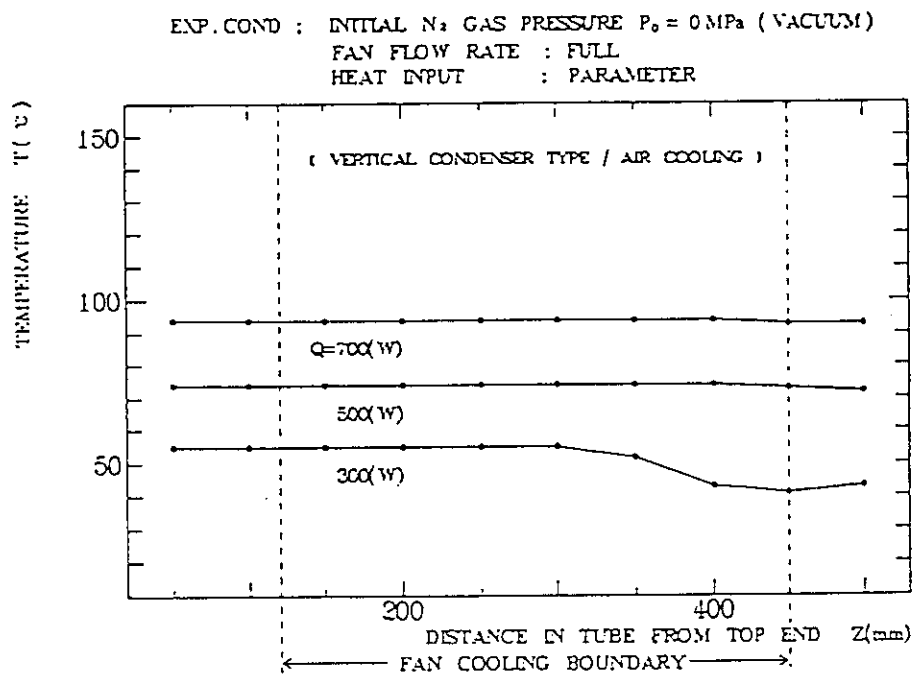


Fig.8. Temperature distributions in the tube in response to  
various heat input  $Q$  in the case of  
"WITHOUT  $N_2$  GAS (VACUUM)"

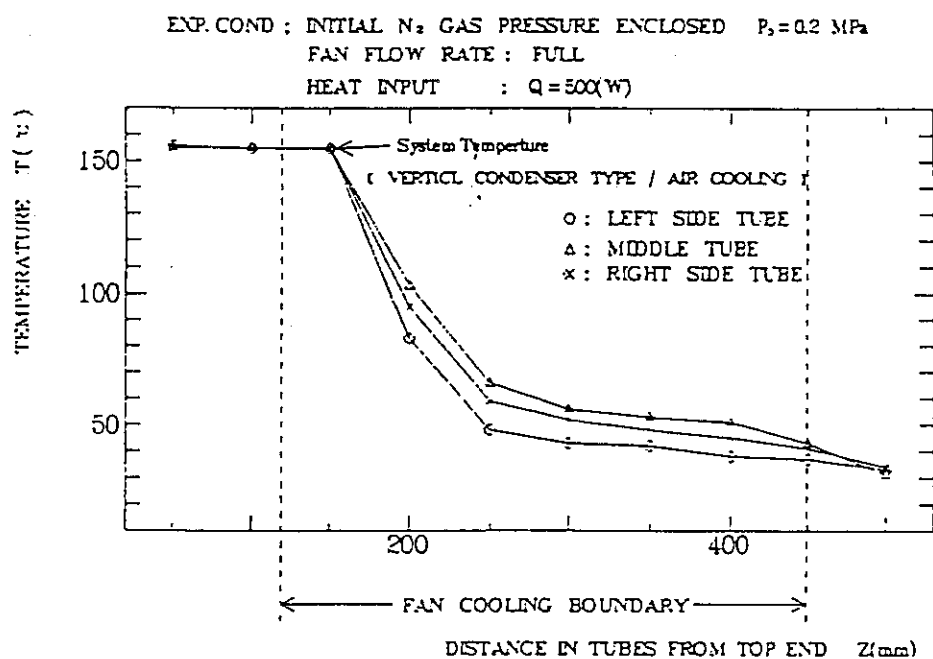


Fig.9. Temperature Distributions in the condenser tubes in the case of "N<sub>2</sub> GAS ENCLOSED"

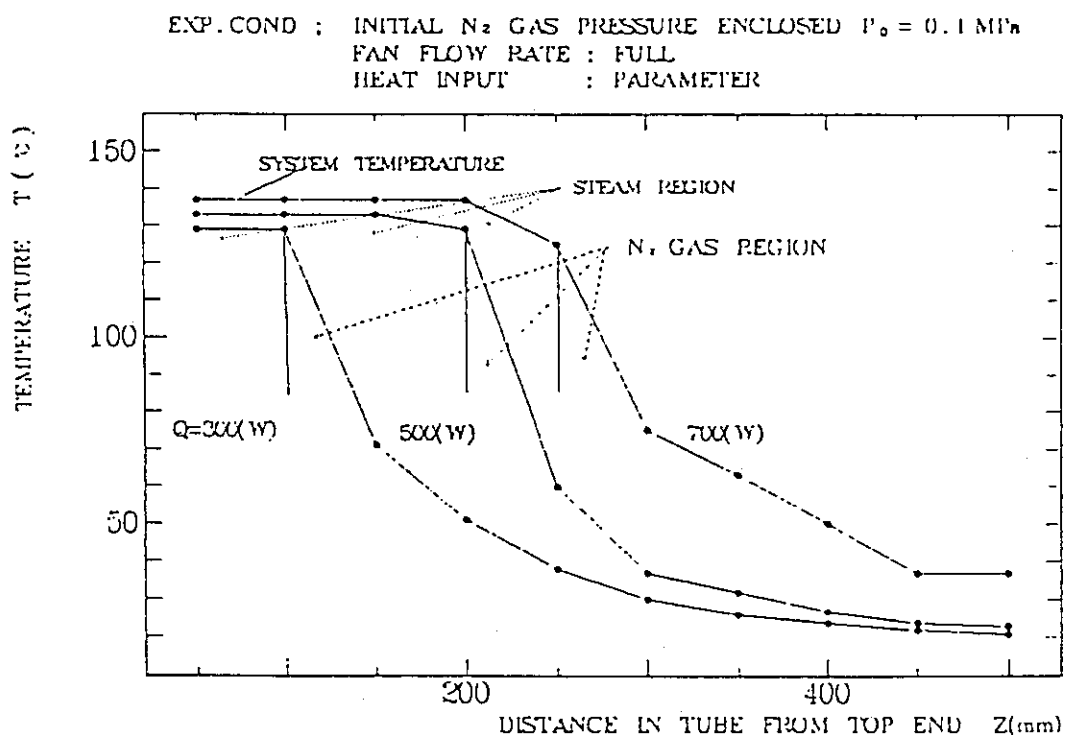


Fig.10. Temperature distributions in condenser tube in response to the heat input increase in the case of "N<sub>2</sub> GAS ENCLOSED"



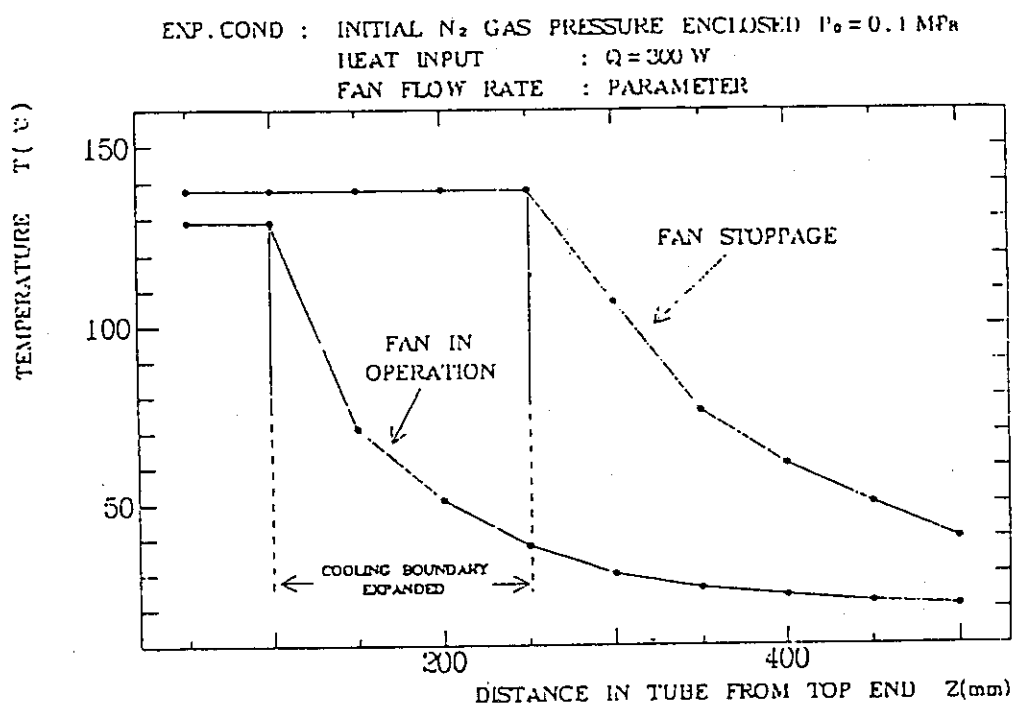


Fig.11. Temperature distribution behaviors in condenser tube in response to the change of the forced air cooling condition

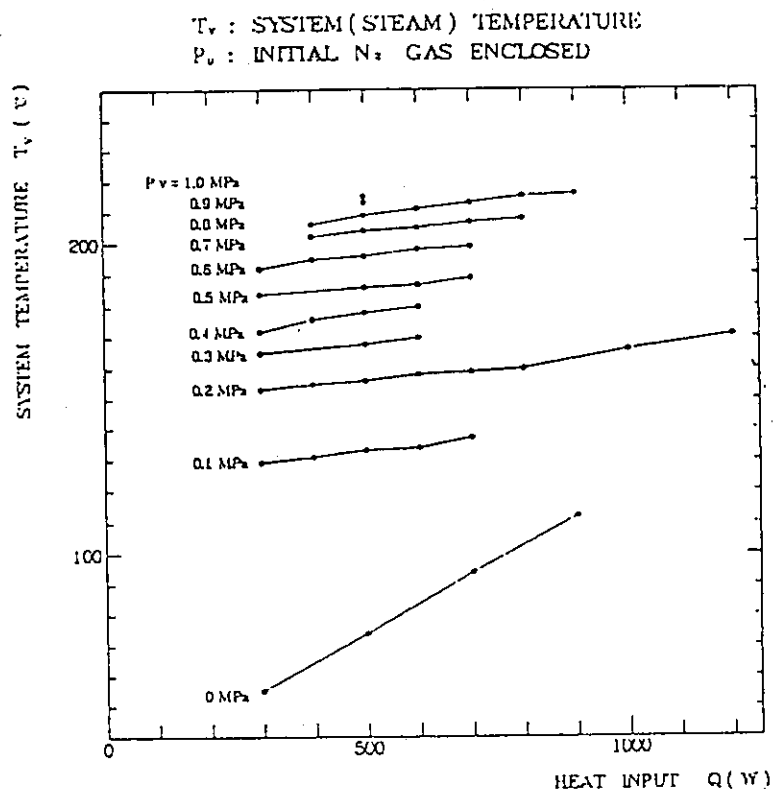


Fig.12. System temperature ( $T_v$ ,  $^{\circ}\text{C}$ ) behaviors in response to the parametric changes of heat input ( $Q$ ,  $\text{W}$ )

## 7. Concluding Remarks

In this panel discussion the participants in the auditorium and on the panel received information on the present status of nuclear heat utilization technology and application of multiphase flow researches in the keynote lecture and from 5 contribution on the various aspects of multiphase flow researches. These information were discussed with many questions from the auditorium and some answers from the panel, leading to the below mentioned conclusion and perspective. The subject of information and discussion was very broad starting from multiphase flow importance for the conversion of nuclear energy into high temperature heat, via phenomena of heat transfer enhancement and contributions to improvement of nuclear safety, up to sustainable applications in the energy market. Nuclear heat utilization technology can beside nuclear electricity production and of course can contribute to solutions in energy supply to mankind and in environmental benign as well as sustainable future development in the world.

Multiphase flow phenomena are important in nuclear heat utilization technology, because their development and application in the technology is of big help for progress with respect to performance, safety and economy.

Research in multiphase flow phenomena in the various aspects and the different fields needs to be continued and in some areas to be intensified. The final goal is application in nuclear energy conversion processes as well as in the energy industry.

The efforts in research and development on the theoretical and the experimental areas of investigation of the various phenomena should be continued in the experienced balanced way on the demonstration side, reflecting the progress in the various fields timely and properly. In particular, the international cooperation should be promoted with the High Temperature Engineering Test Reactor HTTR, as strongly recommended and proposed by Dr. Kunihiro Uematsu, Director General of OECD NEA because the HTTR is the only HTGR in the world available for R&D of nuclear heat utilization.

This panel discussion was really a success from scientific, technical and also organizational point of view. The "dialogue of ideas" should be continued in all possible ways, including international cooperation, and also on a next conference of this type.

April 20, 1995

Chairmen

Yoshiaki MIYAMOTO

Heiko BARNERT

## Acknowledgments

The coordinators would like to express their hearty gratitude to following persons for planning and carrying out this panel discussion on the occasion of ICMF-'95 - Kyoto:

Dr. Akimi SERIZAWA, Prof., Univ. of Kyoto	Mr. Hirofumi SATAKE, Executive Director, JAERI
Dr. Yohichiro MATSUMOTO, Prof., Univ. of Tokyo	Dr. Shinzo SAITO, Deputy Director General, Tokai Res. Est., JAERI
Dr. Isao KATAOKA, Assistant Prof., Univ. of Kyoto	Dr. Toshiaki TOBIOKA, Director General, Oarai Res. Est., JAERI
Dr. Mamoru AKIYAMA, Prof., Univ. of Tokyo	Mr. Yoshiaki MIYAMOTO, Director, Dep. of High Temp. Eng., JAERI
Dr. Akihiko SHIMIZU, Prof., Univ. of Kyushu	Mr. Toshiyuki TANAKA, Director, Dep. of HTTR Project, JAERI
Dr. Subrata SENGUPTA, Prof., Univ. of Michigan, USA	
Dr. John CLEVELAND, IAEA	
Mr. Hitoshi HAYAKAWA, Fuji Electric Co., Ltd.	Mr. Norio AKINO, JAERI
Mr. Masao YAMADA, Fuji Electric Co., Ltd.	Mr. Nozomu FUJIMOTO, JAERI
Dr. Shigeru YAMAGUCHI, Babcock Hitachi, Ltd.	Dr. Kazuhiko HADA, JAERI
Mr. Toyokazu INOUE, Toshiba, Ltd.	Mr. Katsuhiko HAGA, JAERI
Mr. Isao MINATSUKI, Mitsubishi Heavy Industries, Ltd.	Dr. Ryutaro HINO, JAERI
	Dr. Makoto HISHIDA, JAERI
	Mr. Soh MARUYAMA, JAERI
	Dr. Masuro OGAWA, JAERI

Especially the technical contribution of Dr. R. HINO, JAERI, is highly appreciated for his elaborate preparation and arrangement for the panel discussion.