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Symposium

Nuclear Energy Applications other than Electricity Production

Jülich, April 29-30, 1976

Edited by

H. Reents and P. Eich

Jül - Conf - 23
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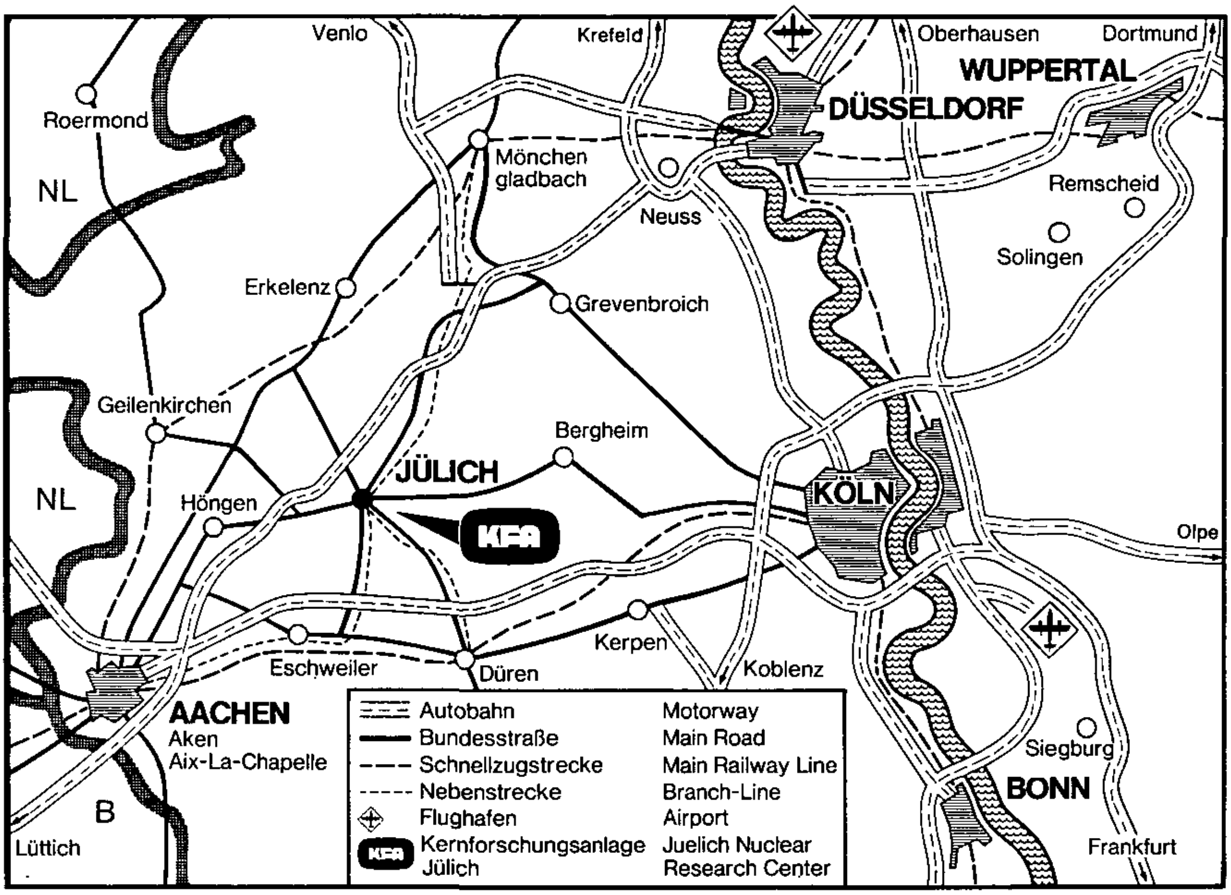

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Symposium

Nuclear Energy Applications other than Electricity Production

Jülich, April 29-30, 1976

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Edited by

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PREFACE

It was the aim of this Symposium to give information on the different possibilities of employing Nuclear Process Heat and to point out the chances of this technology under technical, economic and national economic aspects.

For the introduction of Nuclear Process Heat the following arguments can be put forward:

- Approximately 75 % of the entire final energy applied in an industrial country (for example FRG) is used for the sectors "Space Heating" and "Process Heat".
- At present nuclear energy is only employed for electricity production. But with electricity production only 13 % (for example FRG) of the final energy requirements are covered.
- By the conversion of primary energy into electricity, two thirds of the primary energy is wasted. With the help of Nuclear Process Heat, a considerable improvement in efficiency can be achieved.
- With the introduction of the high temperature reactor a maximum temperature level of 1000 °C may be reached. In this way, there is an opportunity for coal gasification, district heating and for producing chemically bound energy and hydrogen.

On the basis of the heat requirement of an industrial country, as illustrated by the example of the Federal Republic of Germany, possible applications were shown for the following processes:

- Industrial processes
  (process steam applications, gasification and liquefaction of coal, steel industry, zinc and aluminium making processes).
- District heating and low temperature applications
  (district heating, desalination, agricultural and aquacultural applications).
- New energy carriers and systems
  (chemically bound energy, hydrogen).

In this connection, statements were made on problems related to technology, economics and national economics.

Essential results can be summarized from the corresponding contributions and discussions as follows:

- There is an extremely high potential for the application of nuclear energy outside the electrical field.
- The application of nuclear energy within the scope of the heat production market requires extensive infrastructural measures. For this purpose, it is possible either to create a new infrastructure for an existing heat source (district heat model) or to produce a new heat

source for an infrastructure already existing (SNG production) and, in certain cases, even both (chemically bound energy, hydrogen). Such an infrastructure can only be built up on a long-term basis and will entail great expense.

- There is relatively wide interest in the hydrogen technology and the utilization of waste heat from light water reactors, particularly in the form of district heat.

- The participants showed great interest in the development prospects of the high-temperature reactor, all the more since the potential applications of the nuclear process heat, particularly in the high-temperature range, are dependent on the introduction of the high-temperature reactor. Regret was expressed as to the failure of the DRAGON Project and it was hoped that it would be possible to form a new and integrated European high-temperature reactor program.

- Despite the fact that many countries maintain activities regarding non-electrical nuclear applications, there was a lack of any coordination of these activities between the individual countries. It was found that the efficiency of such work could be substantially increased within the framework of international cooperation.

- Special attention was drawn to the necessity of carrying out joint system analyses.

This symposium with its most interesting speeches and prolific discussions gave an almost complete view over the main possibilities of non electric-nuclear applications.

Thanks are due to the authors and all those who helped to make this Symposium successful.

K.H. Beckurts

REPORTS

NATIONAL ECONOMIC ASPECTS OF NON-ELECTRIC SECONDARY ENERGY CARRIERS PRODUCED BY NUCLEAR PLANTS

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Abstract

The potential for nuclear process heat is being disclosed on the basis of energy requirements and, in particular, with a view to heat demand. Secondary energy carriers, which can be produced with the aid of nuclear process heat, are gaining particular significance in a time where shortages in oil and natural gas are to be expected. Competing with electric power, they will acquire a noticeable share in the supply of final energy for reasons of an increased security of supply as well as for economical reasons.

The various technical possibilities for the production of line-dependent secondary energy carriers are being demonstrated. Following this, it will be pointed out that the long lead times required for these technologies necessitate an expeditious and energetic pursuance of adequate developments even today.

Finally it will be shown at what rates an implementation of the different technologies is possible.

1. DEVELOPMENT OF ENERGY DEMAND

The demand for energy in the FRG increased steadily until 1973. The average rate of increase amounted to 4.5 % per year. In the years 1974 and 1975 the energy demand fell by 3.4 % and 5.7 %. From the beginning of this year the demand has started to rise again.

The development of the demand for energy is very difficult to assess. This applies particularly to long term developments. In spite of these difficulties it has been attempted to evaluate the energy demand and the structure of the demand with energy models which take into consideration the effect of price increases and energy savings as well as changes in the structure of the economy and the future availability of resources.

The assessment is based on the relationship between GNP and energy consumption (Fig. 1). This relationship has in the past been constant. The input of 1 t HCE produced a GNP output of 1700 DM. In the forecasts it has been assumed that this relationship will change in such a way that a higher GNP will be produced per tonne HCE. The effect would be achieved by energy savings and changes in the structure of energy consumption. The details of the assumptions shall not be discussed here as they are part of an extensive study. Changes in the technology of energy conversion have also been considered.

The demand forecasts have been made for three different assumptions of GNP growth (Fig. 2). The variant 1 corresponds to the thinking of the government of FRG in the year 1974 but accounting for the recession in the last two years. Variant 2 corresponds to a slowed-down growth in the economy and variant 3 to a near zero growth rate. All following considerations of the importance of nuclear energy for the production of secondary energies in addition to electricity production have been based on the more cautious variant number 2.

The structure of the consumption of final energy decides the demand for secondary energies. It has been assumed for the FRG that also in the more distant future the demand for heat will be greater than for light and power, although the fraction for light and power has in the past increased relative to other energies and will presumably continue to increase (Fig. 3).

The demand profile for heat is of particular interest and Fig. 4 shows the profile for industrial process heat with maxima around 150 °C. The profile for the total heat demand including private households is shown in Fig. 5. The heat demand can also be supplied by nuclear reactors. This can either be in the lower temperature range as hot water or steam from nuclear power plants, or in both the low and high temperature range by secondary energies produced from nuclear heat.

2. POSSIBILITIES OF ENERGY SUPPLY AND THE IMPORTANCE OF NUCLEAR POWER

The possibilities to satisfy the energy demand are determined on the one hand by the availability of primary energy resources and on the other by the available technology to convert primary energy in an economical and environmentally acceptable fashion.

A survey of the supply situation of primary energies in the FRG reveals that the greater part has to be imported. The only indigenous reserves of some size are in the form of hard coal and lignite. The former of which is increasingly loosing its economic competitiveness.

Consequently, the FRG has to join in the consumption of the global reserves and to recognize that in the long term oil and natural gas will be depleted. This will lead to a gap which based on today's structure of the energy market amounts to 70 % of the total energy supply.

According to the present state of knowledge only nuclear power can in the long term substitute oil and natural gas. Even with variant 2 corresponding to a moderate growth rate , nuclear power will in the future play a dominant role. Also in the case when non-nuclear and non-fossil energies like solar, geothermal, wind etc. are used extensively (Fig. 6).

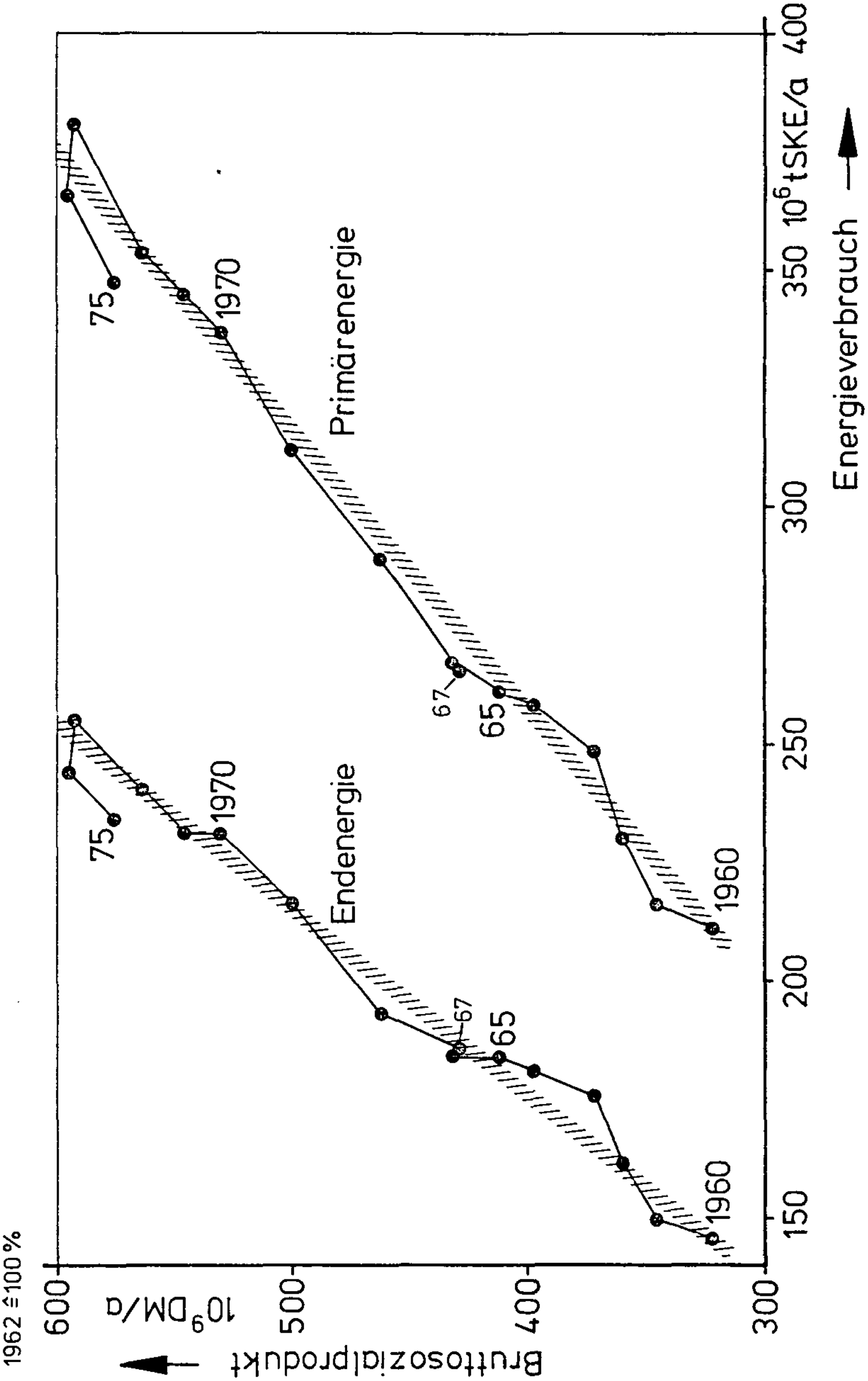

FIG. 1 Relationship between GNP and Energy Consumption

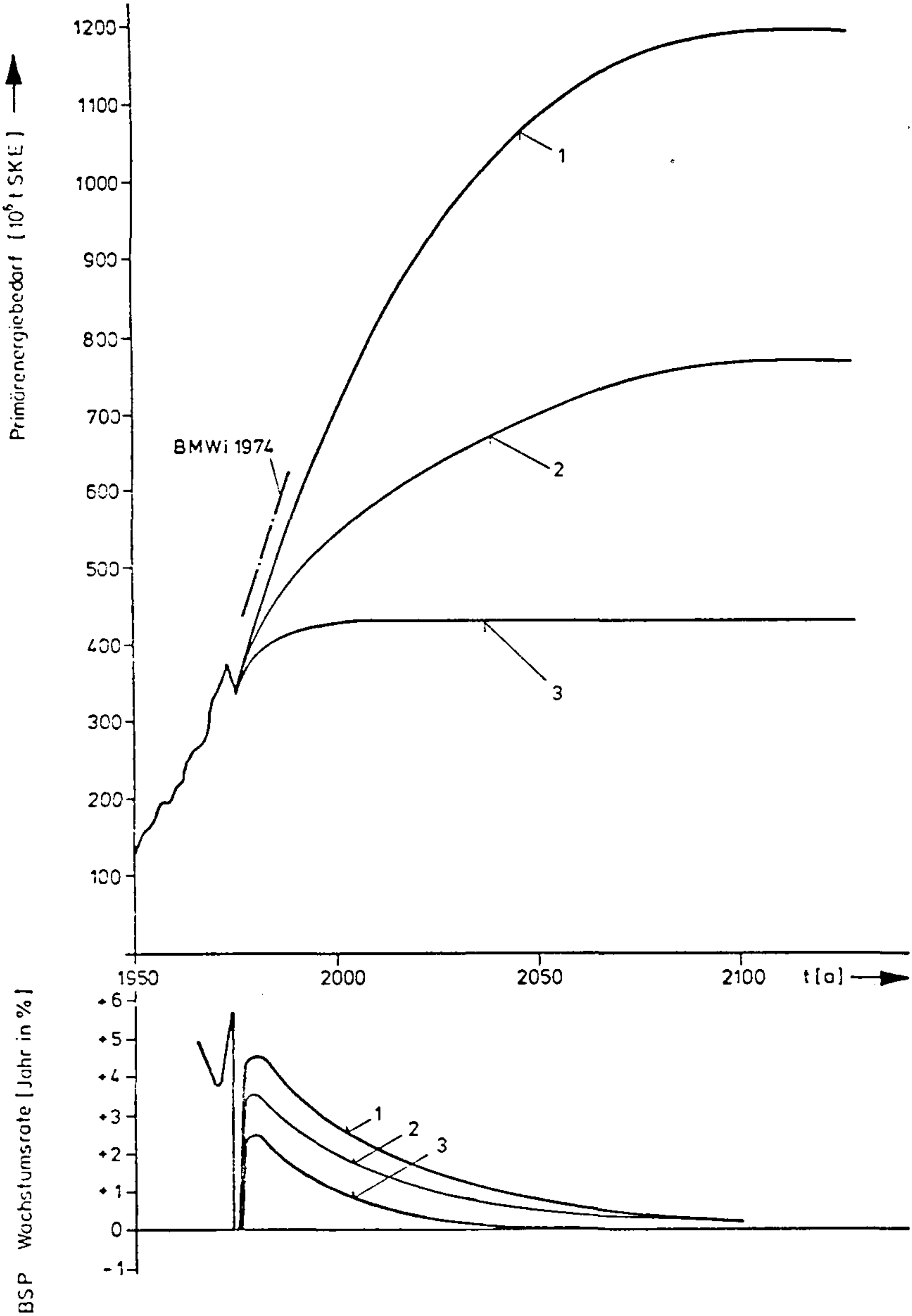

FIG. 2: Demand forecasts - three assumptions

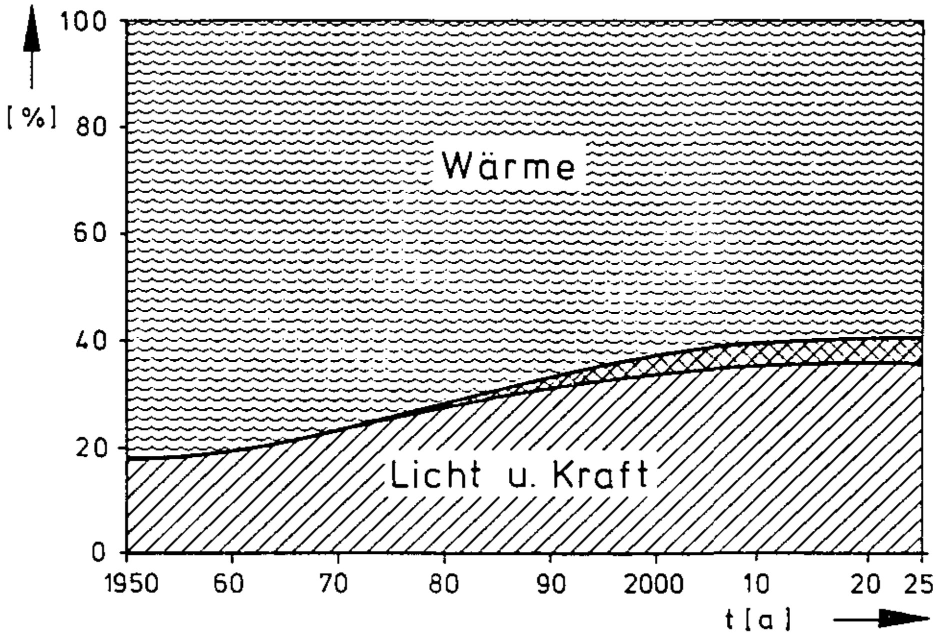

FIG. 3: Structure of the Consumption

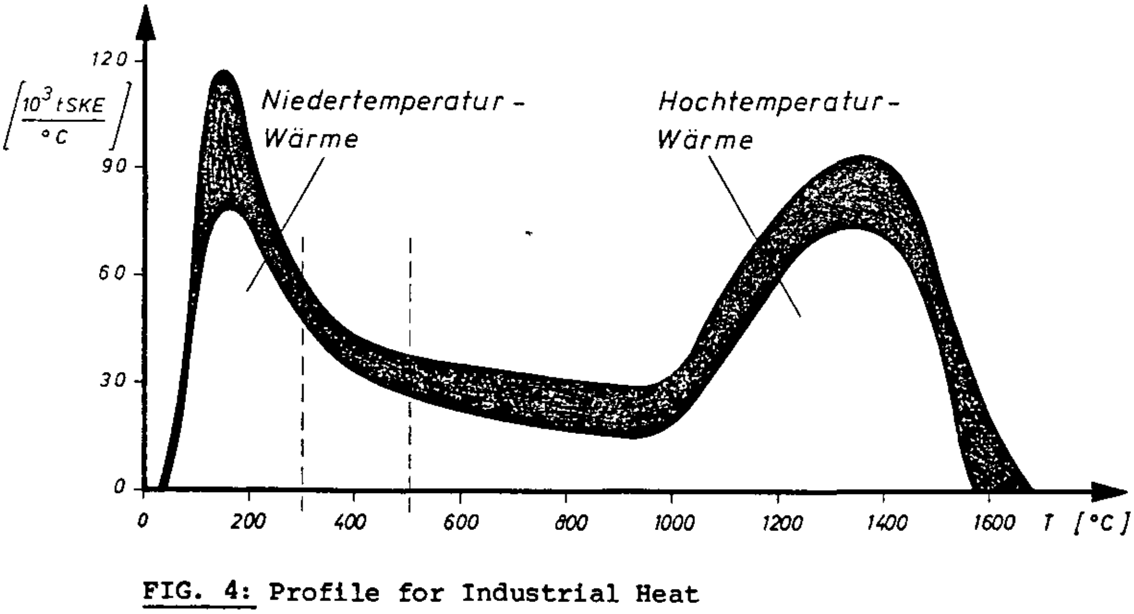

FIG. 4: Profile for Industrial Heat

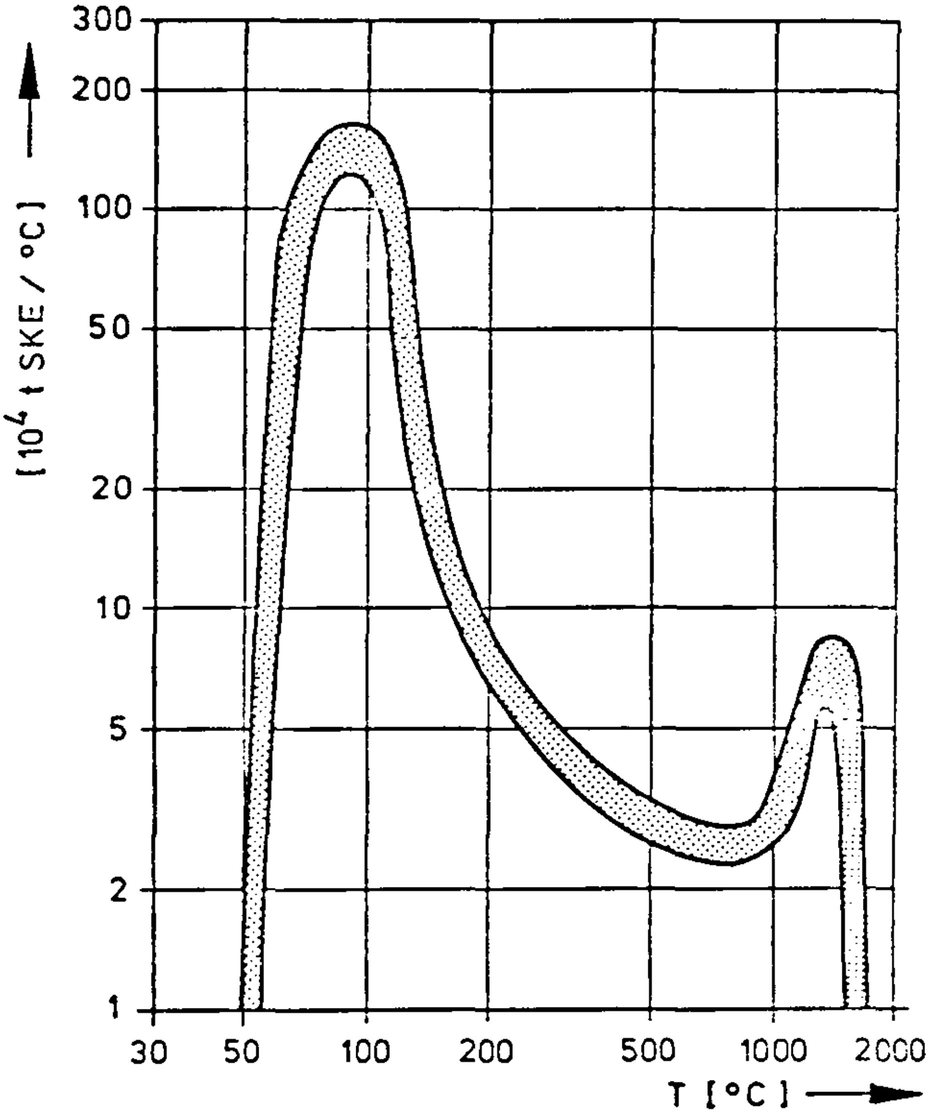

FIG. 5: Profile for the total heat demand including private households

The large fraction of nuclear energy results primarily from the necessity to replace the gradually dwindly resources-oil and natural gas. This leaves the FRG with three primary energies as the long term option to satisfy the energy requirements:

- coal with a fraction of 10 - 15 %,
- NNF " " " " 10 - 15 %,
- Nuclear Power " " " " 70 - 80 %.

It is inefficient and would constitute a waste of primary energy resources to utilize the 70 to 80 % of nuclear power for electricity production only. A sensible approach in the FRG is to deploy nuclear power to coal gasification, and liquefaction, nuclear long-distance energy systems and hydrogen production in addition to electricity. This implies the imparative require-

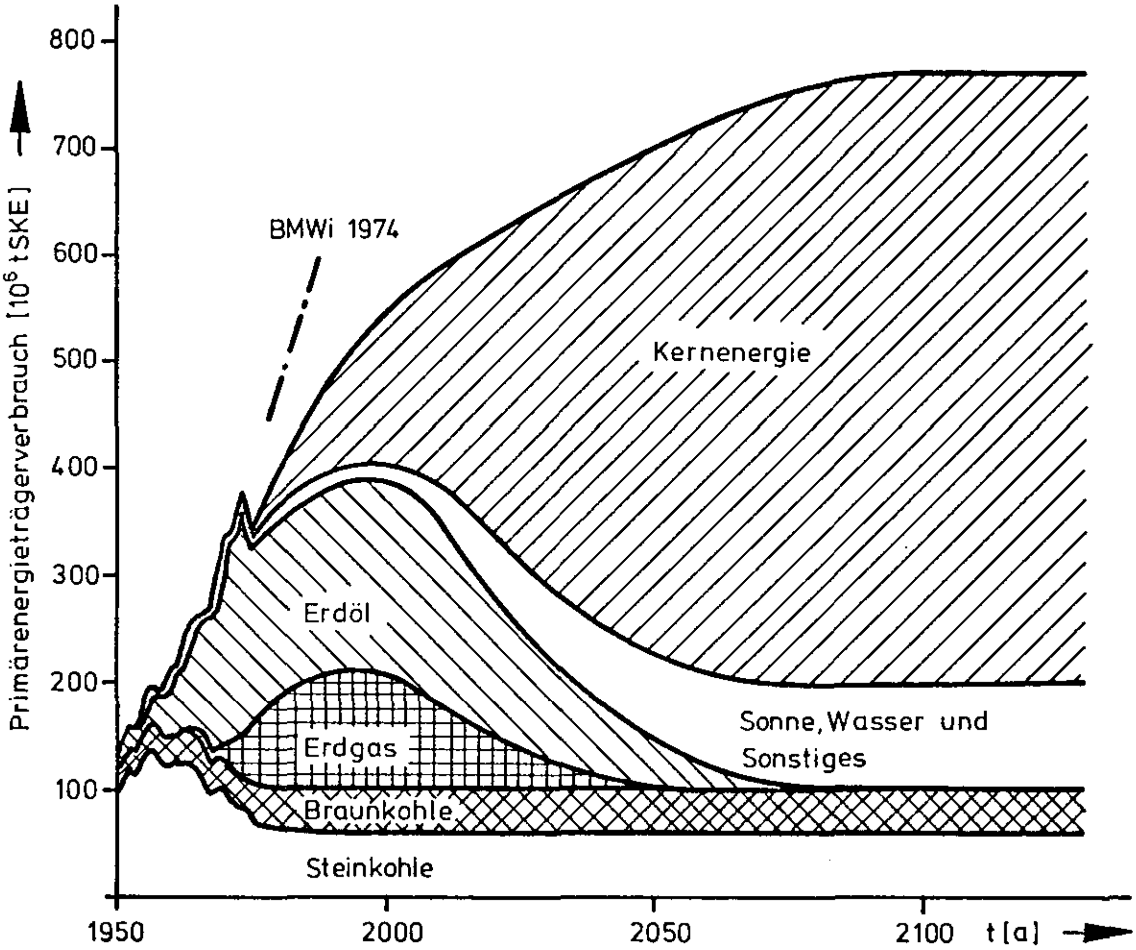

FIG. 6: Demand Forecast - Variant 2

ment to develop the high temperature reactor to its full commercial realisation.

On the assumption that this development is completed by 1985 HTRs could in the FRG be utilized for the production of secondary energy carriers already around the year 2000 (Table I).

	Production of SNG	Coal Liquefaction	Chemical bound Energy	Number of the 3000 MW HTR
1990	3	-	3	3
2000	20	5	13	17
2010	30	20	26	35
2025	40	30	40	49
2050	45	45	65	85
2100	50	50	130	120

TABLE I: Energy Supply by Nuclear Process Heat
(10^6 HCE*/a)
HCE* = Hard coal equivalents

3. PROCESSES FOR THE PRODUCTION ON NON-ELECTRIC SECONDARY ENERGY CARRIERS

3.1 Nuclear District Heat and Process Steam

For the production of heat energy from nuclear energy for heating and other purposes the combined production of heat together with the electricity is economically and from energy conservation considerations of advance. In this way produced heat energy has relatively low temperatures, and therefore water can be used as a secondary energy carrier in the form of warm water, hot water, and steam. These energy carriers are used for residential and commercial warm water and heating applications, for district heating, for industrial heating, and for industrial process steam applications. In future applications of hot water and steam from nuclear power plants for water desalination and in agriculture etc. are feasible.

Table II gives a breakdown of cost figures for the production of district heat from large nuclear power plants with steam cycles (light water reactor or high temperature reactor) for the conditions in the Federal Republic of Germany in 1974.

1.	Maximum Heat Output	1250	Gcal/h
2.	Load factor for Transportation	4000	h/a
3.	Transportation Distance	30	km
4.	Temperature Conditions	130/50	°C
5.	Credit for Electricity	3 - 5	Dpf/kWh
6.	Cost of Production at the Plant	5 - 9	DM/Gcal
7.	Cost of Transportation, 30 km	12 -15	DM/Gcal
8.	Cost of Distribution	18 -20	DM/Gcal
9.	Cost at the Consumer	35 -45	DM/Gcal

TABLE II: Breakdown of cost figures for the production of district heat from nuclear power station (LWR or HTR) in the FRG in 1974, as one example

The production costs for the district heat (5 - 9 DM/Gcal, Table II) are calculated on the basis of the reduced electricity production of the nuclear power plant. For economic reasons the maximum transportation distance for hot water is about 30 km, and for steam it is a few kilometers only. Because of the relatively high distribution costs of hot water the nuclear district heating is limited to areas of relatively high population density.

With costs at the consumer of 35 to 45 DM/Gcal (1974) the "Nuclear District Heat" is economically competitive compared to conventional district heating systems.

In Table III technical data and cost figures for the production of process steam in a nuclear power plant are given for the conditions in the Federal Republic of Germany in 1973.

With the costs of 10 - 12 DM/t (1973) the "Nuclear Process Steam" is competitive with steam produced in a fossil fired steam plant.

1.	Thermal Power of the Reactor	500 MW t
2.	Process Steam Production Rate	500 t/h
3.	Electricity Production Rate	70 MWe
4.	Process Steam Temperature	265 °C
5.	Process Steam Pressure	20 bar
6.	Load Factor of the Plant	7200 h/a
7.	Credit for Electricity	4 DPf/kWh
8.	Cost for Process Steam	10-12 DM/t

TABLE III: Technical data and cost figures for an industrial nuclear power plant with the thermal power of 500 MW for the production of process steam at a production rate of 500 t/h, in the FRG in 1973.

3.2 Nuclear Long-Distance Energy

The process of "Long-Distance Supply of Nuclear Energy" is a method for the conversion of nuclear heat into an energy which can, compared to hot water, economically be transported over longer distances. The energy carrier is a chemically reacting system, which is transported at room temperatures and which consumes and produces transportation of the chemical substances pipe-lines, trains, or ships may be used.

Among numerous possible chemical systems a very promising one is the "EVA/ADAM System", which uses the steam reforming of methane as the heat consuming step and the methanisation of reformer gas as the heat producing step. The nuclear heat course is a high temperature reactor, for the transportation pipe-lines are used, the produced heat at the town work can be used for the production of electricity, process steam and hot water.

Table IV gives technical data and cost figures for a "Nuclear Long-Distance Energy Supply System".

1.	Thermal Power of the High Temperature Reactor	3000 MWt
2.	Heat transported by EVA/ADAM System	1770 MW
3.	Production of Electricity at Plant Side	235 MW
4.	Use as Steam for Industrial Processes	725 MW
5.	Use as Heat for District Heating	725 MW
6.	Use as Electricity Produced in the Town Work	320 MWe
7.	Transportation Distance, e.g.	70 km
8.	Load factor	6000 h/a
9.	Efficiency in Winter	67 % %
10.	Efficiency in Summer	49 %
11.	Efficiency Average during the Year	59 %
12.	Credit for Electricity at Town Work	5 DPf/kWhe
13.	Cost of Heat at Town Work	36-41 DM/Gcal

TABLE IV: Technical data and cost figures for a Nuclear Long-Distance Energy Supply Plant on the basis of the EVA/ADAM System in the FRG in 1974.

Since 1975 there exists the project "Nukleare Fernenergie, NFE" with the partners Rheinische Braunkohlenwerke AG and KFA Jülich. The duration of the project is scheduled until the end of 1980. The total expenses of the NFE project will amount to about 83 Mio DM. The objectives of R&D in the project NFE are: Tests for the methanisation process; planning, construction and operation of ADAM 1 and of a big pilot plant EVA 2/ADAM 2; and planning and lay-out of a prototype plant for NFE.

3.3 Nuclear Coal Gasification and Liquefaction

The process of "Nuclear Coal Gasification" is a method to convert the energy of coal and nuclear energy from high temperature reactors into gaseous energy carriers. The heat from the high temperature reactor is used as process heat in the gasification process and to supply process steam and electricity.

The process of the "Nuclear Coal Gasification" offers, compared with existing process, the following advantages: Saving of coal, less CO_2 emission, no SO_2 and NO_x emission, higher overall efficiency, and lower costs of the products.

The products of the Nuclear Coal Gasification and Liquefaction are: Substiture natural gas, water gas, town gas, and hydrogen as gaseous energy carriers, hydrogen and synthesis gas for the chemical industry, reducing gases for reduction processes and methanol and gasoline as fuel for motor cars.

The following different processes have to be distinguished: With respect to the fossil source: lignite or hard coal, with respect to the process scheme: hydro-gasification or steam gasification, and with respect to the coupling of the HTR to the chemical process: the steam reforming of methane, the preheating of the gasifying agent and the recuperative heat exchange into the gas generator.

In Tables V and VI technical data and cost figures for the Nuclear Hydro-Gasification of Lignite and the Nuclear Steam Gasification of Hard Coal for conditions in the Federal Republic of Germany in 1974 are given:

1.	Thermal Power of the High Temperature Reactor	3000	MWt
2.	Feed Rate of Lignite	2200	t/h
3.	Methane Production Rate	380	10^3 m^3/h
4.	Net Electric Power Generation	110	MWe
5.	Production Rate of Residual Char	270	t/h
6.	Carbon Gasification Degree	63	%
7.	Overall Efficiency (High Heating Value)	68	%
8.	Load Factor of the Plant	8000	h/a
9.	Cost of the Lignite (Lower Heating Value)	7	DM/Gcal
10.	Cost for the Produced SNG	20-23	DM/Gcal

TABLE V: Technical Data and Cost Figures for the Nuclear Hydro-Gasification on the Lignite, Variant: Coupling of Nuclear Heat by Steam Reforming of Methane, FRG 1974.

1.	Thermal Power of the High Temperature Reactor	3000 MWt
2.	Feed Rate of Hard Coal	250 t/h
3.	Methane Production Rate	178 10^3 m^3/h
4.	Net Electric Power Generation	815 MWe
5.	Production Rate of Oil and Tar	48 t/h
6.	Gasification Efficiency (High Heating Value)	110 %
7.	Overall Efficiency (High Heating Value)	65 %
8.	Load Factor of the Plant	8000 h/a
9.	Cost of the Hard Coal	15-20 DM/Gcal
10.	Credit for Electricity (than)	3 DPf/kWh
11.	Cost for the Produced SNG	32-36 DM/Gcal

TABLE VI: Technical Data and Cost Figures for the Nuclear Steam Gasification of Hard Coal, FRG 1974

The costs for the produced substitute natural gas on the basis of lignite are 20 to 23 DM/Gcal (1974), and on the basis of hard coal are 32 to 36 DM/Gcal (1974). With these costs the nuclear coal gasification is economically attractive in the future energy market.

The nuclear coal liquefaction, e.g. with the H-coal process, gives costs for the production of gasoline of about 250 DM/t (1974) on the basis of lignite.

R&D work in the field of nuclear coal gasification has been done since a few years in the frame of the project "Development of processes for the conversion of solid fossil raw materials by heat from HTRs" in cooperation between Bergbauforschung, Rheinische Braunkohlenwerke AG, and KFA Jülich. Since 1975 there exists the project "Prototype Nuclear Process Heat, PNP" under the contractual agreements made between the partners Bergbauforschung, Rheinische Braunkohlenwerke, Hochtemperaturreaktorbau, Gesellschaft für Hochtemperatur-Technik, and KFA Jülich. The objectives of the project PNP are as follows: Elaboration of details,conceptual designs for a flexible large scale high temperature reactor for various applications and for large scale coal gasification plants, performance of detailed analysis on the economics, detail safety research, evidence of the technical feasibility, construction of a prototype plant for proving the gasification of lignite and hard coal.

3.4 Nuclear Hydrogen Production by Water Splitting

The process of "Nuclear Water Splitting" is a method for the direct conversion of nuclear heat from a high temperature reactor into the chemical energy of hydrogen by the splitting of water into hydrogen and oxygen. A nuclear hydrogen plant consists of the high temperature reactor and of the thermochemical plant.

Hydrogen, as a gaseous energy carrier, is in a large energy supply system used for transportation, distribution and storage of energy and will be used by the energy consumer for room heating, for the production of electricity, for conditioning, and as a motor fuel. Hydrogen can also be used as a reducing agent in reduction processes, for the gasification of coal, and as a chemical raw material oxygen can be used as a chemical raw material and for oxidation processes.

A thermochemical cycle for the splitting of water consists of a number of chemical reactions, which form together the overall reaction of the splitting of water into hydrogen and oxygen. Up to now many thermochemical cycles have been proposed. The most promising ones are those, which use fluid substances only. One example of a thermo-electro-chemical cycle is the "Sulfuric Acid-Hybrid-Cycle" which consists of the thermal-splitting of Sulfuric Acid and the electro-chemical oxidation of sulfur-dioxide.

In Table VII technical data and cost figures are given for the nuclear water splitting by the "Sulfuric Acid-Hybrid-Cycle" for USA conditions in 1974.

1.	Thermal Power of the High Temperature Reactor	3220	MWt
2.	Hydrogen Production Rate	420	10^3 m^3/h
3.	Hydrogen Power (High Heating Value)	1500	MW
4.	Hydrogen Purity	99.9	%
5.	Oxygen Production Rate	306	t/h
6.	Sulfur Dioxide Impurity in Oxygen	few	ppm
7.	Overall Efficiency (high heating value)	46.7	%
8.	Load Factor of the Plant	7000	h/a
9.	Credit for Oxygen	20	\$/t
10.	Cost of Hydrogen without Oxygen Credit	42-48	DM/Gcal
11.	Cost of Hydrogen with Oxygen Credit	30-36	DM/Gcal

TABLE VII: Technical data and cost figures for the Nuclear Hydrogen Production by Thermochemical Water Splitting for the Sulfuric Acid-Hybrid-Cycle (Westinghouse), USA, utility ownership, 1974

The results in Table VII are reported from a NASA-funded report: Studies of the use of heat from high temperature nuclear sources from hydrogen production processes. After this study the cost for the produced hydrogen without respectively with oxygen credit are: 42 to 48 respectively 30 to 36 DM/Gcal.

R&D work in the field of the water splitting is done in many places of the world.

SESSION A

NUCLEAR ENERGY FOR INDUSTRIAL PROCESSES

A 1

PRODUCTION DE VAPEUR PAR RÉACTEUR À EAU DU TYPE C.A.S.

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Commissariat à l'Energie Atomique
FRANCE

La communication présente les techniques et les caractéristiques des réacteurs PWR de petite et moyenne puissance développés par le CEA et TECHNICATOME pour des applications calogènes et production mixte vapeur/électricité.

Les modèles présentés sont:

- Modèle compact pour des puissances de 110 MWth à 420 MWth.
- Modèle à deux boucles de circulation du réfrigérant primaire pour des puissances de 600 MWth à 1300 MWth.

La communication met l'accent sur l'adaptation du NSSS et de sa technologie à ces utilisations spécifiques.

Elle situe la compétitivité de ces unités avec des ensembles de production à combustibles fossiles.

Elle présente les problèmes particuliers d'exploitation et de sûreté spécifiques à ce type d'utilisation.

I. INTRODUCTION

Les chaudières nucléaires décrites dans ce rapport couvrent une gamme de puissance de 120 à 1300 Mégawatts thermiques.

Leurs applications concernent:

- le marché industriel: production de vapeur procédé
- le chauffage urbain
- le marché du dessalement

Les techniques utilisées dans ces chaudières nucléaires, développées par la Société TECHNICATOME, sont dérivées des réacteurs de propulsion navale mis au point par le Commissariat à l'Energie Atomique (C.E.A.). Il s'agit de réacteurs à eau légère pressurisée utilisant de l'uranium faiblement enrichi.

Les unités de référence sont de deux types:

- Chaudière compacte: Chaufferie Avancée Prototype (CAP) de 120 MWth dont l'exploitation est commencée depuis la fin de l'année 1975. *La puissance d'une unité dérivée de ce type peut être comprise entre* 25 et 125 MWe.

- Chaudière à boucles de circulation de réfrigérant primaire: Prototype à terre de propulsion nucléaire (PAT), en exploitation depuis 1964. Modèle utilisé pour la chaufferie des sous-marins nucléaires actuellement en service.
  Des versions civiles sont proposables dans ce type à partir de 160 MWe.

II. CARACTERISTIQUES DES CHAUDIERES NUCLEAIRES PROPOSEES

Les Chaudières Avancées de Série (CAS)

II.1 Modèles compacts gamme basse de puissance (110 MWth - 420 MWth).

La caractéristique essentielle de ce type de chaudière est la suppression des boucles du circuit primaire.

Cette disposition permet un montage complet en usine où l'on effectue également des essais hors puissance: mise en pression et température du bloc chaudière, et par conséquent un montage final simplifié et une meilleure qualité de réalisation, (limination du nombre de soudures sur site - présentation "à blanc" des équipements, etc.).

Le bloc chaudière ne présente pas de développements du tuyauteries primaires, mais il n'a pas, par ailleurs, les désavantages d'une conception totalement intégrée. Par exemple: les pompes primaires, associées aux générateurs de vapeur sont facilement démontables.

Les générateurs de vapeur et les pompes fixés en chandeliers sur la cuve, sont des modules standards à tous les modèles CAS; ils sont en nombre variable en fonction de la puissance.

L'enceinte de confinement, en acier, est transportée sur le site en éléments préfabriqués, ses faibles dimensions dues à la compacité du bloc chaudière permettent de réduire les ouvrages de génie civil.

SURETE ET FIABILITE

Les dispositions prises sur le plan de la protection de l'environnement d'une part, et de celle de l'installation d'autre part, en font une chaufferie particulièrement bien adaptée à une implantation en milieu urbain et industriel.

- Le combustible en plaques est tel que:

. son procédé de fabrication interdit tout défaut.
. sa température de fonctionnement relativement basse et son compartimentage (combustible "caramel") réduit notablement le risque et les conséquences d'une rupture de gaine.
. l'activité de l'eau primaire reste, en fonctionnement normal, inférieur à 0,25 Ci/m^3 (hors tritium).

Sa température de gaine reste bien inférieure aux limites de sûreté dans le cas d'un accident de dimensionnement correspondant à la rupture sur le circuit primaire d'une tuyauterie de faible diamètre (ex. liaison basse pressuriseur Ø: 90 mm).

- Le circuit primaire est conçu avec:

. un choix de matériaux et techniques de construction garantissant contre le risque de rupture fragile en service.
. un dispositif de surveillance en service et inspections périodiques garantissant l'assurance de santé métallurgique des composants.
. une redondance des circuits de sécurité pour garantir la réfrigération du coeur en cas d'incident ou d'accident, l'adduction d'eau étant assurée dans la cuve.
. une organisation des générateurs de vapeur garantissant en tous points un taux de circulation secondaire suffisant pour permettre une excellente tenue en service du faisceau tubulaire sans réduction des performances.

- L'enceinte de confinement

. contient des circuits contaminés nécessaires au fonctionnement.
. est en dépression permanente (excellente étanchéité aux effluents gazeux).

. Le bâtiment nucléaire assure le confinement et l'élimination d'éventuels effluents gazeux par une mise en dépression.

La qualification des composant importants de la chaufferie (pompes primaires, mécanismes de manoeuvre de absorbants de contrôle ...) effectuée sur bancs d'essai permet de garantir la fiabilité de ces matériels.

Pour limiter le nombre des arrêts d'urgence et améliorer la disponibilité et la sécurité de la centrale, la conception générale est telle qu'en particulier l'organisation du contrôle-commande de la chaudière nucléaire minimise à la fois les interventions nécessaires d'opérateurs et la probabilité de déclenchement intempestif.

Ces chaudières nucléaires produisent une vapeur saturée à environ 47,4 bars à la puissance nominale (température primaire moyenne 285 °C - Pressurisation à 140 bars).

La figure 1 montre une coupe du bloc primaire, passant par les axes de deux générateurs de vapeur, et indique le schéma de circulation des fluides primaire et secondaire. L'aménagement intérieur de l'enceinte est représenté par la figure 2.

Le tableau I indique les caractéristiques principales d'une chaudière à trois générateurs de vapeur "CAS 3G".

II.2 Modèles à boucles gamme haute de puissance (300 MWth - 1300 MWth).

Le réacteur à deux boucles extérieures présente des caractéristiques de fonctionnement du circuit primaire voisines de celles des réacteurs électro-nucléaires de très haute puissance.

- Fourniture d'énergie à un complexe industriel.

Une analyse des exigences de l'utilisation industrielle mixte vapeur/électricité et une interprétation sévère des critères de sûreté ont conduit à des dispositions particulières:
. production de vapeur surchauffée
. redondance des circuits de sauvegarde
. injection de secours dans la cuve
. double enceinte de confinement en béton avec espace annulaire en dépression pour la collecte des fuites internes.

La figure 3 montre en écorché du réacteur de 1100 MWth développé pour une utilisation industrielle particulière. Le tableau II indique les caractéristiques principales de cette unité prévue pour produire 40 % de la puissance sous forme de vapeur et 60 % d'électricité.

- Fourniture d'énergie pour le chauffage urbain

L'application spécifique au chauffage urbain n'exige pas les performances retenues pour la production mixte vapeur/électricité présentée ci-dessus.

C'est pourquoi, une étude est en cours pour adapter le modèle de 1100 MWth à la fourniture de vapeur pour le chauffage urbain. Les options possibles mettront l'accent sur la sûreté, la fiabilité et l'économie.

Les points examinés plus particulièrement sont:
- un détarage, en température et en pression, du circuit primaire du réacteur, de manière à augmenter les marges entre le contionnement et les limitations du combustible.
- une simplification de la boucle intermédiaire entre le circuit primaire et l'utilisation urbaine, visant surtour les générateurs et transformateurs de vapeur qui assurent l'échange thermique entre les circuits.

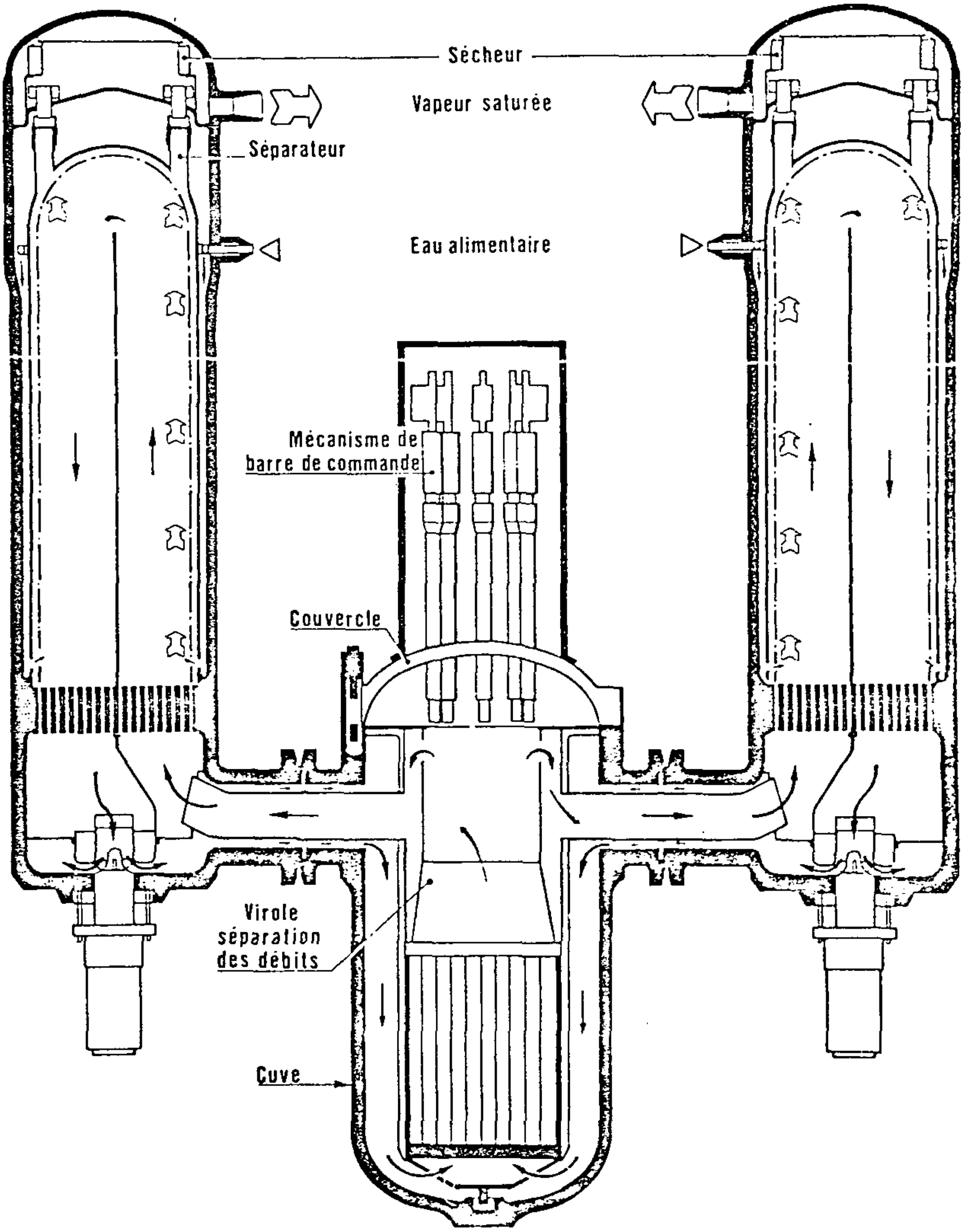
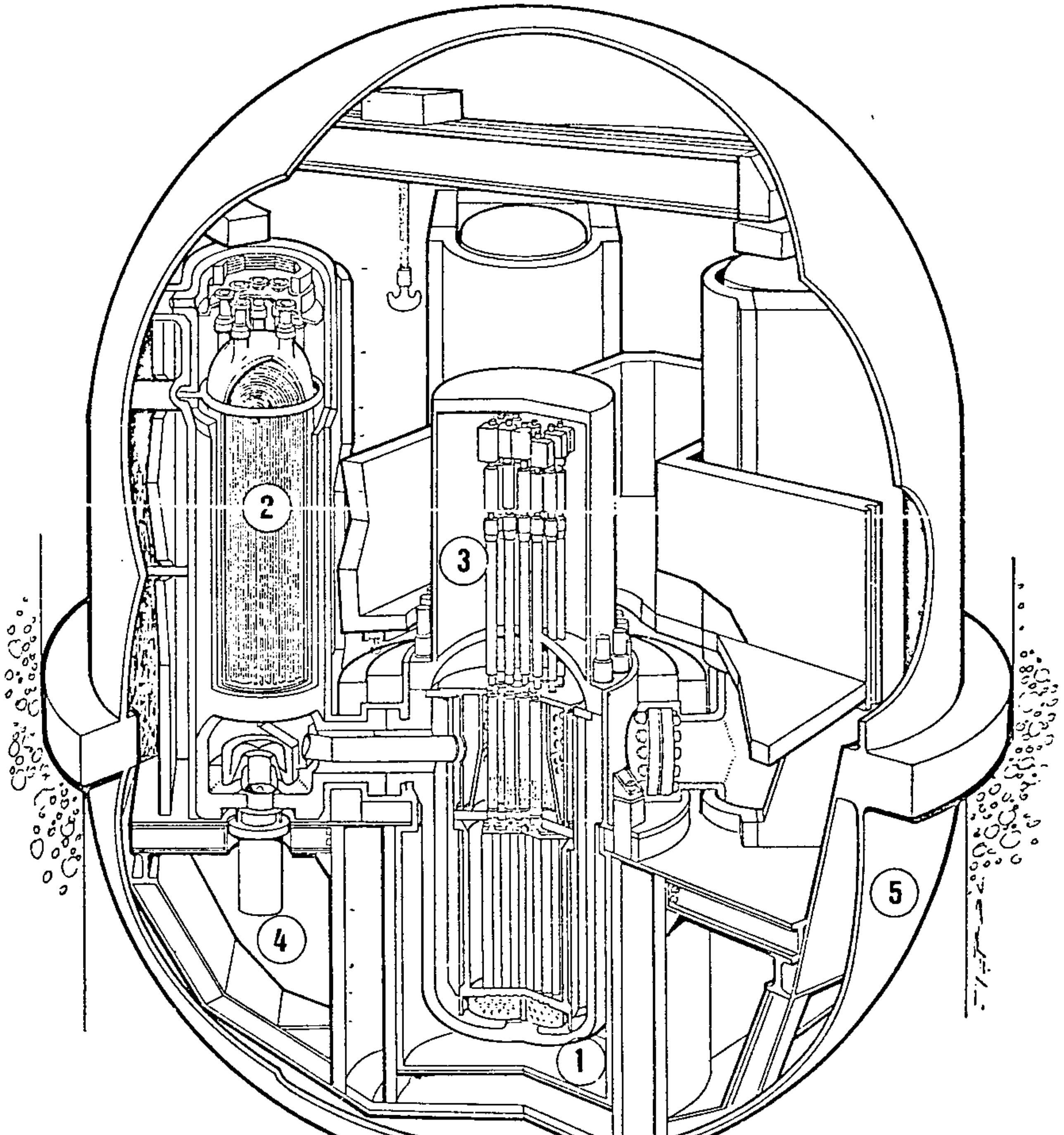


schéma de circulation des fluides

Figure 1



1 CUVE RÉACTEUR
2 GÉNÉRATEUR DE VAPEUR
3 MÉCANISME DE BARRES DE COMMANDE
4 POMPE
5 ENCEINTE DE CONFINEMENT

Figure 2

TABLEAU I

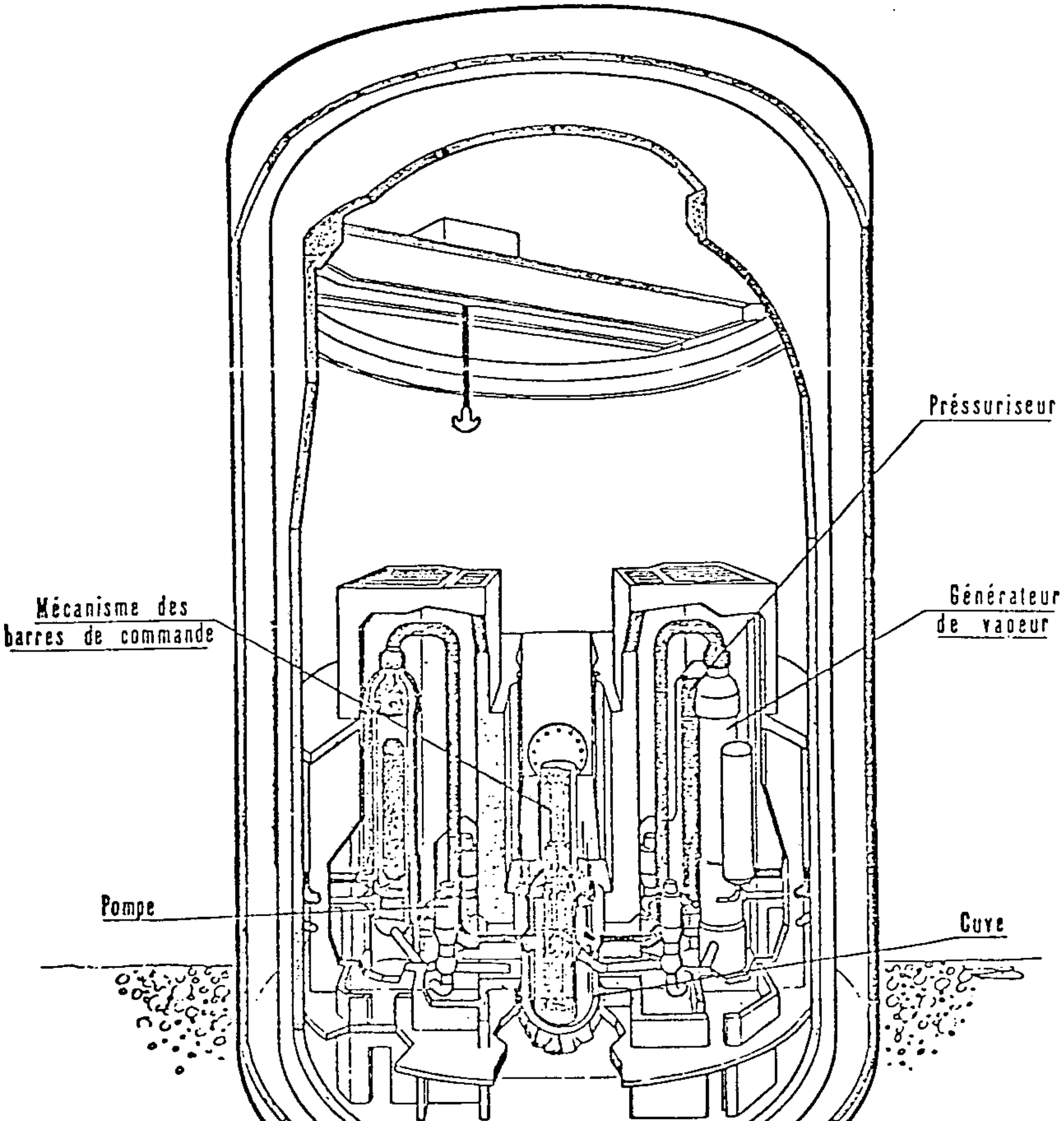
CARACTERISTIQUES DE LA "CAS 3G"

MODELE 420 MWth		
1/ - CARACTERISTIQUES DU CIRCUIT PRIMAIRE		
- Puissance thermique fournie par l'ensemble des 3 GV	MW	420
- Température d'entrée coeur	°C	270
- Température de sortie coeur	°C	300,6
- Pression de fonctionnement	bars	140
- Débit global (pour 3 pompes du type à moteur noyé)	m3/h	12600
2/ - CARACTERISTIQUES DU COEUR		
- Nombre d'assemblages à plaques d'oxyde d'uranium enrichi		144
- Nombre de plaques par assemblage		17
- Combustible fragmenté et compartimenté - Nature du gainage		Zr 4
- Hauteur active d'une plaque	mm	1805
- Pas du réseau de boitiers	mm	215
- Poids total d'uranium pour le coeur	t	13
- Enrichissement de l'uranium	%	< 4
- Nombre de croix de contrôle		24 à 32
3/ - CARACTERISTIQUES DU CIRCUIT SECONDAIRE - (à puissance nominale)		
- Température de l'eau alimentaire	°C	180
- Vapeur saturée à la sortie des Générateurs de Vapeur (GV) du type tubes en U :		
(Pression	bars	47,2
(Température	°C	260
(Taux d'humidité	%	0,1
- Débit global	t/h	743

TABLEAU II

CARACTERISTIQUES PRINCIPALES DE LA CHAUDIERE NUCLEAIRE "CAS 2B"

1/ - CARACTERISTIQUES DU CIRCUIT PRIMAIRE		
- Puissance thermique de la chaudière	MWth	1100
- Température moyenne du primaire constante (entre 20 et 100 % de la charge)	°C	306
- Pression de fonctionnement	bars	155
- Débit primaire total	kg/s	5683
2/ - CARACTERISTIQUES DU COEUR (version crayon)		
- Nombre d'assemblages		112
- Nombre de crayons par assemblage		256
- Hauteur active UO2	mm	2400
- Pas de réseau d'assemblages	mm	215
- Poids total d'U dans le coeur	t	31,4
- Enrichissement de l'U à l'équilibre	% U5	3,35
- Nombre de barres de commande		45
3/ - CARACTERISTIQUES DU CIRCUIT SECONDAIRE		
- Température de l'eau alimentaire à Wn	°C	225
- Pression de vapeur (sortie GV)	bars	58
- Température de vapeur (surchauffée) (sortie GV)	°C	298
- Débit de vapeur	t/h	2060
4/ - CARACTERISTIQUES DES PRODUCTIONS		
- Production électrique nette (avec aéro-condenseur)	MWe	185
- Production de vapeur industrielle surchauffée à 31 bars et 270°C	t/h	600



CAS
SYSTEME A BOUCLES

Figure 3

II.3 Caractéristiques communes aux deux types de chaufferies nucléaires

- la plus grande partie des composants du circuit primaire et des circuits auxiliaires fait appel à une technologie éprouvée sur les chaudières de référence PAT et CAP.

- les temps d'indisponibilité de ces chaufferies devraient être réduits.

L'arrêt programmé pour le déchargement est de 360 heures/an (travail continu).

III. APPLICATIONS

Dans les pays dont les réseaux électriques sont fortement interconnectés, la production d'électricité par les chaufferies nucléaires de petite ou moyenne puissance n'est pas à considérer. Il existe cependant un marché à l'exportation dans les pays dont les réseaux électriques ont des puissances modestes. On peut également prévoir des centrales mixtes fournissant de l'électricité et de la chaleur à un client particulier:

- Complexe industriel
- Installation de chauffage urbain
- Dessalement.

Nous comparerons ci-dessous les solutions électrogènes et celles qui produisent de la vapeur. Il s'agit de 3 installations comportant chacune 2 chaufferies nucléaires CAS 3G de 420 MWth chacune.

1ère installation: tout électrique.
La production est évaluée à 261 MWe bruts à pleine charge.

2ème installation:
C'est une variante de la précédente: la centrale est installée à proximité d'une ville dont le réseau de chauffage urbain absorbe 200 MW thermiques produits par la centrale. La pointe d'hiver de la demande de chauffage (400 MWth) est assurée par des chaudières classiques au fuel, par surchauffe de l'eau en sortie de la centrale nucléaire.

Cette solution nucléaire est prévue pour fonctionner avec variation journalière de la charge des réacteurs, qui de 100 % le jour, peut passer, la nuit en saison creuse, à 30 % par exemple.

Le chauffage urbain peut être alimenté à partir de l'une ou l'autre des chaufferies, permettant d'assurer une bonne disponibilité de la fourniture de chaleur.

La figure 4 présente le schéma général de l'installation.

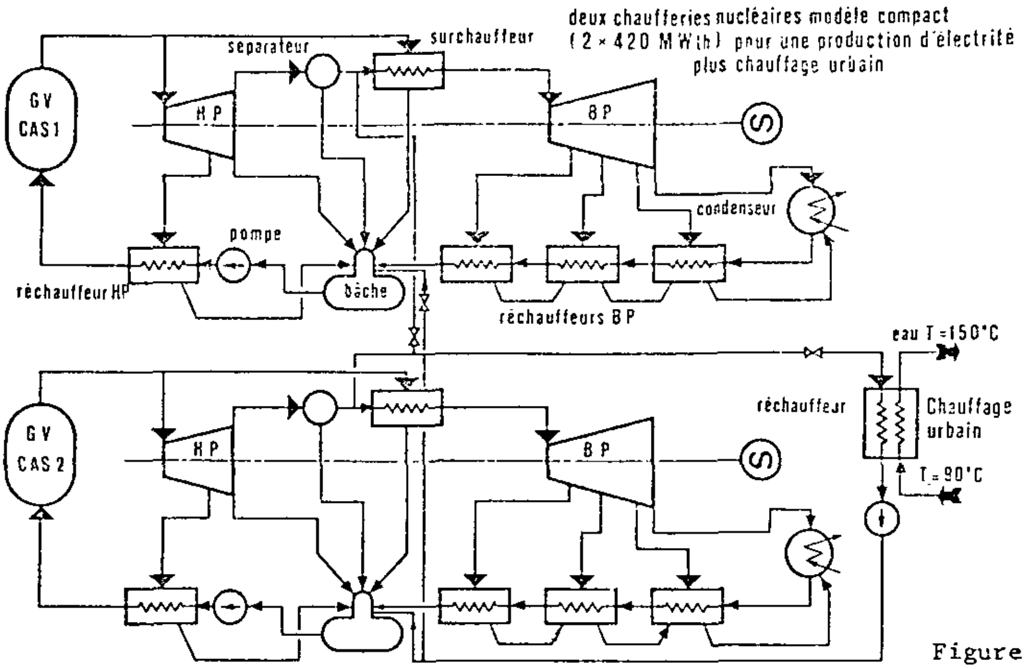


Figure 4

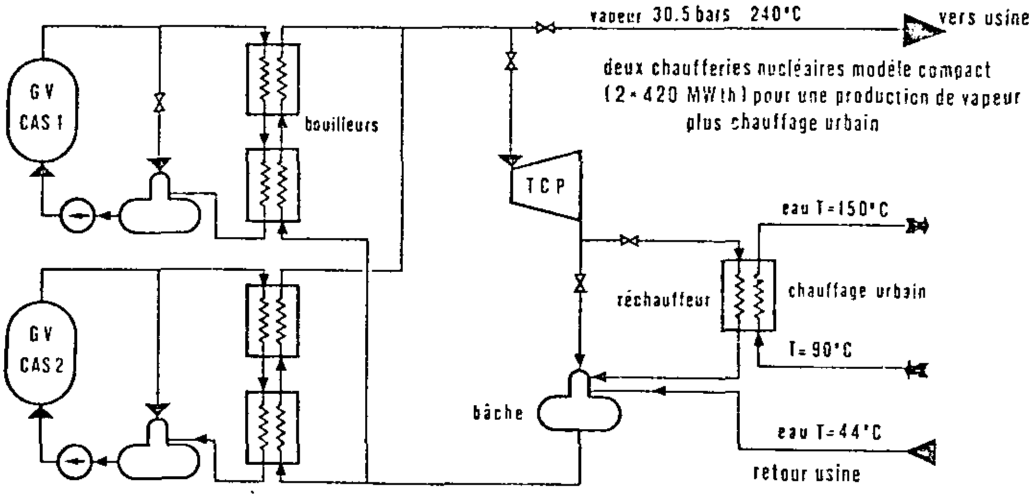


Figure 5

Diagramme de répartition de l'énergie pour deux chaufferies nucléaires modèle compact (2 x 420 MWth)

(les arrêts non programmés et les réductions de puissance ne sont pas pris en compte)

Fourniture de 200MW au chauffage urbain (85% de l'énergie)

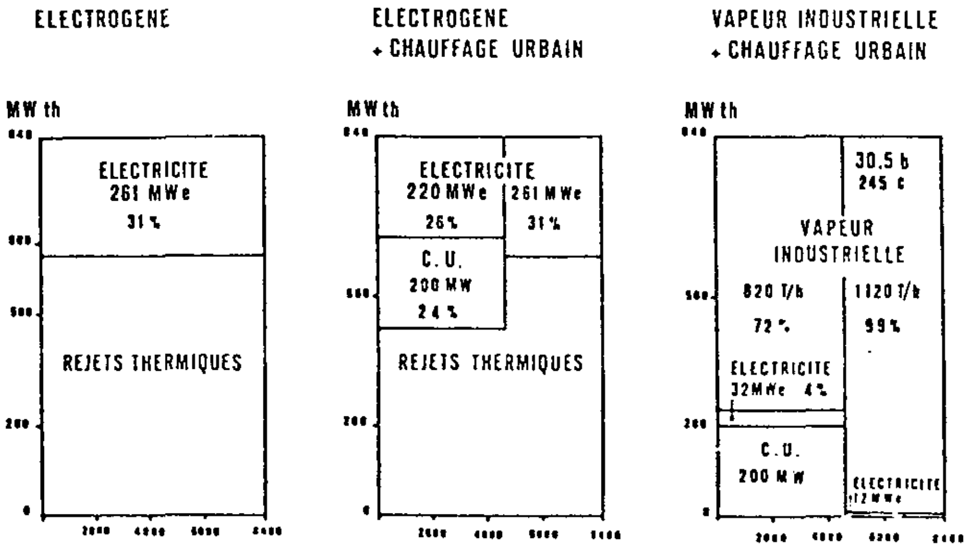


Figure 6

3ème installation

Il s'agit ici de produire de la vapeur (30,5 bars, 245 °C) pour un complexe industriel, tout en assurant comme auparavant la fourniture de chaleur urbaine.

Une partie de la vapeur produite est détendue dans une turbine à contre-pression, et assure l'alimentation en électricité des auxiliaires de la centrale, l'excédent étant fourni au réseau local.

La figure 5 montre le schéma choisi pour cette installation.

Les trois installations apparaissent sur la figure 6, qui présente les diagrammes de répartition de l'énergie thermique produite dans les coeurs des réacteurs. Pour les installations avec chauffage urbain, la répartition a été simplifiée pour ne faire apparaître que les conditions de fonctionnement extrêmes, chauffage urbain à 200 MW en hiver et à 0 en été, sans mettre en évidence les variations continues de la demande, journalières et saisonnières.

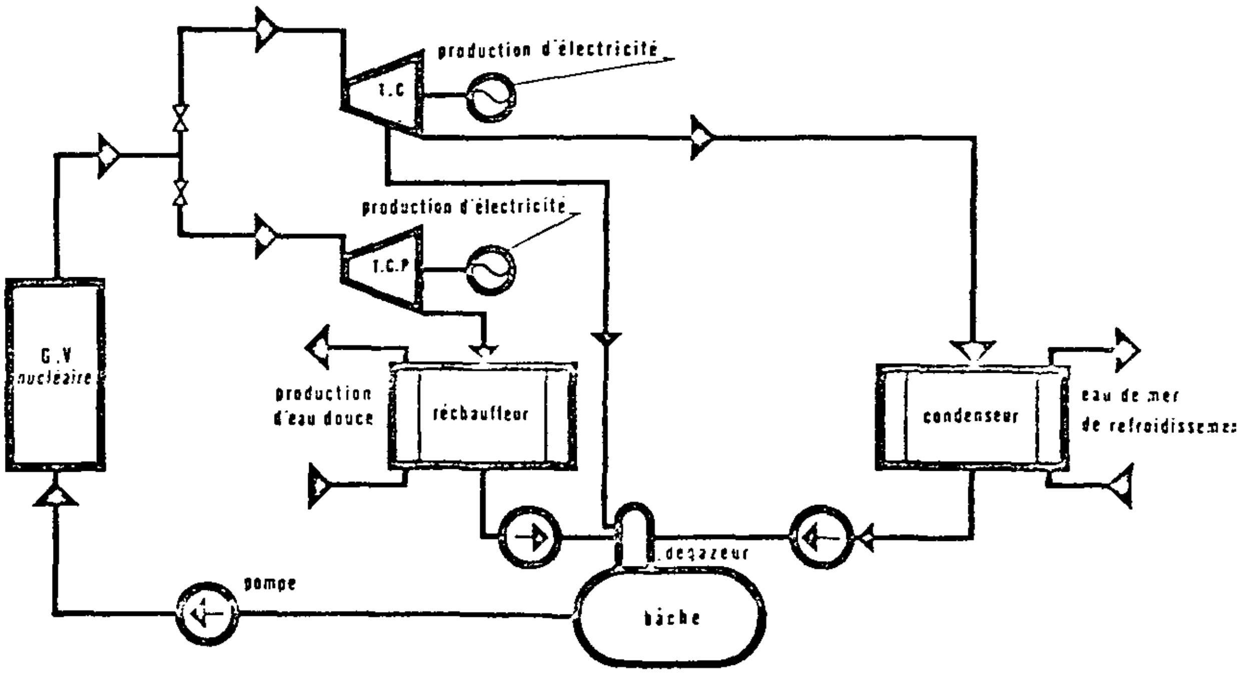
Dessalement

Les chaudières nucléaires doivent répondre aux besoins suivants:

- fourniture d'énergie vapeur à basses caractéristiques (pression 2,5 bars) pour l'usine de dessalement.
- fourniture d'énergie électrique pour les besoins propres à l'usine de dessalement (4 kWh par m^3 d'eau produite) et pour l'alimentation des auxiliaires de la chaufferie.
- éventuellement fourniture d'énergie électrique pour le réseau de distribution local.

Les chaufferies nucléaires du type considéré présentent d'une façon générale des caractéristiques de vapeur relativement hautes, eu égard aux besoins vapeur de dessalement (pression de 47 bars et 50 bars en vapeur saturée). Le détarage en pression de ce type d'unités ne semble pas présenter d'avantage économique très marquant.

Ces considérations conduisent à adopter un schéma type d'alimentation d'une usine de dessalement comme indiqué sur la figure ci-dessous.



**TURBINE A CONTRE-PRESSION POUR LA PRODUCTION D'EAU DOUCE
ET TURBINE A CONDENSATION POUR LA PRODUCTION D'ÉLECTRICITÉ**

IV. ASPECTS ECONOMIQUES

Nous présentons comment si situe, dans l'état actuel de not techniques, la compétitivité des centrales nucléaires, productrices soit d'électricité, soit de chaleur, soit mixte, par rapport à des unités à combustible fossile assurant le même service.

Il s'agit d'une étude effectuée à partir de coûts réels.

IV.1 Hypothèse de l'étude

Les données de base sont les suivantes:

- durée prise en compte dans les calculs économiques ... 20 ans
- facteur de charge de la chaudière nucléaire 0,85
- durée de construction .... 5 ans
- prise en compte des frais de conduite et d'entretien
- les centrales classiques de comparaison sont construites en France
- coût de fuel à moins de 0,5 % de soufre (pour le chauffage urbain) .... 400 F/T
- alimentation des auxiliaires de la centrale nucléaire assurée par autoproduction d'énergie électrique
- chauffage urbain (monotone des charges) - nombre d'heures équivalentes à pleine puissance .... 2882 h
- le coût de l'énergie est donné à la sortie de la chaudière, transport exclus.

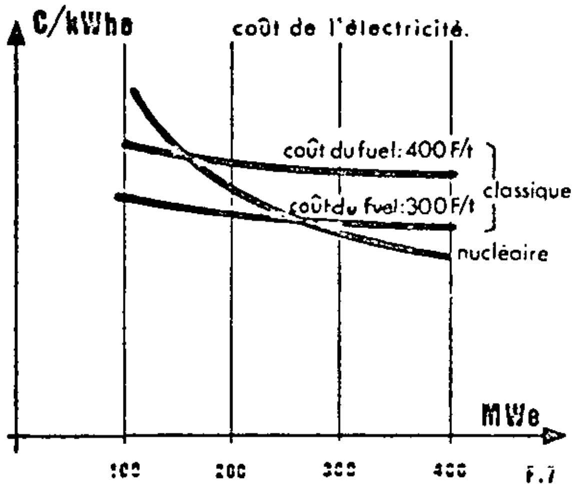
Tous les calculs économiques ont été effectués en francs constants sur les bases du 1er Janvier 1976 et actualisés au taux de 10 % par an.

IV.2 Résultats

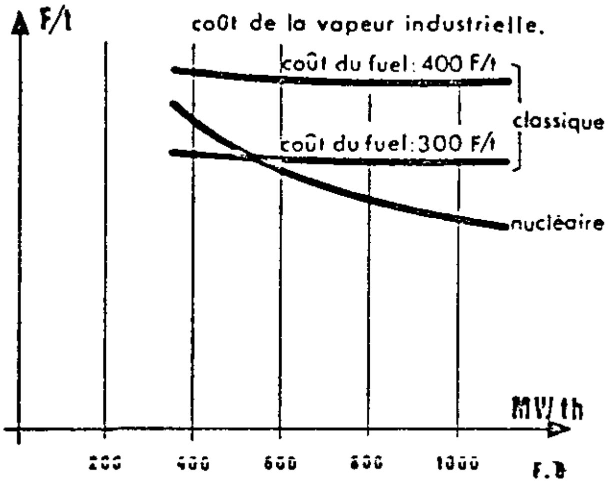
Les résultats obtenus à partir des hypothèses indiquées sont présentés sur les figures suivantes.

Les figures 7 et 8 donnent le coût de l'énergie dans les applications électrogène et production de vapeur industrielle; elles font apparaître que:

- la production d'électricité par les centrales nucléaires dans cette gamme de puissance n'est pas compétitive avec l'achat au réseau EDF.
- la production de vapeur nucléaire est compétitive par rapport à une installation classique à partir d'une puissance de 500 MWth pour un combustible à 300 F/tonne.



F.7



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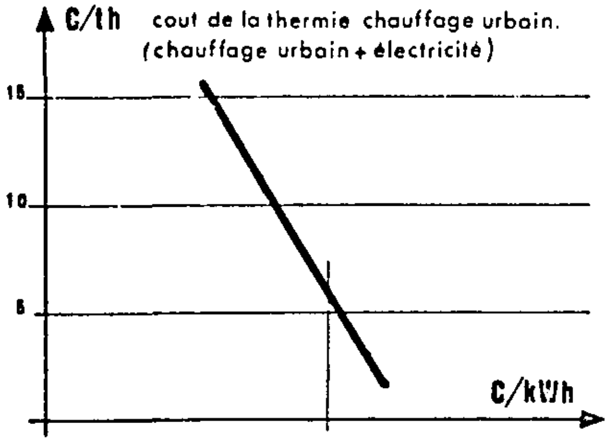

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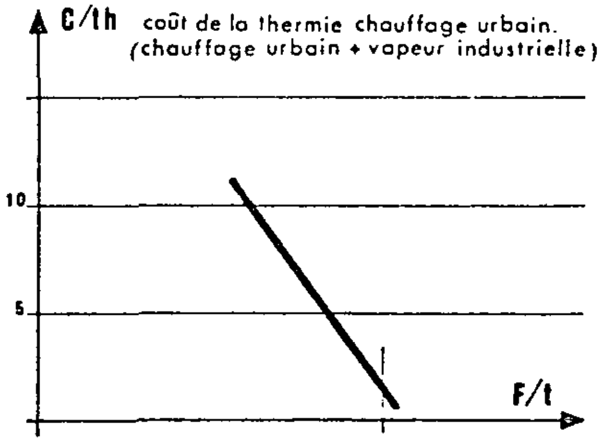

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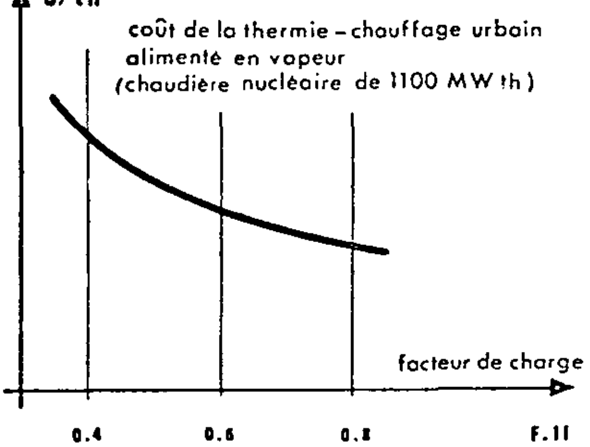

F.11

Cette application du nucléaire est intèressante grâce à la taille relativement modeste du réacteur qui est à la mesure des complexes industriels existants.

Les figures 9 et 10 présentent les coûts de l'énergie correspondant à deux chaufferies nucléaires, modèle compact CAS 3G (2 x 420 MWth) pour la production:

- d'électricité et de chauffage urbain,
- de vapeur industrielle et de chauffage urbain.

Dans ces deux applications, le nucléaire fournit 85 % de l'énergie de chauffage urbain, correspondant à la moitié de la puissance appelée, soit 200 MWth, avec une température d'eau de 150 °C.

Le complément est fourni par surchauffe jusqu'à 190 °C aved des chaudières à combustible fossile (pour la pointe d'hiver).

La figure 9 indique le coût du chauffage urbain en fonction de la valorisation de l'énergie électrique.

Pour un coût de l'électricité fournie par des installations classiques, fuel 400 F/tonne, le coût de l'énergie du chauffage urbain nucléaire est à la limite de compétitivité par rapport au chauffage par combustible fossile.

La figure 10 indique le coût du chauffage urbain en fonction de la valorisation de la vapeur industrielle.

Pour un coût de vapeur fourni par des installations classiques, fuel à 400 F/tonne, le coût du chauffage urbain nucléaire est inférieur à 1,5 c/thermie.

La figure 11 se rapporte au modèle à boucle CAS 2B (1100 MWth) fournissant de la vapeur à un réseau de chauffage urbain.

Cette courbe montre l'influence du facteur de charge sur le coût de l'énergie de chauffage urbain nucléaire. La compétitivité, avec le chauffage par combustible fossile, est atteinte pour un facteur de charge d'environ 45 %.

A 2

PROCESS STEAM APPLICATIONS, U.K. STUDIES

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1. INTRODUCTION

The Programmes Analysis Unit (PAU) is a techno-economic study group jointly sponsored by the UK Department of Industry and the UK Atomic Energy Authority. Studies have been carried out recently by the PAU of ways in which nuclear energy could be substituted for fossil fuels in applications other than central electricity generation; industrial process heat is one such area.

This paper attempts to summarise our investigations and tentative conclusions, while recognising that in a paper of this length much of the supporting material and detailed assumptions must be omitted. It is hoped to publish a more detailed account of some aspects of this work in the near future.

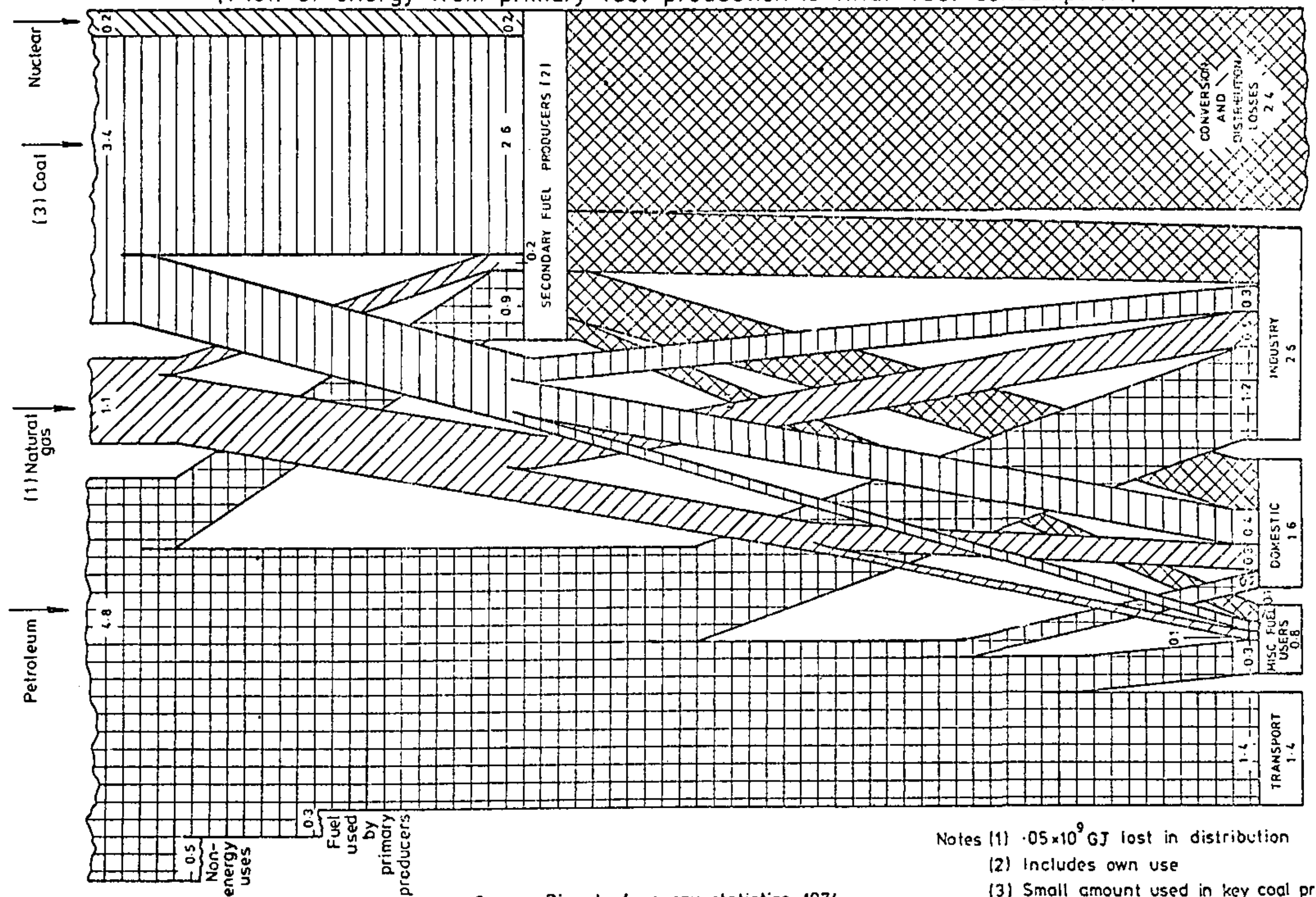
2. ENERGY USE IN THE U K

The supply of primary fuels to secondary fuel producers and to final consumers in the UK is shown in Fig. 1, for a recent year (1973). The industrial sector used about 43 % of final energy consumption (or 41 % in primary energy terms), as shown in Table I.

	Percentages			
	1950	1960	1970	1973
Industry	45	43	43	43
Domestic	33	29	25	24
Transport	9	17	20	21
Other Final Consumers	13	12	13	13

Table I: Share of Final Energy Consumption by Four Major Sectors 1950 - 1973
Source: Dept. of Energy (1975)

FIG. 1 ENERGY USE IN U.K. 1973 —
(Flow of energy from primary fuel production to final fuel consumption)



Source: Digest of energy statistics 1974
(HMSO 1975)

Notes (1) $\cdot 05 \times 10^9$ GJ lost in distribution
(2) Includes own use
(3) Small amount used in key coal producers ($\cdot 03 \times 10^9$ GJ)
(4) All figures x 10^9 GJ

Not to scale

Table II gives a breakdown of consumption by the industrial sector on a heat supplied basis, electricity being included at its heat energy equivalent. Industry consumes 36 % of all purchased electricity, but this represents only 11 % of the energy it uses. In addition, private generation of electricity by manufacturing industry represents approximately 2.5 % of its energy use. The majority of the electricity is used for machine drives and electrolytic processes.

		10^6 GJ	Per Cent
Iron and Steel		689	25
Engineering & Metal Trades		447	16
Food, Drink, Tobacco		222	8
Chemicals & Allied Trades		447	16
Textiles, Leather, Clothing		150	6
Paper, Printing, Stationery		155	6
Bricks, Tiles, Fireclay		71	3
China, Earthenware, Glass		74	3
Cement	134	134	5
Others	333	333	12
TOTAL		2722	100

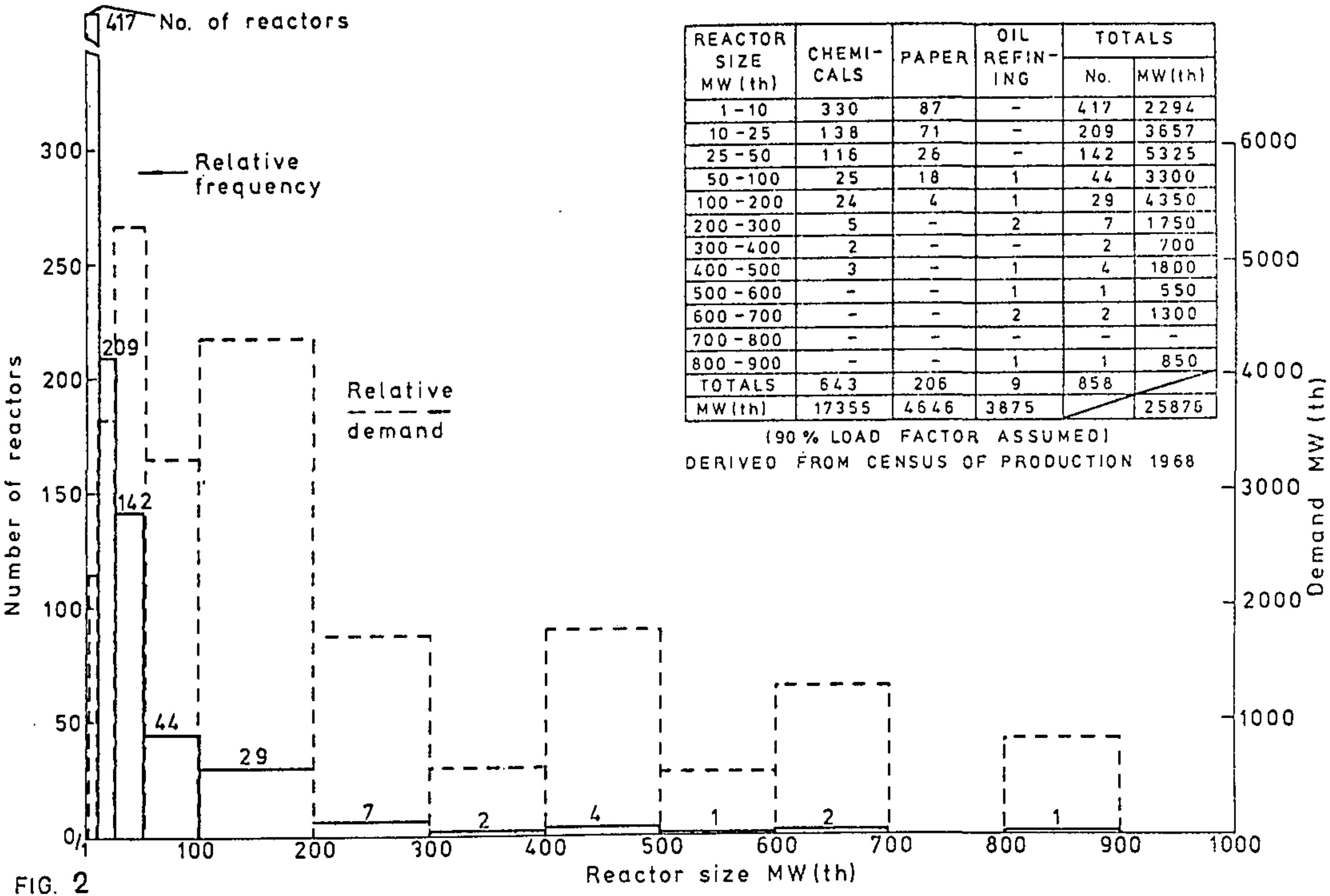
Table II: UK Industrial Fuel Consumption, 1973
Source: Dept. of Energy (1975)

Little published information could be found on the ways in which industry uses this energy, which excludes petroleum chemical feedstocks. From limited UK data and by analogy with the USA it appeared that about half of the non-electric fuel consumed was used to produce process steam and about one-third provided direct heat. In terms of 1973 consumption, this represents approximately 1.2×10^9 GJ to process steam and 0.8×10^9 GJ to direct heat.

In view of separate PAU studies of the Iron and Steel industry, this was excluded from the present study. Investigations showed that of the industries the major consumers of process steam were Chemicals, Oil Refining, Paper and Board, Food Processing and Textiles, of which the first three operate in the largest production units with continuous processes and would be of most interest for possible nuclear supply.

Enquiries showed that much of the process steam is used at temperatures less than 250 °C. This requirement is within the limits obtainable from water-cooled reactors such as SGHWR, PWR or BWR. On the other hand, direct-heat applications are commonly at temperatures within the range 750 °C to 1,500 °C. As these temperatures were judged to be beyond the capability of reactors so far fully developed for commercial service, this end of the spectrum was regarded as more suitable for later investigation.

As no energy statistics to the required detail were available for individual establishments within the industries selected, the probable size structure of demand was estimated by an indirect method, making use of employment statistics and assuming constant average energy use per capita for each industry. To simplify the analysis it was considered reasonable to assume that 100 % of the energy used by the Chemicals and Paper and Board industries and 35 %



REACTOR SIZE MW (th)	CHEMICALS	PAPER	OIL REFINING	TOTALS No.	TOTALS MW(th)
1 - 10	330	87	-	417	2294
10 - 25	138	71	-	209	3657
25 - 50	116	26	-	142	5325
50 - 100	25	18	1	44	3300
100 - 200	24	4	1	29	4350
200 - 300	5	-	2	7	1750
300 - 400	2	-	-	2	700
400 - 500	3	-	1	4	1800
500 - 600	-	-	1	1	550
600 - 700	-	-	2	2	1300
700 - 800	-	-	-	-	-
800 - 900	-	-	1	1	850
TOTALS	643	206	9	858	
MW(th)	17355	4646	3875		25876

(90 % LOAD FACTOR ASSUMED)

DERIVED FROM CENSUS OF PRODUCTION 1968

FIG. 2

TOTAL POTENTIAL MARKET FOR ON SITE NUCLEAR REACTORS IN PROCESS INDUSTRIES. (SINGLE REACTORS) (CHEMICALS, PAPER AND OIL REFINING) of that used by Oil Refining was applied to steam-raising. The results thus obtained are combined in the form of a histogram in Fig. 2; this shows the numbers of reactors which would be needed in various size intervals to meet the demand of the three industries named, as derived from the 1968 Census of Production, assuming 90 % demand load factor. It is apparent from Fig. 2 that to meet this demand by privately-owned in-house plants would require large numbers of very small reactors and a small number of medium size, but not large, reactors.

3. PROCESS STEAM PRODUCTION

Nearly all industrial process steam is generated in boilers fired by fossil fuels, oil being assumed to be the dominant fuel determining the price structure in the UK. Some steam is produced at high pressure and temperature for electricity generation, before being extracted or exhausted for process steam use, but the simple case is considered here. Estimated production cost for industrial steam at two hypothetical prices of crude oil are shown in Table III. Feed water cost and condensate return credit are excluded, and the exchange rate and other cost are based on 1.1.75 values.

Crude Oil landed UK price $/bbl	Oil Price by weight (1) £/ton	Fuel oil cost inc. 2 % handling (2) p/GJ	Boiler efficiency (3) %	Fuel cost of steam p/GJ	Capital + operation + m't'ce charges (3) p/GJ	Total cost of steam production (4) p/GJ
10	31.9	75	80	94	15	109
20	63.8	149	83	180	18	198

Notes:
1. At £ 1 = $ 2.35 and 1 ton = 7.5 bbl.
2. At 43.5 GJ (412 therms) per ton.
3. Assumed response to increased oil price.
4. Excluding cost of feed water.

Table III: Cost of Steam from Oil-Fired Boilers

Estimates were made of the cost of steam production from nuclear reactors expected to be available for this purpose in the mid-1980's; these include small Burnable Poison Water Reactors (BPWR) and various size of Steam Generating Heavy Water Reactor (SGHWR) ranging from the 290 MW(th) Winfrith prototype to 4000 MW(th) central power station size. Intermediate circuits and heat exchangers were assumed necessary to ensure complete separation of process steam from radioactive primary circuits.

The resulting nuclear process steam cost are displayed in Fig. 3, for single and twin reactor installations. These cost are in terms of 1.1.75 currency values and dollar exchange rate, and are based on a load factor of 80 %, 10 % discount rate and 25 year amortisation. The cost of feed water is excluded and no credit taken for return of condensate. Fig. 3 also shows the steam cost from oil-fired boilers at two oil prices as given above. Uncertainty tolerances of plus or minus 10 % are applied to both sets of estimates.

Fig. 3 shows that on the basis of the cost data used in our estimates, nuclear steam would be competitive with oil-firing using $ 10/bbl oil only at outputs of 1,000 'MW(th) or more. This is too large to match the needs for in-house plants shown in Fig. 2. If oil prices rise to $/20/bbl the economical size falls to around 300 MW(th) but this is still too large to match the greater part of the in-house market, at its current level. This market is expected to grow by rather more than one-third of its present size by the end of the century even with increased fossil fuel prices, but there would still be relatively few establishments for which reactor ownership would appear to be economically attractive, even if licensing requirements could be satisfied in all such cases.

4. THE THERMAL UTILITY

This analysis leads to consideration of the concept of a common process heat supply shared by industrial consumers, and perhaps by others, in areas possessing a high concentration of demand. Many such areas in the UK are at coastal or estuarine sites. In the absence of energy consumption statistics on a localised basis it was again necessary to use an indirect method of estimation using employment exchange data for selected industries and to convert this to energy demand from average per capita consumption. In this scenario it is feasible for smaller consumers to be connected to the supply and so Food and Drink and Textiles were added to Chemicals, Oil (35 %) and Paper to arrive at estimates of total process steam demand in a number of selected areas. These estimates have been increased by 35 % to allow for expected growth to the end of the century and the results of this procedure are displayed as a bar-chart, Fig. 4.

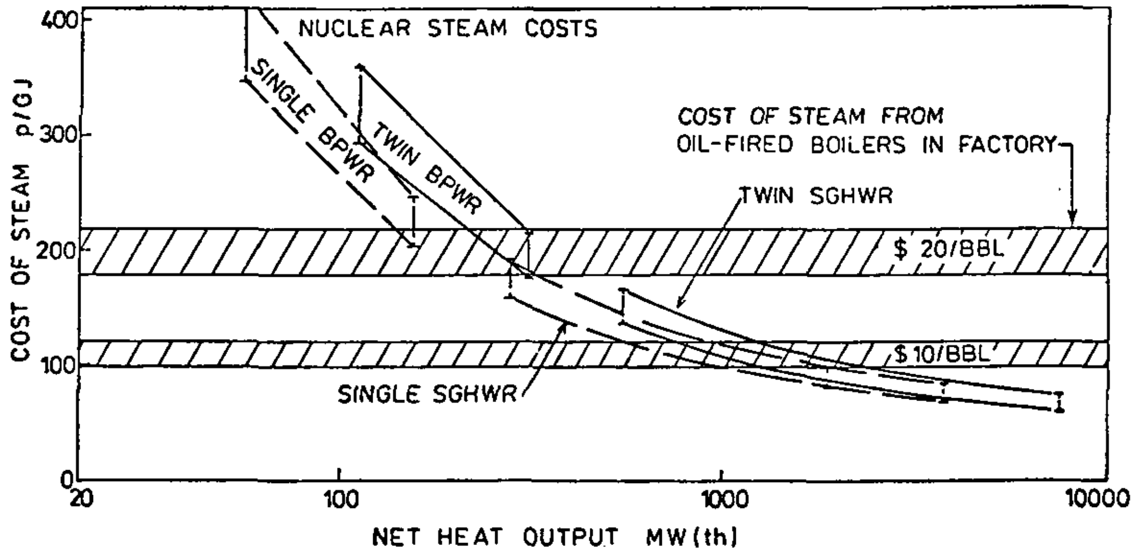


FIG. 3: Cost of Nuclear Steam at Reactor Site

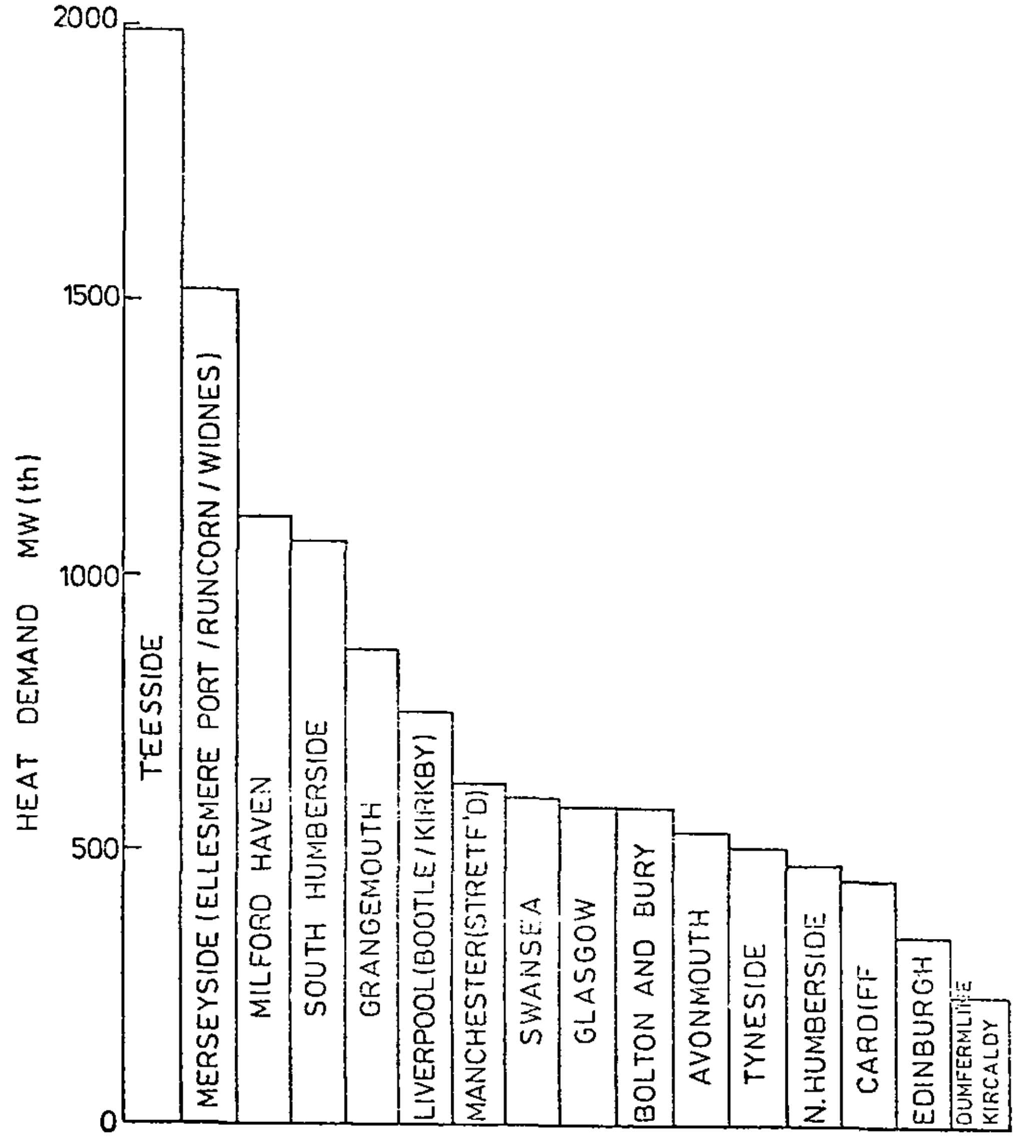


FIG. 4: Bar-Chart of Estimated Process Steam Demand in Various Areas in AD 2000

It is not envisaged that it will prove possible to find central reactor sites in these areas which are, for the most part, highly populated, and typically 250 to 500 km^2 in area. There is a need for feed water but not for large volumes of cooling water such as would be required for electricity generating stations, and this should facilitate siting on the edges of the areas. The problem is then one of transmission of heat energy from the station to the demand centre, followed by local distribution. Various solutions to this problem are possible, using different media. It was decided to study the most direct and most obvious method, namely steam transmission by pipeline.

Quite moderate steam conditions were assumed for the transmission pipeline, namely 2.3 MN/m^2 absolute pressure and 240 °C temperature at inlet (20 °C superheat) and 1.7 MN/m^2 outlet pressure. The pipe insulation thickness was held constant at 0.1 m and the steam enthalpy must not be permitted to fall below its saturation value. Using an analytical method taking heat loss and acceleration terms into account and a simple computation program, the results shown in Fig. 5 were obtained. The shaded region represents possible solutions for distances from 10 to about 25 km, while avoiding wet steam and limiting the pipe diameter to 1.5 m, for practical reasons.

Rough estimates were made of the capital cost of steam pipelines supported in shallow concrete trenches and the resulting transmission cost per unit of heat delivered are plotted in Fig. 6 and 7 for two different sets of assumptions, as detailed in Table IV.

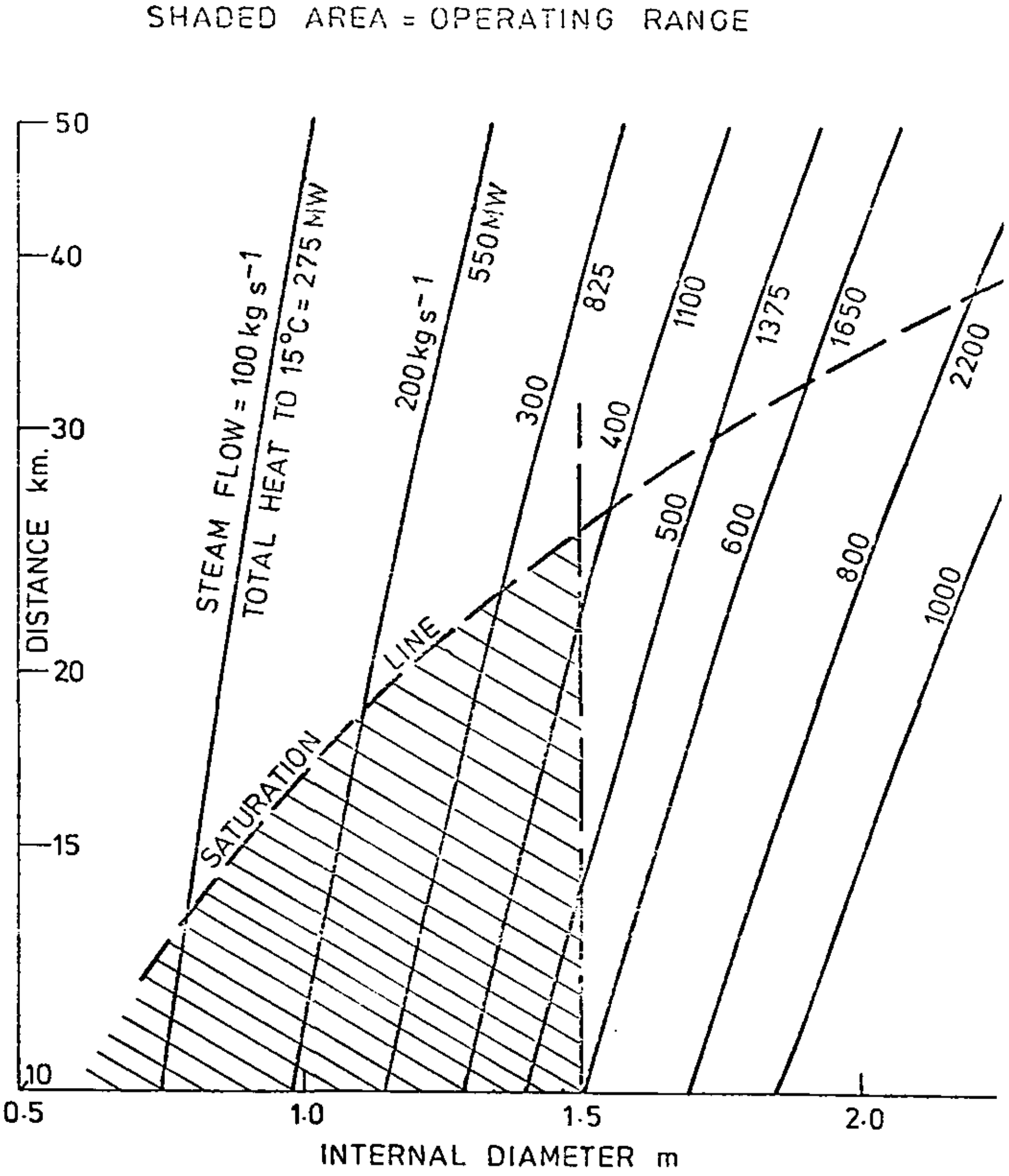


FIG. 5: Transmission Pipe Size and Capacity

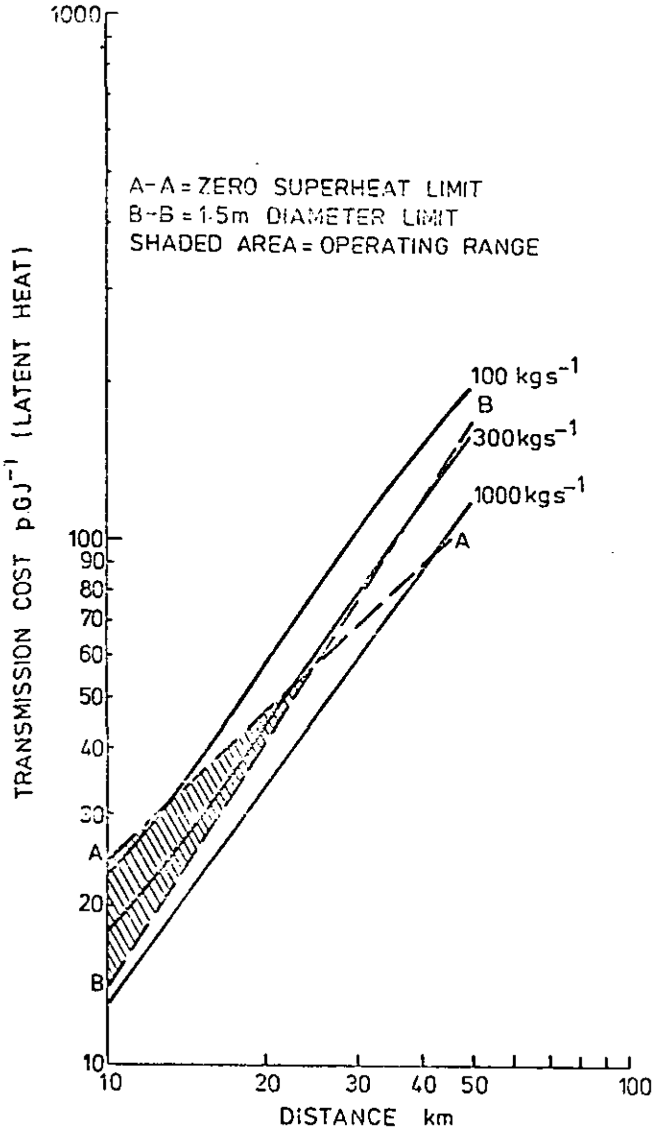


FIG. 6: Unit Cost of Steam Transmission (First Assumptions)

Case		1	2
Capital cost	£/m length/m dia/mm thickness	80	40
Financial sector		Private	Public
Capital Charge	% p.a.	20	-
Discount rate	%	-	10
Life	years	-	20
Load factor		0.8	0.8
Heat charged		Latent heat	Total heat above 15^{o}C
Figure No.		6	7

Table IV: Parameters Assumed for Steam Transmission Cost

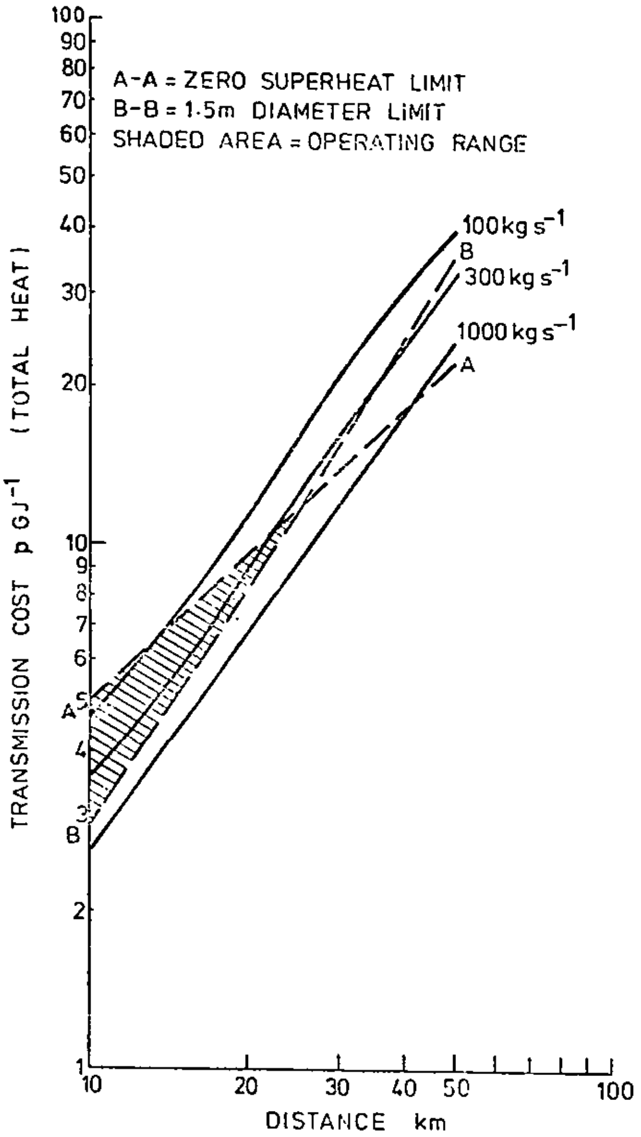


FIG. 7: Unit Cost of Steam Transmission (Second Assumptions)

Inspection of Figures 6 and 7 shows that the combined effect of the changes made from case 1 to case 2 assumptions is to lower the unit cost of steam transmission by a factor of 5. Expressed as a cost per unit distance, for distances between 10 km and 20 km, Fig. 6 corresponds to approximately 2 p GJ^{-1} km^{-1} and Fig. 7 to 0.4 p GJ^{-1} km^{-1}. While detailed engineering studies would be needed to establish the cost accurately, we should expect the final cost to lie between these two values.

To arrive at the cost of steam delivered to consumers' premises, we have added the 10 km transmission cost obtained from Fig. 7 and an estimated distribution cost of 6.3 p/GJ to the production cost of nuclear steam shown in Fig. 3; the results are displayed in Fig. 8. This demonstrates that the break-even heat output at an oil price of $ 10/bbl has now increased to about 2,000 MW(th), while at $ 20/bbl it would be some 300 to 400 MW(th).

Comparing these heat outputs with the demands shown in Fig. 4 reveals that with $ 10/bbl oil there is only one area, of those examined, in which a nuclear heat utility might prove to be viable. If, however, the oil price rises

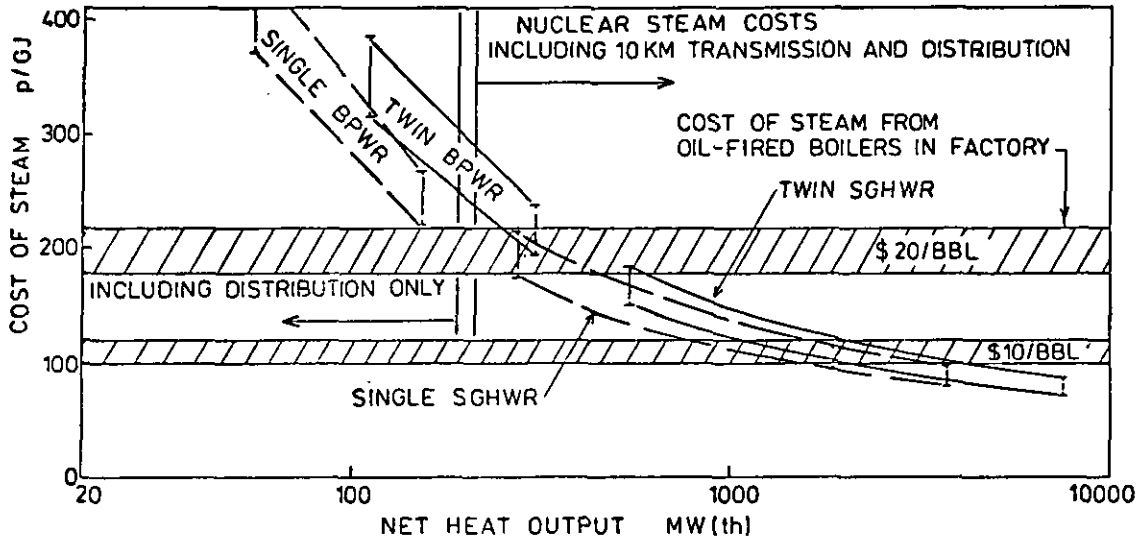


FIG. 8: Delivered Cost of Steam from Nuclear Heat Utility

to $ 20/bbl (in 1.1.75 terms) at least a further fourteen industrial areas would appear to merit more rigorous and detailed consideration.

In conclusion, it is suggested that if further relative price increases for fossil fuels are going to occur, there appears to be a direct economical case for the thermal utility concept, without invoking fossil fuel conservation arguments. To test this hypothesis, we have recommended field studies of process steam conditions and consumption in favourable areas, reactor siting, steam transmission system design, route selection and cost estimation. Careful consideration is also needed of the question of ownership, financing and management of such thermal utilities.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance received from Professor G.R. Bainbridge and Dr. N.J.D. Lucas of The Energy Centre, University of Newcastle-upon-Tyne, during part of these studies. We also wish to thank our colleagues in the PAU and many individuals in the industries concerned who contributed useful advice or assistance.

A 3

HIGH TEMPERATURE REACTORS FOR GASIFICATION AND LIQUEFACTION OF COAL

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1 PROCESS

1.1 Hydrogasification

Hydrogasification is the exothermal conversion of coal by means of hydrogen to methane according to the reaction $C + H_2 \longrightarrow CH_4$ (H = -86 kJ/mol C). The hydrogen for this process is produced by steam reforming of a part of the methane coming from the hydrogasification. In case of nuclear hydrogasification all the heat for hydrogen production, gaspurifications, coal preparation and gascompression is taken from the nuclear reactor. Fig. 1 shows a principle of this process which uses lignite as feed.

In the helium circuit of the nuclear reactor (950 °C, 40 b) first there is a steam reformer which produces the hydrogen (reaction temperature 800 °C, pressure 40 b). In a second step the enthalpie of the helium is used to produce steam. The product gas coming from the steam reformer is converted to nearly pure hydrogen by shift conversion, CO_2 purification and a low temperature separation stage for H_2 and CH_4. The gasification reaction takes place at 800 °C and 80 bar in a fluidized bed gasifier. Behind the gasifier there is a fluidized bed drier which is fed with coal coming from a predrying stage using steam (lignite contains nearly 60 % H_2O).

The gas which is produced in the gasification stage is cleaned from dust in cyclones and then recycled to the gas purification. A product of such a plant could be methane or hydrogen or synthesis gas. The data corresponding to lignite or hard coal are given in Table I.

1.2 Steam Gasification

Coal can be gasified using the endothermal reaction $C + H_2O \longrightarrow CO + H_2$. Fig. 2 shows the principle flow sheet of the process. Using an intermediate

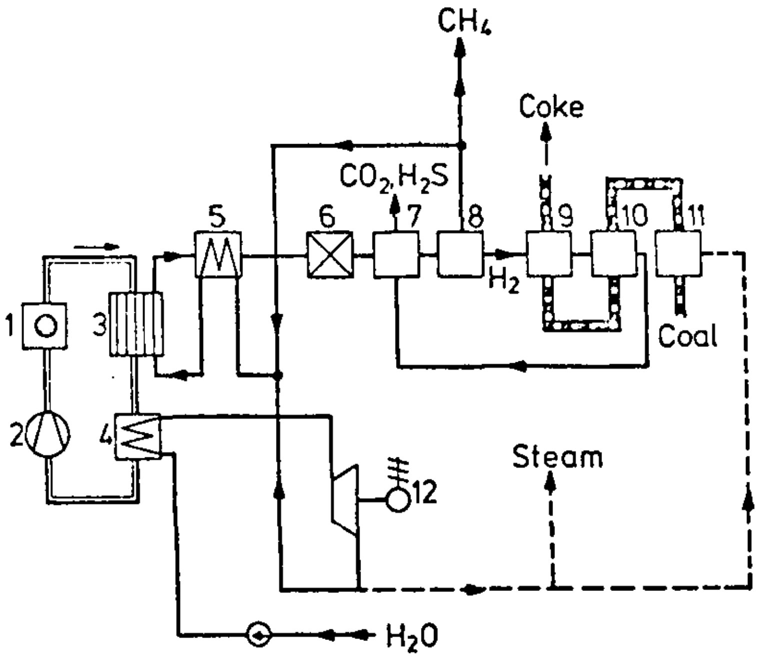


FIG. 1:

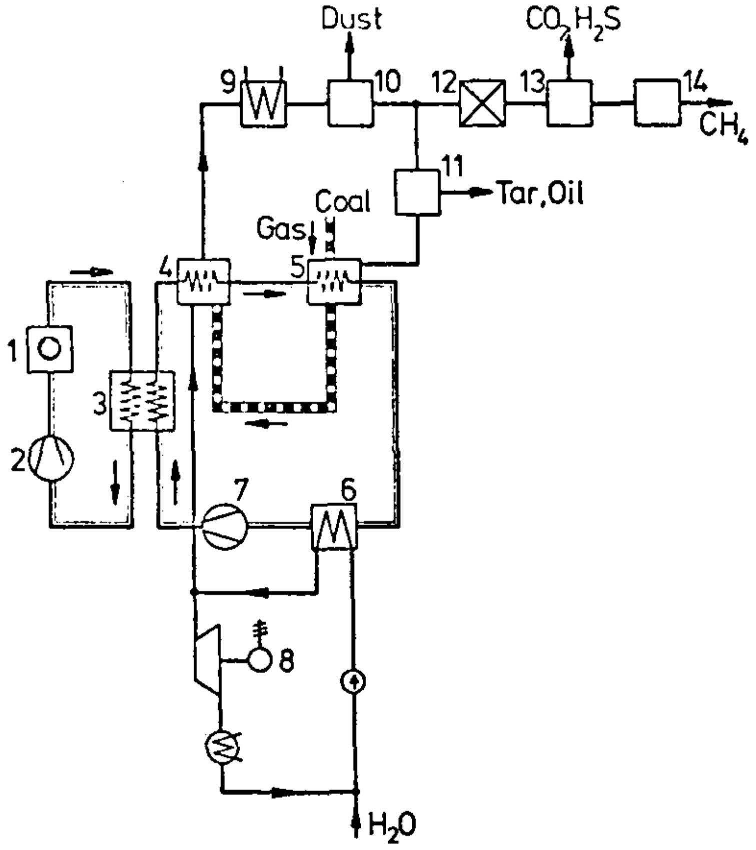
Flow sheet of hydrogasification

1	Nuclear reactor	7	Gas purification
2	He-circulator	8	H_2/CH_4-separation
3	Steam reformer	9	Gasifier
4	Steam generator	10	Dryer
5	Waste heat utilization	11	Predryer
6	Shift conversion	12	Steam turbine plant

Coal Parameter	Lignite	Hard Coal
Reactor power	3000 MW	3000 MW
Feedrate coal	2200 t/h	870 t/h
CH_4 production	3.8×10^5 Nm^3/h	3.95×10^5 Nm^3/h
Net electric power	110 MW	400 MW
Residual char	270 t/h	346 t/h
C gasification	63 %	55 %
Specify energy consumption	6167 kcal/Nm^3 CH_4	4350 kcal/Nm^3 CH_4

TABLE I: Data for Hydrogasification

heat exchanger system the nuclear heat in the second helium circuit is used to gasify the coal, to carbonize the coal and to produce steam for the process and for a steam turbine plant. The gas leaving the gasifier is cleaned from dust, tar and oil. Behind these stages there will be a shift conversion, H_2S and CO_2 purification and a final methanation stage. The main data for a plant using hard coal as feed are given in Table II. Naturally lignite can be gasified too by this process. In this case the amount of the by-product electricity is smaller, because the coal itself has a high additional demand on low temperature energy for drying and because of the lower gasification temperature, the amount of heat used for the gasification process can be higher.



1	HTR	8	Steam turbine plant
2	He-circulator	9	Waste heat utilization
3	Intermediate heat exchanger	10	Dust removal
4	Gas generator	11	Tar + oil-separation
5	Carbonizer	12	Shift conversion
6	Steam generator	13	Gas purification
7	He-circulator	14	Methanation

FIG. 2: Steam Gasification

Reactor power	3000 MW
Feed coal	250 t/h
CH_4 production	1.78×10^5 Nm^3/h
Oil + tar production	47.5 t/h
Electricity production	800 MWel
Specific energy consumption	4830 $kcal/Nm^3CH_4$

TABLE II: Data for Gasification of Hard Coal

1.3 Coal Liquefaction

Following the catalytic reaction $CH_{0,8} + H_2$ —— $CH_{1,8}$ coal can be converted to gasolin. Fig. 3 shows the flow sheet, in which a coal conversion process corresponding to the H-coal process is combined with a steam reformer plant using a nuclear reactor for heat supply. In the reformer plant hydrogen is produced in nearly the same way as in case of hydrogasification. The feed for the steam reformer is gas (C_1 ... C_4) coming from the coal conversion plant.

The hydrogen is used for the hydrogenation step itself, which takes place at high pressure (40 b, 400 °C), for the hydrotreating of the products, and for the hydrocracking of the light and the heavy components of the product of hydrogenation. The byproduct gas (C_1 ... C_4) which comes out of all the different stages of conversion is cleaned and converted to methane in a side gas stage.

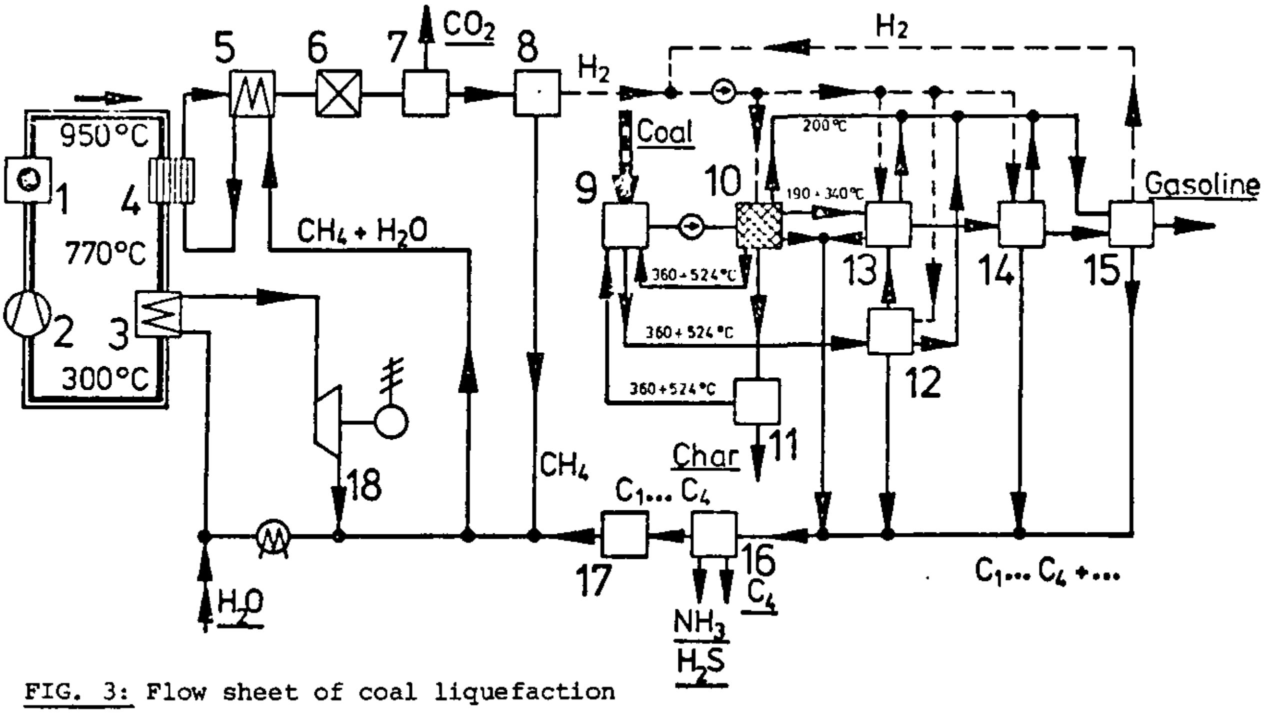


FIG. 3: Flow sheet of coal liquefaction

1 Nuclear reactor
2 He-circulator
3 Steam reformer
4 Steam generator
5 Preheater
6 Shift conversion
7 Gas purification
8 H_2/CH_4 separation
9 Coal separation
10 Hydrogenation reactor
11 Char production
12 Hydro cracking of heavy fuel oil
13 Hydrotreating
14 Hydrocracking
15 Reforming plant
16 Gas separation
17 Rich gas stage
18 Steam turbine plant

The amount of gas produced is sufficient as feed gas for the production of hydrogen. All the heat for the hydrogen production, gas purification and gas compression is taken from the nuclear reactor.

LIQUEFACTION OF COAL

$$CH_{0,8} \xrightarrow[\text{Kat.}]{H_2} CH_{1,8}$$

$$\begin{aligned} 1{,}95 \text{ t coal} + 1730 \text{ Nm}^3 H_2 \longrightarrow\ & 1 \text{ t gasoline} + 0{,}269 \text{ t } C_1 \ldots C_3 \\ & + 0{,}142 + C_4 + 0{,}326 \text{ t coke} \\ & + H_2S,\ NH_3,\ H_2O, \text{ losses} \end{aligned}$$

$$\begin{aligned} 367 \text{ kg } C_1 \ldots C_4 + 2{,}85 \text{ Gcal reactor heat} \longrightarrow\ & 1730 \text{ Nm}^3 H_2 \\ & + 0{,}9 \text{ Gcal waste heat} \end{aligned}$$

$$\begin{aligned} 14{,}8 \text{ Gcal coal} + 4{,}6 \text{ Gcal reactor heat} \longrightarrow\ & 1 \text{ t gasoline} + \\ & 2.2 \text{ Gcal coke} \end{aligned}$$

Reactor power	3000 MW
Feed coal	1190 t SKE/h
Gasoline production	565 t/h
Specific H_2 consumption	1730 Nm^3/t gasoline
Specific nuclear heat cons.	4.6×10^6 kcal/t gasoline
Electricity production (process demand)	470 MWel
Specific coal consumption	2.11 t SKE/t gasoline

TABLE III: Main data of coal liquefaction

2 STATE OF TECHNOLOGY

2.1 Nuclear reactor

The heat source for the above mentioned processes is the pebble-bed high temperature reactor. As Fig. 4 shows, the fuel element consists of a ball of graphite containing some thousands of coated particles which contain the fissile and fertile material. 3.25 millions of these balls form the core of a 3000 MW plant. The numbers in Fig. 4 indicate the expected fuel and surface temperatures for process heat application. Fig. 5 gives an impression on the helium flow in the primary system for the typical process of steam reforming (it is explained on the example of a non-integrated system.

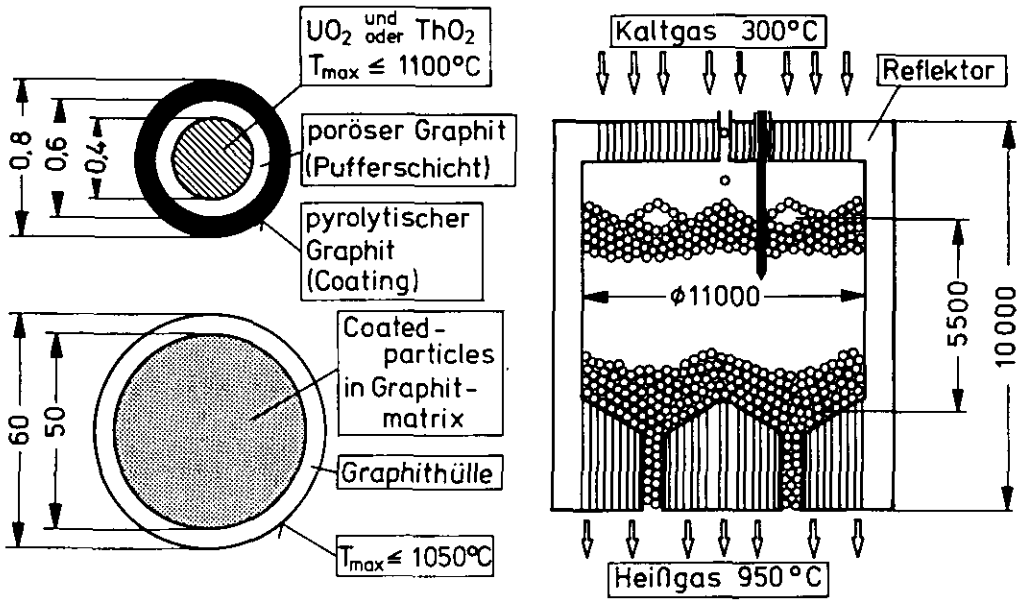


FIG. 4: Fuel element and core of a pebble-bed reactor for process heat.

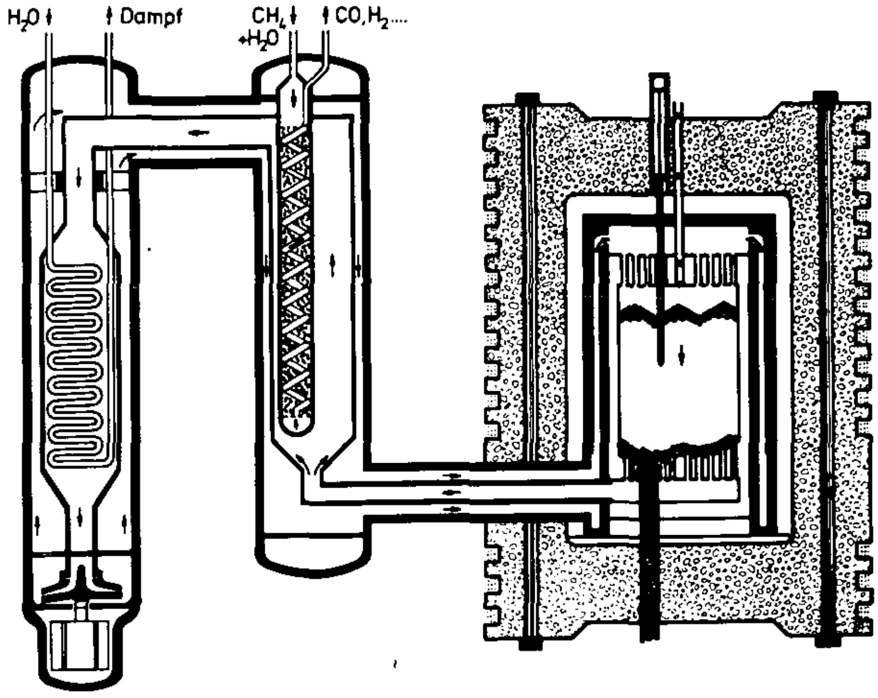


FIG. 5: Flow of helium in primary circuit of a process heat reactor.

The hot gas (950 °C) leaving the reactor core is sampled in a hot gas chamber on the bottom of the reactor, is ducted through a coaxial pipe to the steam reformer. From here the helium (800 °C) is ducted to the steam generator and enters the circulator with 300 °C. This cold helium cools in counter-flow all ducting systems and vessels and is again entering the reactor vessel through the outer ring of the coaxial pipe. From here the helium flows through the thermal shield to the top of the reactor and again enters the core.

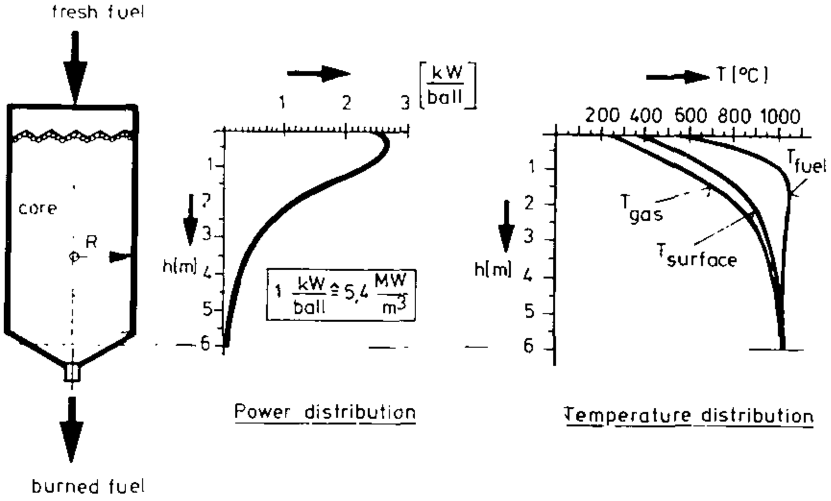
The main question of such a reactor for producing hot helium for the above mentioned processes are as follows:

- fuel element design for 950 °C helium,
- fission product release and contamination,
- corrosion of fuel elements and core structure,
- tritium permeation
- hot gas ducting,
- use and design of intermediate heat exchangers,
- arrangement of heat exchangers in the primary system (vessel concept)
- design of the containment (inert gas filling)
- licensing (explosion in containment and gas plant)

The question of production of high temperatures in the cooling gas seems to be solved by the introduction of the OTTO cycle, in which the fuel elements pass the core only one time. Fig. 6 shows the typical axial profiles of power density, gastemperature, surface temperature, and fuel temperature, which are the consequence of this fuel management. All temperatures stay in allowed limits for a helium outlet temperature of 950 °C.

The fission product release and corrosion of fuel elements and graphite by impurities in the helium can be tolerated, as calculations show until now.

The permeation of tritium through the hot walls of the heat exchangers produces activity levels of the tritium in the product gas which can be tolerated in nearly all cases of application.



Power distribution

Temperature distribution

FIG. 6: Typical power and temperature distribution in a HTR pebble bed reactor using the OTTO cycle

The realisation of hot gas duct systems for 950 °C is a major question of development and qualification. Coaxial ducts and ceramic insulation seem to be a reasonable solution.

The arrangement of vessels requires new solutions because the power density in the heat exchangers (steam reformer or intermediate heat exchangers) is much smaller than in steam generators. Fig. 7 represents some possible arrangements.

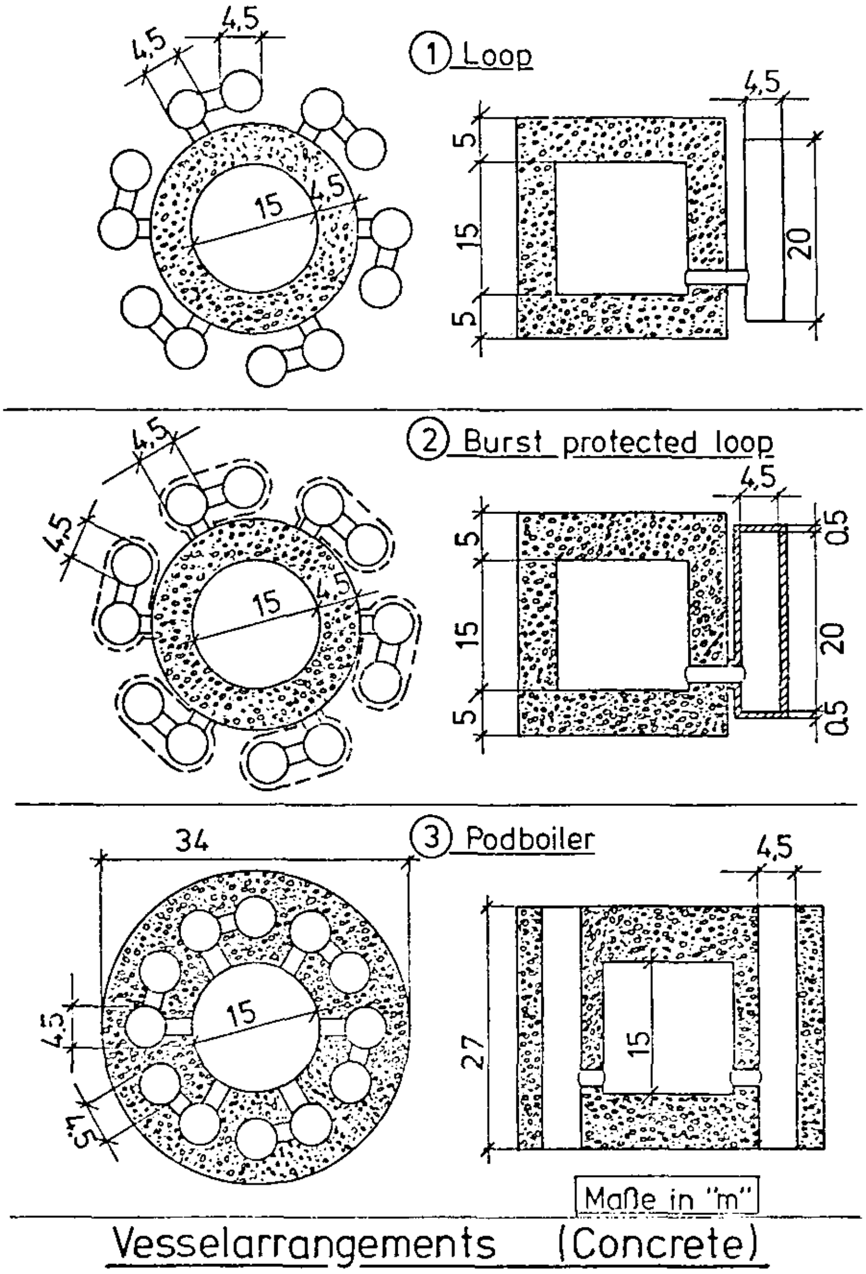


FIG. 7: Arrangements of primary system

This question has to be studied in the future in more detail to find a solution which fulfills all safety requirements, which is flexible enough for all process applications, can long inspected and repaired and which has the lowest costs.

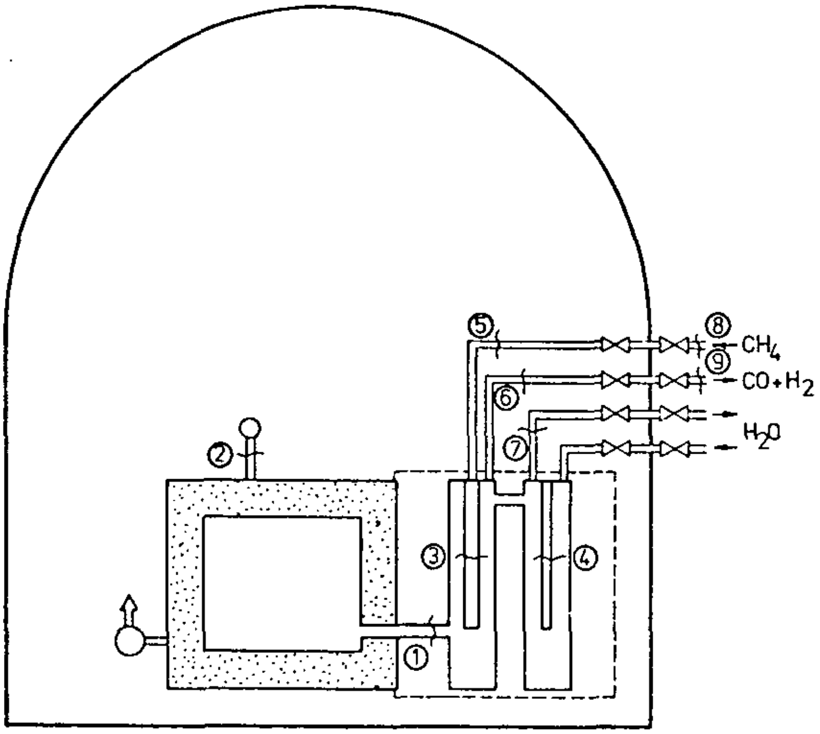


FIG. 8: Flow sheet for safety considerations

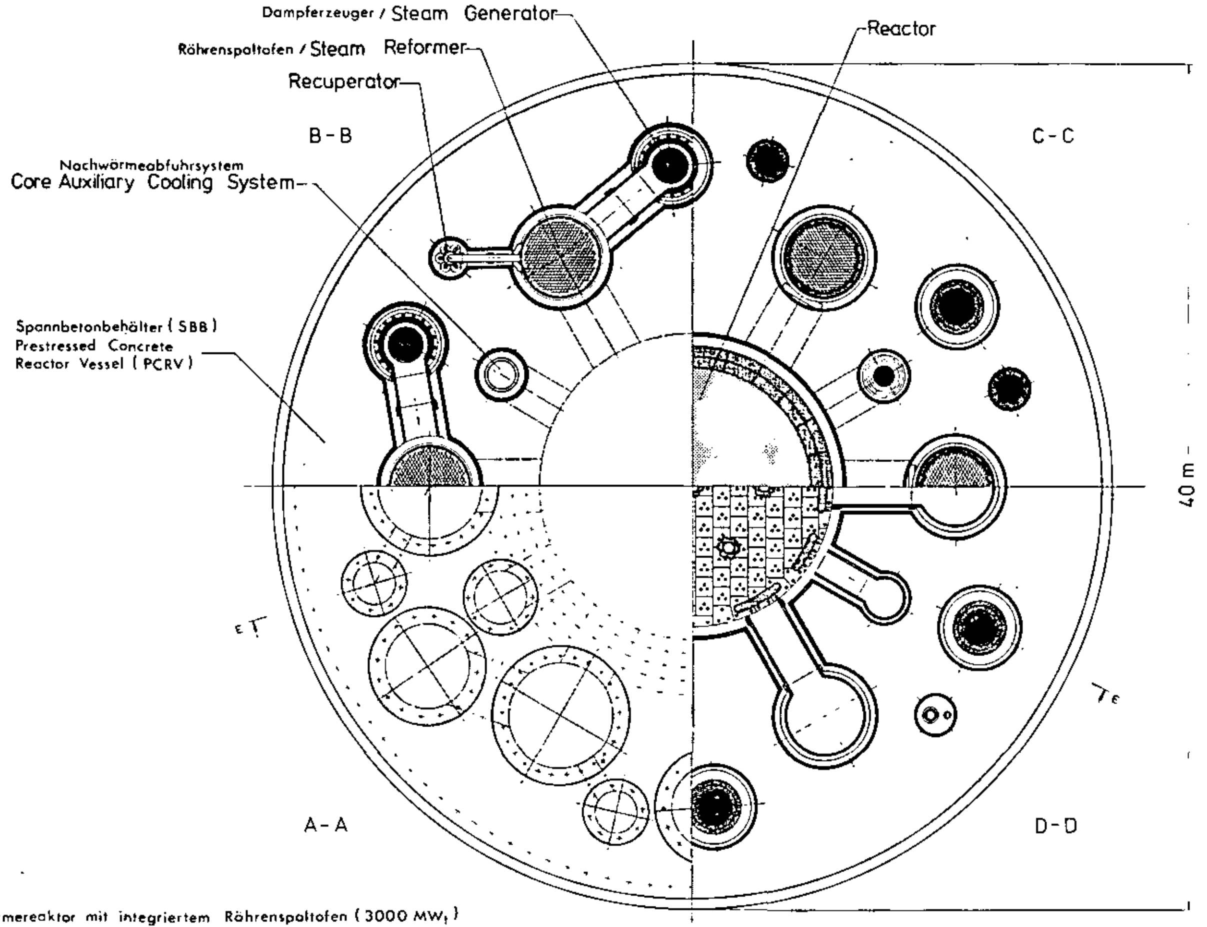
1	*break of coaxial duct*	*5*	*break of methane pipe*
2	*break in auxiliary systems*	*6*	*break of product-gas pipe*
3	*failure of steam reformer tube*	*7*	*break of steam pipe*
4	*failure of steam generator tube*	*8/9*	*break of gaspipes or vessels in gas plant*

As far as the safety analysis of such a new principle as nuclear process heat is considered, there are a lot of new accidents connected with the gas-production, as Fig. 8 shows. The internal accidents (3) and (4) can be tolerated, too, as calculations show. (5) and (6) can be handled by bunkering the gas pipes and inertisations of these rooms. (7) is known from steam generating plants and can be tolerated. The external breaks and failures in the gas plant (8) and (9) require special solutions to protect the containment. In order to give an impression how such a process heat reactor could look like, in Fig. 9 and Fig. 10 there are design examples for an integrated and for a non-integrated system. Both are 300 MWth plants and include steam reformers.

2.2 Steam reformers

The steam reforming process has been well known for more than 20 years. It

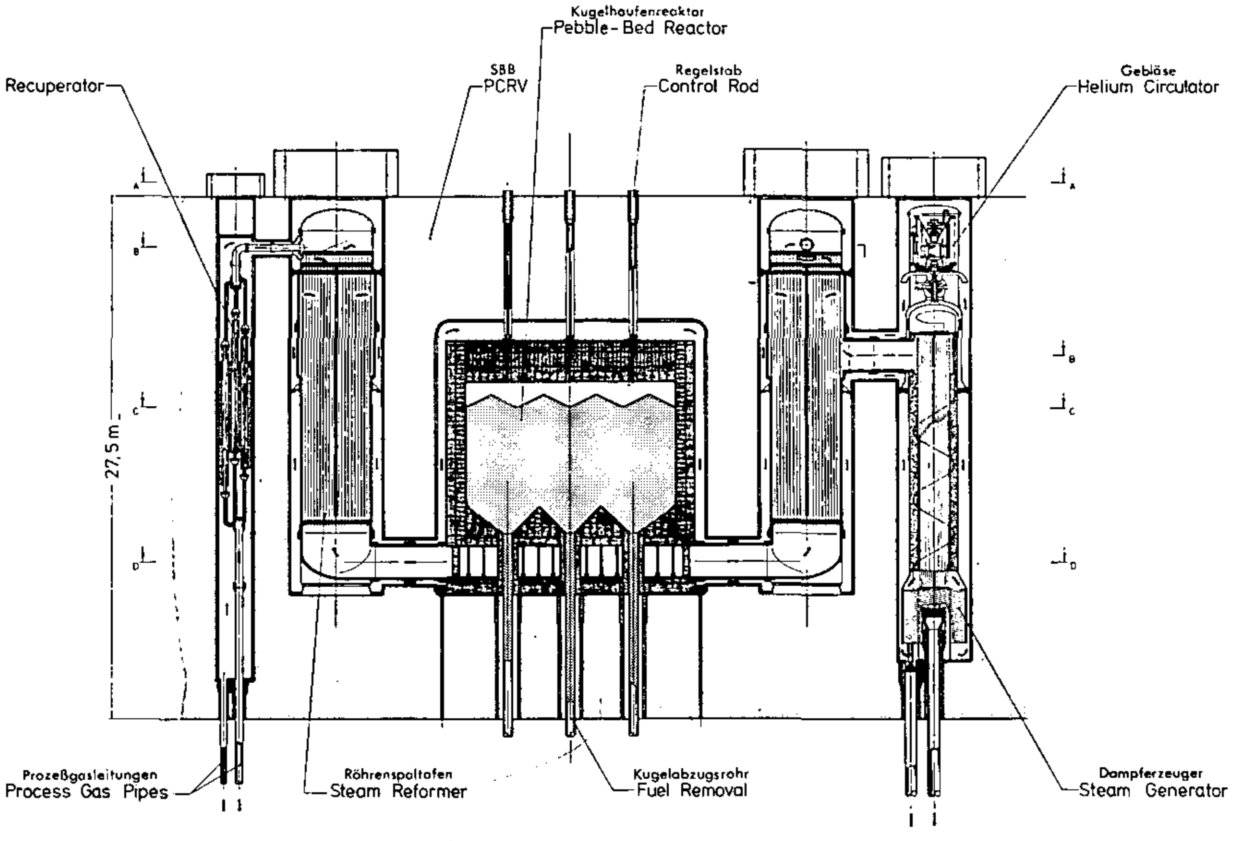
Horizontalschnitte
Horizontal Sections



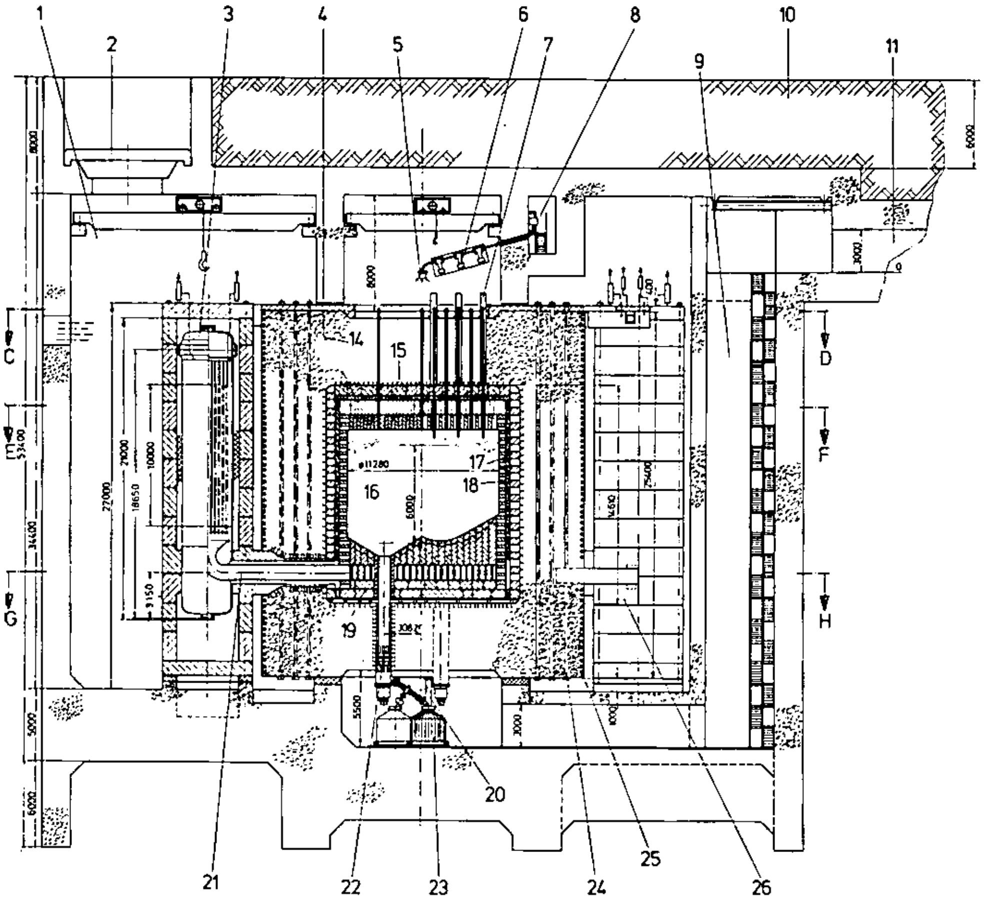
Prozeßwärmereaktor mit integriertem Röhrenspaltofen (3000 MW$_t$)

FIG. 9:
Integrated 3000 MW reactor

Vertikalschnittabwicklung E - E
Vertical Section E-E



Prozeßwärmereaktor mit integriertem Röhrenspaltofen (3000 MW$_t$)



Section A-B

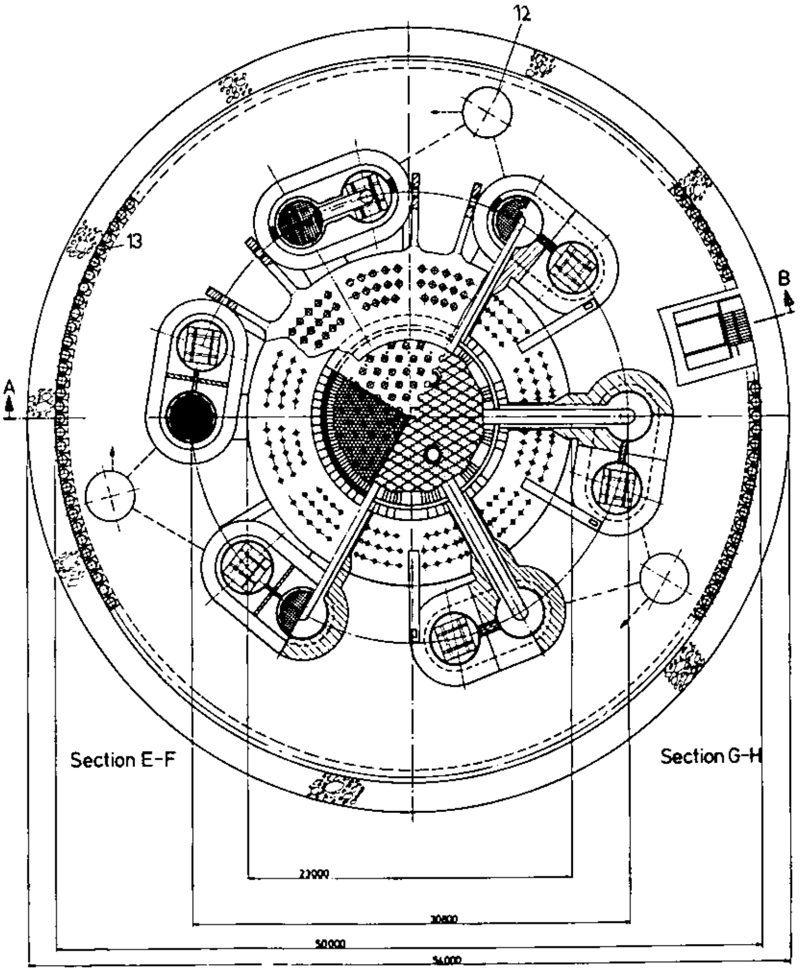


FIG. 10:

Non-integrated 3000 MW reactor.

has been developed world-wide in a large number of conventional ammonia, methanol and hydrocracking plants for the production of hydrogen. The main difference in adapting this process to a nuclear heat source with the HTR is to change from heating the reformer tubes with flue gases at normal pressure to helium at 40 bar pressure. However, the heating temperatures are much smaller for helium (950 °C) than for flue gases (1500 °C including heat transfer by radiation).

Following the experience which we have obtained by the operation of the helium-heated pilot plant EVA in Jülich, from kinetic experiments and from laboratory work concerning the hydrogen and tritium permeation and from a lot of studies for a large pilot plant (30 tubes) and commercial nuclear production plants today, the following ideas are obtained about nuclear-heated steam reformers:

(1) Due to the large reaction velocity of the steam reforming reaction the process is only limited by the heat transfer possibilities. The theoretical equilibria are fulfilled.

(2) A maximum helium temperature of 950 °C is sufficient to obtain heat fluxes through the wall of the tubes similar to that in conventional plants (of the order of 70 kW/m^2). The reason is the good convective transfer by helium at 40 bar.

(3) If the process parameters are of the order of $p \sim 40$ bar, $T \sim 800\text{-}850$ °C, $H_2O/CH_4 = 2/1 - 4/1$, then the methane conversion is sufficiently high (60 - 65 %) and the stresses in the walls of the tubes are minimized.

(4) With the materials (cast or rolled) available today for 100 000 hr of operation, stress values of 0.5 - 1 kg/mm^2 can be tolerated. For a tube design with $\Delta p \sim 0$ across the wall, and a wall temperature of 900 °C this means a conservative design.

(5) If the ratio of hydrogen/steam is nearly always of the order 0.5 - 1 in the process, the permeation of hydrogen to the helium circuit is limited by inner oxide layers to ~ 1 $Nm^3 H_2/hr$ for a 3000 MW(th) plant. This means a tolerable value for graphite corrosion.

(6) Similar behaviour can be expected for tritium. However, further measurements are needed to be sure. If all the tritium which enters the helium circuit is released to the process gas, then the tritium content of the gas is still below today's tolerated values.

(7) Because of the heat transfer to the reformer tubes by convection, these tubes must be arranged in a very compact heat exchanger. Following the different possibilities of gas ducting (helium) inside the bundle, 30 - 40 $tubes/m^2$ can be accomodated. This corresponds to a volumetric power density of 1 - 1.5 MW/m^3 for the steam reformer.

(8) Tests for understanding the behaviour of materials in helium with impurities (H_2, CO, CO_2, H_2O and CH_4) have been started, but further experiments are required.

(9) The materials for the reformer tubes must be qualified for nuclear applications in a very broad material programm including codes, creep tests, burst tests, low and high cycle fatigue tests in helium, and manufacture and quality control.

(10) The reformer tubes should be constructed with inner pipes for the reformer gas. The advantages in using these inner gas ducts were mentioned earlier.

(11) The lifetime of 100 000 hr of the reformer tubes should be possible because the requirements in helium-heated tubes are not so high as in conventional plants, i.e. no hot spots above 950 °C; no pressure difference in the hot part during operation; no axial and azimuthal unsymmetric fluxes; and no corrosion by flue gases.

(12) From the point of view of safety, the tubes can be arranged inside the primary circuit of the reactor, because in the case of failure of the tubes the amount of gas coming to the helium circuit is limited to a small amount (production of a tube is about 400 Nm^3 (H_2 + CO/hr).

(13) The contamination of the reformer tubes after 10^5 hr is obtained by extrapolating the experience of AVR to low enough values, so that the reformer bundles can be changed without too many difficulties. The deposition of fission products will be less than 0.5 Ci/tube $\hat{=}$ 10 μCi/cm^2 on the tubes after ten years.

While the work done to date has shown that the process is feasible, we now have to demonstrate the feasibility of the bundle. This will be done in a 30 tube bundle experiment (SUPEREVA), which will also be heated by helium. Fig. 11 shows the flow sheet and design of this plant, which will be built in Jülich. We hope that from the operation of this plant a lot of technical know-how will be gained, including:

(a) the mechanical behaviour of different types of reformer bundles,
(b) the testing of the support and insulation systems,
(c) the measurement of hydrogen permeation rates,
(d) the operational behaviour (start-up and shut-down), and
(e) the testing of the methanation plant.

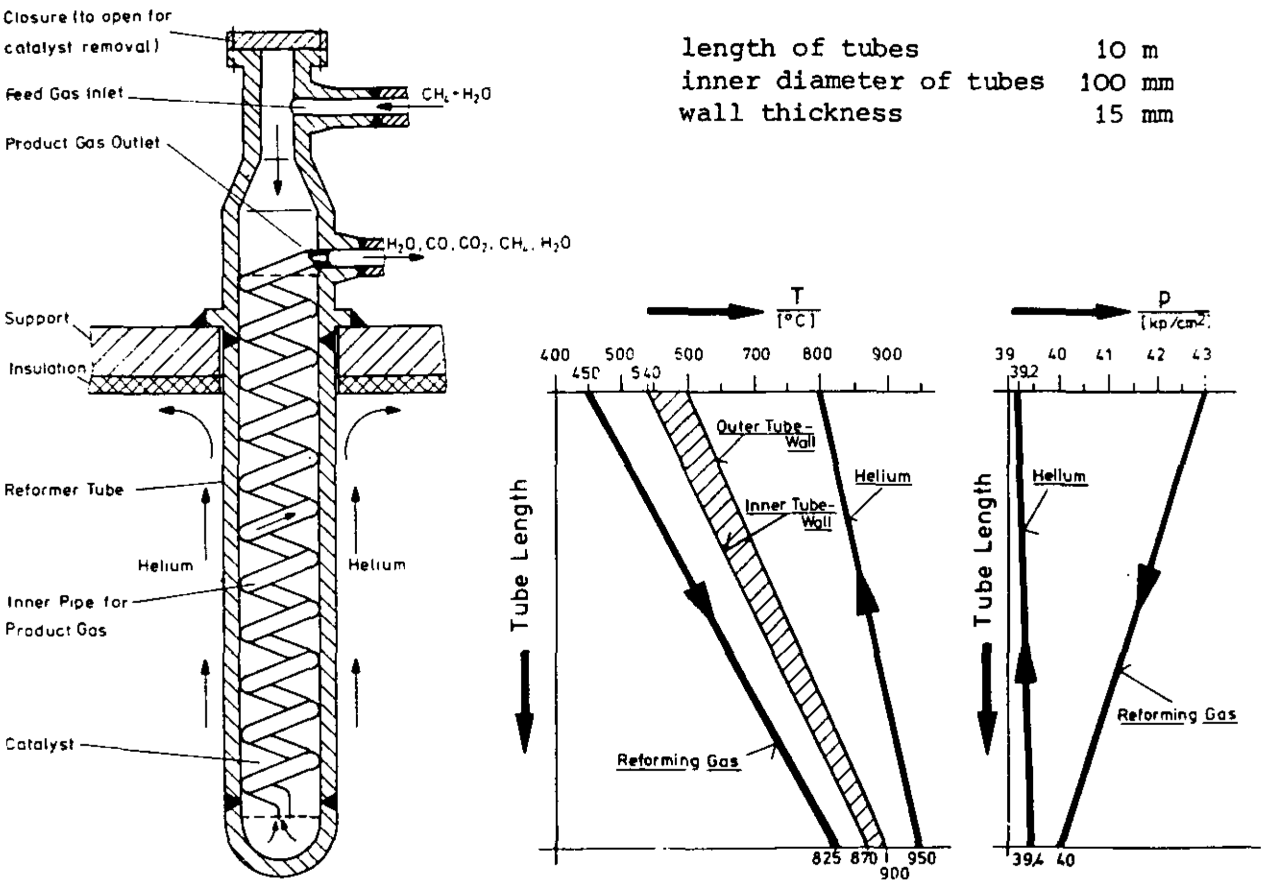
Fig. 11 gives an impression on a typical reforming tube using an inner return duct for the product gas. On the outside the helium temperature is 950 ... 800 °C, the process gas enters the catalyst bed with ~ 500 °C, the end temperature of reaction is ~ 800 oC, and the outlet temperature of the pigtail is nearly 650 °C.

2.3 Intermediate Heat Exchangers

The today impression is that an intermediate heat exchanger must be used for steam gasification of coal. Additionally this component must be developed as a back-up solution for steam reforming if there are difficulties with licensing.

Fig. 12 shows some possibilities of the flow sheet using the example of steam reforming. Only the high temperature part of nuclear heat is transfered through the IHX in this example.

For the design of such a heat exchanger there are a lot of different possibilities. One special which is similar to the steam reformer design is shown in Fig. 13 and 14. It is a modular type heat exchanger, consisting of tubes with an inner return duct (length ~ 10 m, outer diameter 50 mm, wall thickness ~ 5 mm, gap ~ 2 mm).



length of tubes	10 m
inner diameter of tubes	100 mm
wall thickness	15 mm

FIG. 11: Principle, temperature and pressure profiles, and main data of a reformer tube for hydrogasification plants

heat flux	60 ... 70 kW/m^2
maximum wall temperature	900 °C
maximum pressure difference	1 bar (in hot part)
H_2 + CO production/tube	300 Nm^3/h
number of loops	6
number of tubes/loop	400

The heat flux in these arrangements is in the same order as in steam reformers (60 ... 70 kW/m^2, therefore these combined heat exchanger system (IHX and steam generator) can be located in the same holes in the integrated pod boiler vessel or in the same vessels of the non-integrated system. Because the pressure difference in the hot part of the tubes is nearly zero, the mechanical design does not make difficulties. The materials require nuclear qualification, however.

The need and the implications on the safety behaviour of the IHX on the different processes will be studied very carefully in the next time.

2.4 Hydrogasification

It is well known that hydrogasification takes place in two reaction steps with different velocities. In the first fast reaction step groups of coal containing hydrogen or oxygen, which easily can be separated are converted.

The second reaction is much slower, it takes place between the hydrogen and the carbon skeleton.

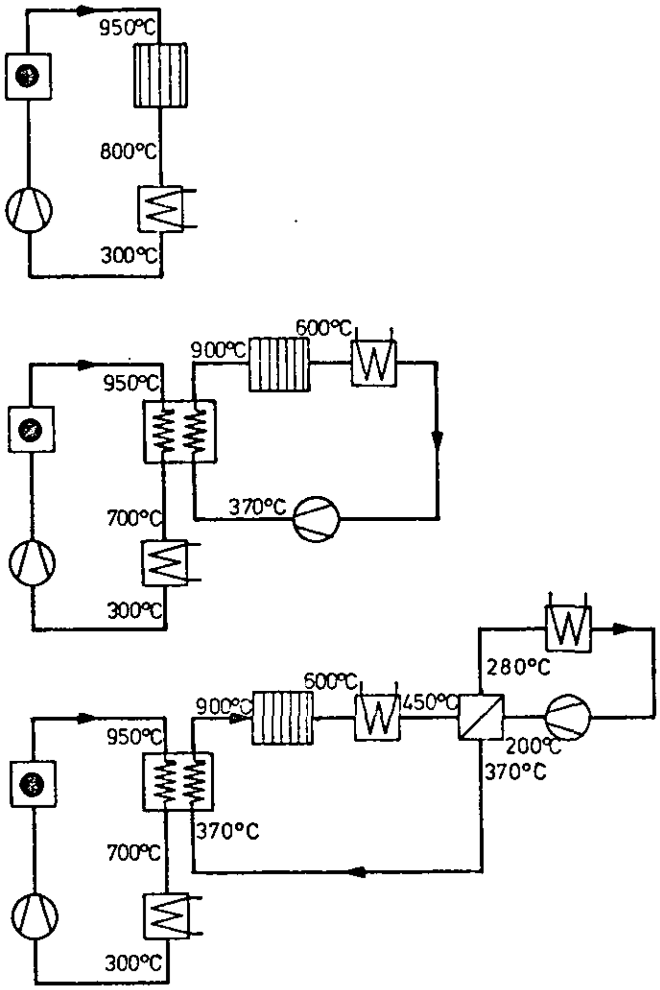


FIG. 12: Possible flow sheets for an intermediate heat exchanger (in all cases 692 MW for steam reforming)

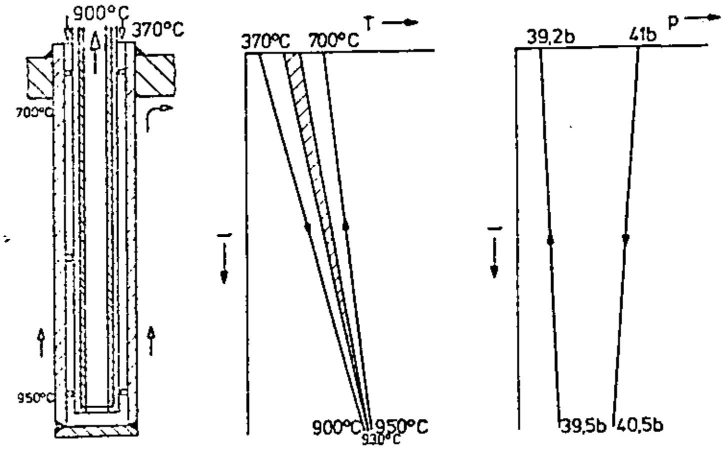


FIG. 13: Modul for IHX

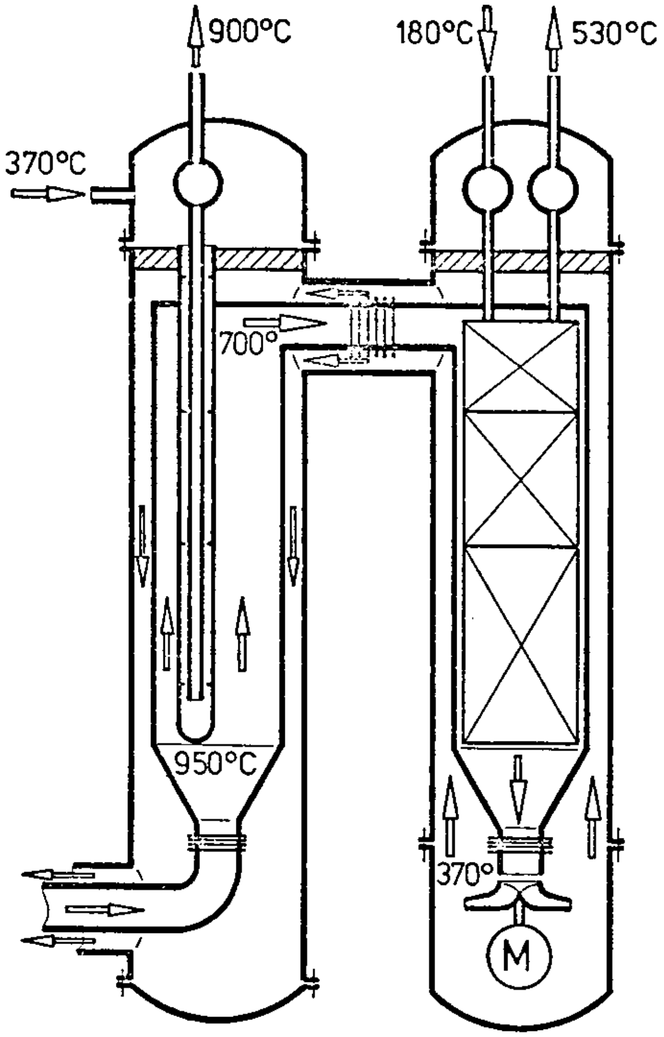


FIG. 14: Arrangement of intermediate heat exchanger and steam generator

Fig. 15 shows that following this behaviour of coal 60 ... 70 % of coal (lignite) can be gasified easily, the rest requires much more space in the gasifier.

In the company Rheinische Braunkohlenwerke AG Köln, a gasification plant with a throughput of 200 kg C/h has been constructed to study the gasification of coal with hydrogen. The operation now has been started with first good results. Fig. 16 gives the flow sheet of this test facility.

2.5 Steam Gasification

A lot of laboratory work and tests in pilot plants have been done for this special process by Bergbauforschung GmbH Essen. Some of their results on gasification velocity using steam is represented in Fig. 17.

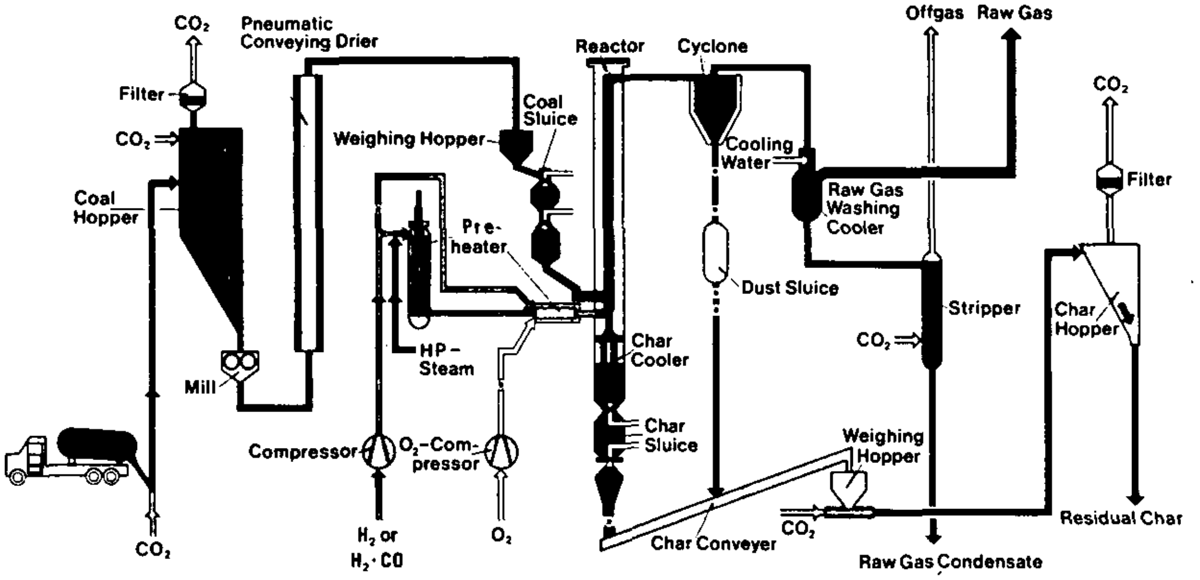
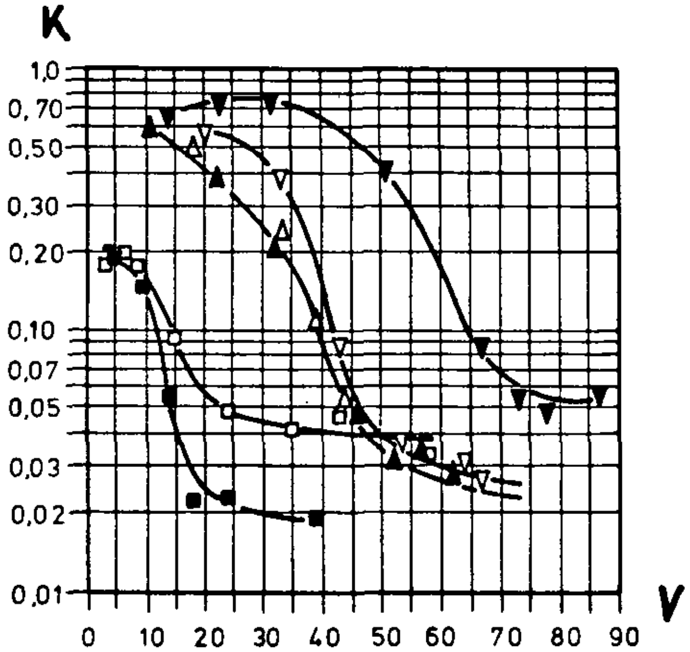


FIG. 16:

Pilot plant for hydrogasification of coal (Rheinische Braunkohlenwerke AG, Köln)

FIG. 15:

Reaction velocity of different coals dependent on burn-up (V) (following US publication)



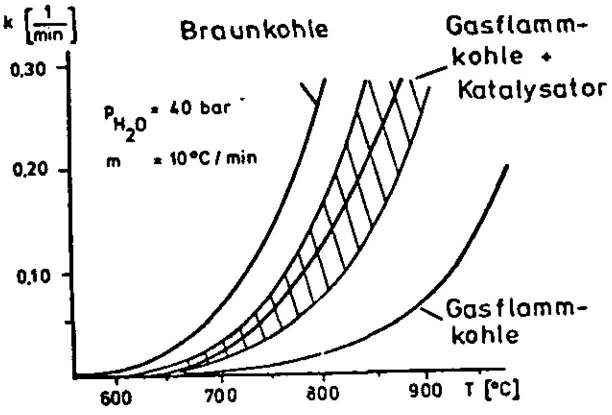


FIG. 17:

Gasification velocity (steam gasification)

Following these curves, lignite (Braunkohle) can be gasified with temperatures of 700 ... 750 °C in the reaction. Hard coal (Gasflammkohle) would require 800 ... 850 °C.

To verify these results in a big experiment, a test facility with a throughput of 200 kg C/h has been constructed in Essen which starts operation now.

Additionally a lot of material testing in gas mixtures corresponding the process gases have been made. There seems to be a good chance to avoid material problems if wall temperatures in the fluidized bed stay below 870 °C.

3 ADDITIONAL INFORMATION

3.1 Cost Estimation

Of course it is difficult to give cost estimates for plants which have not been developed and built until now. Following a lot of studies done by companies and following the experience with conventional gasification and liquefaction plants, the following two Figures 18 and 19 may give an impression on the comparisons of conventional and on the nuclear processes. Especially for lignite gasification (today ~ 7.5 DM (Gcal coal costs) there would be even today a good chance for economical production if the technology already would be available. The breakdown of costs show that an error in estimation of the nuclear reactor costs (nuclear island) is not as important as for instance a rise in coal cost.

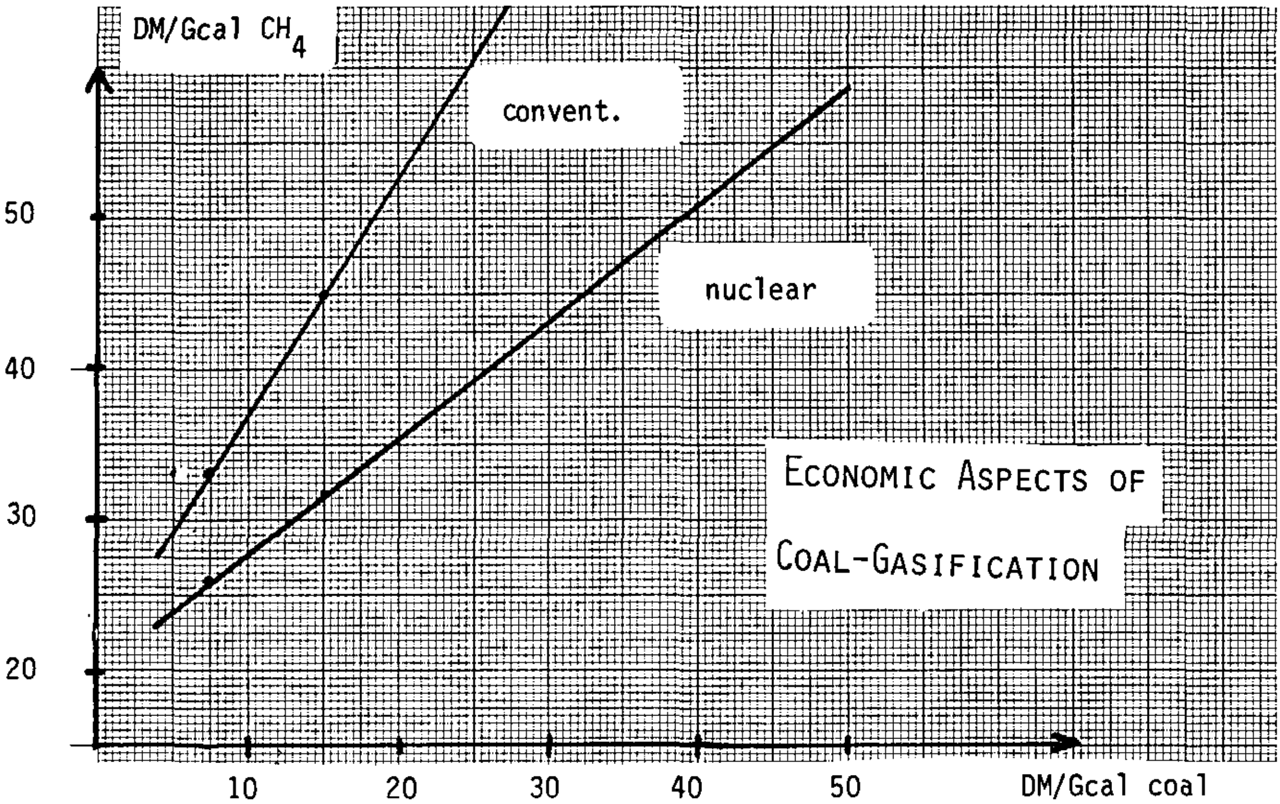
The main advantage of a nuclear plant will be that after the time that a plant has been built there will be a 30 years operation time during which the capital dependent costs stay constant; in the Federal Republic of Germany the coal costs rise up more and more by time, the conventional system has raising production costs because of the higher coal demand. The growth in maximum price can be compensated for the pebble-bed reactor by the introduction of a near breeder concept for the fuel element. The economical competition for the product of coal gasification will be light fuel oil which today already costs about 35 DM/Gcal or imported natural gas, which requires very high transportation cost (for instance from Iran).

Coal liquefaction is a process which will be very interesting in the future if the today well known cheap oil reserves will be consumed (after 1990) and if either oil shale or oil sand must be used to produce oil.

3.2 Market Potential

The main reasons for the introduction of nuclear process heat are as follows:

- there is the possibility of substitution of oil or natural gas by synthetic methane.
- by the nuclear process more gas can be gained from the same amount of coal than in the conventional process (~ 60 % more).



Balance:

3000 MW(th) + 2200 t/h lignite $\longrightarrow$ 3.8 x 10^5 Nm^3 CH_4/h
+ 110 MW(el) + 270 t/h coke

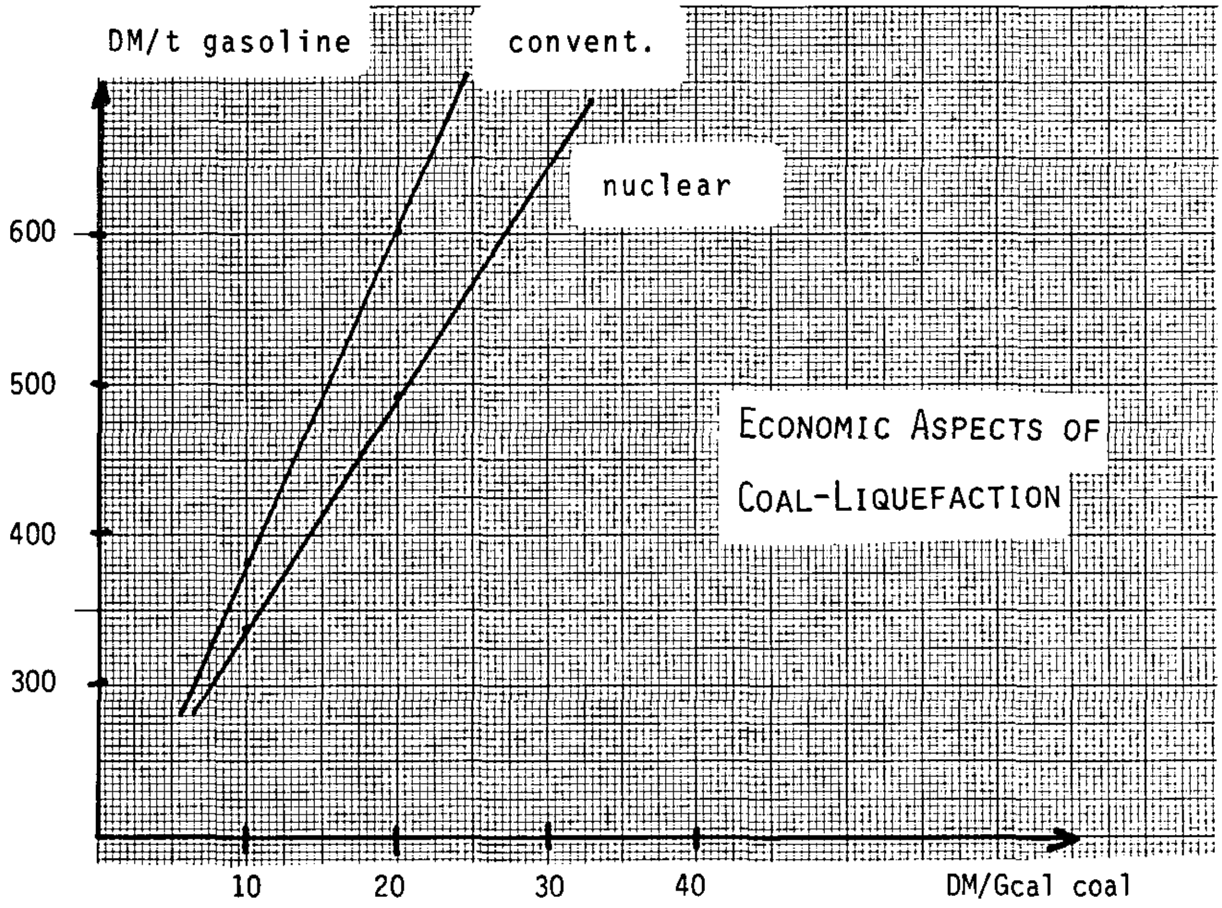
Estimations

Nuclear reactor	800 Mio DM
Heat exchanger system	500 Mio DM
Steam turbine plant	250 Mio DM
Gasification plant	1200 Mio DM
Annuity	18 %/a
Load factor	8000 h/a
Credit electricity	4 DPf/kWh
Credit coke	30 DM/t ...
Nuclear fuel cost	4 DM/Gcal

Breakdown

Nuclear reactor	18.7 %
Heat exchanger system	11.7 %
Steam turbine plant	5.8 %
Gasification plant	28.1 %
Coal	34.3 %
Nuclear fuel	14.3 %
Credit electricity	-4.5 %
Credit coke	-8.4 %
	100.0 %

Fig. 18: Gasification



Balance

3000 MW + 9.5 t SKE/a ⟶ 4.5 Mio t gasoline/a

Estimations

Nuclear reactor	800 Mio DM
Heat exchanger system	500 Mio DM
Steam turbine plant	200 Mio DM
Liquefaction plant	2700 Mio DM
Annuity	18 %/a
Load factor	8000 h/a
Nuclear fuel cost	4 DM/Gcal

Breakdown (Ref. 10 DM/Gcal)

Nuclear reactor	9.4 %
Heat exchanger system	5.9 %
Steam turbine plant	2.3 %
Liquefaction plant	31.7 %
Coal	43.4 %
Nuclear fuel:	7.3 %
	100.0 %

FIG. 19: Liquefaction

- in the nuclear process there is a higher efficiency,
- nuclear heat is cheaper than heat from coal, especially if oxygen is included,
- for 30 years operation of a plant the nuclear gasification is much weaker dependent on rising coal prices than conventional gasification plants,
- the production of CO_2 is less for the nuclear than for the conventional gasification process, because no coal is burned.

A 3000 MW plant is capable to produce $3.5 \cdot 10^6$ tSKE/a gas and consumes $4 \cdot 10^6$ tSKE/a coal. Corresponding to this numbers 30 mio tSKE/a lignite coal and ~ 80 mio tSKE/a hard coal will be available in a long future in Germany. This could correspond to an additional gas supply of $100 \cdot 10^6$ tSKE/a methane and would help to fulfill the requirements of the gas market in Germany after 1990.

3.3 Development Program

Before these technologies are available, a lot of work has to be done. In Table IV the main information on the German program for the next 7 years are summarized. If the development can be done as far as technology is considered and if the economical boundaries do permit it in 1982, there will be the starting point of a prototype plant. Following this development work there will be a construction phase for the prototype and for the demonstration plant.

Perhaps after 1995 these technologies will be applicable in a large number of plants. This fits in with the requirements as they can be seen from Fig. 20 **for instance for the oil market.**

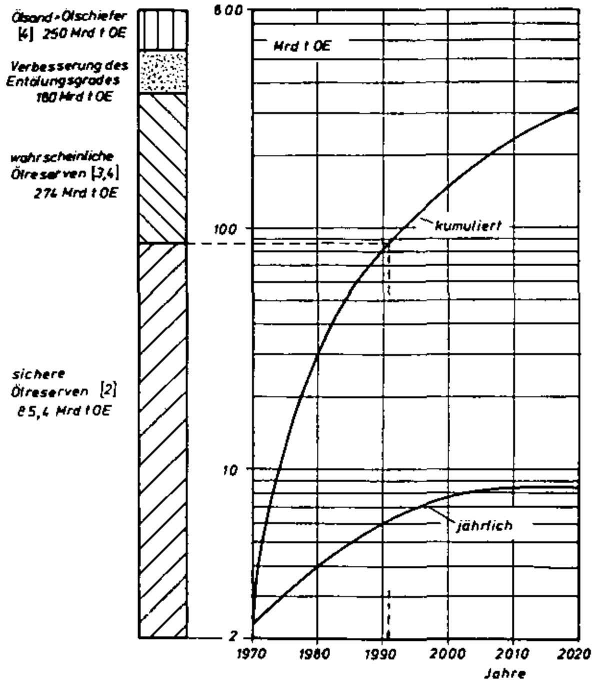


FIG. 20:

Oil reserves and consumption

Partners: GHT, HRB, BF, RBW, KFA

Time: 1975 ... 1982

Money: 700 mio (70 mio for NFE)

Goal: Plans ready for construction of prototype plant (750 ... 1500 MWth)

Work:
- Hydrogasification (200 kg C/h plant, 2 t C/h plant, Engineering)
- Steam gasification (200 kg C/h plant, 2 t C/h plant, material program, Engineering)
- Steam reforming (EVA plant (1 tubes); SUPEREVA plant (30 tubes), material program, detailed experiments)
- Reactor experiments (core, reflector, hot gas ducts, control rods, IHX heat exchangers, components)
- Fuel elements + graphite
- Detailed engineering for reactor
- Layout of total plant (safety report, bids)

TABLE IV: Development Program for Process Heat

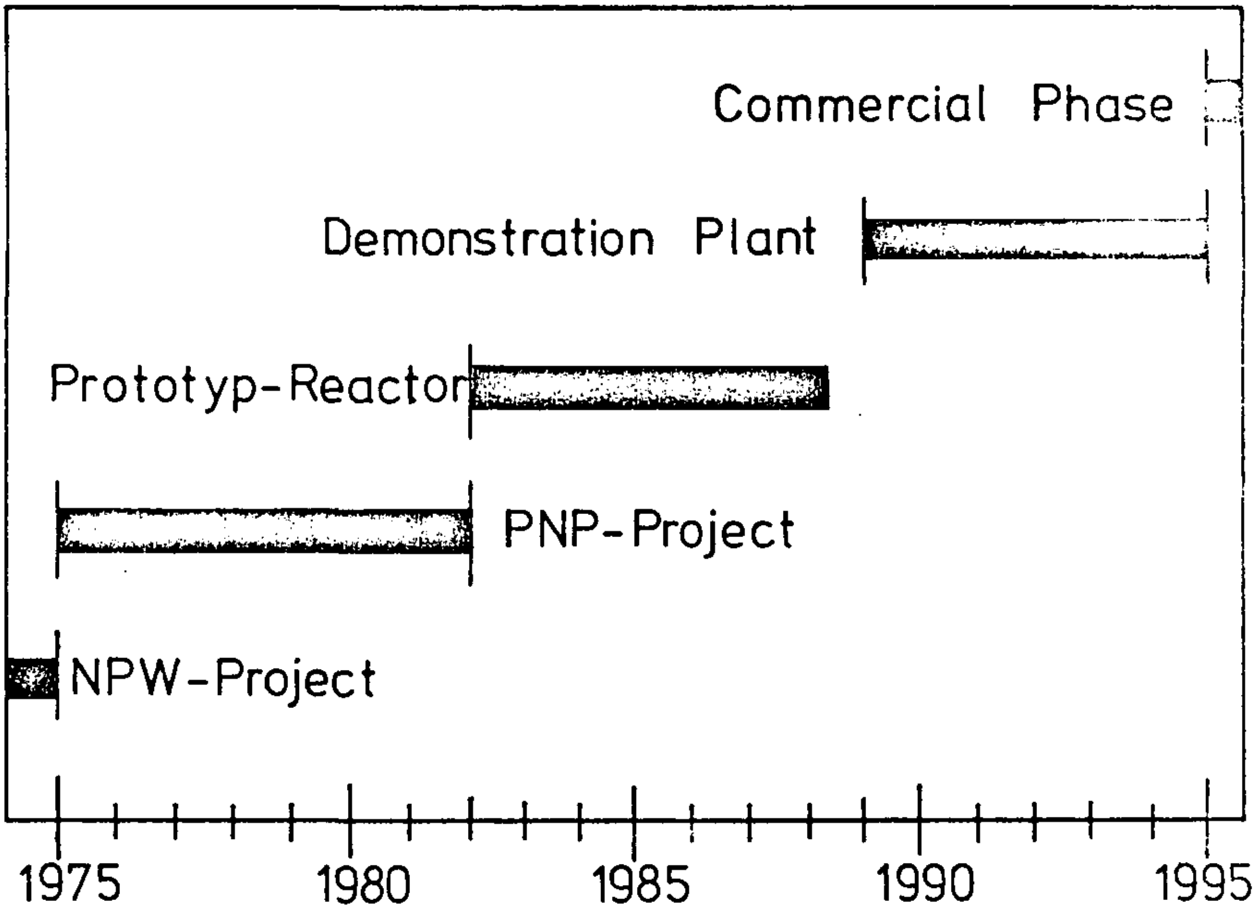


FIG. 21: Time Schedule for Development of Process Heat

NUCLEAR PROCESS HEAT FOR THE STEEL INDUSTRY

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UNITED KINGDOM

Abstract

There are various possibilities for using nuclear process heat from a high temperature reactor to reduce iron ore, each using different proportions of nuclear energy. The advantages in separating the high temperature reactor with its associated reducing gas producer from any steel complex, include the ability to supply such gas to other consumers additional to the steel industry. The potential for nuclear gas-producing complexes in Western Europe is discussed as is the need for appropriate co-operation in the considerable research that will be needed to bring this new technology about.

Outline of Steelmaking Processes and of Nuclear Steelmaking

More than 75 % of the steel manufactured throughout the world is made by reducing iron-ores to molten iron at about 1400 °C in a Blast Furnace using coke as the reductant and subsequent refining of the molten iron to liquid steel: this refining process is now largely carried out in Basic Oxygen Furnaces. The liquid steel is then cast either into batches of ingots, or increasingly into continuously cast elongated shapes, for subsequent rolling. A diagrammatic outline of this process, the Blast Furnace - Basic Oxygen Furnace (B/F-BOF) Route is given in Figure 1.

Most of the remainder of the world steel production is made by melting and refining solid ferrous scrap in an electric arc furnace to produce liquid steel for subsequent casting and rolling. Increasingly, but still on a small scale, the steel scrap is augmented by pellets of prereduced iron. This prereduced iron is made by passing hot reducing gas either through pellets of iron-ore in a shaft furnace or through a fluidized bed of fine ore particles: the reduction taking place in the solid state at about 850 °C, - well below the temperature needed to produce molten iron. A diagrammatic outline of this process, the Direct Reduction - Electric Arc Furnace (DR-EAF) route, is shown in Figure 2.

Present studies related to "Nuclear Steelmaking" are concerned with the use of hot helium from a High Temperature Nuclear Reactor (HTR) to produce reducing gas by endothermic reforming of hydrocarbons: the reducing gas then

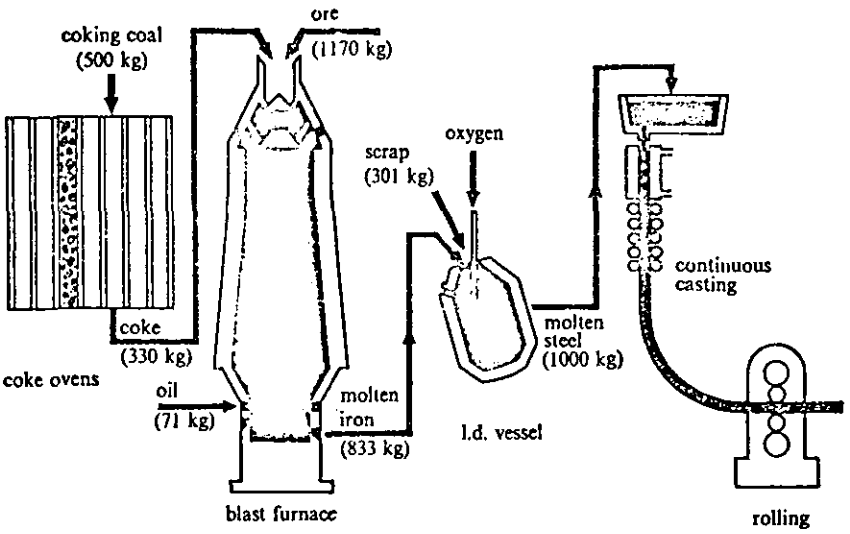


FIGURE 1: Blast Furnace - Basic Oxygen Furnace (B/F - BOF) Route

would be used either in partial replacement of coke in the blastfurnace or to meet the gas requirements of the reduction plant in the DR-EAF route. Electricity generated from the HTR would also be used for all steelworks needs.

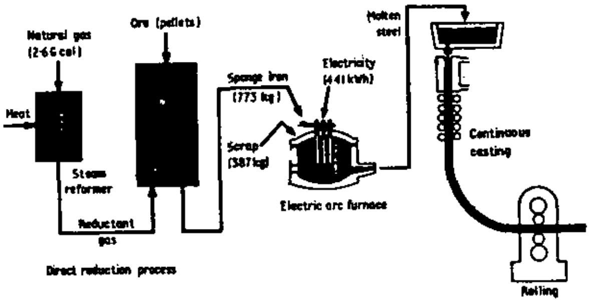


FIGURE 2: The Direct Reduction/Electric Arc Furnace Route

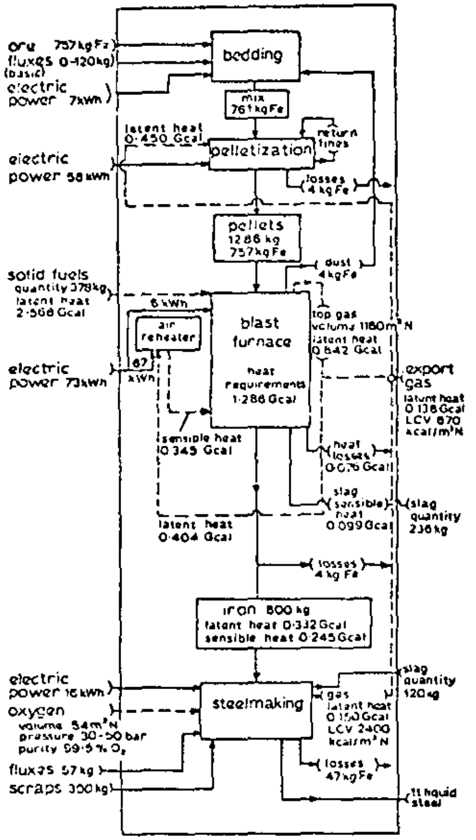
Energy Requirements of Steelmaking Processes

The amount of energy required to produce one tonne of liquid steel is shown diagrammatically for three possible routes as follows:

Figure 3: The Conventional B/F-BOF route: using coke only as a reductant and no reducing gas.
Figure 4: The B/F-BOF route with the injection of hot gas in the blastfurnace stack to replace part of the coke.
Figure 5: The DR-EAF route using initially cold hydrogen to reduce iron ore in a shaft furnace.

Calculations have been made to determine the percentage of the energy required which could be derived in each case from nuclear heat: the results are summarized in Table I.

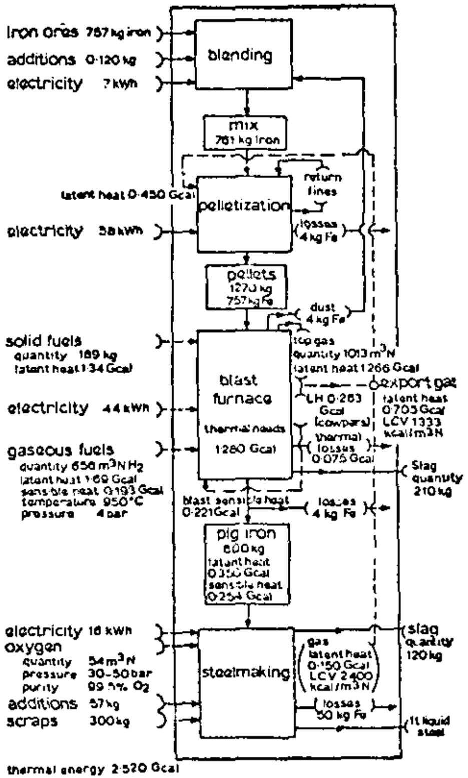
FIGURE 3



thermal energy 2·430 Gcal
electric power 154 kWh
electric power for high-purity O_2 (0·75 kW/m³N) 40 kWh

Reference scheme – blast furnace and BOF steelmaking

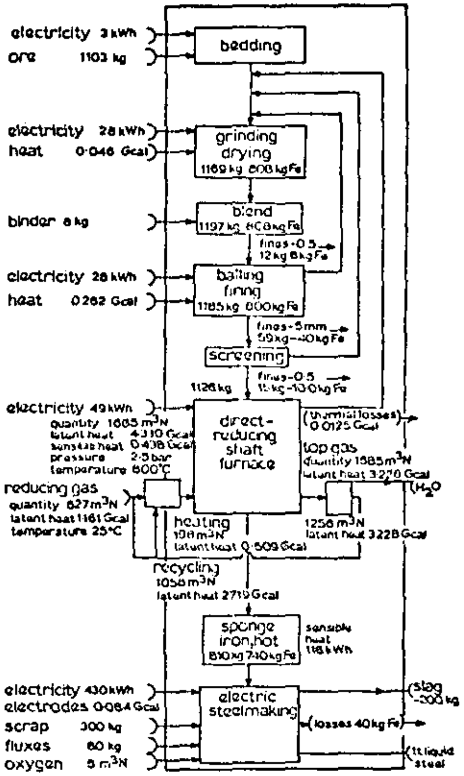
FIGURE 4



thermal energy 2·520 Gcal
electric power 125 kWh
electric power for high-purity O_2 40 kWh

Injection of hot hydrogen at the bosh of a blast furnace

FIGURE 5



thermal energy 2·023 Gcal
electric power 538 kWh
electric power for high-purity O_2 4 kWh

Direct reduction with cold hydrogen in a shaft furnace with hot sponge iron charging for electri steelmaking

FIGURES 3 to 5: Energy Consumption of Steelmaking Processes
NOTE: All figures in these diagrams are related to 1 tonne of liquid steel: assuming 800 kg of iron is required to make 1 tonne of liquid steel in both the B/F-BOF and D/R-EAF routes.

	PROCESS		
	B/F - BOF		DR - EAF
	Coke Only (See FIG 3)	Hot H_2+ Injection at Tuyeres (See FIG 4)	Shaft Furnace Cold H_2+ with Hot Sponge Charging (See FIG 5)
Reducing Gas Volume (m^3N/t liquid steel) Temperature	NIL -	656 950°C	627 25°C
Electrical Energy (KWh/t liquid steel)	194	190	542
Net Energy Requirements* (MJ x 10^3/t Liquid steel)	11.8ϕ	11.9ϕ	13.0ϕ
Percentage of Total Energy Requirement Obtainable from Nuclear Heat	13%	57%	100%

* Excludes energy required to make Coke or reducing gas.

\+ Overall figures for H_2/CO mixture (H_2/CO = 1/1) are not significantly different.

ϕ Processes in an iron and steel works subsequent to the production of liquid steel require a further energy supply of approx 12 x 10^3 MJ per ton of which virtually all, could be provided by nuclear generated electricity.

TABLE I: Energy Requirements of Steelmaking Processes: Percentage Obtainable from Nuclear Heat

The total net energy requirement per tonne of liquid steel is not greatly different for each route: however the proportion of the required energy that could be obtained from the nuclear reactor is 57 % for the B/F-BOF route, as against 100 % for the direct reduction route. If, in the future, high temperature process heat derived from nuclear reactors became cheaper than that derived from fossil fuels, the economic benefit would be relatively greater in direct reduction plants than in B/F-BOF installations.

Choice of an "Integrated" or "Non-Integrated" Nuclear Steelmaking System

The total system for Nuclear Steelmaking would contain:

A complex consisting of a Nuclear Reactor heating helium to a High Temperature. The heat in this helium would be used to produce a reducing gas by reforming a hydrocarbon feedstock (whether gaseous, liquid or solid) and also to generate electricity (probably via steam turbines).

A second complex comprising a gaseous reduction plant for reducing iron ores to solid iron followed by a steelmaking plant (of the Electric-Arc-Furnace type), probably followed by continuous or ingot casting facilities and rolling mills. The reducing gas could, alternatively, be used to reduce the coke consumption in a Blast Furnace.

In an "integrated" system, the two complexes would be sufficiently closely located so that they could be coupled to allow HOT reducing gas to be supplied from the reformer to the reduction plant: in such a case, if the reformed gas required cooling to remove moisture, nuclear heat could be used to reheat the gas to the temperature required for iron ore reduction: furthermore, (apart from coke, if a blastfurnace was used) the steelworks would have no other major energy source but the reactor. A schematic diagram of such a system is given in Figure 6.

In a "non-integrated" system, the two complexes would be located at some distance from one another: the reducing gas would be supplied by the reformer to the reduction plant as cold gas and would need to be reheated at the steelworks using non-nuclear heat (probably waste gases from one or other of the steelwork processes). Cold reducing gas (and electricity) could also be supplied by the Reactor/Reformer complex to more than one steel works and to

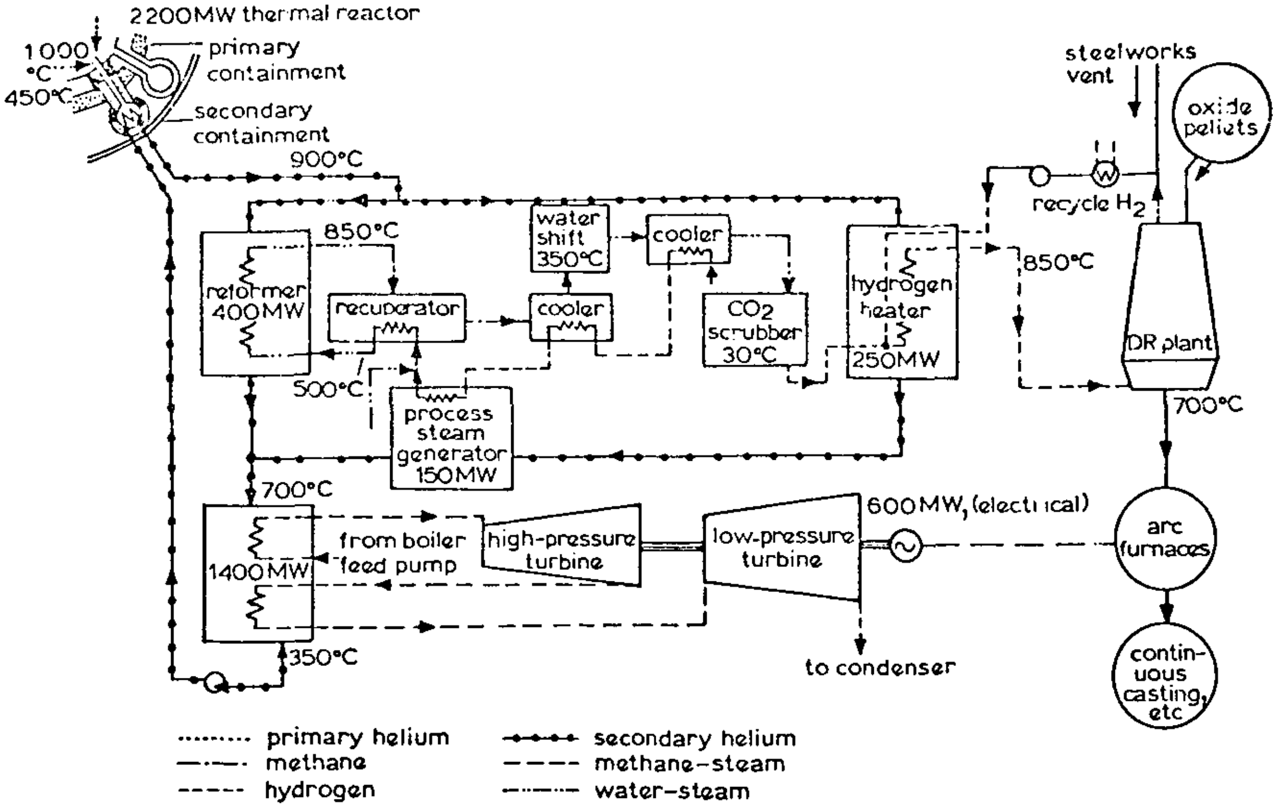


FIGURE 6: Schematic diagram showing a nuclear reactor and reformer complex coupled to a steelworks: "integrated" relationship

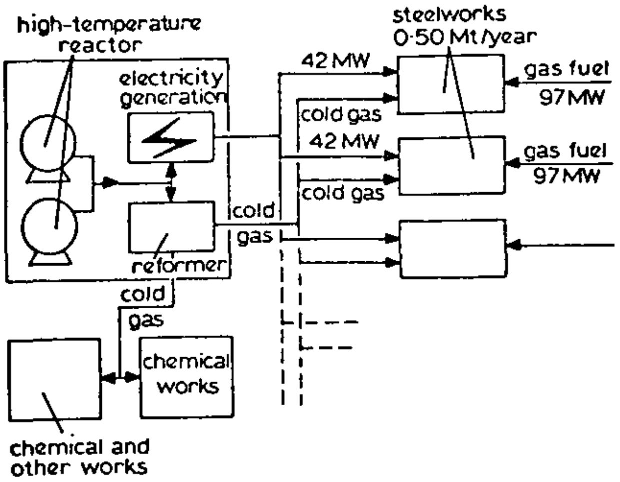


FIGURE 7: "Non-integrated" relationship between a reactor-reformer complex, steelworks, and other gas users

other users of reducing gas. A diagrammatic outline of such a system is given in Figure 7. The advantages and disadvantages of the "integrated" and the "non-integrated" approaches are summarized in Table II.

The European Nuclear Steelmaking Club (ENSEC) decided in 1974 to base its future work on the non-integrated system. Work in Germany and in the USA is largely based on the non-integrated system whereas in Japan the present large research programme is related to an integrated configuration.

The non-integrated system leads to the conception of a nuclear-reformer complex containing more than one HTR providing electricity to a normal grid distribution system and cold reducing gas by pipe-line to several steelworks and indeed to other industrial consumers, e.g. the chemical industry. Such a pipe-line could also accept inputs of gas from other nuclear-reformer complexes and other industrial producers of gas.

Composition of Reducing Gas for Nuclear Steelmaking

Most present DR-EAF plants use H_2/CO mixtures derived by reforming methane: the ratio of H_2 to CO is not critical in the reduction process, though large quantities of CO_2 in the exit gases are expensive to remove - a necessity, since the gas is re-cycled.

The technology for large-scale industrial use of 96 % H_2 for iron-ore reduction needs further development (though pilot-plant operations have been successfully carried out), in view of difficulties related to the sticking of the burden and to re-oxidation of the product. If the gas is to be transmitted through a pipe-line grid system, connected to various other industrial users and producers of gas, an optimization of the choice between pure H_2 and a H_2/CO mixture will need to be made for any pipe-line system envisaged: such a choice will need to hold long-term.

German calculations suggest that, using lignite as feedstock, a H_2/CO: 1/1 mixture can be made about 20 % cheaper than 96 % H_2 and that this mixture is more flexible for a wide range of industrial users. Other opinion favours 96 % H_2 as being more universally acceptable for industrial use and supply

I. <u>The "Integrated" System</u> (See Figure 6)

Advantages	Disadvantages
1. Electrical energy generated with steam derived from a local HTR could be cheaper than when purchased from a national grid or external generating complex. 2. Maximum use is made of nuclear heat (including reheating of reducing gases - approx. 10% of total).	1. Minimum economic size of HTR is about 3000 M W(T): this leads to a minimum size of about 7 mt/pa for a steelworks if all its energy requirements are met by the whole of the output of one reactor. 2. Construction time and plant life for the reactor are both longer than for the steelworks. 3. Safety and organizational problems would greatly restrict both the design and operation of the reactor plant and the steelworks. 4. Due to the high capital cost, over all plant reliability of 90% would be required, necessitating reliabilities of over 90% in the reactor and the steelworks

II. <u>The "Non-Integrated" System</u> (See Figure 7)

Advantages	Disadvantages
1. The reactor gas outlet temperature is governed by the (probably lower) reformer requirements and not by iron ore reduction conditions. 2. A number of steelworks (and other gas - consuming plants) can be supplied from a nuclear station, which could consist of more than one reactor. 3. Size and design of the steelplant could be related to the optimum requirements for steel production, rather than considerations of reactor technology. 4. Availability in the steelplants would be improved due to the use of more than one reactor and less close coupling between the reactor system and the steelplant.	1. Nuclear heat can not be used to reheat the reducing gas to 850°C for iron ore reduction: hence the maximum use is not made of nuclear heat.

<u>TABLE II:</u> Summary of Advantages and Disadvantages of the "Integrated" and "Non-Integrated" Nuclear Steelmaking Systems

(including the production of H_2 from water, where there is considerable development potential).

So far as the steel industry is concerned, the price of the gas will probably be more important than its composition.

Present Activities in Nuclear Steelmaking

United States of America

Two studies have been made by a task force established by the American Iron and Steel Institute, with the object of studying whether nuclear steelmaking would compare economically with conventional routes in USA conditions: one was related to the use of natural gas as feedstock; the other was related to the use of low grade bituminous coal. A summary of the results from the first study are given in Figure 8; it has been concluded that the cost of coking coal in relation to the cost of natural gas would need to rise to about double its present price in USA before nuclear steelmaking could become economically worthy of consideration. The second study suggests that nuclear steelmaking based on gasification of low grade bituminous coal appeared likely to be economical, owing to the wide difference of price between coking and low grade coals in USA and the lower usage of coal in the nuclear steelmaking route (see Figure 9).

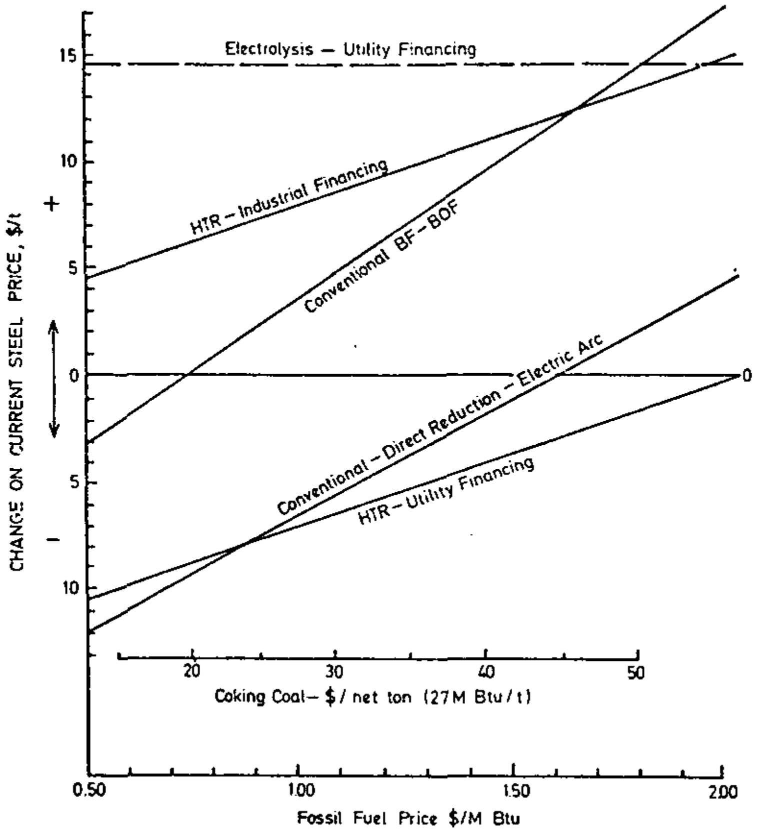


FIGURE 8: Change in Steel Prices Against Fossil Fuel Prices

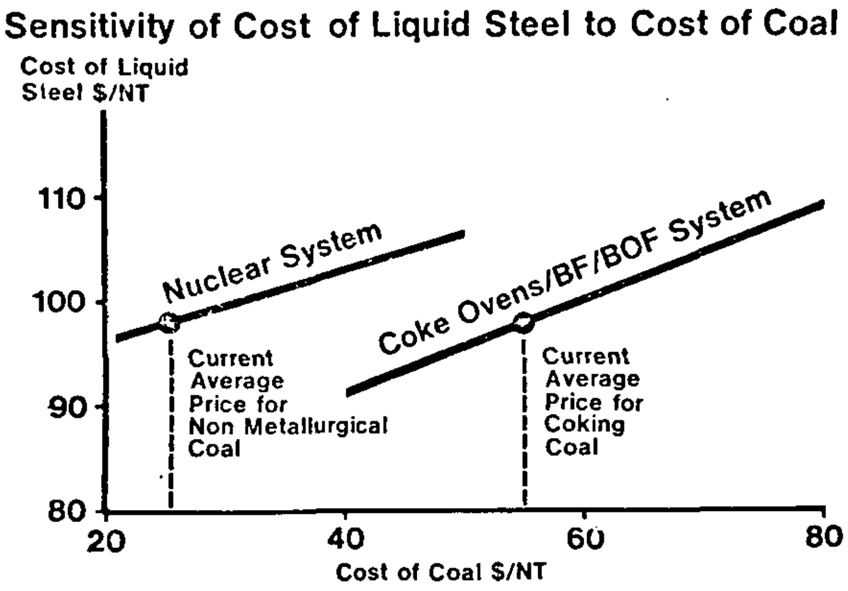


FIGURE 9: Sensitivity of Cost of Liquid Steel to Cost of Coal

Japan

Much has been published on the research programme being operated by the Engineering Research Association for Nuclear Steelmaking (ERANS) and the HTR developments being pursued by the Japanese Atomic Energy Research Institute.

A flow diagram of the proposed Japanese system is given in Figure 10. It will be seen that it is an "integrated" approach. The characteristics of the reducing gas are still under active study within the following parameters:

CH_4 less than 3 %

$H_2/(H_2 + CO)$ higher than 0.5. $(H_2 + CO)/(H_2O + CO_2)$ higher than 10:

C, Sand Dust negligible

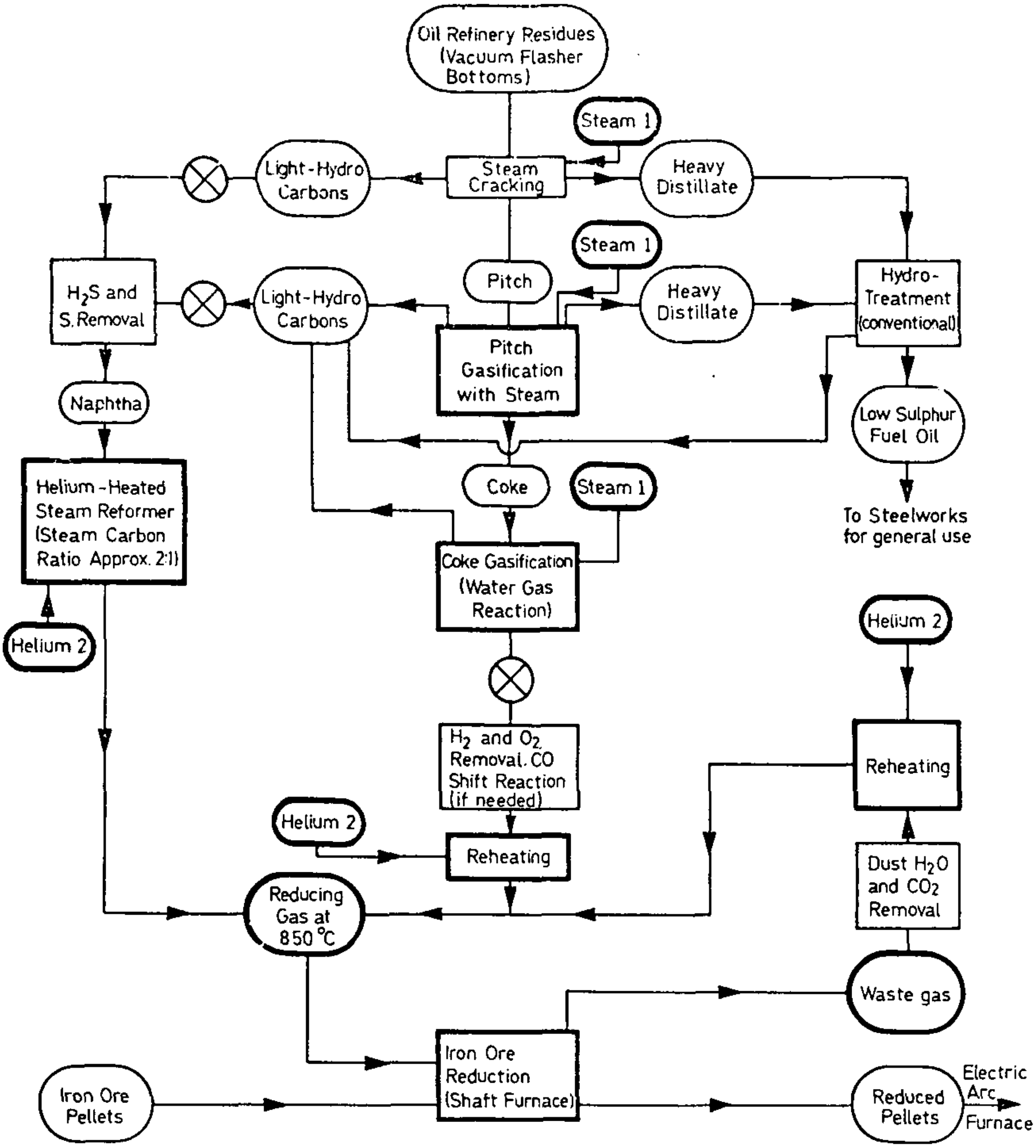
Temperature 800 °C

The question of the pressure is still under active model study.

Germany

Work in connection with the production of synthetic natural gas and reducing gases from coal, using nuclear heat is described elsewhere.

The Arbeitsgemeinschaft für Nukleare Prozesswärme (ANP) study group is also examining the effect of reducing gas composition on the reduction of iron ores.



Notes: (A) Items forming a major part of the development programme shown thus ▬▬

(B) (Steam 1) denotes steam at 850°C produced by a steam-generator heated by HTR intermediate loop Helium at 925 °C

(C) (Helium 2) denotes Helium at 925°C in the intermediate loop of the HTR

(D) Processes are shown in rectangular boxes: Products are shown in eliptical surrounds

(E) The points marked ⊗ represent the left hand side of the diagram in diagrams RGO 1 to 5 in FIG.

FIGURE 10: Processes being Developed by "ERANS" Related to Oil Refinery Residues as Feed Stock

European Nuclear Steelmaking Club (ENSEC)

Following the decision to restrict the studies in ENSEC to non-integrated systems, working parties have studied the energy requirement of steelmaking processes, production of reducing gases and the helium-heated steam-reformer. A fourth working party is studying the technico-economic aspects of various process routes based on a cold gas grid containing either 96 % H_2 or an H_2/ CO : 1/1 mixture.

Possible Demand for Gas

The availability of reducing gas from HTR-Reformer Complexes on any industrial scale is unlikely until after 1990.

Liquid steel production in Europe is about 180 million tons per annum at present, with less than 1 % of this being made by the DR.-EAF route. Even if all the present Blast Furnaces in Europe were to use the maximum amount of injected hydrogen, all derived from reactor/reformer complexes, it would represent the energy output of only about twenty 3000 MW(T) HTRs and an annual H_2 requirement of about 10 m. tonnes.

Current predictions suggest that sponge-iron production in Europe could attain about 15 million tonnes per annum by 1985. If all this sponge-iron were to be produced in DR plants, and all the reducing gas required was obtained from Reactor-Reformer Complexes, it would require about 1.3 m. tonnes of Hydrogen per annum and the output of about three 3000 MW(T) HTRs.

The present estimated requirements of H_2 of the European Chemical Industry are given in Table III. Potentially such demands could rise by a factor of 2 or 3 in the next twenty-five years. However, it is unrealistic to suppose that the total requirement of the Chemical Industry would be drawn from an external H_2 Grid: A substantial part of the requirement would be manufactured internally as a by-product of a number of the processes, rather than being drawn from a nuclear complex: the output of only two or three HTRs would be likely to be involved.

	M TON/YEAR	M TON H_2
Ammonia	15	2.6
Methanol	3	0.4
Petrochemical	-	c 1
Total		4

TABLE III: Current Hydrogen for Chemical Use-Western Europe

The potential demand for the steel industry in Europe for reducing gas derived from Reactor/Reformer Complexes would therefore be limited, and in the next twenty-five years is unlikely to involve more than two or three HTRs. The likely demand for the Chemical Industry is of the same order as that for Direct Reduction Plants. Only if the price of the reducing gas were such as to make its use in the Blast Furnace would the potential market be enlarged by an order of magnitude.

If nuclear process heat became cheap enough in Europe for such largescale use in the steel industry, it could also become economic for use in lignite gasification. German outline calculations suggest that if all the requirements for Natural gas in Germany by 2000 AD were produced by gasification of lignite using heat from HTRs, about twenty 3000 MW(T) HTRs would be required.

Areas for Research

The feedstock to be used for the production of reducing gases will vary in different parts of the world. In Japan, oil refinery residues have been chosen for study: in USA, work is oriented towards low grade bituminous coal and in Germany emphasis is largely centred on lignite.

The technology to use an HTR to reform methane, which would help to eke out natural gas reserves, is likely to be the starting point for many of these systems.

All these investigations will almost certainly proceed independently in the various countries: however they nearly all lead to production of methane or naphtha to be steam reformed to H_2 or to a H_2/CO mixture in a helium-heated steam reformer, with generally cryogenic separation of residual methane. Work is proceeding in several places on the development of such a reformer: closer coordination than at present seems desirably to avoid duplication of effort.

On the purely steelmaking side, research is needed on the use of hydrogen in direct reduction plants of the shaft and fluidized bed types and also in the blast furnaces: here also cooperation would be beneficial.

The most costly and probably the most time consuming part of the total development is that of the high temperature reactor itself, particularly if there is a need to appreciably increase the outlet helium temperature and also if the problems of the total fuel cycle are to be tackled. These development costs will need to be shouldered by a wider range of users than those represented by the steel industry and the chemical industry. The development of the reactor for electricity generation and other process heat applications would probably be necessary to justify the total expenditure.

Surely in these circumstances it should be our aim to cooperate in all these research activities with a proper apportionment of the various parts so that nuclear process heat can be a commercial possibility in say fifteen years time.

A 5

ZINC- AND ALUMINIUM MAKING PROCESSES USING HTGR PROCESS HEAT

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Abstract

The high temperature gas-cooled reactor (HTGR) has frequently been suggested as a source of process heat for steel-making; now it has been suggested that it could also be used in the zinc- and aluminium-making processes. For that purpose, several procedures are proposed whereby the key steps in the reduction of zinc oxyde are the use of a gas produced and heated by the HTGR process heat source. Also for the aluminium making process a series of new techniques in connection with the Toth and Grothe processes, coupled to a HTGR, are discussed.

1. INTRODUCTION

It is well known that the high temperature gas-cooled reactor (HTGR) as a producer of reducing gas can be utilized in steelmaking processes. A promising method is the direct reduction process of iron ore: the HTGR provides a mixture of carbon monoxide and hydrogen by steam reforming of light hydrocarbons (coal or heavy oil) or the HTGR provides hydrogen directly by electrolysis or - in a future stage - by water cracking in a thermochemical cycle. AISI /1/ in the United States and the "European Nuclear Steelmaking Club", founded in 1973 in Europe, are involved in this field. To our knowledge the utilization of HTGR process-heat for metal extraction methods other than for iron has not yet been considered.

In this paper the HTGR process-heat is proposed for utilization in the zinc- and aluminium-making processes. The key process here is the reduction of zinc oxide using a reducing gas produced and/or heated by an HTGR.

Currently two principal techniques exist for the zinc-making process: chemical reduction using coal and electrolysis of zinc oxide formed by roasting zinc ores with hot air. The first method is performed at temperatures of 1200 - 1400 °C and needs a correspondingly high supply of coke to provide these high temperatures. For the electrolysis method, which operates near room temperature, zinc oxide must be dissolved in sulfuric acid. A considerable amount of electrical energy is needed, about 3600 kWhel per metric ton of zinc.

Zinc oxide might now be conveniently reduced using methane or hydrogen /2/ with an HTGR as the process heat source. In this case temperatures far below 1000 °C are necessary, i.e., a temperature range which can be delivered by today's HTGR technology. The theoretical energy consumption (excluding heat losses) has been calculated to be 725 kWth per metric ton of zinc if hydrogen is used as the reducing gas and about 1800 kWth per metric ton of zinc for the case of methane gas. In the case when hydrogen is produced by electrolysis, about 1500 kWhel per metric ton of zinc are additionally consumed in the electrolysers assuming an efficiency of 80 %. The choice either hydrogen or methane gas depends on the economics and the availability of light hydrocarbons.

2. ZINC-MAKING PROCESSES

The following different processes are possible:

- The simplest approach is the case if natural gas (i.e. CH_4) is available. This gas is heated by a topping cycle of an HTGR to 800 °C and fed into the furnace containing zinc oxide. The block diagram of this process is shown in Fig. 1. It should be noted that the exhaust (a mixture of CO and H_2) is no waste gas but it is a potential chemical energy source.

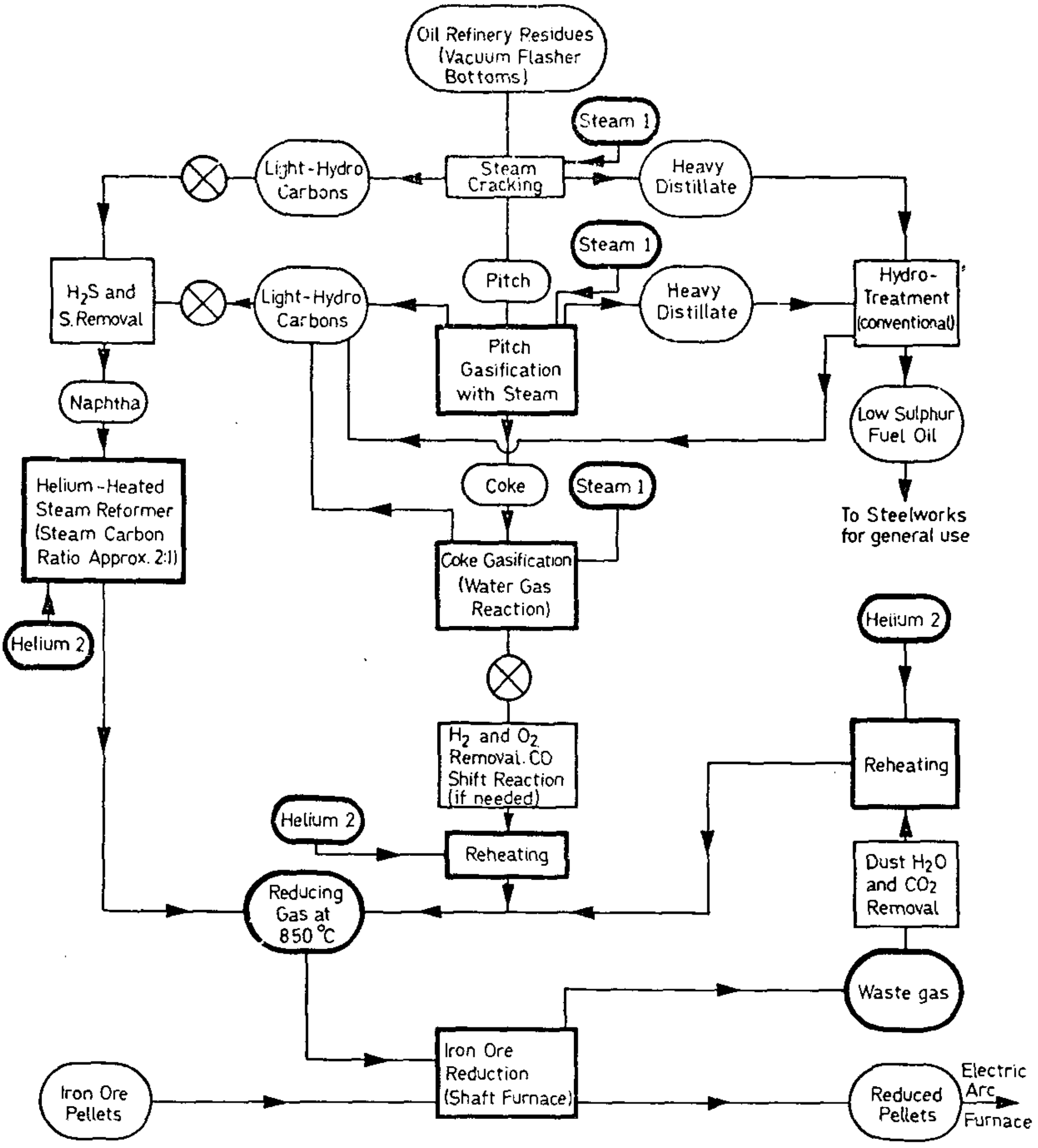
- Preheated steam-methane mixture may be passed through a reformer in which H_2 and CO are formed in the presence of a nickel catalyst. For this purpose heat from the helium in an HTGR topping cycle is used. Downstream processing transforms the CO into H_2 and CO_2 which will in turn be scrubbed out. In this case the reduction gas consists of about 87 % H_2 and the remainder CH_4. The scheme of this process is outlined in Fig. 2.

- If coal is available the well-known coal gasification process is utilized in which methane reforming accompanies the hydrogen plus carbon (coal) reaction. The heat source is again an HTGR, and the resulting reducing gas is in practice the same as above. Fig. 3 contains the block diagram of this scheme.

It is clear that in all three cases a steam bottoming cycle can be coupled to the HTGR in order to produce electricity in addition. Thus the HTGR in our case has been equipped with a chemical topping cycle and a steam bottoming cycle according to the available temperature levels. For the sake of simplicity, the bottoming cycles are not included in Fig. 1 - 3.

- If no coal or hydrocarbons are available, H_2 may be produced by electrolysis using electrical energy from the turbogenerator. The H_2 is heated by a topping cycle in a helium/hydrogen heat exchanger and fed into the furnace containing ZnO. The oxygen which is simultaneously produced by the electrolyser may possibly be used in a first step to roast the zinc ore to get ZnO.

- In a later stage, H_2 and O_2 may be directly produced by a closed loop thermochemical process or by a hybrid cycle whereby oxygen and hydrogen are produced thermo-chemically and by electrolysis, respectively.



Notes: (A) Items forming a major part of the development programme shown thus ▬

(B) Steam 1 denotes steam at 850°C produced by a steam-generator heated by HTR intermediate loop Helium at 925 °C

(C) Helium 2 denotes Helium at 925°C in the intermediate loop of the HTR

(D) Processes are shown in rectangular boxes: Products are shown in eliptical surrounds

(E) The points marked ⊗ represent the left hand side of the diagram in diagrams RGO 1 to 5 in FIG.

FIGURE 10: Processes being Developed by "ERANS" Related to Oil Refinery Residues as Feed Stock

3. ALUMINIUM-MAKING PROCESSES

3.1 The Modified Toth-Process

Zinc metal which is produced by one of the above mentioned methods may be sold (the zinc consumption in FRG in 1973 was 450'000 metric tons) or may be used in the aluminium-making process. Currently molten salt electrolysis of alumina dissolved in molten cryolithe is the principal method of producing aluminium metal. However, there is a series of substantial disadvantages: considerable electrical energy requirements (22'800 kWhel/ton Al /3/) for the overall process from bauxite to aluminium, high investment costs for the preparation of alumina and the electrolysis and the environmental impact mainly due to the release of waste gases containing fluorine. A new purely chemical reduction method, the so-called Toth-process /4/, appears to avoid these drawbacks. It is based on a four step process in which aluminium metal is obtained from an ore containing aluminium oxide via aluminium chloride. The process steps are as follows:

1. Chlorination of the ore (e.g. clay) yielding aluminium chloride
   ($Al_2O_3 + 3\ C + 3\ Cl_2 \longrightarrow 2\ AlCl_3 + 3\ CO$ at 925 °C)
2. Reaction of aluminium chloride with manganese metal yielding aluminium metal and manganese chloride (2 AlCl
   ($2\ AlCl_3 + 3\ Mn \longrightarrow 2\ Al + 3\ MnCl_2$ at 300 °C)
3. Oxidation of manganese chloride yielding manganese oxide and recovery of gaseous chlorine
   ($3\ MnCl_2 + 1{,}5\ O_2 \longrightarrow 3\ MnO + 3\ Cl_2$ at 600 °C)
4. Reduction of manganese oxide with coal
   ($3\ MnO + 3\ C \longrightarrow 3\ Mn + 3\ CO$ at 1750 °C)

However, the fourth step can be difficult because of the necessity of very high temperature (1750 °C) and the partial forming of manganese carbide during the reduction with coal.

As an alternative for manganese as the reducing metal, zinc might be used. In such a modified Toth process, zinc fulfills the role of the manganese in the fourth step discussed above. In contrast to manganese oxide, the zinc oxide formed can be reduced by hydrogen or methane at temperatures far below 1000 °C. This method would have the following advantages:

- Since temperatures are below 1000 °C, all steps can use process-heat of today's HTGR technology.
- Using purely electrolytic or thermochemical hydrogen or hydrogen from a hybrid watersplitting process, only a small amount of coal is necessary in the first step as a chemical reagent.

3.2 The Grothe-Process Coupled to a HTGR

In a metal production process by electrolytic decomposition of a metal salt the enthalpy of decomposition ΔH (comprising the free enthalpy of decomposition ΔG and the term $T\Delta S$) is currently fed entirely in form of electrical energy. However, theoretically only the free enthalpy of decomposition has to be fed in form of electrical energy, $T\Delta S$ could also be provided in form of thermal energy. Nuclear process heat would be appropriate for it.

As already mentioned, molten salt electrolysis at 960 °C of alumina dissolved in cryolithe is the principal method of producing aluminium metal. Utilisation of nuclear process heat to provide heat corresponding to $T\Delta S$ would be difficult because of the high temperature of electrolysis. However, there is an aluminium making process which operates at lower temperature ($\simeq$ 700 °C): the electrolysis of aluminium chloride. Invented in 1920, this process was thoroughly treated by GROTHER /5/ in 1936. Recently, the American aluminium firm ALCOA announced the construction of a plant with a capacity of 15'000 metric tons per year /6/. ALCOA claims that their process will lower electrical energy consumption by as much as 30 % over the most efficient conventional practice. Owing to the formation of chlorine at the anodes, the aluminium chloride electrolysis has to be performed in closed cells.

According to PEACY /6/, a cell of an aluminium chloride electrolysis shows the following performance:

$$\left.\begin{array}{l} J = 13'000 \text{ A} \\ U = 3,3 \\ \quad = 86\ \% \end{array}\right\} \begin{array}{l} \text{corresponding to a specific energy} \\ \\ \text{consumption of 11'500 kWh/metric t Al} \end{array}$$

The electrolyte consists of a mixture of 50 % NaCl, 45 % LiCl, and 5 % $AlCl_3$ and is kept at a temperature of 700 °C. The decomposition voltage of $AlCl_3$ at 700 °C amounts to 2 V according to GROTHE. Therefore, 2 V of the total cell voltage of 3.3 V are consumed by the decomposition voltage which necessarily has to be delivered in form of electrical energy. The remaining energy, 1.3 V x 13'000 A = 16.9 kW, could be, at least theoretically, fed in form of HTGR heat. In the practice, the whole amount of 16.9 kW can not be replaced by thermal energy, because the electrical resistances of the busbars, the electrodes and the bath cannot be kept arbitrarily low.

These resistances cause Joule's heat. By lowering the distance between the electrodes and/or by increasing the conductance of the electrolyte using a greater amount of LiCl in the bath, the resistance of the bath which is the major part of the resistances of the cell is diminished. It is assumed that by these means the cell voltage can be reduced at least 0.5 V. This would result in savings of 15 % of electrical energy compared with an ordinary electrolysis of aluminium chloride and of 40 % compared with a cell used in the alumina electrolysis, respectively.

4. CONCLUSIONS

Since zinc and aluminium are important industrial crude metals it would be worthwhile to proceed with studies of this kind in more detail. It is obvious that this paper is only the first step in a new field, namely, the use of HTGR process heat for metal-making processes others than the steel-making process.

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SESSION B

NUCLEAR DISTRICT HEATING AND LOW TEMPERATURE APPLICATIONS

B 1

THE CHALLENGE OF NUCLEAR DISTRICT HEATING

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SUMMARY

During recent years, the cost of most forms of heat supply has increased strongly as a result of

a) the four fold increase in the price of oil since the beginning of the oil crisis, and
b) the substantial increase in the cost of electricity, beyond the increase motivated by general inflation alone - due to the increasing impact, impact of safety measures and the rising cost of enrichment, uranium and the back end of the fuel cycle on nuclear power costs.

Even though the domestic prices of coal and natural gas may still, in some countries, be below world oil prices, it can only be a matter of time before they catch up, and even now the Governments concerned are subsidising marginal fuel consumption as they have to pay world prices on oil imports. Even though electricity prices for electric space heating may still, in some countries, lag behind the marginal cost of producing this electricity in a mix of new nuclear and fossile fuel power stations, the countries concerned pay the full marginal cost as nations. Thus practically all types of heat supply are directly affected by a) or b) or both, at least from the aspect of national economics.

The only heat supply forms affected only to a minor extent is waste heat from nuclear power plants and industry. At source, waste heat costs only about the cost of the small quantity of electricity lost by making this heat available, i.e. only 1/6 th to 1/10 th kWh of electricity per kWh of heat recovered - depending on the temperature at which the heat is extracted. At the receiving end this heat costs, of course, more than this because of the cost of the heat transmission and distribution. But these latter costs are affected only by general inflation and are thus subject to lower percentage cost increases than costs affected by either a) or b). Moreover they can be kept low by transmitting large heat rates and using modern technology as illustrated in detail in the attached paper.

The message is obvious - the economic changes which have taken place since the beginning of the oil crisis greatly improved the calculable competitivity of nuclear district heating schemes. Newer technology under development or demonstration for heat transport distribution, storage and usage in the homes can further improve this competitivity. In addition a wider use of nuclear district heating would have a tremendous impact on the environment, fuel conservation and the balance of trade of Western European nation, as space- and tapwater heating alone are responsible for 25 to 50 % of the energy consumed by most European countries.

District heating using fossil fuels is already used fairly widely in about ten West European countries as illustrated by the examples on Table I and widely in most East European countries. Projects for Nuclear district heating are under study in several European countries as illustrated by Table II. Nevertheless the interest still falls short of the interest justified by the points listed above.

In view of these points, the main obstacles to a wider introduction of nuclear district heating can only be institutional. Protective pricing of domestic fuels or off-shore fuels to values below world market prices, time delays in adjusting electricity prices to the prices reflecting the costs of new generating stations - such measures (where they exist) subsidise, at the expense of the national budget, the heat forms competing with nuclear district heating. Exaggerated reliance on the mechanism of free competition for different heating sources in a field where this result in up to four expensive heat distribution systems in a given area instead of one, aggavates the situation, especially when some of these four have also severe negative influences on the environment. Absence of utilities with a clear mandate in the heat distribution field tend to preserve the status quo. The remedy to such institutional problems (where they exist) seems to be an increasing emphasis on national regional and local energy plans in which heat - as one of the few energy forms servable by many alternative routes - merits particular attention. Of course tools which make it possible to implify such plans, are also needed, including some legislation. I believe that many international organisations could help in this transition which could do much to reduce the fuel wastage, pollution and cost of energy supply in Europe in the coming decades. They could (if their terms of reference allow this) transfer some of the R&D efforts hitherto devoted mainly to nuclear reactors and the nuclear fuel cycle to efforts in the heat transmission, distribution, storage and usage areas, which up to now have had the benefit only of very small R&D efforts. They could, with their competence of complicated systems and strategy studies, help National Governments to analyse the alternatives and allocate the most favourable energy form to each type of region - nuclear district heating for most cities and their surroundings, nuclear electricity for rural areas, fossil fuel and stored energy for peaks.

In the attached paper prepared very recently for an overseas audience I have analysed the factors which support the economic conclusions described above and illustrated them from examples taken from the Swedish scene both regarding economy and institutional issues. In the course of this I have also outlined what our company, AB Atomenergi, is doing in the field. Even though local conditions differ for the West European countries, I believe that the general picture has sufficient in common to make a serious study of the merits of nuclear district heating on the basis of the technological and planning opportunities which exist today well worth the effort.

Attachments:

1.	Tables from ref. 1 showing examples of:
Table I	The extent of the use of district heating schemes (and typical technical data) for the West European countries.
Table II	Nuclear district heating schemes under study in Europe.
2.	The paper "The future trend of District Heating" giving the detailed analysis in support of the preceding summary.

Item		Countries			
		Germany	Sweden		Finland
1. Population	millions	54	8		4
2. Number of heat utilities		109 (16)^{x}	50	(9)	29
3. Heat supplied by district heating stations	GWh(t)/yr	42 300	16 200	(10 600)	6 800
4. Total connected heat load	MW(t)	22 300	9 300	(5 760)	4 221
5. Maximum heat demand during year (4 hour period)	MW(t)	9 200	6 500	(3 500)	
6. Annual utilization period					
a) network = (3)/(4)	hours	1 450	1 750	(1 840)	1 620
b) gen plant = (3)/(5)	hours	3 520	2 500	(3 020)	
7. Length of networks	km	5 100	1 960	(1 320)	906
8. Connected heat load/m	kW/m	4.4	4.7	(4.4)	4.7
9. Back pressure electricity production	GWh(e)/yr	(4 476)^{x}		(2 690)	2 623
10. Installed back pressure capacity	MW(e)		1 450		473
11. Ratio, el/heat (4)/(3)				(0.25)	0.39
12. Average efficiency:					
a) electricity generation^{xx}	%		20		
b) overall, all plants	%		80		
13. Percentage of houses connected					
a) in cities with district heating schemes	%				38.6
b) in whole country	%				14.1
14. Source for information (Ref.No.) and year for statistics		1 (2) 1974 (1973)	1 3 74/75,73/74	2 1973	1 1974
15. Other European countries with important district heating networks		All East European countries; Belgium, Denmark, France, Austria, Switzerland (+ UK with a few small schemes)			

x *Refers to heat utilities forming part UNICHAL, i.e. the international organization of district heating utilities (mainly larger utilities)*

xx *(electricity produced by back pressure generation)/(heat in fuel consumed by stations having back pressure plant)*

TABLE I: District heating data for some West European countries with highly developed systems.

Country	Project name	Approximate heat transmission rate MW	Probable date for start of operation	Status - (detailed or outline project study)
Sweden	Barsebäck/Malmö-Lund	950	1985/86	detailed
	Greater Stockholm	2100	> 1986	detailed
	Greater Gothenburg	~800	late 1980s	outline
Finland	Greater Helsinki	2000	Middle 1980s	detailed
Denmark	Gylling Naes/Storårhus	700	late 1980s	outline
Germany	Super Grid for whole country	(multi GW)	early 1980s for first parts	outline
France	Saclay/West Paris	1100	Middle 1980s	outline
Switzerland	Bern			outline
Checkoslovakia	Brno	~ 1000	~ 1990?	outline

* heat only; all other projects refer to combined heat/electric stations

<u>TABLE II:</u> List of some major nuclear regional district heating projects under study

Literature
(in addition to documents cited in attachment 2):

1. PETER MARGEN
The use of heat from nuclear stations for residential heating.
ASME/ANS International Conference. March 13-16, 1976, Pittsburgh, Session VII, Paper A.

2. KJELL LARSSON
An energy model for the optimization of a total nuclear based district heating system.
IAEA-Symposium, March 1976.

3. RUTGER ROSEEN
Development work on new hot water transport and distribution system.
IAEA-Symposium, March 1976.

Attachment:

THE FUTURE TREND FOR DISTRICT HEATING

Nuclear regional district heating schemes
and improved
hot water transport, distribtuion and utilisation techniques

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1. INTRODUCTION

Other articles in this series describe the engineering practice for district heating schemes in Sweden, and the general merits of district heating from the viewpoints of fuel conservation, environmental improvement and overall economy. In this article I shall analyse the factors which tend to make nuclear district heating in large regional schemes particularly important and describe the part which current and improved techniques for heat transport and distribution can play in this development.

2. RELATIVE ECONOMICS OF FOSSIL FUEL AND NUCLEAR DISTRICT HEATING SCHEMES

2.1 Conditions in pure oil economy

In Sweden there exist district heating schemes in some fifty towns. All started by central heat-only oil fired boilers (initially often temporary units) and all except the largest schemes still rely entirely on these. Their economic advantages compared to domestic boilers is based on their ability to use cheaper fuel (heavy fuel oil), their higher thermal efficiency and the centralised service. These factors have proved sufficient to offset the extra cost of the required hot piping systems in most residential districts with reasonably high heat densities. The central heat-only boiler may therefore be regarded as a reference standard for district heating economy. If combined heat/electric stations are to be economic they must produce heat of a cost lower than that from the heat-only boiler.

Oil-fired heat-electric stations were introduced in the ten largest Swedish cities when the base load part of the heat load had grown sufficiently to accomodate a heat/electric station of reasonable capacity. As shown by Fig. 1, such a plant would take over about 50 % of the maximum system heat demand, but more than 80 % of the annual heat quantity.

For every two kWh of heat delivered by such a back-pressure heat/electric plant about one kWh of electricity is generated at the "marginal efficiency" of the boiler only - 85 to 90 %. Compared to condensing steam stations with efficiencies of 38 to 40 % the marginal fuel required for the additional electricity is reduced by a factor of 90/40 = 2.25, i.e. by 55 %. Capital charges on the other hand are higher - because of the smaller size of the district heating plants. Moreover the heat/electric station has to be backed

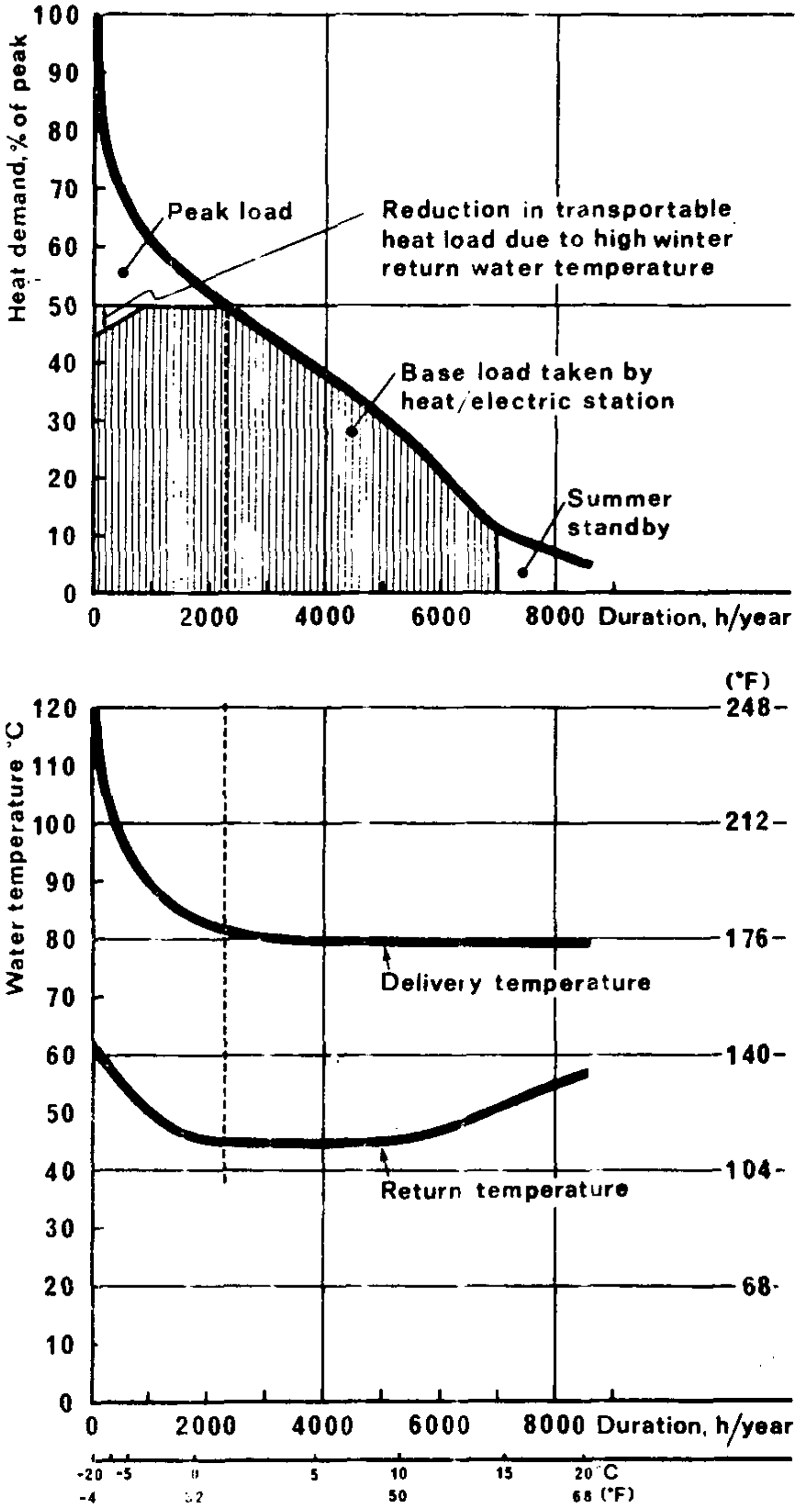


FIG. 1: Heat load-duration, load allocation and water temperatures under typical conditions in Sweden.

up by reserve heat-only boilers (being the largest unit on the heat system) so that it can not be credited with any substantial reduction in the required heat-only boiler capacity.

Provided the above mentioned 55 % reduction in fuel cost achieved is sufficient to balance the "small size penalty" on capital charges and operating costs, the combined plant is in business on systems on which condensing steam stations are the main alternative to heat/electric stations for electricity production. This requirement determines the minimum size of district heating systems on which a heat/electrical station can be justified.

In Sweden the bulk of the electricity produced during the 1950s and 1960s came, however, from hydro plants having lower generation costs than oil fired condensing stations. This further reduced the credit obtained for the electricity generated by heat/electric stations and therefore impaired their economy compared to the case considered above. The fact that nevertheless all the larger schemes in Sweden (about 10 in total) could justify such combined heat/electric plants indicates how strong the position of heat/electric stations should be in countries having to generate their electricity mainly from fossil fuels.

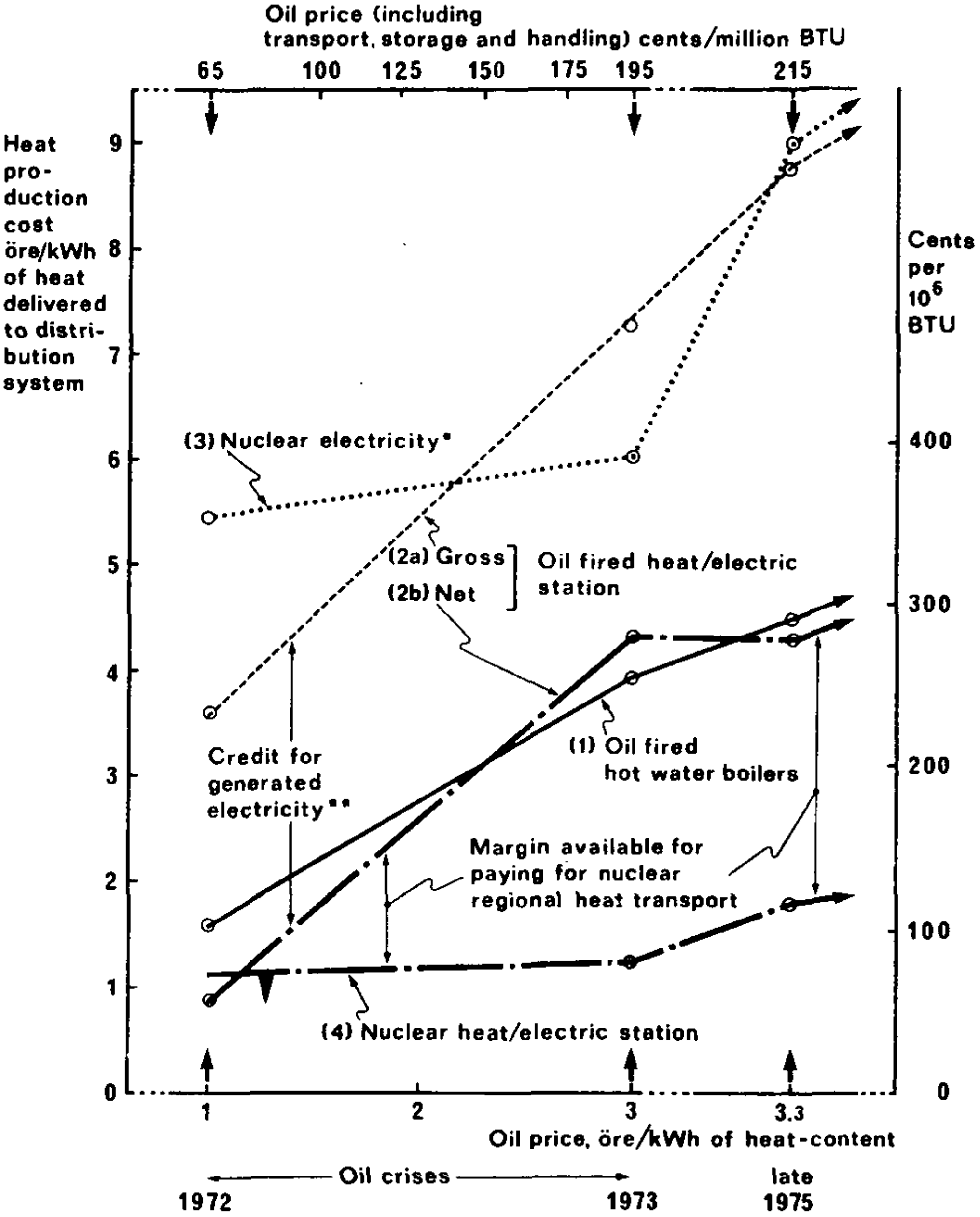
2.2 The impact of the oil crisis

a) Competitivity of oil-fired heat/electric units

Just before the oil crisis, most economically exploitable hydrostations in Sweden had been built or ordered, so that the electricity produced by heat/electric stations had (from the aspect of national economics) to be compared with the cost of producing electricity in new oil burning or nuclear thermal stations. Initially both these types of station had about the same electricity cost when operated at the typical load factor of heat/electric stations (about 4500 full load hours/yr). During the oil crisis, however, the price of fuel oil was more than trebled, whilst, because of the short time period involved, capital costs increased only slightly. Thus nuclear electricity stations become more competitive than oil fired condensing stations even at fairly low load factors.

The cost of heat from oil fired heat-only boilers increased in accordance with curve 1, Fig. 2, and the gross cost of generation from heat/electric stations (before deducting the electricity credit) increased in accordance with curve 2 a.

In the simplified system we considered in the first part of para 2.1 where all electricity was supplied by oil fired stations, such an increase in oil price would have increased also the cost of electricity and therefore the credit obtainable for the electricity produced by heat/electric stations. This would have improved the competitivity of the other product - the heat. On a system however, having nuclear power the effect of the large oil price increase did not noticably affect electricity costs as shown by curve 3. The credit obtainable for electricity produced from heat/electric stations was therefore kept nearly constant, whilst the cost of generation in these stations (curve 2 a) still increased due to rising oil prices. Hence the net cost of heat production in the combined station still rose steeply as shown by curve 2 b (= (curve 2 a) - 0.5 (curve 3)). A comparison of curves 1 and 2b shows that heat/electric stations of about 100 MWe output which were much



*) Curve (3) is expressed per kWh electricity

**) 0.5 kWh electricity generated per kWh of heat delivered

Assumed conversion: 4.5 öre = 1 cent

FIG. 2: Changes in production costs of heat from various sources (for base load 4500 h/year supply including cost of reserve boilers); see Table I.

	Beginning of oil crisis (early 1972) c = 1	End of oil crisis (mid 1973) c = 3	Late 1975 c = 3.3
A. HEAT ONLY BOILERS, 50 TO 100 MW/BOILER			
1. Capital charges and operation including 33 % reserve capacity: a) Cr/kW & year	18	20	27
b) öre/kWh	0.40	0.44	0.60
2. Oil costs at 85 % boiler efficiency, öre/kWh	1.17	3.51	3.86
3. Total (curve 1 Fig. 2) "	1.57	3.95	4.46
B. COMBINED OIL FIRED STATION			
1. Capital charges and operation on combined plant* Cr/kW(th) & year	68*	75	114
2. Reserve heat only boiler "	14	15	21
3. Total fixed costs a) Cr/kW & year	82	90	135
b) öre/kWh	1.82	2.00	3.00
4. Oil costs (= 1.5 x item A.2 öre/kWh	1.76	5.27	5.76
5. Total generation costs (3) + (4) (= curve 2a Fig. 2) "	3.58	7.27	8.76
6. Cost of electricity at 4500 h/yr (= curve 3 Fig.2)** "	5.43	6.00	9.00
7. Credit for electricity per kWh of heat = (item 6)/2	2.71	3.00	4.50
8. Net cost of heat = (5) - (7) (= curve 2b Fig. 2)	0.87	4.27	4.26
C. NUCLEAR STATION			
1. $\Delta P/Q_u$ (assuming $120^{\circ}/60^{\circ}$C water temperatures and three stage condensation kWh(e)/kWh(th)	0.125	0.125	0.125
2. Cost of electricity sacrifice öre/kWh = (item C.1) x (item 6)	0.68	0.75	1.12
3. Cost of terminal equipment "	0.13	0.14	0.20
4. Reserve heat only boiler (from B.2) "	0.30	0.33	0.47
5. Total cost of heat at nuclear station site (i.e. excluding " transport cost (= curve 4 Fig.2)	1.11	1.22	1.79
6. Highest permissible heat transport cost from nuclear plant = (C.4) - (A.3) or (B.8) (whichever is lower) "	0.24	2.73	2.46

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* *Corresponds to an investment of 1240 Cr/kWe and 1 kWe/2 kW(th) annual cost expressed per kW net heat delivery to district heating scheme!*

** *200 Cr/kW & year plus 1 öre/kWh for nuclear power*

TABLE I: Changes in cost of 4500 hours/year base load heat supply from different sources 1972 to late 1975 (10 % total capital charge rate on plant) *c = cost of fuel oil, öre/kWh of heat content, including storage, handling, etc. This table is used to plot Fig. 2.*

more economic than heat-only boilers at the beginning of the oil crisis were, for these reasons, hardly competitive at the end of the oil crisis. A definite deterioration of their competitivity had occured.

b) Competitivity of nuclear units

Let us now turn from relatively small oil-fired heat/electric stations to central nuclear stations using reactors of standard size and output. Heat can be obtained from these, by using pass-out or back-pressure turbines instead of condensing turbines (as discussed later). This would not significantly change the total generation costs in crowns/year at such plants, but reduce the electricity output by an amount P, and make an additional heat quantity Q_u available for district heating. The ratio P/Q_u would depend on the turbine arrangement and electric heating water temperatures and as shown in Fig. 3 and would typically be about 1/8. Thus, roughly speaking, 1 kWh of heat could be made available at the cost of 1/8 th of the generation cost of one kWh of electricity. When electricity costs are dictated by the costs of nuclear power, the cost of heat from such a plant would thus be independent of the cost of oil. This is shown by curve 4 in Fig. 2. The curve shows that the cost of making available heat (in the form of hot water) at large nuclear station sites would be well below that of the cost of the fossil fuel alternatives curve 1 or curve 2 b by the end of the oil crisis.

Of course the heat must also be transported to load centres. As nuclear stations are located at some distance from these, the cost of heat transport can be significant. The maximum amount which this heat transport can be allowed to cost for an economically viable scheme is the difference between the lower of curves 1 and 2a and curve 4 in Fig. 2. It will be seen that this difference rose sharply during the oil crisis. Towards the end of the period it rose to about 2.7 öre/kWh, which would have been sufficient, for instance, to transport large base load heat rates (1000 to 2000 MW) some 50 to 60 miles even using conventional pipe techniques.

2.3 After the oil crisis

Since the end of the oil crisis, nuclear plant and fuel costs have risen more rapidly than oil prices. The effect of this, as shown by the rough trend indicated by the right trend hand side of Fig. 2, is to make

a) fossil fuel heat electric plants somewhat more economic relative to heat-only boilers than at the end of the oil crisis.

b) somewhat increase the cost of heat at the nuclear sites. The strong viability of nuclear district heating schemes is not significantly changed by this increase.

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* *The above discussion is slightly simplified compared to real conditions in Sweden as the existence of large hydro-storage capacity in Sweden reduces the cost of electricity in the intermediate load factor range. However, the purpose of the discussion is to show the general trend which the price changes occuring during the oil crisis had on the calculated competitivity of oil fired unit nuclear district heating, and is sufficiently accurate for this purpose.*

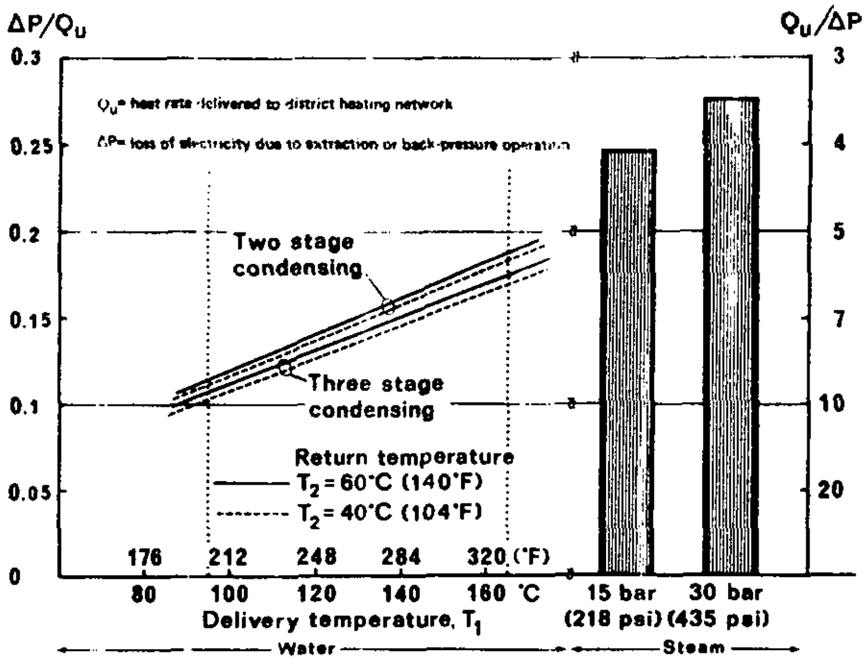


FIG. 3: Electricity Sacrifice (ΔP) due to Reject Heat Utilization (Q_u) at various temperatures

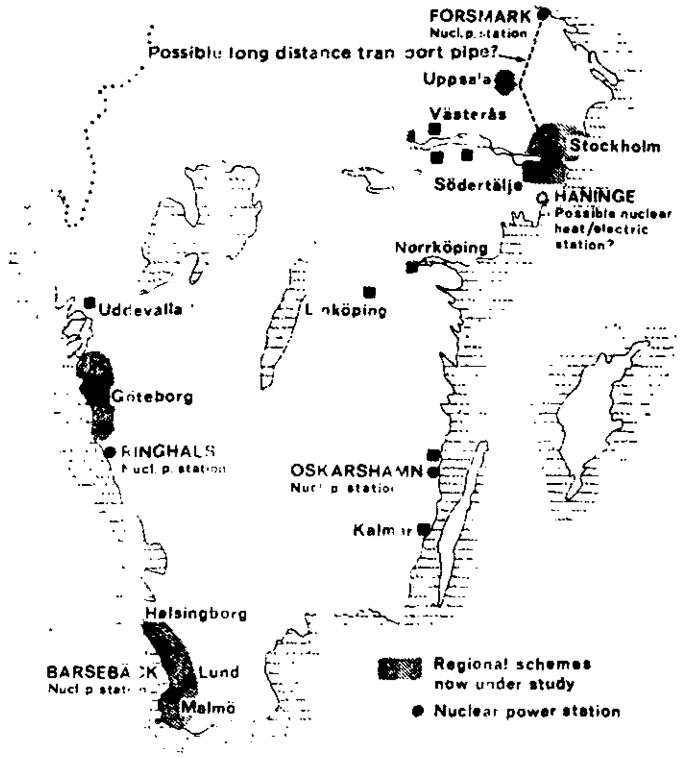


FIG. 4: Map of Sweden showing location of regional district schemes under investigation

For the near term future one may expect oil prices to keep pace with plant costs so that the economic advantage of nuclear heat electric stations should be maintained, also in the near term future. In the long term future when approach to the exhaution of oil and natural gas resources must result in more rapid fossil fuel price increases than nuclear power cost increases, the economy of nuclear district heating should be further improved.

2.4 Pin points for the future

The price trends in Fig. 2 bring out the following points:

a) The potential for fossil fuel district heating schemes has become more limited due to the fact that the electricity credit they could obtain did not keep pace with oil prices. Also the increasing competition of electric space heating in low density heating areas contributed to this trend. Hence nuclear heat/electric stations are essential if district heating is to achieve a dominant and lasting role in a country's heat supplies.

b) How heat transport costs are important for the economies of nuclear heat/electric stations. The lower these costs the more customers can be reached economically. Methods of adapting conventional hot water pipe techniques are needed (including proper optimization) and the development of newer techniques which could further reduce heat transport costs are necessary if the potential of nuclear heat/electric stations are to be fully achieved.

c) The larger the heat load transported the lower is the specific cost of the heat transport. If cheaper methods of distributing heat to lower density suburbs can be developed, this would increase the capacity of the connected and transported heat load, and therefore further improve the economics. It will also further increase the extent of fossil fuel conservation.

In Sweden the importance of these three points is fully appreciated by all parties concerned. Hence serious efforts to prepare for regional nuclear district heating schemes are being made and development work is in progress to further improve heat transport and distribution techniques, as discussed in subsequent parts of this article.

3. NUCLEAR DISTRICT HEATING PROJECTS IN SWEDEN

Ågesta, the world's first nuclear heat/electric station has been supplying district heating to the South Stockholm suburb, Farsta, for about ten years very successfully. Plant availability has been high, and on the occasions when the reactor was stopped, the Stockholm Electricity Board telephone exchanges have been busy with callers complaining about the smoke produced by the oil fired reserve boiler, which is located right in Farsta. The clean air associated with nuclear heating had become a habit. The plant was, however, built only to gain experience as it was too small to be economic. Hence just before the oil crisis, a decision to shut down the plant was taken and effected one year later.

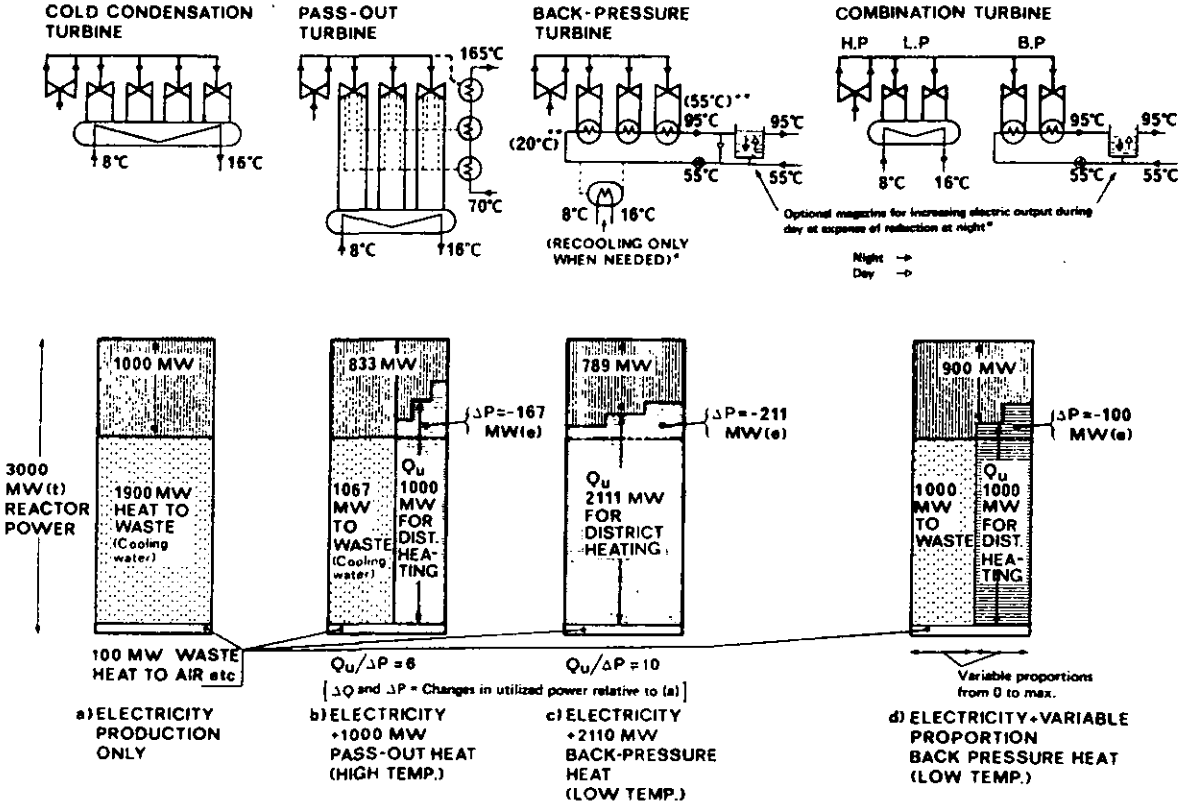
To be really economic, new nuclear heat/electric stations have to be large, for the same reasons that nuclear electricity stations have to be large, namely, the relatively high minimum capital investment. Also, with current safety practice, they would have to be located outside the densely populated areas. Hot water will thus have to be sent some distance and this can be economic only when the heat quantities being transmitted per pipe are large. Large heat load, in turn are often spread over fairly large regions, at least in Sweden. Therefore regional networks of large pipes are necessary for spreading the heat from the nuclear heat/electric stations to the various regional distribution centres.

In Sweden attention has been concentrated on the three regions having the greatest population aggregations - South Western Skåne, greater Stockholm and greater Gothenburg. All three regions are shown on the map, Fig. 4. In South Western Skåne the proposal under examination is, that the third unit at Barsebäck (which at present houses two nuclear units, one of which is operating) will have a turbine suitable for combined heat/electric supply. Pipes parallel to the coast line, in both directions, would supply the towns of Malmö, Lund, Landskrona and Helsingborg. In greater Stockholm plans visualizing until recently a station at Haninge, south of the most southerly suburbs. Currently the site has become uncertain due to local opposition and alternative sites (even the established nuclear site at Forsmark 130 km from Stockholm) are being examined. Both Barsebäck and Haninge are further from population concentrations than many nuclear stations in Europe which supply electricity only. The three areas mentioned house together nearly half the country's population. If nuclear heat/electric stations can contribute to a major reduction in heat costs in these areas, the contribution to the National and local economy will thus be large. Above all, however, tremendous quantities of oil will be saved and air pollution be reduced. At some future date, even other regions may be affected by the development.

The nuclear heat/electric stations will not, however, replace fossil fuel plants even in the regions mentioned, but only supplement them in a very important way. On the typical projected load-duration curve, Fig. 1, the nuclear heat/electric plants would take the base heat load supplying some 80 % of the heat energy but only 50 % of the maximum demand. Existing oil fired heat/electric stations would supply the intermediate heat loads and cheap existing and new oil fired hot water boilers the peak loads and reserve duties on the local networks.

4. TURBO GENERATOR ARRANGEMENTS AND MAGAZINES

Fig. 5a shows a typical turbine schematic for a nuclear electricity station, and 5c turbine schematic for a very large nuclear heat/electric station, fitted with back pressure turbines only. This type of station would, because of the back pressure operation, have lower electricity output than the pure electricity station, as illustrated by the lower part of Fig. 5a. The amount of the reduction in electricity per unit heat delivered to the district heating scheme depends on the water temperatures used and the number of stages in which the water is heated, as shown by figures 3 and 5. For the conditions of Fig. 5c,



* This applies when average Q_u during the day is less than total station heat rejection

** Temperature terms in brackets apply when operating turbine with recooler only during day, while charging magasin at night

FIG. 5: Turbine Arrangement

$\Delta P/Q_u = 0.1$. Fig. 5b shows a heat/electric station with a pass-out turbine suitable for smaller heat demands than the pure back pressure turbine. Basically the same values of $\Delta P/\Delta Q_u$ can apply for given water temperatures as in the back pressure turbine case.

In Fig. 5d parallel low pressure and back pressure cylinders are used and a cheap magazine at atmospheric pressure can be used. For maximum electricity production during the day all steam is diverted to the LP cylinders whilst the district heating load is supplied from the magazine. At night all steam is diverted to the BP cylinders, allowing the entire heating load to be supplied directly and the magazine to be recharged. For the previously mentioned Barsebäck 3 proposal, the use of a passout turbine with fairly high water temperature as represented by Fig. 5b is currently assumed, giving $\Delta P/Q_u = 1/6$.

Fig. 5 thus illustrates the flexibility afforded by turbine designs. Currently a pass-out turbine is favoured for Barsebäck and a back pressure turbine for Greater Stockholm.

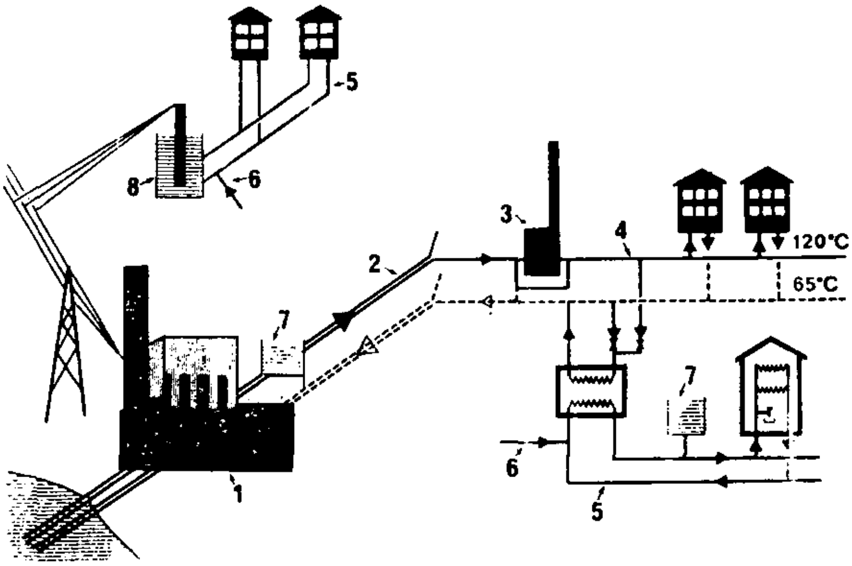
In comparing different schemes one must take account of variations in water temperature during the year. A high water temperature scheme $T_1 = 165$ °C, $T_1 = 65$ °C on the coldest winter day and $\Delta P/Q_u = 0.175$ at these conditions would have a lower average elasticity sacrifice ($\Delta P/Q_u = 0.15$) over the year. A low temperature scheme with $T_1 = 98$ °C, $T_2 = 53$ °C (except on the coldest winter day when a reduction in heat transmission rate would be accepted) would give about $\Delta P/Q_u = 0.1$ during winter but 0.09 average. If electricity production costs in 1975 at 4500 hours/year are 9 öre/kWh (for new plant), the cost of electricity sacrifice in the two cases would be 0.15 x 9 = 1.35 öre/kWh and 0.09 x 9 = 0.81 öre/kWh in the two cases. The total cost of heat at the generating station in these two cases including cost of terminal equipment (0.2 öre/kWh) may then be about 0.155 and 1.01 öre/kWh respectively.

5. REGIONAL HOT WATER TRANSPORT SYSTEM

At present, most district heating systems in Sweden are dimensioned for a delivery temperature of 120 °C on the coldest winter day (which would fall to about 80 °C in mid summer see Fig. 1) and return water temperature of 60 to 65 °C, also in mid winter.

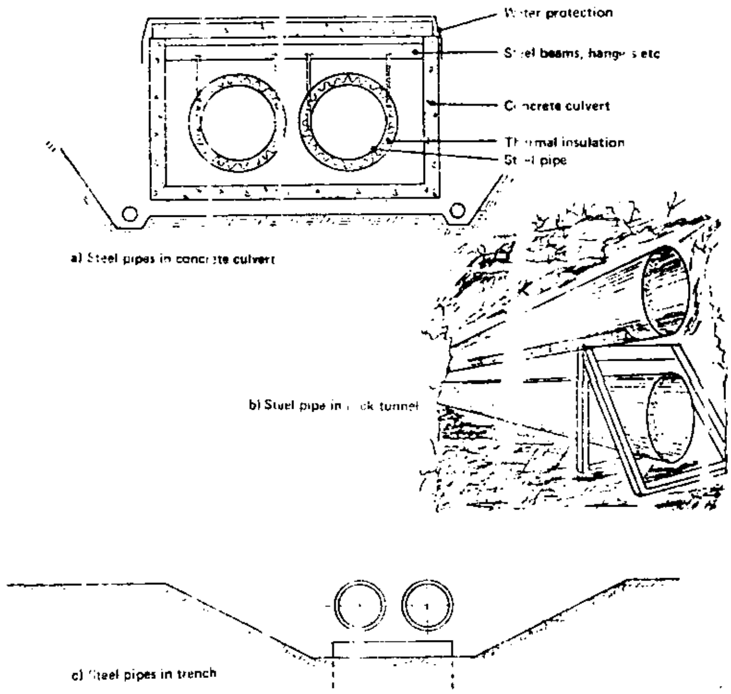
There is a trend for return water temperatures to be reduced as system design and regulation improves. Sometimes the oil fired heat/electric stations are dimensioned for 90/60 °C and local hot water boilers raise the temperature from 90 °C to values up to 120 °C during the colder part of the winter. This form of "temperature topping" thus allows the heat/electric station to provide more electricity during the winter.

For the large regional networks of the future a similar approach would be possible. The networks can, as illustrated in Fig. 6, be designed for a moderate delivery temperature, e.g. 90 °C, and fossil fuel heat/electric stations and hot water boilers connected to the existing network of intermediate pipes can raise the temperature of the water from 90 up to 120 °C when necessary, as shown by the right hand half of the diagram. For local systems not designed for such high maximum temperatures, the local oil fired heat/electric stations and hot water boilers can instead be connected in parallel



1. Nuclear Heat/Electric Station
2. Regional network of large pipes
3. Local fossil fuel plants, for peak load and reserve
4. Local distribution system
5. Secondary low pressure distribution system of plastic pipes, common for space heating and hot tap water
6. Cold water make-up
7. Optional magazine
8. Hot water magazine for night electricity storage and contionuous heat distribution to isolated housing estate

FIG. 6: Simplified schematic of regional district heating scheme with some development possibilities



a) Steel pipes in concrete culvert

b) Steel pipe in rock tunnel

c) Steel pipes in trench

FIG. 7: Big hot water mains with current (steel pipe) technology

with the hot water supply from the regional network, thus transmitting water at the same temperatures as the regional networks.

The flexibility of these arrangements allows the temperature of the regional network to be optimized almost regardless of the requirements of existing intermediate networks. Low temperatures minimize sacrifice of electricity. High temperatures minimize required pipe diameters. Economic optimization should thus decide what temperatures are most appropriate for the transport pipes.

5.1 Costs with present technology

At present hot waterpipes for 120/60 °C systems are in operation in Sweden at dimensions up to 1 m diameter. Big steel pipes are provided with thermal expansion bends at intervals, and the pipes are supported in a manner allowing them to accomodate this expansion by sliding. Fixtures prevent movement perpendicular to the direction of the pipes. The pipes are covered by thermal insulation and contained in concrete ducts or culverts to prevent ground water from affecting insulation and corroding the outside of the pipes, Fig. 7a. Where good rock exists and the pipe dimensions are very large the concrete culverts are often replaced by rock tunnels - as in the case for the pipeline between the Värtan heat/electric station and Stockholm, Fig. 7b.

For certain stretches trench location of pipes (Fig. 7c) may be permissible in future which would reduce costs. This is currently proposed for parts of the Barsebäck scheme, but not considered acceptable from the amenity aspect for many other locations.

A recent investigation has shown that the cost of a long delivery and return pipe of large dimensions of the type shown in Fig. 7 a and 25 bars (~350 psi) pressure for average conditions in Sweden at 1975 price levels can be presented approximately by the formula

$$\text{cost/km} = 300 + 4700\ D + 2000\ D^2 \text{ Swedish Crowns}^{*}$$

where D = internal pipe diameter in m (at 16 bars the cost would be about 8 % lower). When applied to a 100 km (60 miles) long pipe line for 2300 MW thermal power at 165/65°C (the heat rejection from one 3000 MW(t) reactor) this would give a 1.4 m diameter pipe in each direction and represent about 470 Cr/kW thermal power. Allowing for capital changes and maintenance costs at 10 % p.a. and the cost of pumping stations and pumping power and heat losses, such a line would cost about 1.36 pre/kWh at 4500 (full load) hours utilization per year. Adding this to the previously given cost of heat at the nuclear stations site (1.55 öre/kWh) one would obtain a total cost of about 2.91 öre/kWh at the delivery point. As the 1975 oil cost alone at world market prices plus charges in oil storage, handling etc. was about 3.8 öre per kWh heat supplied, even so long a transport would be justified.

Fig. 8 compares the cost of heat transmission at low and high temperatures (curves 1 and 2 respectively) for current technology steel pipes laid underground in concrete ducts for very large heat transports (2100 to 2300 MW corresponding to one 3000 MW(t) reactor). To avoid unduly large pipe dia-

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* *This formula gives about 25 % lower costs than the costs for "difficult ground conditions" given in ref. 2 and 3 for 1974 price levels.*

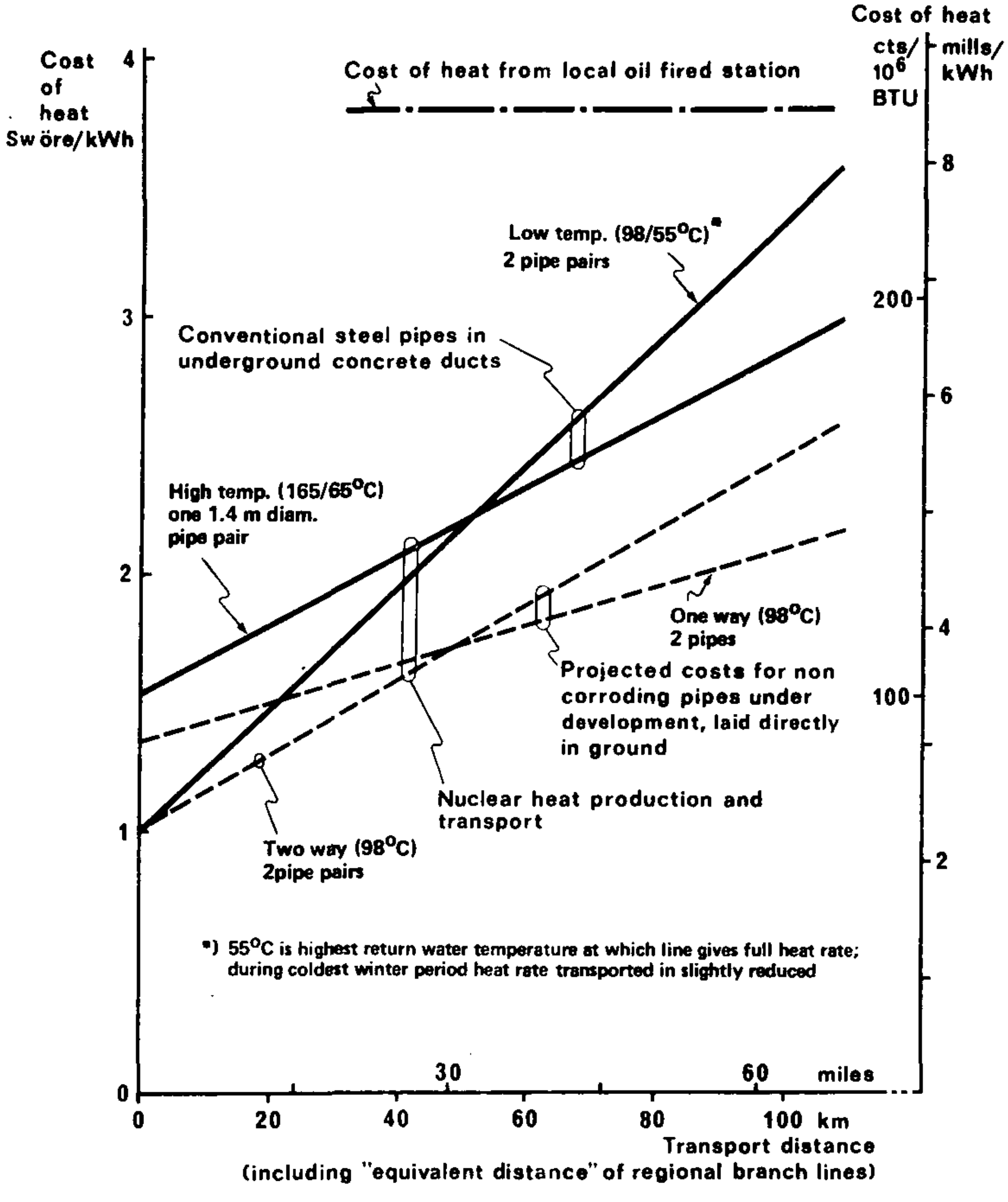


FIG. 8: Example of cost of heat production & regional transport for very large basehold nuclear heat supply. (2300 MW, 4500 h/year; excludes cost of reserve boilers on local systems; 1975 prices, average ground conditions).

meters, it has been assumed in this figure that two pipes in each direction would be used for the low temperature scheme at a cost of 1.75 times of the cost of one pipe pair of the same dimensions. The figure shows that for this case low temperatures are preferable for distances up to about 52 km, high temperatures for distances above 52 km. The two cost equations are

Curve 1: 1.55 + 0.0136 L öre/kWh
" 2: 1.01 238 L "

where L = transport distance. Further cost reductions for the low temperature case becomes feasible when larger pipe diameters (about 1.8 m diameter) become "conventional" as this would allow only one pipe pair to be used for this case also. The results of Fig. 8 should only be taken as a rough indication. In practice many practical considerations can affect such comparisons.

5.2 Technology under development

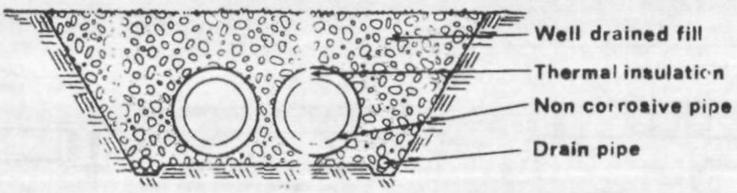
During recent years a programme of developing new techniques for building large pipes has been in progress (ref. 1 to 4), which all have one common feature, namely that they seem feasible primarily at temperatures up to about 100 °C. Table 2 and Fig. 9 give examples. In all cases they avoid the separate provision of ducts for keeping the pipes dry, see Fig. 9a. This is made practicable for instance by using material insensitive to corrosion. Fig 9b and c show photos from tests in progress at Studsvik. Pipes of these types are already used commercially for cold water and gas transports, for industrial hot water transports at limited temperatures (70 to 50 °C) and in small dimensions (100 mm diameter) even for higher temperatures.

Preliminary quotations by the manufacturers involved suggest that the cost of fully installed large pipe lines of this type would reduce the cost per m compared to the conventional pipes type Fig. 7a by about 40 % for a given dimension. In principle these pipes can be used also for "one-way" lines using untreated river, lake or sea water as the pipes do not corrode in such water. A possible application is shown in Fig. 10.

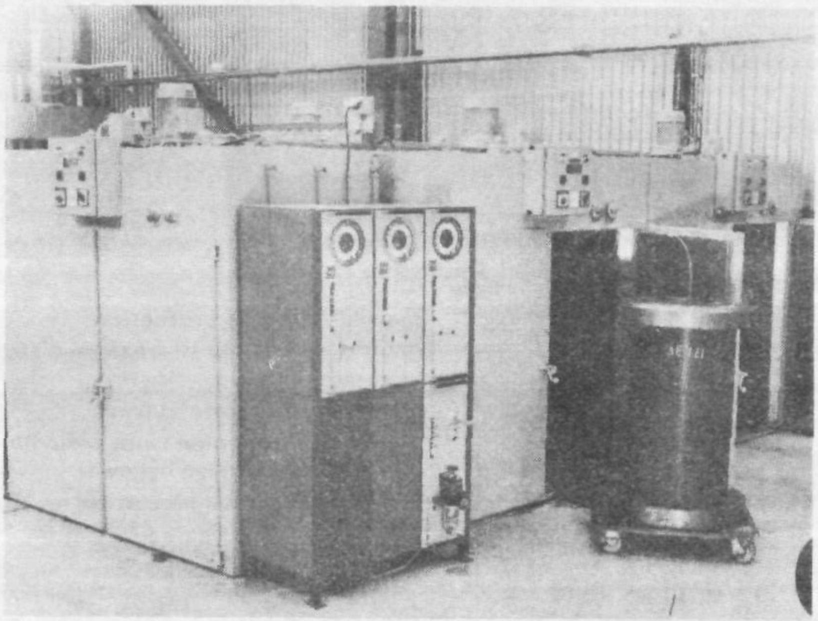
Of course the development and demonstration programme will have to be completed before the new types described above are used at higher temperatures than those for which experience currently exists.

6. DISTRIBUTION

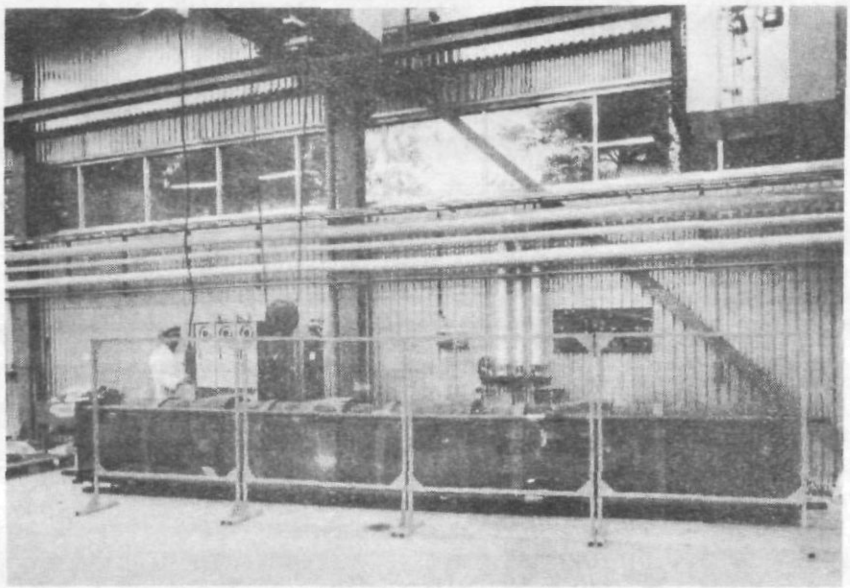
The water taken from the regional networks would be distributed to local housing districts by a system of intermediate pipes, currently made of insulated steel pipes surrounded by ducts of asbestos or other material for keeping the pipes dry (Fig. 11). Even for these networks newer solutions are under investigation. The most interesting part of the distribution system, however, is the last link which covers the small bore pipes distributing water to individual houses. This system is responsible for a considerable part of the total cost, at least where low load density areas are concerned such as one-family housing districts.



a) Non-corroding pipes laid in the ground (armoured plastic or prestressed concrete) without protection culvert.



b) Glasfibre armoured pipe, 500 mm, being loaded for hot, long term pressure test, Studsvik.



c) Prestressed concrete pipe with 5 joints prepared for test (Studsvik)

FIG. 9: Development of new non-corroding pipe types for regional network.

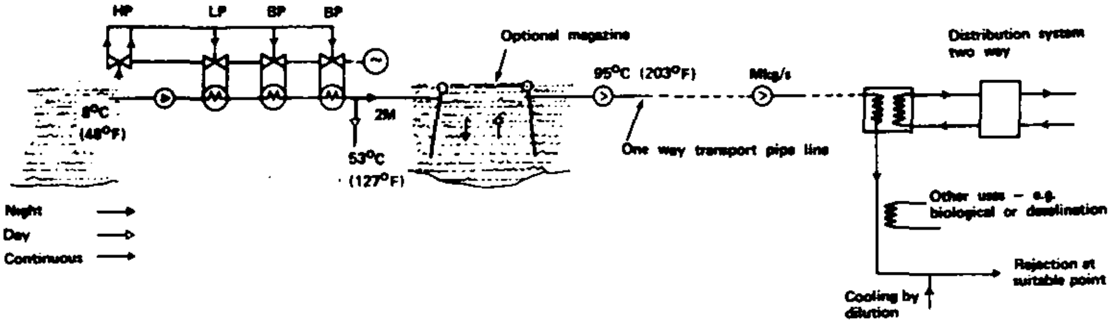


FIG. 10: Long distance one-way transport of warm water in non-corroding pipe

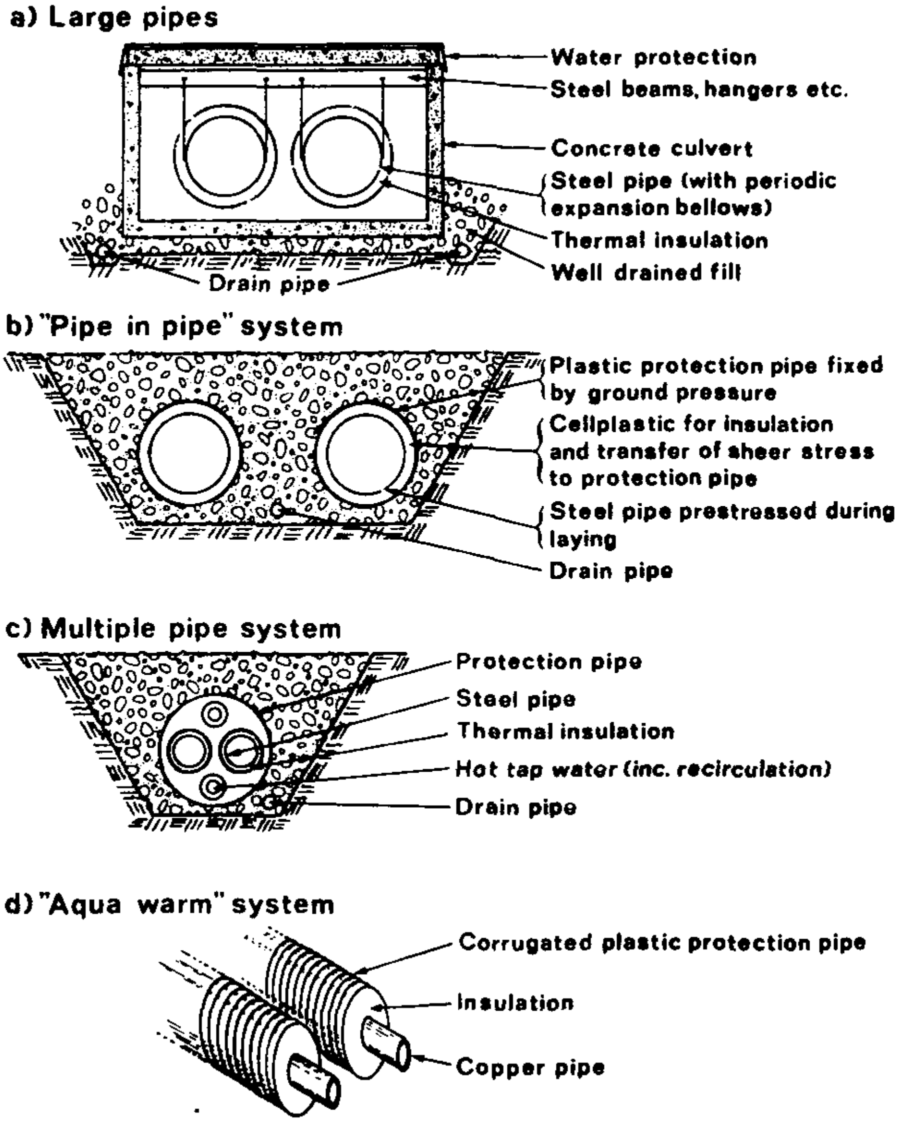
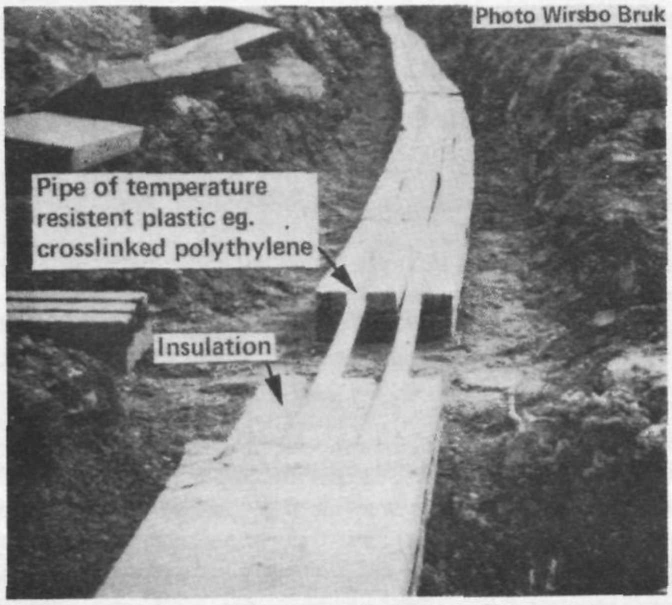
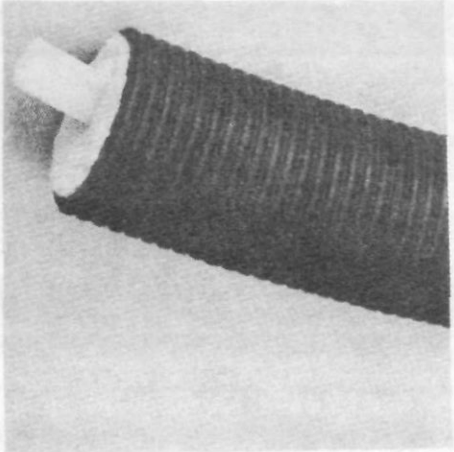


FIG. 11: Conventional hot water distribution pipes



a) Plastic pipes (PEX) mounted in pre-fabricated insulation blocks (Wirsbo bruk)



b) Plastic pipes (PEMX with factory added cellular insulation in corrugated polythene protection pipe (Gränges Essem)

FIG. 12: Swedish plastic pipes for secondary distribution.

The latest tendency for such local networks for small houses is to provide common heat exchangers for a group of houses - e.g. 100 one-family houses, and to distribute from there in a low pressure system at somewhat reduced temperature. Some of the conventional pipe types being used today are shown by Fig. 11c whilst Fig. 12a and b show the latest types. Plastic pipes of crosslinked polyethylene which can be rolled up on drums in lengths of some 100 meters, are put directly in the ground with a simple type of insulation in trenches refilled with sand. This system of installation considerably reduces costs of site work and thus the costs of the local distribution system as a whole. The tests carried out at Studsvik showed no damage after a large number of extreme temperature cycles (90 to 20 °C) at twice design pressure. Long term creep and creeping tests have also been carried out at the Studsvik laboratories. Several housing districts using pipes of the type shown by Fig. 11a are in operation in Sweden.

In principle such plastic piping systems can be used at the temperature now being used for apparatus within houses - typically 80 °C delivery, 60 to 55 °C return. On the other hand reductions in pipe wall thicknesses (and in future possibly the use of cheaper plastics) is possible when lower temperatures are used, e.g. 60 °C delivery, 45 °C return. These lower temperatures can for instance be obtained by the "series type connection" shown for the network parts in the right hand corner of Fig. 6, where the new districts concerned take their water primarily from the return water of other districts. A pipe connection to the delivery side of these other districts allows, however, temperature to be increased on occasions when the return water temperature is too low.

7. EQUIPMENT WITHIN HOUSES

7.1 Existing houses

Existing houses with central hot water heating systems or the hot air systems often used in Canada can easily be adapted to district heating by replacing the domestic boiler by a heat exchanger using hot water from the district heating mains.

For new houses in districts to be supplied from regional district heating networks it is worthwhile examining solutions adapted to give optimum overall economy. Some examples of such solutions are listed below.

7.2 Series connected housing estates

The cost of water delivery from the regional piping network could be reduced by substantial amounts if the return water temperature could be reduced from 60 to 45 °C, especially when long pipe lines and/or low delivery temperatures are used. The part of the load responsible for these reductions - e.g. series connected districts which use water at 60 °C and recool it to about 45 °C - should receive the entire credit of the above mentioned cost reduction. In a similar way, the reduced return water temperature would also reduce the cost of the intermediate piping systems. The reduction in return water temperature also achieves a slight increase in the amount of electricity generated. Total savings of more than 1 öre per kWh used by the series connected districts are feasible.

For the equipment in the houses, however, the lower water temperatures are responsible for cost increases because of the increased surface areas needed for heat transfer at reduced temperature difference. In the cases of standard radiators which have relatively low heat transfer coefficients even at the current relatively high water temperatures and considerably lower coefficients for the reduced water temperatures proposed (and for the increases surfaces necessary which tend to shield the inner part of the radiators), this increase in cost is significant and may absorb the biggest part of the above benefit. This is one of the reasons why we have, at Studsvik, developed a plastic radiator which has already been proved to have much higher heat transfer coefficients than conventional radiators (due to the use of cross air flow over the plastic pipe system) and a considerably lower marginal cost for increasing surface. When such units are produced in longer series they should thus be economic even at the lower water temperatures, and leave a considerable net cost saving due to the use of the reduced temperatures.

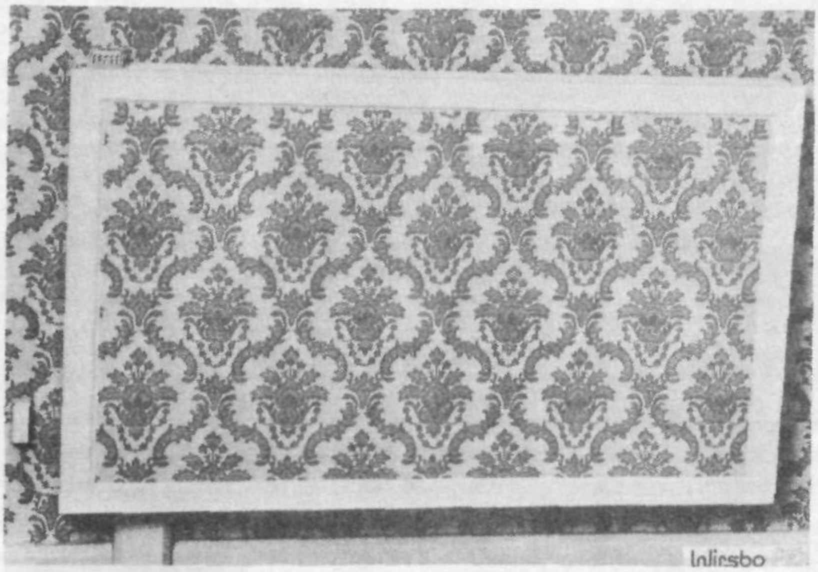
Fig. 13 shows a section through the plastic radiator. It is made of a single long pipe of cross-linked polyethene wound into the desired shape. Prototype units heat have a two store office block in Studsvik since 1973 very satisfactorily. Commercial introduction is expected shortly.

7.3 Reduced water temperatures by hot-air schemes

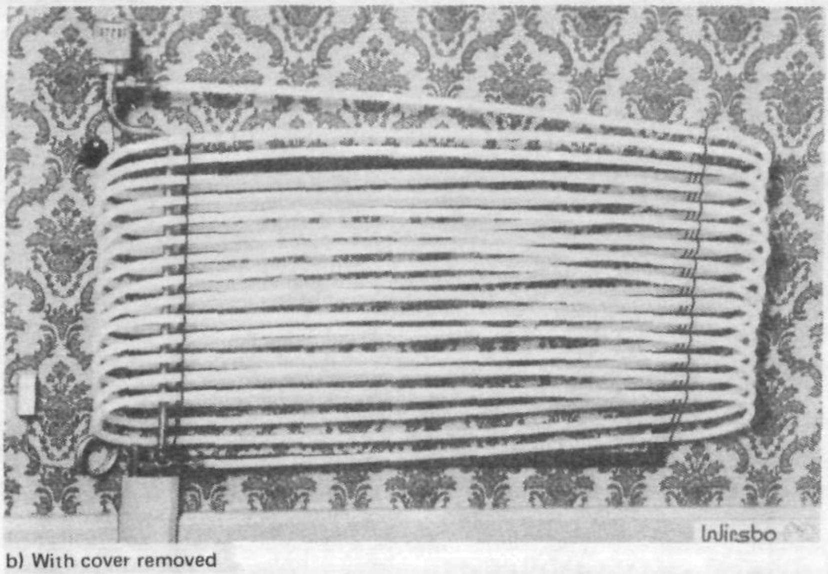
Another interesting possibility is the use of warm air and floor schemes. Fig. 14 shows such a scheme where the air is pumped past the water/air heat exchanger in forced circulation by a fan, and then recirculated from the rooms in a one-family house or flat. Off-air from toilet and bathroom is evacuated by a separate fan. The air ducts are located in prefabricated hollow pre-stressed concrete beams at no extra cost. As these beams have only thin covers, the floors get warm ($\sim$27 °C) and provide 60 to 70 % of the heat transfer to the rooms. The remainder is provided by allowing the hot air to leave the beams through slits under the windows. In the heat exchangers of such warm air schemes, very high heat transfer coefficients can be obtained due to forced circulation, and hence a lower water temperature can be compensated by a very small additional surface. A plastic tube heat exchanger developed in Studsvik gave heat transfer coefficients of about 60 W/m^2 °C, compared to about 8 W/cm^2 °C for typical steel plate radiators at comparable water temperatures. This plastic heat exchanger is now in regular service. The cost increase for lowering the water temperature in the delivery lines from say 80/40 to 60/30 °C is about 30 kr/kW at 1975 price levels corresponding to about 0.15 öre/kWh. Hence this cost increase leaves most of the previously mentioned cost saving, of about 1 öre/kWh untouched. Fig. 15 shows that when applied to blocks of flats further economies can often be obtained by having a common air intakes and exhausts and by recovery arrangements for the heat in the exhaust air.

7.4 Combined heating and hot tap water system

The use of plastics (or copper, which, however, is more expensive) for



a) With cover mounted



b) With cover removed

FIG. 13: Radiator of plastic tubes, Studsvik

radiators or heat exchangers instead of ordinary steel gives also greater freedom to use water containing oxygen. This opens the way to the use of combined heating water and hot tap water systems with commom pipes as illustrated by the local networks in the right hand bottom corner of Fig. 6, thus eliminating a number of pipes, local hot tap water storage tanks etc. Considerable additional savings can then be achieved. The previously mentioned office block in Studsvik heated by plastic radiators already uses such a common plastic piping system for heating water and hot tap water. All pipe fittings must use metals resistant to oxynized water,e.g. brass without zinc. No problems have been met.

7.5 Points to be observed with plastic pipe systems

Some care should be exercised generally in plastic pipe systems with mild steel components, even when closed systems are used. A certain amount of oxygen diffusion takes place through the plastic pipe walls, and if the water has an agressive composition, the presence of oxygen can result in corrosion of steel. Whilst this can often be prevented by additives to the water, the safest solution in the presence of corrosive water is to eliminate the steel components, e.g. by using plastic radiators or heat exchangers instead of steel plate radiators or heat exchangers. Water chemistry tests at Studsvik provide a basis for decisions in this field. Plastic pipes with very high diffusion resistance are under development but will cost somewhat more than the pipes of normal resistance.

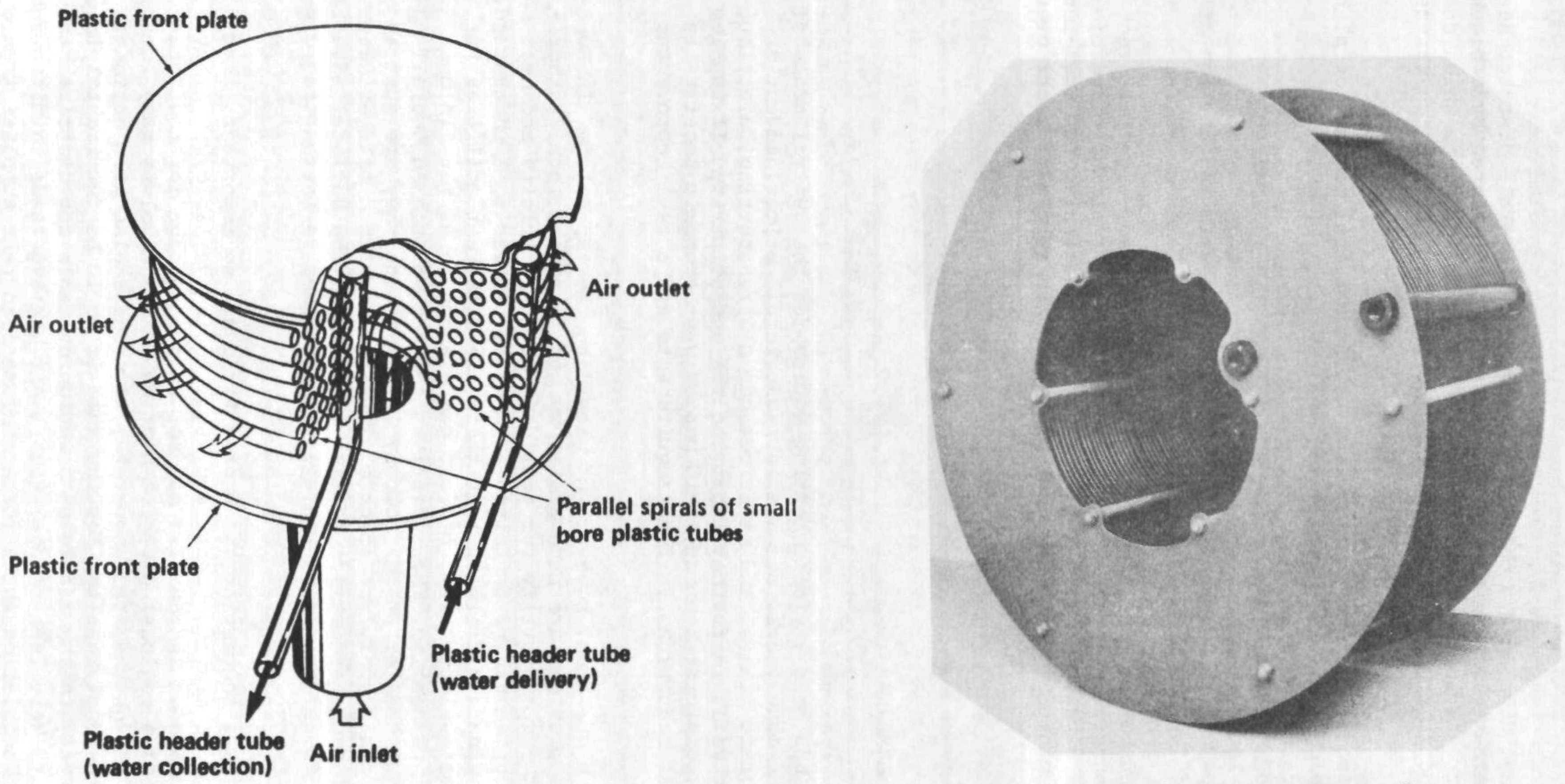
8. USE OF INDUSTRIAL WASTE HEAT

Many industries have waste heat exceeding the amounts they can use for heating their own buildings. The temperatures are often below 100 °C - sometimes as low as 70 °C - and therefore the new cheap piping techniques described in section 5.2 are particularly suitable. They can greatly extend the economic range of heat transport. To make the networks suitable for using low temperature industrial heat every effort should be made to reduce return water temperatures on the system, by good design and regulation of the substations on the local networks serving existing houses and by measures of the type described in sections 7.2 to 7.5 for new houses.

An obstacle to the use of industrial waste heat is often the presence of corrosive substances in the air or cooling water containing the water heat. Plastic heat exchangers illustrated in Fig. 16 have been developed in Studsvik to cover this need at a low cost.

9. SYSTEM OPTIMIZATION

In comparing different solutions it is very important that each solution is optimized for its specific conditions (e.g. permissible temperatures to enable correct comparisons to be made.



a) Schematic of water/air heat exchanger (reverse flow directions possible)

b) Photo of prototype (10 000 m^3/h)

FIG. 16: Air/liquid heat exchanger for recovery of industrial waste heat

At *Studsvik we have developed a computer programme for overall district heating* schemes optimization. Each part of the system is represented by a block (see Fig. 17) with the appropriate performance and cost functions which can readily be adapted to other conditions. Amongst the parameters which can be optimized are:

- heat load subdivision between nuclear and fossil fuel production plants,
- temperature of delivery water on regional system,
- pipe diameters,
- number of pumping stations on the way,
- insulation level on pipes (and walls of new buildings)
- seasonal operation of scheme - i.e. variation in rate as function of heat demand

In addition a number of discrete options can be compared, e.g. different turbine arrangements; conventional or newer technology for piping; type of heating system in houses, etc. The optimization can be carried out even for a growing system minimizing for instance present worth values of costs over say twenty years.

10. CONCLUDING REMARKS

District heating has been a viable heating source for the central areas of Swedish cities for many years, and the increase in oil prices, advent of nuclear heat/electric plants, and newer methods of transporting, distributing and using hot water is further improving the competitivity. If tackled on a national scale, district heating could bestow vast economic benefits as well as very great reductions in fuel requirements and a real improvement in the environment.

It is not merely a question, however, of providing the technology. In Sweden some of the other problems are made easier by the fact that local authorities have a joint responsibility for providing both electricity and heat service. Hence the system can be optimized as a whole. As far as I understand, the situation in Canada differs in that there are different utilities for different services - electricity, oil and gas - and none as yet (in most cities) for district heating. The incentives for making such an overall optimization are thus smaller at the company level, though they are just as great at the national level. The absence of utilities with a self evident responsibility to promote district heating if it is to the National advantage *may therefore in itself be a disadvantage when it comes to introducing district heating.*

The problems at issue concerning the energy field are so important, that the relatively good administrational and legal tools available which have been available in Sweden in the past may not be good enough for the future. The introduction of a regional district heating scheme involves many local authorities, and though they can cooperate, it needs a plan at a national level to obtain the best results. For instance it would be detrimental to the national interest if, in the middle of a region suitable for district heating, some districts were left to deal with their heating loads in different ways. Hence even legislation which force consumers to take supplies from a district heatings scheme where this can be shown to be in the general interest and does not increase the cost of supplies to the individual consumer may be

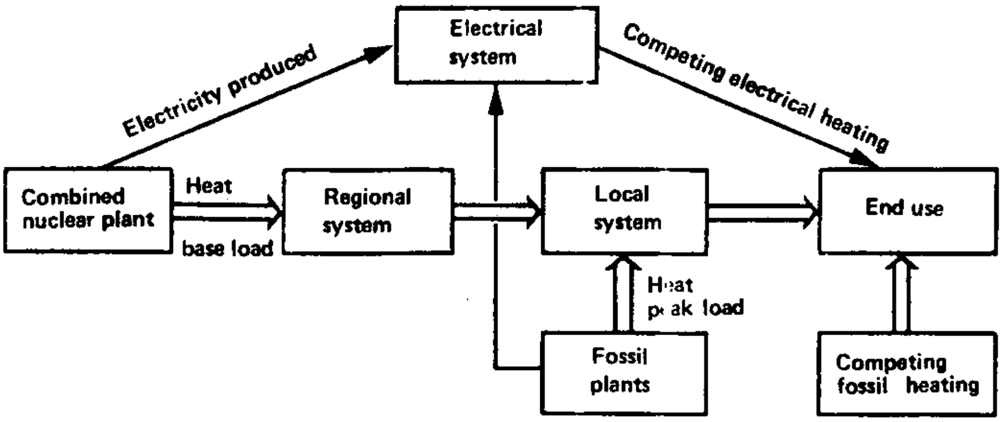


FIG. 17: Block representation of the district heating system optimization model.
All power on system plants (nuclear; fossil fuel; hydro & hydro storage) represented

necessary. Such legislation has now been prepared in Sweden, with special appeal clauses to protect consumers. I understand that also in Canada local government has some possibilities to influence these matters where new housing estates are concerned, but that the problem is more difficult regarding existing housing. However, most people have now accepted that there can be no freedom of choice concerning other public services such as electricity, sewage, and drinking water. If it can be shown to be in the national interest to have a wider energy plan with some legal teeth to back up the plan also for heat, would this be so very different?

It is thus my hope that those prepared to examine district heating, will do so with a few historical or psychological restraints as possible and really explore the vast possibilities this heating method provides with the modern technology now becoming available.

ACKNOWLEDGEMENT

Proposals mentioned in this article include ideas from many sources, including Allan Haag, Bengt Oknemark, proposer of the wet rock tunnels scheme, J. Sintorn, Sweden's "Grand Old Man" of district heating, and others. The overall proposals have been studied in an investigation (1,2,3) chaired by the author, in which the Swedish District Heating Association and Central Operation Authority were strongly represented.

LE RÉACTEUR DE CHAUFFAGE URBAIN THERMOS

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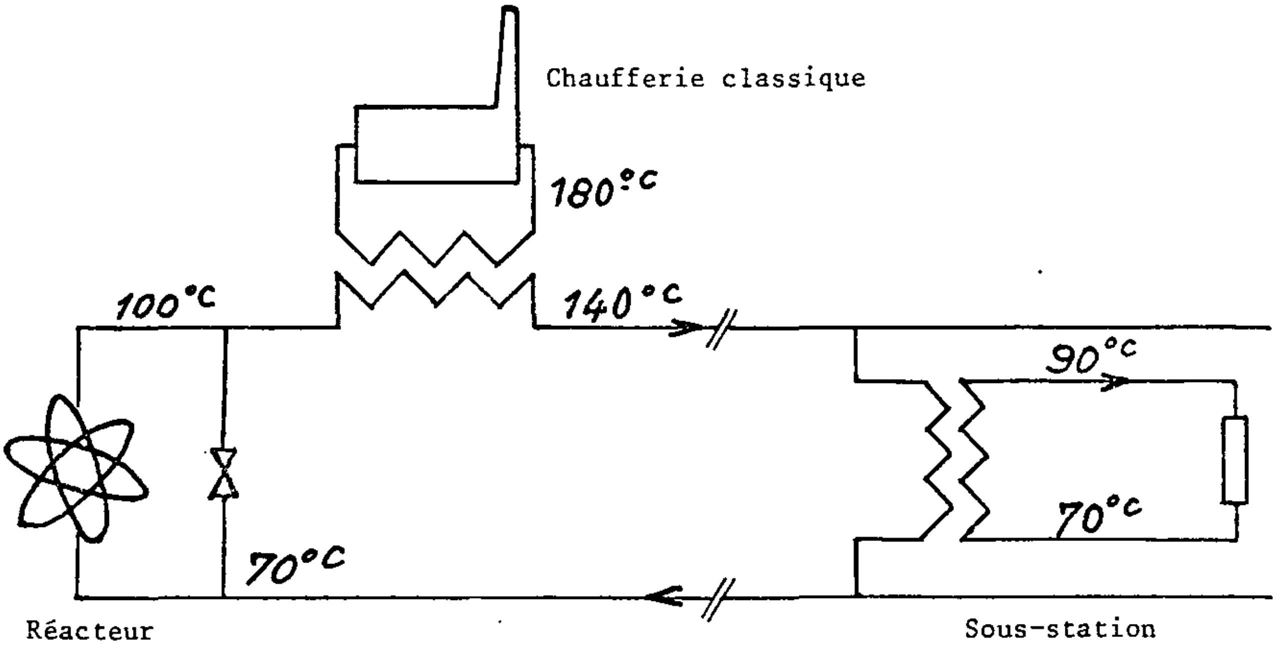
I. GENERALITES

L'idée de produire de l'eau chaude à des fins de chauffauge à l'aide d'un réacteur spécialisé d'une puissance d'environ 100 MW a déjà été présentée à plusieurs reprises /1, 2/.

Rappelons brièvement les principales étapes du raisonnement:

- la plupart des réseaux de chauffage urbain peuvent se contenter pour leurs besoins de "base", d'une eau à une température voisine de 100 °C,
- lors des pointes de demande d'énergie, cette eau qui dans le cas présent serait produite par un réacteur, pourrait être réchauffée jusqu'à 130 ou 140 °C par une installation conventionnelle, placée en aval du générateur nucléaire, selon le schéma I, et servant à la fois d'addpoint et de secours.



SCHEMA POSSIBLE DE CHAUFFAGE URBAIN

- les caractéristiques techniques d'un réacteur capable de fournir de l'eau à 100 °C peuvent être très différentes de celles des réacteurs électrogènes usuels.

La simplification qui peut être obtenue doit être mise à profit sur quatre plans:

- fiabilité (matériel soumis à des contraintes moins sévères),
- sûreté (probabilités d'accident plus faibles, système permettant de faire face à des accidents plus étendus),
- coût d'investissement (le gain sur la technologie mise en oeuvre doit compenser la perte due à l'effet de taille),
- coût d'exploitation (le système et la technologie correspondante exigent peu de surveillance, d'entretien et de renouvellement du matériel).
- la puissance du réacteur la plus intéressante à étudier est de l'ordre de 100 MW. Au delà, le marché français se rétrécit beaucoup. En deçà, l'effet de taille conduit à des réalisations probablement trop coûteuses au kW installé.
- *il faut donc concevoir un outil qui satisfasse aux deux critères suivants:*
  - acceptabilité par les autorités de sûreté et la population de sites très proches d'une ville (banlieue immédiate),
  - prix de revient de la thermie produite sur place inférieur à celui obtenu à partir d'une chaufferie au fuel placée au même endroit, ou à partir d'une centrale nucléaire mixte situé à 25 km.
- à la suite d'un vaste tour d'horizon des solutions techniques envisageables, le Commissariat à l'Energie Atomique a décidé d'approfondir les idées émises autour du concept de pile piscine. Il a en effet acquis une expérience très importante de la conception, de la construction et de l'exploitation de ce type de réacteur, édifié jusqu'ici uniquement à des fins de recherche mais qui peut être adapté à des fins nouvelles.

2. EXPERIENCE ACQUISE SUR LES REACTEURS DE RECHERCHE DU TYPE PISCINE

Le CEA dispose de cinq réacteurs de recherche du type piscine (x) sur lesquels nous pensons intéressant de donner quelques indications.

	Puissance	Lieu	Durée annuelle de fonctionnement	Disponibilité
TRITON	6,5	Fontenay aux Roses	8000 h	99,9 %
MELUSINE	8	Grenoble	5300 h	99,9 %
SILOE	35	Grenoble	5500 h	99 %
PEGASE	35	Cadarache	7500 h	99 %
OSIRIS	70	Saclay	6200 h	98 %

(x) L'un de ceux-ci, le réacteur PEGASE, a été définitivement arrêté fin 1975.

Ces statistiques sont des valeurs moyennes établies sur les années 1969 à 1974. La disponibilité indiquée tient compte des pannes dues au réacteur, et non pas de celles dues aux expériences qui y sont placées, ni des arrêts pour rechargement du combustible. Les indisponibilités sont dues essentiellement au contrôle commande. Les conséquences d'une chute de barre sont d'autant plus gênantes que le niveau de flux est plus élevé, du fait de l'empoisonnement Xénon qui risque ou non de s'établir.

Dans l'ensemble, on note un très bon fonctionnement des matériels, qu'il s'agisse des circuits ou des structures. La technologie eau, basse pression, est donc parfaitment maitrisée.

Le personnel d'exploitation est réduit malgré des servitudes considérables qu'entraîne l'expérimentation en pile. Les réacteurs les moins puissant fonctionnent la nuit avec une équipe de quart réduite à deux personnes. Après discussion approfondie avec les exploitants de ces réacteurs, il apparait qu'un réacteur de chauffage utilisant une technologie basse pression pourrait fonctionner avec un personnel réduit à 20 agents, à condition que lors des arrêts annuels d'une durée de 15 jours environ ce personnel puisse bénéficier d'un renfort important assuré par une Société de Service Extérieure compétente. C'est sur ces bases qu'ont été estimés les coûts d'exploitation.

3. LA SOLUTION RETENUE

La solution retenue présente un dessin original, inspiré par les nombreuses études faites au Commissariat sur des réacteurs divers, et pas seulement sur les réacteurs de recherche.

Dans l'état actuel des études, le réacteur se présente comme suit (voir Fig. 1).

Le coeur (I) est placé au centre d'une cuve (2) en acier inoxydable qui contient l'ensemble des composant du circuit primaire de refroidissement: quatre pompes (3) et quatre échangeurs (4). La température moyenne de l'eau de la cuve est de 110 °C.

Le contrôle du réacteur est réalisé par des croix absorbantes (5) actionnées par des mécanismes implantés dans une salle sèches (6), située au dessous de la cuve et accessible peu après l'arrêt du réacteur.

La cuve est surmontée d'une piscine (7), à température modérée (40 °C environ) qui permet de stocker les combustibles (8) déchargés précédemment pour les lassier se refroidir, et de réaliser sous eau l'ensemble des manutentions nécessaires à l'évacuation des combustibles irradiés (par immersion de châteaux de plomb).

La piscine est elle-même surmontée d'un hall (9) protégé des agressions d'origine externe par une dalle anti-missile (10) en béton. Ce hall permet de réaliser les manutentions nécessaires pendant la période d'arrêt prévue chaque année (out tous les deux ans) durant l'été. Il est entouré de locaux servant aux circuits annexes du réacteur (circuits d'épuration de l'eau, de ventilation, etc. ...) également protégés contre les éventuelles agressions extérieures. Le hall du réacteur constitue une enceinte étanche dont les fuites sont récupérées par les bâtiment adjacents puis filtrées.

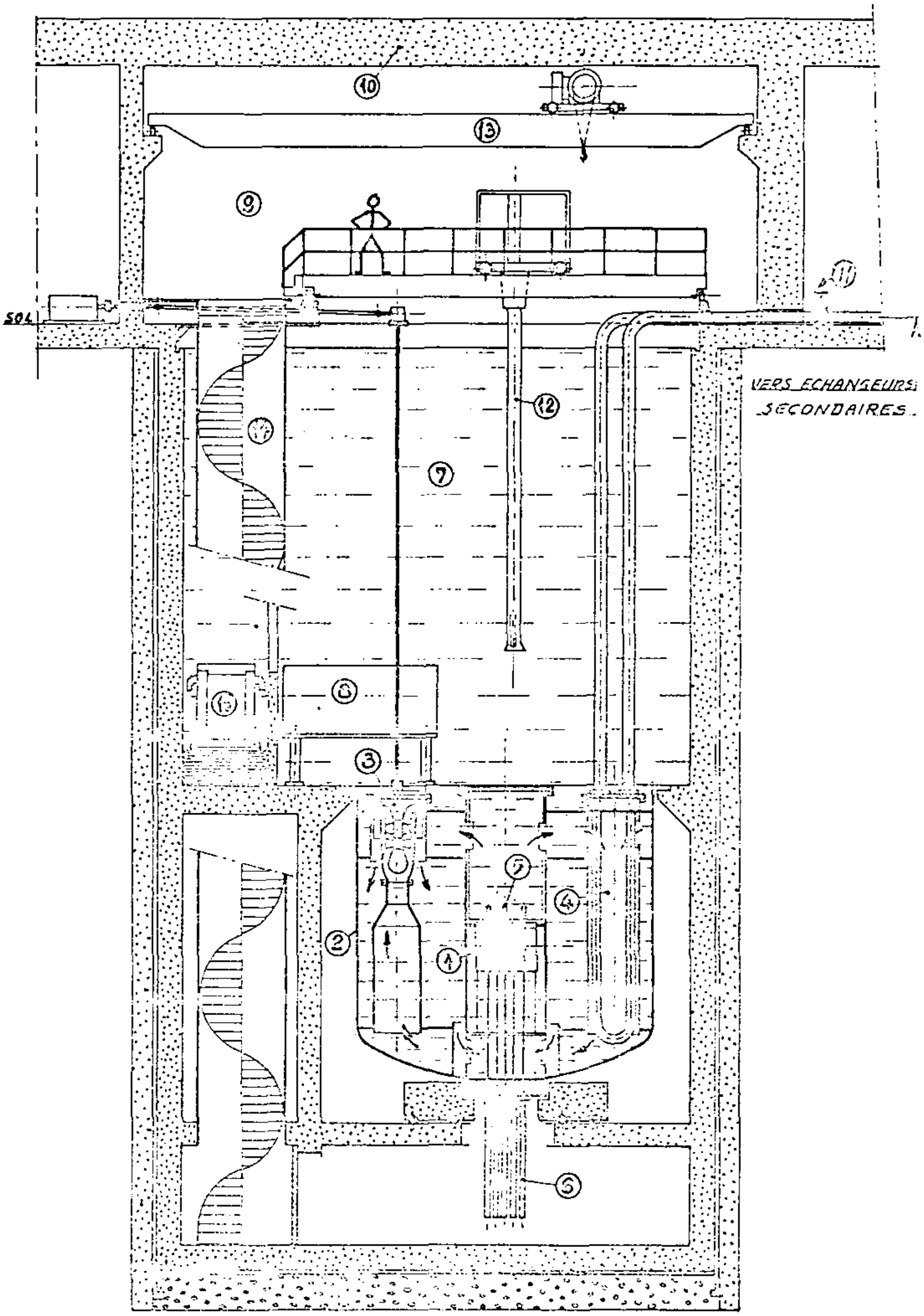


FIGURE 1

L'évacuation de la puissance vers le réseau s'effectue par l'intermédiaire d'un circuit d'eau déminéralisée (11), inactive, en surpression permanente par rapport au circuit primaire, lui-même à 4 ou 5 bars absolus durant le fonctionnement du réacteur, et à 2 bars (soit la pression statique due à la piscine avec laquelle il se met en communication) lorsque le réacteur et les pompes sont arrêtés.

Le tableau I indique les principales caractéristiques techniques du réacteur.

Puissance du réacteur	100 MW
Masse d'uranium	3,6 T
Enrichissement	3 %
Combustible	UO_2 gainé Zircaloy 4
Renouvellement du Coeur	par I/4 annuel ou par I/3 tous les 2 ans
Barres de contrôle	Croix en Hafnium
Nombre de barres	21 à 29
Nombre de moteurs de barres	6 à 8
Température circuit primaire entrée coeur	108 °C
sortie coeur	115 °C
Température circuit intermédiaire	
entrée coeur	85 °C
sortie coeur	106 °C
Température réseau entrée bâtiment	70 °C
sortie bâtiment	100 °C
Cuve hauteur	5,7 m
diamètre	6,4 m
épaisseur latérale	15 mm
Pression dans la cuve	4 à 5 bars
Piscine hauteur	10 m
diamètre	10 m
Nombre de boucles primaires et intermédiaires	4

TABLEAU I: Caractéristiques Générales

4. LES OPTIONS DE SURETE

Diverses options techniques ont été prises pour assurer une très grande sûreté du réacteur, lors d'accidents de mode commun our lors d'agressions du type sabotage. Les plus importantes sont les suivantes:

a- Combustible - Un combustible type PWR a oxyde d'uranium légèrement enrichi gainé de zircaloy a été choisi. Deux géométries sont étudiées en parallèle, la géométrie "grappe" type 17 x 17 et la géométrie "plaque". Ce combustible est bien connu, présente un effet Doppler et une tenue en température intéressants.

La puissance spécifique est limitée de manière à ce que l'oxyde ne dépasse pas une température de 1200 °C en fonctionnement normal. Il n'y a donc que très peu de dégagements de produits de fission.
Les ruptures de gaine ne sont pas admises. Dès détection, le réacteur est arrêté et le combustible défectueux remplacé.

b- Contrôle - Les barres de commande sont de type cruciforme, donc très robustes; elles assurent à elles seules le contrôle du réacteur (pas de poison soluble). Elles sont commandées par le dessous du réacteur.

c- Circuit primaire - Il est entièrement placé sous 10 mètres d'eau, dans une cuve en acier inoxydable qui reste inactive et qui peut être inspectée entièrement de l'extérieur lorsque le coeur est déchargé.

d- Piscine - La piscine contient 850 m^3 d'eau environ. Cette eau joue un rôle multiple:
- effet de filtre pour les produits de fission et particulièrement les iodes,
- effet de pressurisation minimum en cas d'arrêt de toutes les pompes,
- effet de volant thermique pour le refroidissement après du coeur (5 à 7 jours avant d'atteindre la température d'ébullition à la pression atmosphérique),
- effet de noyage du combustible en cas de rupture de la cuve.

e- Ventilation - Le hall pile, de dimensions réduites, est traité en enceinte étanche avec reprise de fuites. Deux circuits de ventilation indépendants sont installés. L'un, qui fonctionne en permanence sur filtres à iode, climatise le hall pile seul. L'autre, traite l'ensemble des autres locaux. En cas de détection d'activité, le débit d'extraction de ce circuit est réduit et passe sur filtres à iode.

f- Précautions particulières envisagées -
- interdiction d'entrée dans le hall pile réacteur en marche (chute des barres sur ouverture des portes du sas),
- injection d'un poison soluble dans l'eau, commandée manuellement depuis la salle de contrôle pour faire face à des évènements très peu probables tels que: coincement de plusieurs barres, non chute des barres, attaque de commando de saboteurs.
- minimisation des effluents liquides. Les résines ne seront pas régénérées mais remplacées après usage. L'enrobage des résines sur le site même du réacteur est envisagé avant évacuation. Les autres effluents liquides de faible activité et de faible volume, sont évacués par camion, une fois par an.

5. CONSEQUENCES DES ACCIDENTS IMAGINABLES

Une première analyse probabiliste des accidents a été conduite, après définition détaillée des circuits d'eau, des circuits de ventilation et de la plupart des composants importants.

Même en cas de fusion complète du coeur, accident dont on n'a pu réussir à imaginer les causes initiatives, la dose externe intégrée par la population avoisinante à 1000 m, avec un vent faible de I m/s et de mauvaises conditions de diffusion ne peut dépasser 100 mrems en 10 jours, la dose thyroide restant inférieure à 0,2 mrem.

Un accident ne peut avoir des conséquences radiologiques importantes que lorsque la fusion du coeur se conjugue avec une défaillance du confinement. La probabilité de tels évènements est très faible, inférieure à 10^{-8} par an. Ils ne peuvent résulter que d'agressions de mode commun hors dimensionnement, essentiellement un séisme d'intensité supérieur au séisme majoré de sécurité, en avion particulièrement lourd et rapide, non pris en compte dans l'étude de l'enceinte de protection, un sabotage systématique avec complicité de l'équipe de quart.

6. POINT ACTUEL

Un dossier d'options générales de sûreté a été remis en avril à l'Institut de Protection et de Sûreté Nucléaire du CEA.

Des estimations financières, fondées sur des consultations industrielles sont attendues pour la fin du mois de juin.

Les études économiques actuelles laissent bien augurer de la rentabilité de l'opération, mais il faut encore étaiyer l'ensemble des hypothèses adoptées sur les coûts d'investissement et de fonctionnement et examiner dans des cas d'implantation réels, les éventuelles modifications à apporter aux réseaux de chauffage existants et les coûts correspondants.

Une douzaine de sites ont déjà été répertoriés. Tous présentent des aspects particuliers. Le premier site n'est pas encore défini. S'il peut l'être dans les six mois à venir, un rapport préliminaire de sûreté pourrait être déposé à la fin de l'année, ce qui correspond à une mise en service industriel en 1980.

L'avenir de ce type de réacteur dépend sans doute du dégré d'acceptation du public et des collectivités locales.

Si on compare le réacteur THERMOS à une chaufferie conventionnele, il convient naturellement de faire remarquer au public:

- la suppression de toute pollution atmosphérique,
- les dimensions plus réduites des bâtiments,
- le gain considérable sur le transport du combustible (2 camions par an seulement) et les encombrements de la circulation qui en résultent,
- la meilleure garantie d'approvisionnement du combustible, à un prix moins sensible aux variations économiques conjoncturelles.

Si le public assimile le réacteur à une Centrale Electronucléaire, il conviendra de renforcer l'argumentation précédente par les remarques globales suivantes:

- la puissance installée est cent fois plus faible,
- les rejets thermique inutilisés ne dépassent guère 1 % de la puissance installée. Ils sont faits directement dans l'atmosphère,
- la consommation d'eau est nulle, les rejets d'effluents dans le milieu ambiant sont nuls ou trop faibles pour être decelés,
- les dimensions modestes des bâtiments le font passer inaperçu. Il n'est relié aux usagers que par des canalisations souterraines.

On devrait pouvoir faire accréditer l'opinion selon laquelle il s'agit bien là d'une autre énergie nucléaire.

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B 3

SOME TECHNICAL AND ECONOMICAL ASPECTS OF THE NUCLEAR HEAT POWER PLANT AND THE HEAT TRANSPORT SYSTEM

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1. INTRODUCTION

The combined production of electricity and heat by dual-purpose power plants is a widely applied practice for the energy supply of the process industry and communities in Finland. Generally speaking, the use of this method will be extended whenever applicable, because, among others its energy efficiencies is high as compared with the alternative energy supply forms, and because of its decreasing and controllable impact on the environment. On the other hand, a considerable part of the future electrical energy demand will be covered by nuclear energy. As this being the situation, it is quite natural that in Finland the district-heating system based on nuclear dual-purpose plants has been considered as one of the most important energy supply alternatives in the near future. In particular, several investigations concerning the future energy supply of the Helsinki Area have been carried out and - according to our present know-how - it could be concluded that the combined power and district heat supply based on nuclear energy is the most economical alternative for Helsinki Area, as compared to oil, natural gas and coal energy provided that moderate heat transport distances are used. In addition, the use of nuclear energy offers other advantages like decreasing the air pollution of the region.

The forecasts of the growth of power and heat demand of the Helsinki Metropolitan Area (HMA) are given in Fig. 1 and Fig. 2. The present electric power capacity is 630 MW, and the present district heat demand is 1920 MW. In Fig. 1 and 2 the future construction plans are given with the nuclear heat power plants (NHPP) suggested.

2. PROBLEMS

If the planned nuclear plant is based on a light-water reactor, and if the heat transport system for district heating is of the conventional type, no basical obstacles should be met in the realization of the system. However,

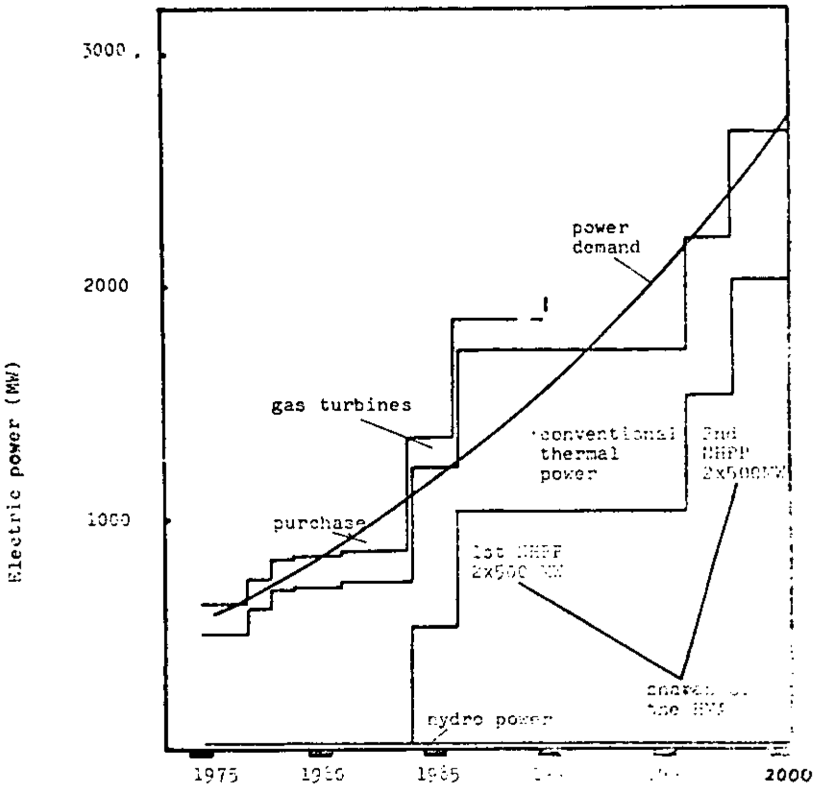

FIG. 1: The growth of electricity demand and the construction plan of electric power plants for HMA

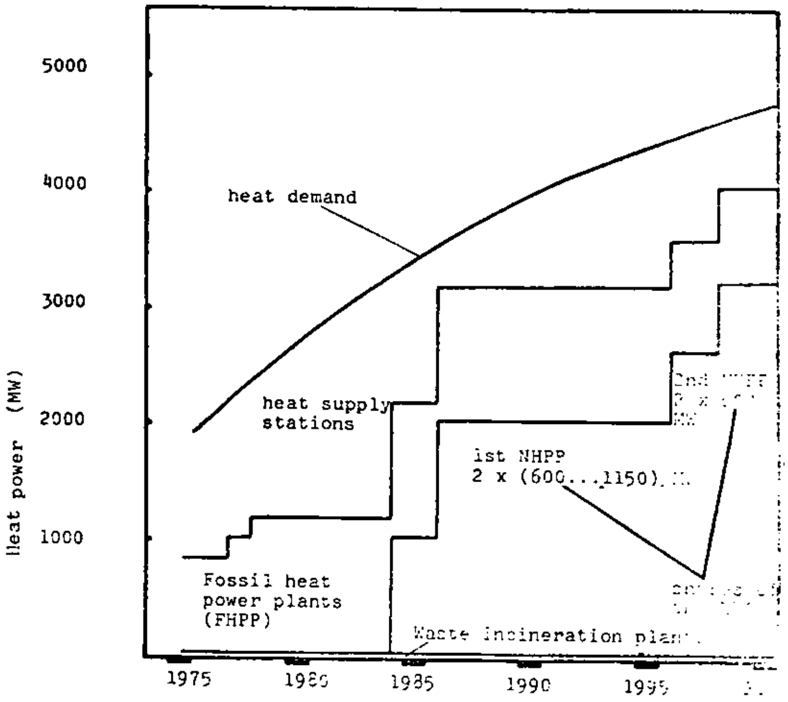

FIG. 2: The growth of heat demand and the plan of covering the demand for HMA

the high energy flow in the system throughout the transport distance from one side and the huge investments needed from the other cause many important social and economical questions to rise. Some of the technical questions, which have to be investigated - apart from the siting problem - are the following:

- The optimal power and heat capacity of the plant and the optimal timing of the projects.
- The dimensions of the heat transport system, the determination of the temperature levels of the heat transport medium, the specification of the transport and distribution systems' technology etc.
- The coupling of the nuclear heat transport system to the existing district heating transport and distribution systems, together with the determination of the area which should be heated by nuclear energy and the time schedule for extension of the distribution system, etc.
- The optimal turbine construction.
- The parallel operation of the plant with the whole electrical power grid and with the district heating system.
- Also the reserve electrical power, and reserve and peak heat power questions ...

Further, each of the subjects mentioned above can be divided into smaller subproblems in a natural way. On the other hand all these subjects are strongly interdependent. This means that the subjects mentioned form together a vast global problem. To treat the problem in a proper way, fairly sophisticated methods - if available - are also needed.

3. TOOLS

To solve the optimization and suboptimization problems included, to calculate the costs of various system alternatives and, in general, to create analytical methods for a better understanding of the whole problem and its parts, we have been developing several energy models to simulate the system. Some of the work we are doing has been reported recently /1, 2/.

In Ref. /1/ an energy model is described. The model performs two main functions; first it optimizes the dimensions of the heat transport system when the cost parameters of the selected transport technology are given. Second, it optimizes the operation of electrical power generation and heat production in the local energy system. An iteration technique links these two processes together.

In Ref. /2/, a more ambitious work is reported. The work is in progress at Ab Atomenergie in Sweden with participation from other organisations, among those Technical Research Centre of Finland. This model will consist of submodels for the electrical system, turbine, heat transport system, and the distribution and utilization models, and a general optimization routine as a problem "co-ordinator".

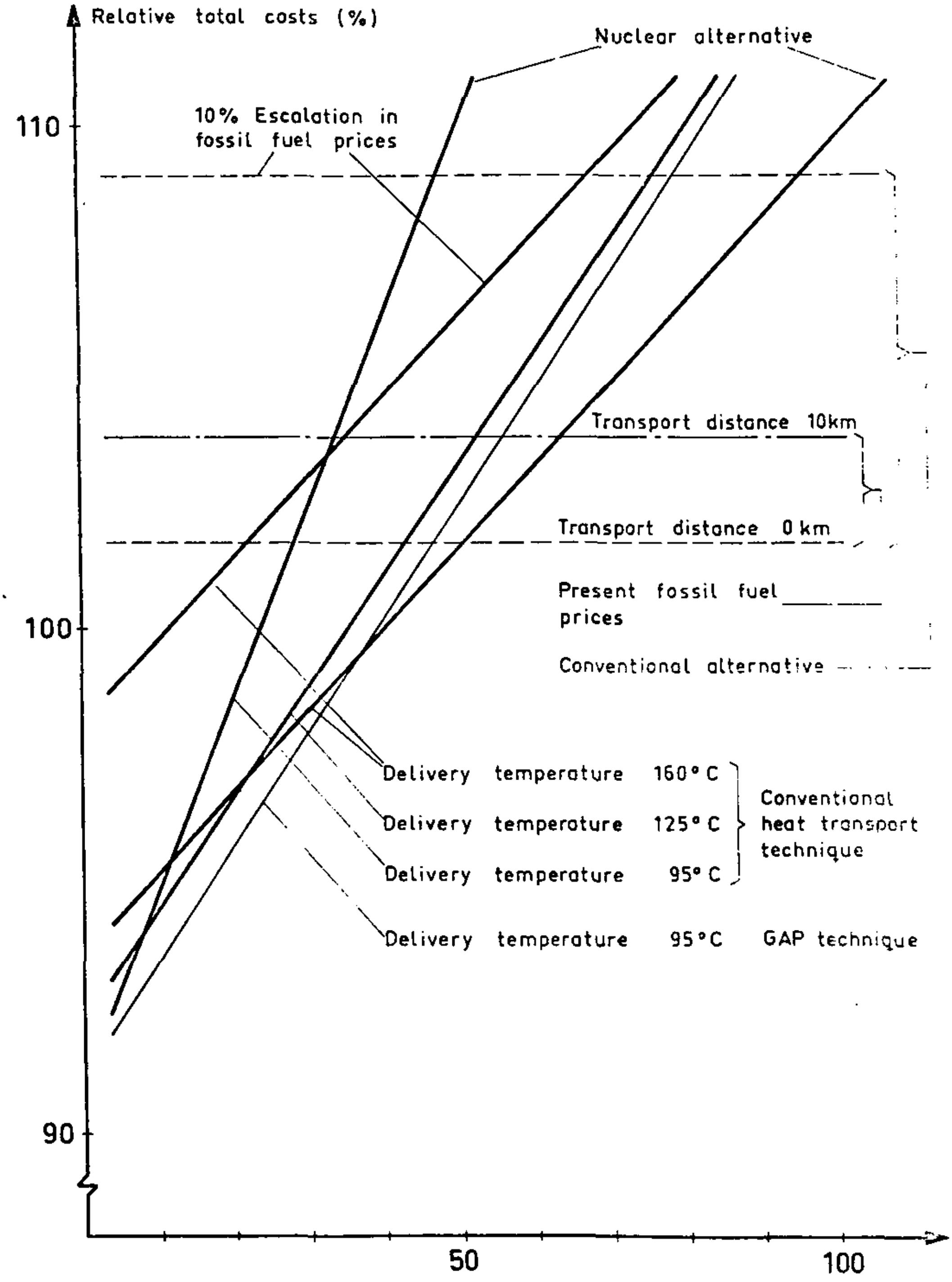

FIG. 3: The economy of NHPP as a function of the heat transport distance

4. RESULTS

In Fig. 3 some preliminary results are given concerning the economy of the nuclear heat power plant (NHPP), as a function of the heat transport distance. The basic case presented here, included two NHPP units producing 1000 MW and 500 MW heat and 500 MW heat and 500 MW and 520 MW electricity respectively. These units are to be start operation during the year 1984 and 1988. The heat transport distance was assumed to be 40 km and the delivery temperature 160 °C. The heat transport system consists of steel pipes isolated and laid in concrete culverts. For the basic case the total cost was 7000 million Fmk (≈1800 million US dollars). This amount represents the investment cost of all the new plants (producing electricity and/or heat) in the system described in Fig.1 and 2, and all the regional heat transport systems with accessories, constructed in the period 1984 ... 2000 plus all the operating cost during the same period, all these discounted to the year 1984. The rate of interest was assumed to be 10 %.

As a summary of Fig. 3, the following observations can be made:

- A change of 10 km in the heat transport distance will cause a change of about 2 % in the total cost respectively.
- For transport distances over 25 km it is more economical to use the higher delivery temperature (160 °C). The low temperature solution (95 °C) - provided that the same heat transport technique is applied and the same heat power is produced - is economically attractive only for very short transport distances. According to the cost data we have at the moment, the most economical alternative for transport distances below 37 km seems to be the low temperature system with GAP (Glassfibre Armoured Plastic) transport technology.
- The conventional alternative is a system where three coal-fired plants, each producing 330 MW electricity and 540 MW heat, were thought to be built in the years 1984, 1986 and 1989, respectively. This alternative was considered as one of the most economical fossil combinations. The break-even point of the conventional alternative with the nuclear one (160 °C delivery temperature) occurs at the heat transport distances of 50 km or more, depending on the fuel prices and the investment cost assumed.

The division of the cost between electricity and heat is a rather arbitrary task and depends on many factors, which are not discussed here. However, the combined production will lead in any case to more economical electricity and heat energy prices than the separate production.

The main alternative of constructing the heat transport system are

- a conventional culvert alternative,
- a tunnel alternative.

Costwise these alternatives are quite near each other. The total time needed for construction the heat transport system over 40...50 km distance for the tunnel alternative is in the range of 7...9 years and the corresponding time for the concrete culvert alternative is 6...9 years.

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SOME ASPECTS OF DESALINATION BY NUCLEAR MEANS

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At first sight, one might think that the two main sub-systems in a nuclear desalination system may be considered independently: the nuclear boiler, on the one hand, and the distillation process evaporator, on the other.

Yet the quality of the steam handled in a desalination plant is a critical factor: at best, i.e. when the sea-water intake is acid treated, the input required is saturated steam, at no more than 125 to 130 °C, steam pressure being then of 2 to 2.5 bars. These are not the characteristics of the steam generated by a nuclear boiler, in the present state of art, but are nonetheless mandatory, owing to the scaling that results at temperatures above those indicated, despite prior treatments, and which can seriously affect the operation of desalination plants.

As things stand today, the steam output of nuclear boilers is incompatible with the input requirements of existing evaporators. Direct coupling of the two is excluded. The steam must be expanded. This constraint can however be made to shed some profit, by associating power generation with desalination.

We note, incidentally, that the simplified THERMOS reactor, designed by TECHNICATOME essentially for collective central heating systems, could perhaps change this picture, whereas on the evaporation side, there may be some hope of being able to raise input steam temperatures: tests towards this end, run in the USA several years ago, involved elimination of the calcium and magnesium contents of the sea-water intake, but, unfortunately, by input processing that was far too expensive.

So, pending the appearance of small reactors delivering cheap steam of a quality directly accepted by the distillation evaporators, there is a coupling problem located at the turbine interface between these two main sections of desalination plants.

Before considering the flow-charts that can be applied to solve the problem, we should first enquire into the power requirements of a desalination plant.

Optimisation is a key-word in desalination plant design: power consumption for a given fresh water output will vary in inverse proportion to capital investments, so that the plant achieving the best product output to power input ratio, will also be the most expensive. This ratio, in desalination, is usually expressed in tonnes of fresh water per tonne of steam condensed in the reheater. Twenty years ago, the figure was 3 to 4. Today, it ranges from 8 to 10, and a rising tendency persists, owing to the premium on power. A ratio of 12 to 13 is currently demanded of certain plants.

Let us take a sufficiently representative, modern plant as an example. It will have an input/output ratio of 10, will employ sulfuric acid processing of sea-water intake, and will have an output capacity of 100,000 cubic meters per day (a very large plant, in fact). Its power consumption will be:

Main: - 420 tonnes per hour of saturated steam at 125 °C, condensed in the evaporator's reheaters.

Auxiliary: - 10 to 15 tonnes per hour of steam at 12 to 20 bars to exhaust the process through ejectors.
- About 15 MWe for pumping.

For a ratio of 10, this gives us about 50,000 kilo-calories per tonne of product, requiring 180 MWth installed power for the stated capacity of 100,000 cubic meters per day.

This figure helps us to situate the economics of desalination with a nuclear primary heat source, and its liminations.

Two alternatives may be envisaged today:

1. Small nuclear boilers

These would be equivalent to the pressurised reactors developed by TECHNICATOME in France. They offer the advantage of associating small to intermediate electrical power generation with high fresh water outputs, and seem to be ideal for arid regions lacking in industrial development, where water is vital for the improvement of living conditions, and the development of tourism and natural resources (oil, minerals, beef).

Unfortunately, the cost of the fresh water excludes its use for the development of crop-agriculture.

The water output-commercial power output balance can be rendered adjustable within appreciable limits, by using either a back-pressure turbine and a bypass, or a back-pressure and a condensation turbine in parallel.

In this latter respect, a recent TECHNICATOME study furnishes the following figures, which are by no means restrictive:

- a CAS 420 MWth reactor and a ratio 10 plant:
  50,000 cbm water per day, 85 MWe surplus power, or
  100,000 cbm water per day, 50 MWe surplus power

- a CAS 1100 MWth reactor and a ratio 10 plant:
  100,000 cbm water per day, 255 MWe surplus power, or
  300,000 cbm water per day, 137 MWe surplus power

The price of the water can be arbitrarily set, within certain limits, and the price of the power determined as a result, or vice-versa, depending on local conditions and policies, which may give preference to specific forms of development.

2. Large power reactors

Power generation would in this case be preponderant, and the price of water more than likely determined after setting the price of power: the water plant would amortise its investments independently, from water sale revenues, while the cost of the power supplied to desalination would be calculated on the basis of the difference in revenues from power generation, due to the proportion supplied to the plant, which would be compensated by suitably adjusting the water price.

The steam for desalination could a) be tapped from the LP stages of a condensation turbine, b) taken from an auxiliary back-pressure turbine, or c) obtained by a combination of these two means.

Use of all the steam generated for desalination purposes, however, as in the Bolsa Island project of several years ago (one or several back-pressure turbines) no longer seems to be a realistic concept: the design results in an excessive water output, too much for a single area (by reason of its cost, which excludes agricultural use), and entails the risks inherent in making such a volume of water production dependent on the continuous operation of a single prime mover.

To give an idea of the magnitudes involved: with a 1,100 MWth reactor and ratio 10 plant, total steam use as indicated above would produce more than a million cubic meters of water per day, and power generation would be no more than 250 MWe.

It is more reasonable to accept a reduction of 10 to 20 % in power generation, which, in our example, would give us a water output of 150,000 to 300,000 cbm/day.

In conclusion, we may note that several countries are showing renewed interest in "nuclear" desalination, by the means outlined here. It must however be borne in mind, that customers now accustomed to the concept of enhanced reliability of supply by the sub-division of desalination plants into several identical processes in parallel, often totally independent (i.e. each including its own boiler), are bound to be extremely demanding, concerning the realiability of a single, nuclear prime mover supplying all the steam used by a plant in total.

WATER DESALINATION PLANT AS A COMPLEMENTARY PART FOR A NUCLEAR DISTRICT HEATING SYSTEM

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The economical and environmental advantages of nuclear heat power plants (NHPP) have been emphasized in numerous investigations. A multi-purpose nuclear power plant (MPNPP) producing electricity, heat for district heating, and fresh water is a natural extension of nuclear heat power plants (NHPP), (Fig. 1 b) in case a need for fresh water exists. In addition to the economical and environmental advantages of such three-product plant resulting from the saving in the total capital cost, the consumption of less energy and the use of clean source of energy, the MPNPP has attractive technical advantages.

1. TECHNICAL ASPECTS

The desalination unit could be connected in parallel (Fig. 1 c) or in series (Fig. 1 d) with the district heating system. In the first case, the same steam bleeded for district heating could be used as a source of heat in the MSF (multi stage flash) desalination unit. In this case steam distribution between the district heating unit and the desalination unit should be optimized in such a way that more steam is led to the desalination unit when the district heat demand decreases and vice versa.

In the case of Fig. 1 d, the desalination unit is connected in series with district heating system and the return hot water is led to a NAVE (nord aqua vacuum evaportator) unit where its relative low-grade heat is used in fresh water production. When the district heat demand decreases, the fresh water production could be increased, within certain limits that are to be optimized.

The desalination unit could be also connected to the NHPP (nuclear heat power plant) in such a way that fresh water production is independent on the district heat demand. In this case, a NAVE unit could be connected to the NHPP in the same way it is connected to a nuclear power plant (NPP), Fig. 2.

As the NAVE unit is situated at the consumption centre in the case of a connection in series, the MSF unit could be also situated at the consumption

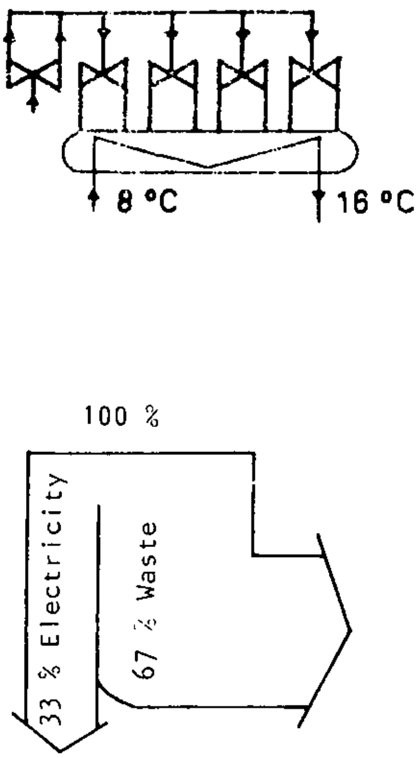

FIG. 1a: Nuclear power plant

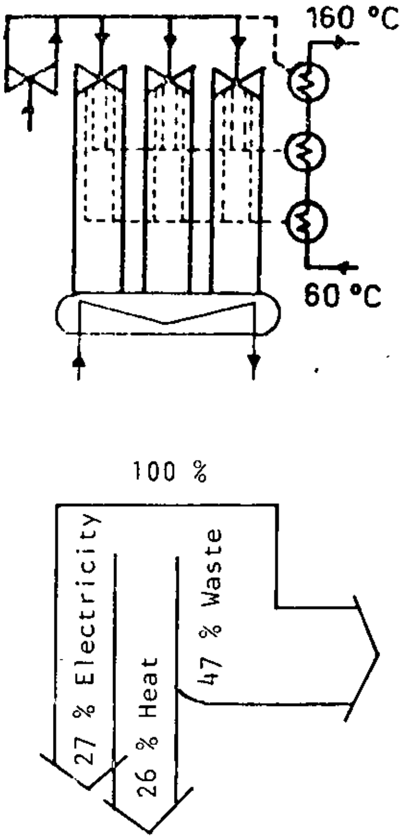

FIG. 1 b: Nuclear heat power plant

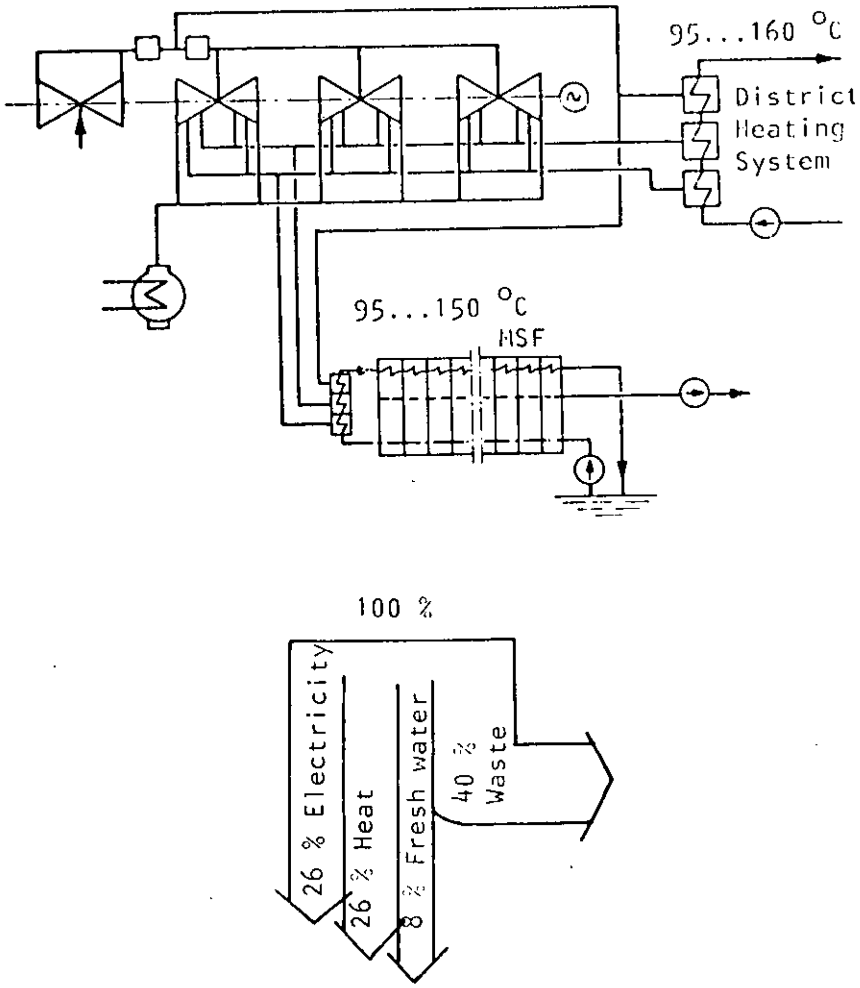

FIG. 1c: Multipurpose nuclear power plant with desalination unit connected in parallel

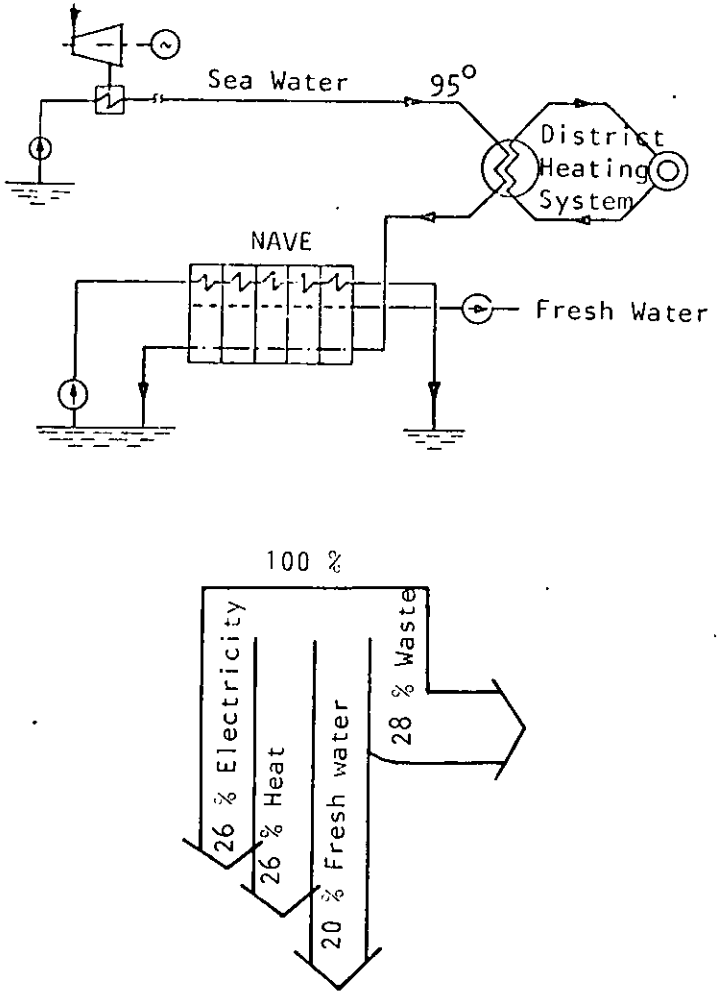

FIG. 1d: Multipurpose nuclear power plant with desalination unit connected in series

centre in the case of a parallel connection (Fig. 3) In this case liquid-to-liquid heat exchangers are to be used at the desalination unit.

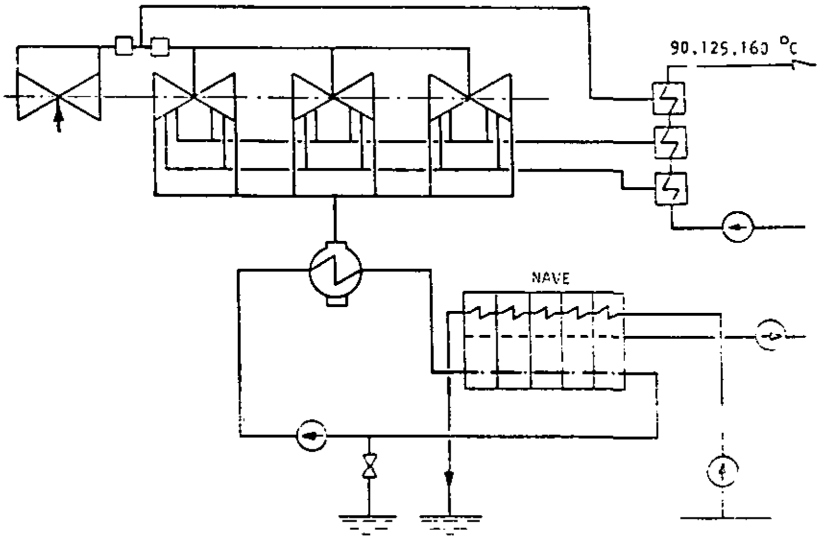

FIG. 2: A NAVE desalination unit connected to a NHPP

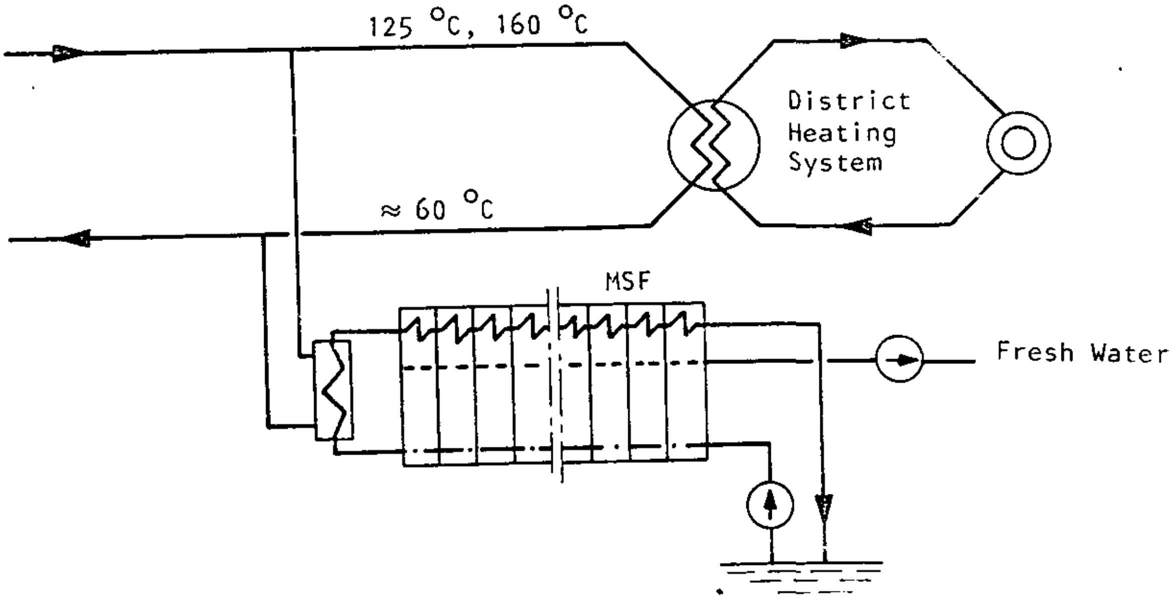

FIG. 3: MSF desalination unit connected in parallel to an NHPP and situated near the consumption centre

In case that the heat demand and/or the fresh water demand are relatively high, the extraction turbine could be replaced in Fig. 1c and 1d by a back-pressure turbine. An example of such connection is shown in Fig. 4.

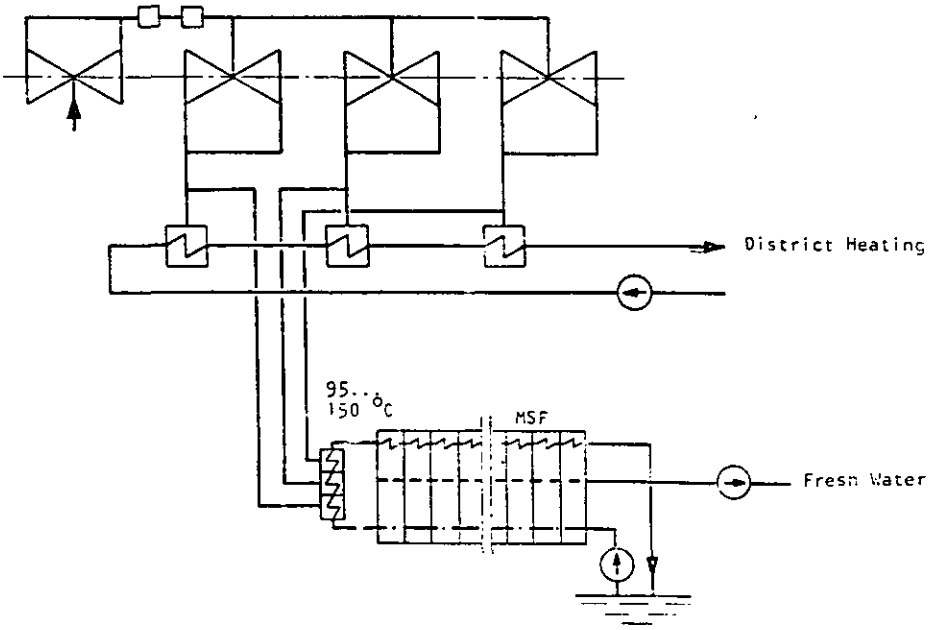

FIG. 4: MSF desalination unit connected to an NHPP with a back-pressure turbine

2. ECONOMICAL ASPECTS

In order to have an accurate idea about the economy of an MPNPP producing electricity, heat and fresh water, it is necessary to consider it as a producing unit in electric, heat and fresh water systems. As an energy model, on the scale of a locality, was available, it was thought to expand that model to comprise fresh water optimization. A simplified representation of the model built is shown in Fig. 5. The rectangles indicate the producing plants, the circles, the end products and the rhombi, some additional systems like heat and fresh water transport systems.

The cost of fresh water production could be estimated from the formula:

$$c_T = c_{in} + c_{ru} + c_{tr} + \Delta c_e + \Delta c_h$$

where

c_{in}	investiment cost of the desalination plant
c_{ru}	running cost including energy cost, operating cost and water purification cost
c_{tr}	transport and stocking cost
Δc_e	cost of electricity that might be lost in view of fresh water production
Δc_h	cost of heat power that might be lost in view of fresh water production

In case of building the desalination unit the nuclear power plant, the possibility of using the heat transport system for fresh water transportation was also examined.

Results of some preliminary runs for a system, which might be of interest in Helsinki area are shown in Fig. 6. The MSF unit considered here is connected in parallel with NHPP and situated at the plant (Fig. 1 c), where as the NAVE

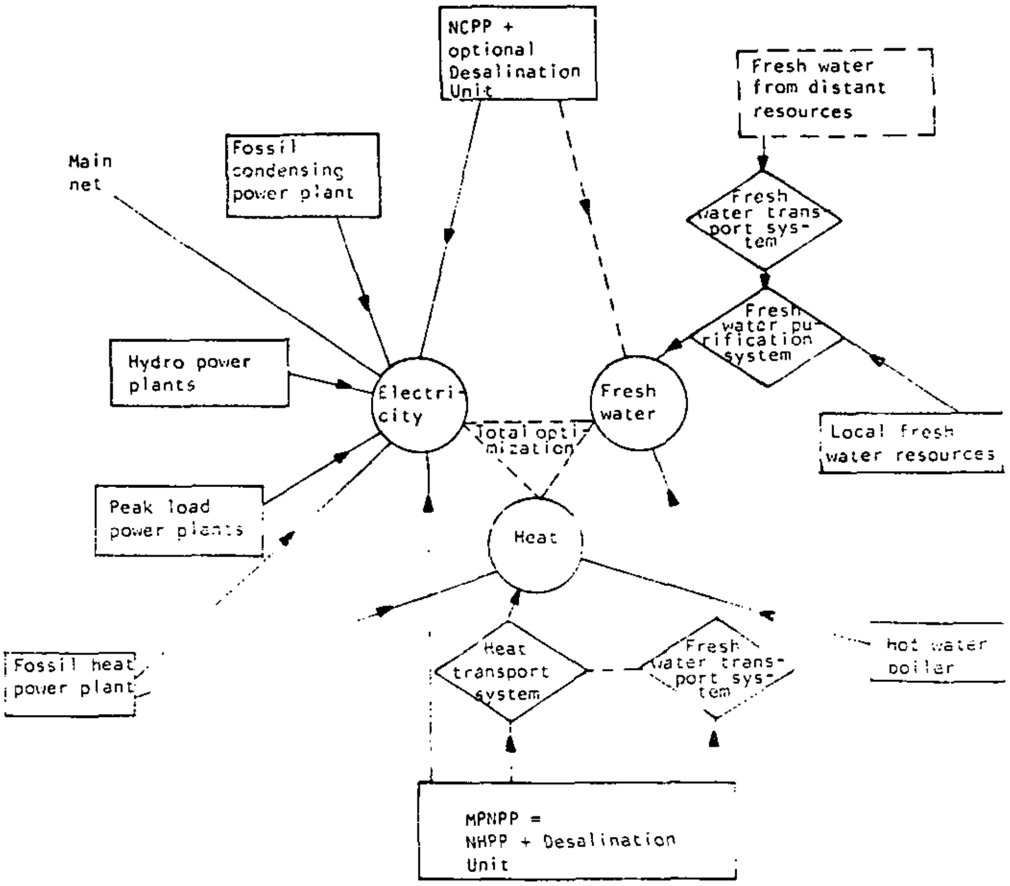

FIG. 5: Simplified representation of electricity heat and fresh water optimization model

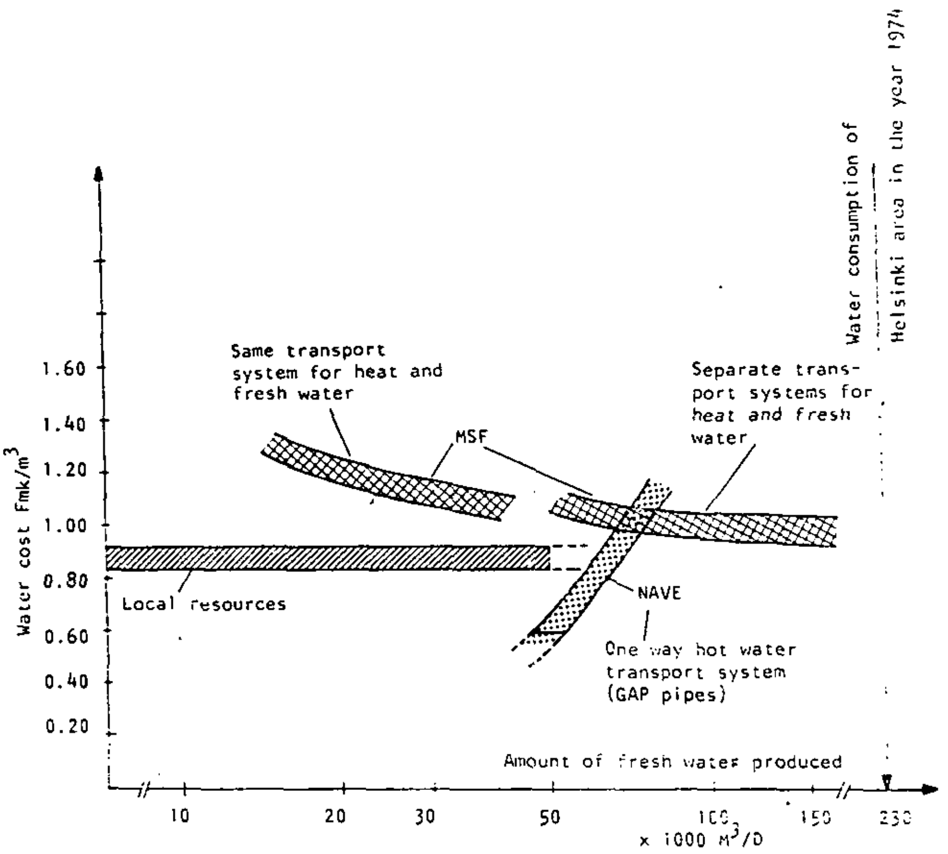

FIG. 6: Cost of water produced by an MPNPP

unit considered is connected in series with the NHPP and situated near the centre of consumption. In the case considered two MPNPP are to be constructed in the years 1984 and 1988. Each plant produces ≃ 1050 MW electricity and 1000 MW heat. The fresh water production was that optimized by the model. The corresponding optimum water costs were then calculated.

For a NAVE desalination unit there exists a production limit corresponding to the current district heat demand. Beyond this limit water cost increases as a result of using high-grade heat in the desalination unit in addition to that priceless heat flowing out of the district heating system. For the example of Helsinki, both the methods considered here produce water with costs competitive with the cost of water obtained from local resources. The maximum capacity of the local resources is about 180,000 m^3/D representing 80 % of the fresh water consumption of Helsinki area. The estimated cost of water obtained from distant resources is remarkably higher than the cost range given in Fig. 6.

THE USE OF THERMAL WASTES FROM NUCLEAR POWER PLANTS

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For just under four years the Commissariat à l'Energie Atomique, as part of its Programs of General Interest, has been interested in the use of thermal wastes from industrial installations, particularly from nuclear power plants. These investigations, which were initiated before the so-called "energy crisis", were originally aimed at the recovery of heat already produced from primary fuels (fossil and nuclear); use of this heat led simultaneously to lower fuel consumption and atmospheric pollution.

Owing to the prices of oil and fuels in general at the time, the use of these calories in economic conditions proved a difficult task. The sudden increase in these prices has radically changed the competitivity aspect.

In order to examine the possibilities of using what we call, for the sake of clarity, "lost calories", we formed a study group in 1972 with representatives of EDF and the research services of the Ministry of Agriculture.

IN WHAT MANNER AND FORM DO THERMAL WASTES FROM NUCLEAR POWER PLANTS OCCUR?

For condensers which are cooled in open circuit with river or sea water, power plant optimization computations led the EDF to set the difference between water discharge and intake temperature to about 10 °C. We state that the discharge temperature is T + 10 °C, T being the temperature of the river. When the river can no longer accomodate new thermal wastes, as is becoming increasingly clear for most of our rivers in France, the power plant is equipped with cooling towers, and an empirical formula gives an estimate of the hot water intake temperature in the cooling towers at T + 23 °C, where F is the river water temperature.

Geothermal waters and industrial discharge wastes do occur at temperatures exceeding T + 23 °C. The recovery processes discussed in this paper may be employed once these wastes have been cooled by an initial use, such as in the case of urban heating by geothermal water.

1 USE OF WATER AT T + 10 °C

1.1 Heating of Outdoor Soils

The Cadarache Nuclear Research Center is equipped with two light water type nuclear reactors (land prototype of submarine engines), an agricultural-forestry site covering about ten hectares, and appropriate scientific and technical support: radioecology service, heat and mechanics department.

Heating tests were performed with reactor cooling water. The temperature of the water reaching the test plots was adjusted to about 10 °C above the Durance River water temperature.

Two heat distribution methods have been tested for these plots:

(a) Open circuit irrigation (ditch, sprinklers, perforated pipes).
(b) Circulation through pipes buried in closed circuit.

The experimental program, which entered its operational phase in November 1974, initially deals with two main subjects: forestry and open field farming.

1.1.1 Forestry

Open circuit irrigation is employed here, with gutters and sprinklers potentially offering the best possibilities. In effect, the means employed are highly rustic and the water is employed throughout the year, especially in the hot season, during which discharge into the rivers is most unfavourable. Prevailing economic conditions also favour increased production of wood, of which the trade balance in France is in constant deficit.

The forestry program deals mainly with conifers and deciduous trees destined for industry and affore station.

1.1.2 Open Field Farming

Closed circuit circulation heating is employed in rustic pipes buried at depths and intervals easily adaptable to the various types of traditional industrial or market-garden crops.

The first results obtained at Cadarache were the following:

- despite the sharp frosts of March 1975 (-15 °C at the ground), the crops did not suffer, and the gain in precocity achieved in an asparagus plantation was two months, and three weeks for strawberry plants, for which the yields were three to four times above normal,

- forcing of new potatoes was effected under plastic mulching,

- the adaptation of heat-requiring priority industrial crops (soya, late varieties of corn) to our climate is proceeding well. With respect to soya, the heated plot yielded 37 quintals per hectare as compared with 25 quintals from the unheated reference plot.

This first portion of experimentation confirms the definite value of these heating techniques in the areas of farming and forestry. The scope for applications is vast and requires neither high investment outlay, as in the case of hothouses, nor an upheaval in conventional open field farming techniques.

It is important to realize the extent of the areas which can be heated in th this way. For example, a 1000 MWe nuclear power plant which releases 45 m^3/second, or 160,000 m^3/hour at T + 10, can provide potential for equipping 1000 hectares with buried pipes. Obviously, the overall cost of the system must be carefully examined for each type of product.

1.2 Pisciculture

Water heated to T + 10°C can be employed in pisciculture. In effect, the growth of certain aquatic organisms is likely to be accelerated if they are maintained in warmer water than that in which they normally live. Moreover, for animals which spend the winter months in a state of physiological rest, maintenance in warm water will result in prolonging their growth possibilities throughout the year.

The species selected for breeding must satisfy a three-fold requirement. It must be able to withstand warm water temperatures (up to 30 °C at least), it must be of national economic value, or at least regional value as a source of food.

For the time being our choice has fallen on the eel, which represents a significant export market (at least 5000 tons in 1971).

The experiment was begun in autumn 1974. The experimental system consisted of two identical 17 m^3 tanks. The warm tank water was kept permanently at 10 °C above that of the reference tank, in order to simulate the waste conditions of a power plant. 36 kg of eels weighing about 30 g (1200 individuals) were introduced into each tank.

After one year, the biomass increase was observed to be substantially higher in the warm tank than in the reference tank. Some eels reached a weight of 800 g, whereas the reference eels weighed no more than 150 g. Furthermore, the former were in excellent health.

Together with this, the EDF, with the assistance of the CTGREFF (Centre Technique du Gênie Rural et des Eaux et Forêts) is organizing a series of experiments in sea water at Martigues and Bordeaux Ambès.

1.3 Hothouse Heating (with auxiliary heating by heat pumps)

The heat pump is a thermodynamic machine designed to transfer calories by cooling a warm water source, to a warmer secondary circuit which is heated by passage through the heat pump.

In mechanical terms, a heat pump is a refrigerating machine of which the cooling coil extends into the warm water, from which the heat is to be extracted, and the rear radiator heats a water circuit.

The temperature difference between the warm source and the hot circuit must be as low as possible to increase the pump's performance factor: in good conditions, the energy savings realized thanks to the heat pump can reach a factor of 5 in relation to heating by Joule effect. Moreover, any temperature drop in the heat exchangers, any unused temperature difference, corresponds to a thermodynamic irreversibility and hence to a waste of energy. Consequently, in order to improve efficiency, the evaporators and heat exchangers of the machine must be carefully designed.

As the warm source is at T + 10 °C or 15 °C approximately in the ground water tables, the problem is posed as follows: What is the minimum temperature above T + 10 °C for water used to heat a hothouse with acceptable results for a given crop?

An experimental installation was built in Grenoble in winter 1973/1974 to solve this problem.

1.3.1 Grenoble hothouse (250 m^2 pilot hothouse)

The lowering of the temperature of the water used to heat the hothouse implies an increase in heat exchange surface and determination of the best possible "coupling" between the heat source and the heated object.

This was achieved, thanks to the suggestion of a hothouse specialist, by causing the heating water to flow at very low speed and under very low pressure inside double-wall polyethylene mulching laid directly on the soil. During the first winter, this provided a heat exchange surface of 52 % of the cultivated area, and excellent coupling with the heated object, namely, the plant and its root ball. In these conditions, a temperature of +9 °C was maintained in the hothouse with an outside temperature of -11 °C and water at 33 °C only.

Last winter, various technological expedients led to a rise in the ratio of heat exchange surface to cultivated area to over 80 %, without harming the crop density, since this enabled the production of 20.8 lettuces per square meter. This made it possible to lower the heating water temperature even more and showed that the following crops were feasible:

- lettuces with water at 18 - 20 °C,
- tomatoes with water at 25 - 28 °C,
- cucumbers with water at 33 - 35 °C.

This process, which earned a prize for its inventors granted by the Acadêmie des Sciences, is covered by a CEA patent and a licence agreement with the company Filclair Ceres (Sunstock process).

The hot water was obtained as follows:

- during the first winter by means of a heat pump installation, for which the warm source was water from the Isére-Drac ground water table, with a temperature of about 12 °C,

- last winter, discharge water from the Siloé reactor, with a temperature ranging from 26 to 18 °C, was brought to the hothouse. The water employed to heat the mulching consisted of this waste water used directly, or water heated by the heat pump, using the same waste as a warm source.

1.3.2 Manduel hothouse

Proceeding from the results obtained in the Grenoble experimental hothouse, other tests were undertaken by Mr. Dalle, a horticulturist at Manduel, near Nimes, who employs tunnel hothouses with Filclair (polyethylene film cover), of low cost per square meter.

The warm source in this case was the ground water table at 14 °C, which is inexhaustible as it must be pumped permanently for dewatering of the terrain. The temperature was raised to 30 °C by two heat pumps, one of 320 thermies/h driven by a diesel motor, and the second of 250 thermies/h driven by an electric motor. Basic operation in current conditions is ensured by the pump driven by the electric motor. The user estimates that for 3850 m^2 of hothouse area, one night of heating by the pumps costs 60 F, whereas this would amount to 360 F for conventional heating employing a fuel-fired boiler. Moreover, the cost of the pumps will be amortized in two years.

The hothouse, installed on 1 April 1975, made it possible to confirm the data gathered at CEN/G (Grenoble Nuclear Research Center) in the 1973/1974 experiments in a full-scale agricultural application, and to orient future production in accordance with the possibilities of significant savings in fuel consumption, derived from the use of heat pumps.

It is too early to draw the final conclusions of this experiment. However, the user has already claimed the following:

(a) Consumption savings forecasts are generally confirmed.
(b) The heat distribution to the soil through the muclhing has a very beneficial effect on the crop.

1.3.3 St. Laurent-des-Eaux hothouse

Also proceeding from the results obtained by the experimental workers in the CEA's Grenoble hothouse in 1973/1974, the EDF, in collaboration with them, established 3000 m^2 of hothouses near the St. Laurent-des-Eaux power station. The hothouse is of the chapel type with vertical walls to facilitate the movement of farm machines. The power plant discharge water is conveyed by a 1200 m long asbestos board duct. The water at T + 10 °C is heated by two heat pumps. This experiment, conducted on a semi-industrial scale with a private producer and the assistance of the Centre de Vulgarisation et d'Etudes Techniques des Maraichers d'Orléans, gave highly interesting results, both from the standpoint of yield and from that of precocity: tomatoes, 6 kg/m^2 the first month, 15 kg/m^2 expected for the overall campaign; cucumbers, 10 kg/m^2 the first month, 5 to 6 kg subsequently.

1.3.4 Innovations underway

The first year of operation made it possible to draw two major conclusions:

- the mulching, laid out over a very wide area, constitutes an outstandding solar collector,

- the hothouses possess very low thermal inertia, which accounts for their very high heat consumption. They must be ventilated whenever the sun shines and heated in cloudy conditions. It was observed that the heating process by mulching substantially increased this inertia, thanks to the soil, which, being significantly warmer than with conventional procedures, can restore part of the stored heat, and thanks to the water contained in the mulching, which represents considerable thermal inertia (only a few centimeters, but distributed over 80 % of the area of the hothouse).

In addition, it is very easy to increase this thermal inertia at will, by extending the circuit by a buffer tank, making it possible to store the excess diurnal heat and hence to account for all or part of nocturnal heating, corresponding to significant savings. This process involving hot water storage has been baptized the "Sunstock" process.

1.3.5 Economics of the system

The heat pump represents a substantially higher investment than a conventional boiler, four to five times higher. However, it outweighs this disadvantage by a considerable decrease in consumption. Hence its profitability increases with greater use throughout the year. Consequently, it should be used for basic heating, with auxiliary heating provided by a boiler. On this point it should be recalled that power capacity of 40 % of peak power is sufficient to cover over 80 % of annual consumption. Moreover, with two independent heat sources, operating safety is considerably increased. The optimum economic return is achieved exactly when power capacity of the heat pump represents 40 % of the total power.

Electrical power rates reveal the necessity to "cancel" peak hours, and the process involving a relatively small storage tank resolves this problem.

When these two conditions are satisfied, the heat pumps are clearly competitive with conventional processes, from the economic standpoint.

2 USE OF WATER AT T + 23 °C OR 30 °C MINIMUM

We have seen that once the cooling towers have been installed, we can be sure of having water at 30 °C virtually throughout the year. The power plants can fairly easily ensure the minimum of 30 °C, if necessary by slightly changing their settings; in any event, auxiliary or emergency systems should help during the few days of extreme cold. Initial agricultural use of water at T + 23 °C is a natural outcome of all the agricultural uses which we have just discussed involving heat pumps. However, the problem is not quite as simple as in the case of the use of heat pumps which, associated with hot water storage during the sunny period of the day, provides an extremely flexible system. The heat pumps offer the advantage of cooling the waste and extracting the maximum available heat. However, with a single passage, the water at 30 °C is liable to exit at temperatures which have been lowered by 3 to 4 °C only. If the water returns to the cooling towers, this does not raise a problem. However, it is likely to be too hot for discharge into the environment; hence two or more processes must be combined.

2.1 Pierrelatte Hothouses

Use is made of the hot water reaching the cooling towers of the plant, in order to heat water taken from the ground water table in a heat exchanger to 36 °C.

An experimental zone covering five hectares of hothouses, of which two have just been put into service, has been created. The farm is worked by a Tricastin hothouse specialist for his own account. The heating system is the Sunstock system without make-up by heat pumps, which are unnecessary in this case. The economics of the project are closely comparable to those of the traditional system, as far as investments are concerned. On the other hand, substantial savings are expected from the operations standpoint: since warm water availability is uninterrupted, fuel costs are nil. This experimental zone will serve as a demonstration area for the agricultural use of cooling waters of the future Eurodif plant.

The water temperature is slightly over T + 23 °C from the power plants with cooling tower. However, we feel that the use of this water at 36 °C will provide valuable data for the future use of water at T + 23 oC from cooling tower equipped plants.

2.2 Bugey Project to Heat 40 Hectares of Hothouses

A preliminary project employing this water in three successive use zones as a function of temperature has been established for the Bugey power plant. Forty hectares of hothouses can thus be heated with the deconcentration water at T + 23 °C from the cooling towers of reactors 4 and 5.

Using the heat pump system, the lost heat of the waste water can be recovered for domestic heating purposes. This system is being examined for the Bugey region. It will not be discussed here as it goes beyond the scope of our exposê, which is devoted to agricultural uses.

3 CONCLUSIONS

A glance at the diagrams which summarize national primary energy consumption expressed in tons of oil equivalent for various needs, industry, transportation, domestic heating etc, shows that 50 % and sometimes more of the energy input is lost during use (thermal power plants, owing to the Carnot principle, release up to 60 % of the thermal energy produced in the boiler into the environment).

It is only logical that an attempt is being made to use this lost energy. However, as with the so-called new energies, the solution is not an easy one, as it generally involves energy which is widely distributed in low temperature wastes, at any event in the case of present-day electrical power plants, and the economics of the project must be carefully examined.

In the case of agriculture, it may be asserted that many solutions for recovery are available depending on the type of waste, provided that space is available near the power plant.

These uses are likely to reduce the fuel consumption of agricultural farms and the areas which can be heated are considerable. However, this means concentrating agricultural installations likely to benefit from hot water discharges around the power plants, and this can give rise to social and economic problems. Finally, the insulation factor is very important for hothouses. From this standpoint, installations in the south of France clearly have the advantage.

As for urban heating with a heat pump, in order for the system to be economical, we feel that water must be available at least at the temperature of the water from cooling towers, a minimum of 30 °C, together with a high user density in the immediate vicinity of the power plant. In addition to the inherent economics of the project, one must still estimate the advantage, on the national level, derived by primary fuel savings that can be realized.

AGRICULTURAL APPLICATIONS.

L'EAU À BASSE TEMPÉRATURE AU PROFIT DE L/HORTICULTURE, DE L'AGRICULTURE ET DE LA PISCICULTURE

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1. INTRODUCTION

L'utilisation de la chaleur dissipée dans les rivières, la mer out l'atmosphère par les centrales thermiques fait l'objet de nombreuses études depuis 2 ans. Des initiatives ont été prises dans la plupart des pays industrialisés en vue de valoriser le sous-produit énergétique constitué par l'eau réchauffée par la condensation de la vapeur.

Il est vrai que les exigences du Cycle de Carnot veulent qu'une grande partie du combustible consommé dans not unités thermiques traditionnelles et nucléaires soit dégradée à une température voisine de l'ambiance. Pour une unité nucléaire notamment, deux tiers de la chaleurs à basse énergie restent encore disponibles à la sortie des condenseurs.

Depuis le renchérissement des combustibles et dans le cadre des économies d'énergie, il est pleinement justifié d'utiliser les rejets thermiques à basse température pour le chauffage du sol à proximité des centrales tenant compte de l'importance de la consommation de gasoil et de fuel-oil en horticulture.

La Société Intercom participe activement à cette promotion dans le cadre de deux stations expérimentales de cultures sous verre ou en plein champ à proximité des Centrales de Ruien et de Tihange.

Il faut également noter une station de pisciculture en eau réchauffée en vue de permettre la croissance accélérée de poissons. Quatre étangs de pisciculture sont prévus à cette fin à Tihange.

2. CHALEUR ET NIVEAU DE TEMPERATURE DISPONIBLE

Les disponibilités hydrographiques des rivières belges permettent encore le fonctionnement de la plupart des centrales thermiques en circuit de réfrigération ouvert. De ce fait les eaux sont réchauffées au passage des condenseurs de 12 ° environ. Si on compte sur une température naturelle de l'eau minimum de 5 °C en hiver, on peut donc disposer d'eau en quantité inépuisable de 17 °C à 20 °C en hiver.

Dans une dizaine d'années les conditions de réchauffement imposeront le circuit fermé sur réfrigérant atmosphérique des futures unités nucléaires. De ce fait, la température de l'eau en hiver atteindra dans ce cas 27 ° environ.

Quelles sont les possibilitiés d'utilisation de cette chaleur en horticulture et en agriculture?

L'employ des chaleurs récupérées est limité par 2 éléments.

Le coût du transport et de la distribution de l'eau réchauffée limite la zone d'application à un rayon de quelques kilomètres de la Centrale.

D'autre part la plupart des cultures en serre ne peuvent s'accomoder à des températures d'eau de 17 à 20 ° en hiver.

Pour les plantes sous abri quelque peu exigeantes il est nécessaire de remonter la température à 35 - 40 oC en utilisant des pompes à chaleur.

Pour certains sites allemands, français on s'oriente vers l'utilisation d'un soutirage en vue d'atteindre une température de l'eau de 60 à 70 ° pour l'application à de grandes superficies de plein champs ou de serres.

Il est vrai que les besoins nécessaires de chaleur (1 à 2 Gcal/ha) sont élevés et dépassent ceux résultant du chauffage urbain de centres d'agglomération à forte densité de construction.

3. IMPORTANCE ECONOMIQUE DES SERRES BELGES ET BESOINS DE CHAUFFAGE

La superficie totale des serres et des abris chauffés est de 2000 hectares environ, dont la majorité implantée dans les Flandres, la Province d'Anvers, 15 % dans le Brabant et très peu en Wallonie.

L'industrie horticole compte 12.000 emplois et la production atteint 20 à 30 milliards de francs par an.

La production maraîchère a doublé depuis 10 ans. Elle compte 160.000 t dont la moitié de tomates et 50.000 t de laitues. La culture fruitière avec 500 ha est en diminution.. La réduction des raisins a été compensée par une promotion des fraisiers soit près de 200 ha. La floriculture compte surtout des plantes en pot, des azalées et des fleurs à couper avec une exportation dépassant annuellement le milliard de francs.

L'horticulture sous abri exige le chauffage en hiver normalement avec de l'eau à 50 - 70 ° en provenance de chaudières alimentées en gasoil our en fuel-oil.

Depuis 2 ans, le budget du chauffage a presque triplé, de ce fait son impact sur le prix de revient des cultures est important (25 à 35 %). En effet d'après les statistiques de l'Institut économique agricole, le coût du chauffage annuel en serre varie de 110 à 210 F/m^2 suivant le type de plantes: salades, tomates ou concombres (ces dernières étant les plus exigeantes).

Si on compte que la consommation globale en gasoil a atteint près de 400.000 t en 1973, il y correspond présentement une dépense estimée de 2 milliards de francs.

Pour gouverne, la puissance thermique nécessaire au chauffage varie entre 100 à 150 kcal/m^2 heure en moyenne soit avec une utilisation de 1.500 à 2.000 heures une consommation de 30 kg de fuel/m^2 et par an.

4. PROMOTION DES CULTURES ET DE L'ELEVAGE PAR DE LA CHALEUR RECUPEREE A BASSE TEMPERATURE

Le développement des cultures sous abri permet l'étalement et l'augmentation de la production horticole, les consommateurs à haut standing exigeant davantage des produits frais le long de l'année.

Le but des recherches en cours est de supprimer une part importante des combustibles coûteux, de permettre la substitution par de la chaleur à basse température et d'adapter des équipements et des échangeurs adéquats.

Quelles sont les possiblilités d'accélération de croissance des cultures, de gain en précocité ou de prolongement de forcing en avant et en arrière saison?

Quel est le bénéfice d'utilisation du chauffage du sol en plein champ appliqué à des grandes étendues de cultures horticoles, fruitières et industrielles?

D'autres part, il est bien connu qu'un échauffement limité de la température de l'eau +10° permet d'accélérer la croissance de poissons en stimulant l'activité de la nutrition et la conversion de la nourriture.

Des données récoltées dans ces centres de recherche permettront de déterminer la rentabilisation d'exploitations importantes à proximité des centrales thermiques, d'assurer une promotion d'emplois nécessaires à la gestion et à la distribution des produits récoltés.

En général, le choix des plantes et des poissons dépend des conditions locales et des chaîne de commercialisation existantes.

Nous avons eu l'occasion d'obtenier des renseignements sur quelques stations expérimentales en service notamment pour les serres de Grenoble (250 m2), Saint-Laurent-des-Eaux (3000 m^2), Manduel (3600 m^2), pour le plein champ à Cadarache (sylviculture) à Brennilis (12 ha) et Aix-la-Chapelle (7 ha).

Pour les poissons des résultat très positifs ont été obtenus dans les rejets de centrales à Cadarache et à Flevoland.

Les résultats obtenus sont souvent surprenants.

A l'effet primeur escompté s'ajoute une amélioration nette du rendement par l'effet biologique de la chaleur.

On obtient des fraises 2 mois plus tôt, la plupart des légumes avec 1 mois d'avance et des rendement de 200 à 300 % superieurs à la normale.

5. PREMIERE EXPERIENCE BELGE A RUIEN

L'installation érigée à 400 m de la centrale comprend 4 serres de 85 m^2, des couverts pour witloof et 300 m^2 de culture en plein champ.

La technologie appliquée est celle de Grenoble à savoir pour 2 serres des gaines en plastique posées à même le sol où circulent l'eau tiède de 35 à 40 °C, des gaines ouvertes pour des plantes tropicales alimentées de la même façon (photo en annexe).

Une serre a été maintenue avec l'alimentation en eau à 10 - 15 °C en provenance directe de la centrale en vue de connaître les possibilités de culture pour des conditions limites en période froide.

Une pompe à chaleur de 20 kW permet un apport calorifique de 64.000 kcal/h correspondant à un coefficient de performance moyen pratique de 4, l'eau d'alimentation étant en moyenne à 12 o et la sortie d'eau chaude 35 oC.

Après la première récolte de laitue et de witloof, des fraisiers sont à maturité dans une serre, des radis à la vente, des graines d'èpiscéas ont été ensemencées et des cultures de diverses primeurs sont en cours dans les 2 autres serres et en plein champ.

Les laitues dans une serre tiède chauffée à très basse température à 12 °C ont pu survivre pendant la période de grand froid (10 jours à -5 oC environ).

La direction des recherches est assurée par le Professoeur Petit et ses collaborateurs de l'Université de Gand.

6. CENTRE PILOTE DE TIHANGE

L'ensemble des installations en cours de réalisation comprend 5 serres de 80 m2 et 4 étangs de 200 m^2 pour la pisciculture dont un réservé à la culture des algues.

Il est implanté dans un parc de 2 hectares jouxtant la première unité de Tihange (plan annexé).

En vue d'utiliser au maximum l'eau sortant des condenseurs en hiver à 17 - 25 °, des réseaux de tuyaux enterrés en PVC sont prévus dans les serres et en plein champ à proximité.

L'appoint de chaleur sera assuré par des convecteurs à air chaud alientés par une pompe à chaleur similaire à Ruien.

Les cultures prévues pour les serres en plastique seront les fraisiers pour la première période de l'année et des légumes tels les tomates, poivrons et laitues pour l'autre période.

Les 2 serres à vitres seront spécialisées pour le bouturage en continu de plantes tels le dracena, le ficus, le croton, le diefflachia et le maranta.

La direction du Centre d'Horticulture est assurée par MM. les Professeurs Sironval, Dubuisson et Nisen de L'Institut Botanique de Liège et de l'Institut Agronomique de Gembloux. Le traivail effectif sera assuré par M. Lemaître du Centre de Fraisiers et d'autres collaborateurs.

En ce qui concerne la pisciculture le Professeur Ruwet et ses assistants de l'Institut de Zoologie de Liège envisagent l'élevage intensif d'anguilles, de gardons et d'autres espèces tropicales à haut rendement de croissance tels le Tilopéa et le Clasia lazer.

Une panier de récolte est prévu en contrebas à l'amont de la vidange de chaque étang.

On considère que 2 à 3 ans seront nécessaires en vue d'établir des règles de promotion d'étangs artificiels alimentés en eau réchauffée.

Un étang est réservé au Professeur Sironval pour la culture des algues en vue d'analyser de près la croissance en eau réchauffée et les perspectives futures de production de méthane ou d'hydrogène à partir de rejets thermiques.

Les 3 Centres de Ruien et de Tihange seront subventionnés par l'Irsia avec prise en charge d'une part (50 %) des frais des équipes de chercheurs et du support logistique nécessaire en appareillage de contrôle.

L'Union des Exploitations Electriques Belges intervient également pour une certaine part dans les frais de gestion des stations de recherche.

Les infrastructures des installations ont été à charge par Intercom (+3,5 millions de rancs) qui pourra récupérer certains frais généraus de pompage, de chauffage et divers.

7. RENTABILITE DE GRANDES SUPERFICIES DE CULTURES

Des terrains agricoles sont disponibles auprès de la plupart des centrales thermiques belges: tels Ruien, Doel, Tihange. On pourrait donc envisager dans quelques années dans chaques site plusieurs dizaines d'hectares réchauffés par les eaux en provenance des unités thermiques.

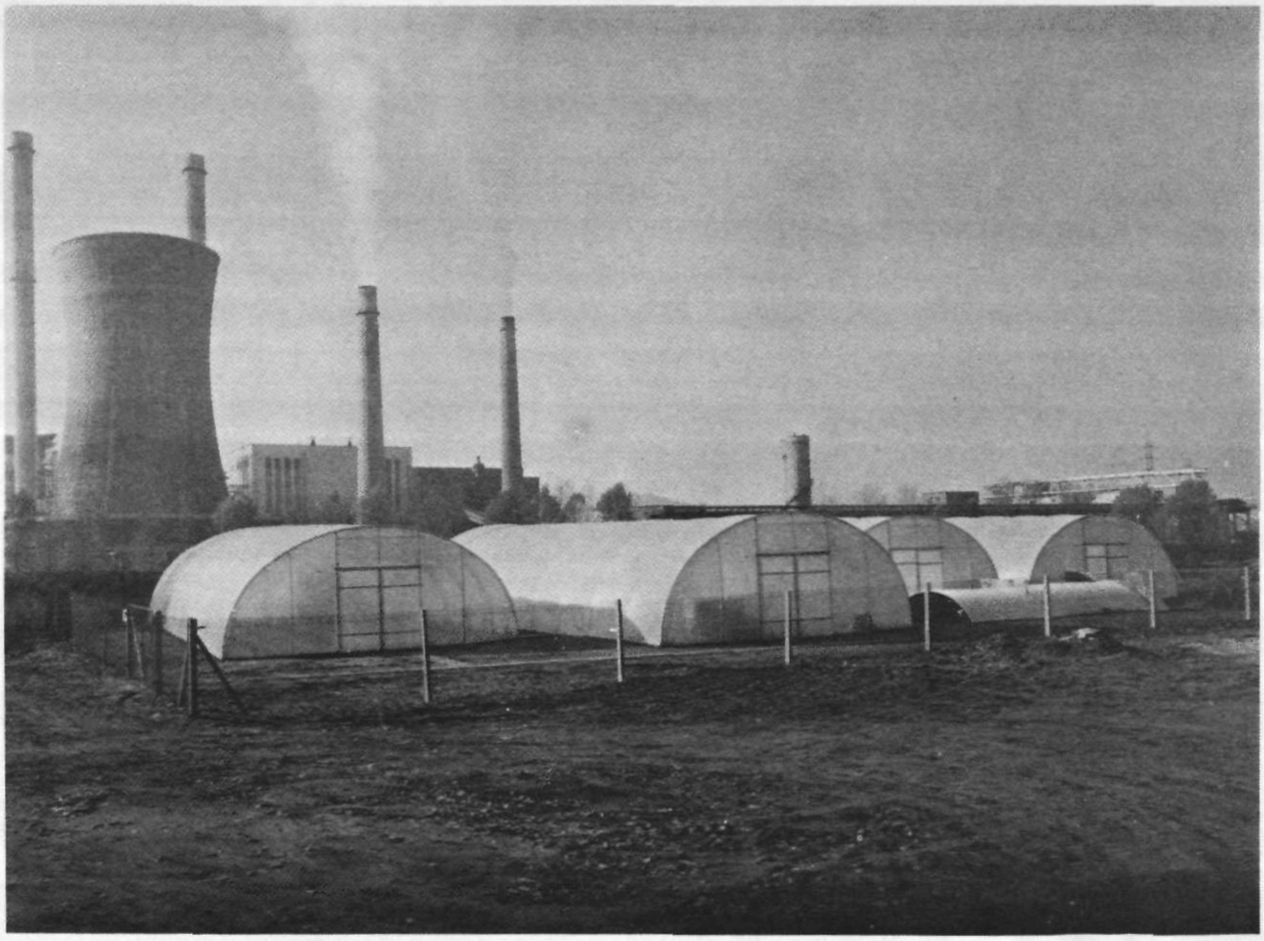
Des possibilités apparaissent intéressantes notamment pour des cultures en plein champ où les investissements à prévoir sont limités à une installation de pompage, de transport et de distribution dont le coûte calculé de la chaleur livrée à basse température est inférieure à 150 F/Gcal. Néanmoins la rentabilisation des rejets thermiques garde une faible incidence sur le bilan des chaleurs perdues puisqu'une unité nucléaire de 1000 MW rejette en rivière ou à l'atmosphère un total de 1700 Gcal/h, alors qu'un hectare de terrain peut seulement absorber 1 à 2 Gcal/h.

Néanmoins l'utilisation de cette chaleur se justifie pleinement dans le contexte de l'économie de combustible et de rentabilité agricole ou piscicole.

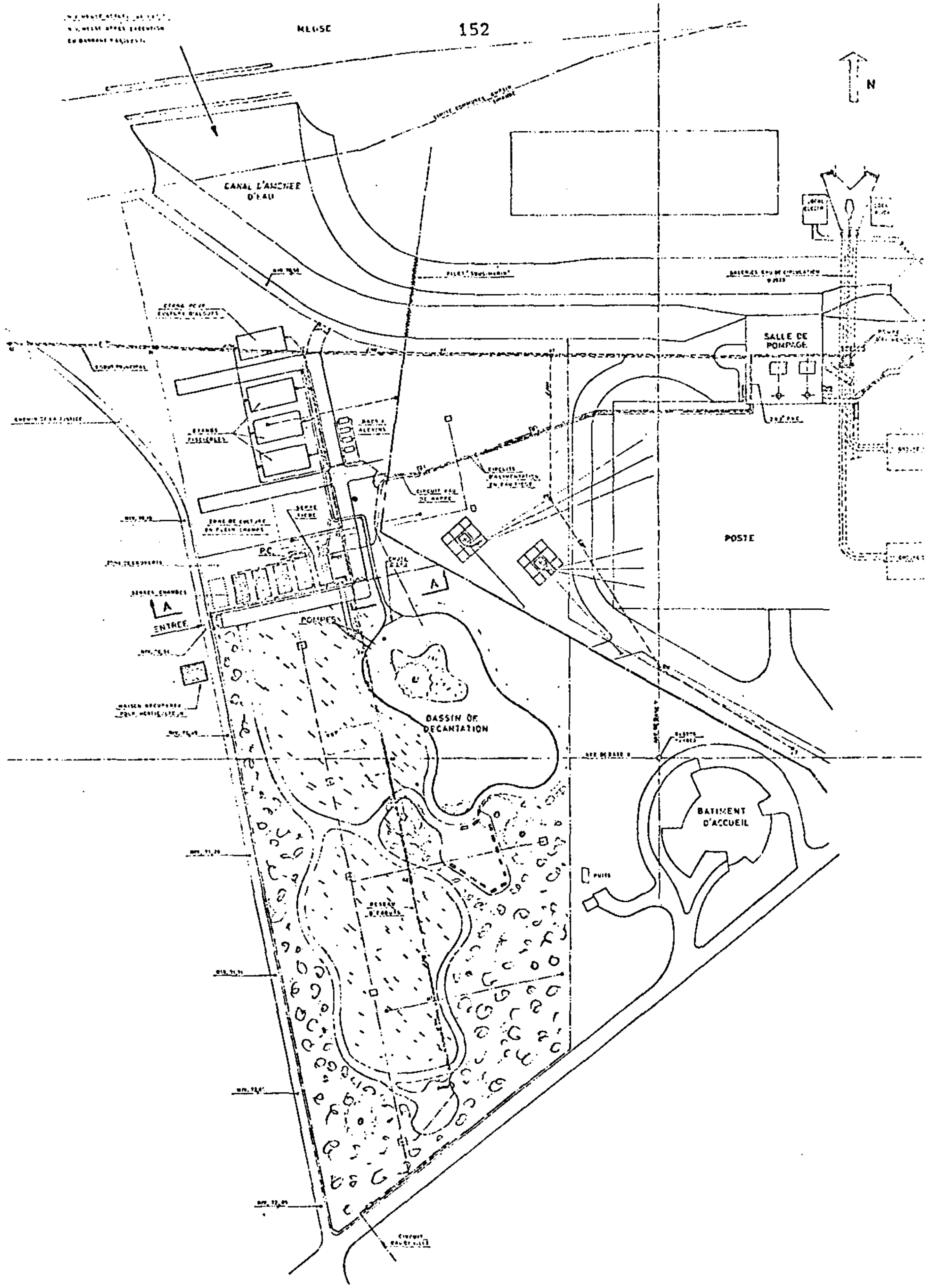
Pour les plantes exigeantes l'utilisation de pompes à chaleur qui permettent d'obtenir de l'eau de 40 à 45 °C, renchérit fortement le coût de la chaleur qui revient à 500 F/Gcal chez l'utilisateur.

Pour assurer la rentabilité, il faut dans ce cas envisager un fonctionnement de nuit avec stockage d'eau chaude et application d'un tarif d'électricité réduit.

Nous pensons que les pouvoirs régionaux et notamment les sociétés de développement SDR pourront stimuler et aider de tels investissement afin de promouvoir des nouveaux emplois et de participer à l'augmentation des ressources agricoles et piscicoles.



SERRES RUIEN



TIHANGE

ENSEMBLE SERRES, ETANGS ET PARC PUBLIC

ANNEXE 6

USE OF INDUSTRIAL WASTE HEAT IN AGRICULTURE

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Some years ago Rhineland Chamber of Agriculture (Landwirtschaftskammer Rheinland) investigated the influence of soil-heating on growth of vegetable and ornamental crops under glass and in the open. Especially in spring-time, but in the autumn, too, yield per unit area with lettuce and raddish under glass increased by 10 %, and did so with French beans by 22 %, and with tomatoes by 30 %.

Furthermore favourable response on soil heating was especially the distinctly earlier harvest date and the partly remarkably increased quality of the product and by this increased returns.

In the open yield was increased with lettuce by 10 %, with kohlrabi by 35 % and with raddish by 32 %, on the other hand yield was decreased with celery and aubergines.

Combined considerations with August-Thyssen-Hütte on the use of waste heat of power stations lead to the lay-out of first trials with usual agricultural crops. Because waste heat must be accepted the year over, it was necessary to consider the plant physiological aspects, how to use this heat economically during the summer, particularly between July and September. Heat compatibility of the crops is of special importance. Another question was to what extent with summer cultivation yield and quality can be improved by soil heating and whether it will be possible to grow plant species from subtropic climates here.

Inspite of 4 weeks later sowing in the year 1974 first trials gave promising results: Yield increases were the following:

silo corn	35 %	potatoes	20 %
corn	40 %	incarnate clover and grass	48 %
sugar beets	70 %	meadows	47 %

In 1974 spring-time began late, and extensive precipitation during the summer months was measured. Nevertheless even soybeans became ripe, though they had been sown 4 weeks too late. In Southern France soybeans not every year reach their stage of maturity.

Winter wheat riped 3 weeks earlier in 1975. Diverse varieties overyielded normally cultivated plots by 11 to 46 %, on the other hand some varieties did not reach the yields of the control plots. Early potatoes planted in February and in part covered with PE-films riped in early June (nearly 4 weeks earlier than normally) and gave remarkably more yield. They were of excellent quality, had a firm skin and gave good prices.

As in 1974 in the year 1975 sugar beets, corn and soybeans reached a leading in growth by 3 to 4 weeks. First harvests of sugar beets showed higher yields by 57 %, with corn the heated plot overyielded the unheated one by 10 %. While the unheated soybeans were in a desolate state, yield and quality of the heated plot were favourable.

After extensive preparations in spring-time 1975 in the Rhineland tropical and subtropical crops, as peanut, sweet potatoes, limabeans, cotton and Physalis peruviana, were sown or planted for the first time. Of course, it is impossible today to give well-grounded results of these first experiments. According to our experience in 1975 these plants grew well under the Rhineland conditions including soil heating.

A founded experimental program will start this year at three points of the Rhineland with the title "Agrotherm". The locations are Experimental Stations Auweiler (near Cologne) and House Riswick (near Kleve) and a field near to the power station Neurath (near Grevenbroich). This research programme is subsidised by Federal Ministry of Technology and technically supervised by Rhineland Chamber of Agriculture and August-Thyssen-Hütte. Kernforschungsanlage Jülich is responsible for scientific supervision of "Agrotherm". The program includes agricultural and horticultural crops. We shall test the conventional varieties, but subtropical and tropical species, too. Besides the problems of cultivation techniques many other questions are to be answered, e.g. on the behaviour of the soil (temperature, humidity, consistency, nutritional content, organic matter, diseases and parasites) and of the climate in the near of soil surface (temperature, humidity, wind velocity).
One of the most important duties will be to solve the causes and the causal relationships of a soil heating in year-round function.

SESSION C

NEW ENERGY CARRIERS AND SYSTEMS

C 1

TRANSPORT OF CHEMICAL BOUND ENERGY

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Abstract

The oil crisis has manifested that it is necessary to use nuclear energy to an increasing extent for purposes of energy supply and, particularly, for the supply of the non-electric energy market. This purpose is served by the energy supply system "Nuclear Energy over Long Distances", by which nuclear energy is transported in a converted form and transformed into the applicable forms of energy such as hot water or water vapour and electricity. The energy transport involves the transport of the "latent heat gas" which by chemical reaction will be absorbing or emitting thermal energy. The latent heat gas "synthesis gas/methane" presents a few substantial advantages. The nuclear heat source of the energy supply system "Nuclear Energy over Long Distances" is the high-temperature reactor.

PRINCIPLES OF ENERGY TRANSPORT IN A CLOSED CYCLE

Apart from the tasks of primary energy generation and of the preparation of energy forms ready to be used, the energy supply system also involves the functions of transport and distribution from the producer to the final consumer. Up to the present, these requirements are bing met to a large extent by the transport and distribution of fossil energy carriers and by electricity. For a minor part, the energy distribution is also handled by the transport of water within a closed cycle system, on which the difference in temperature between initial feed and return of the water is being utilized for energy transport.

A novel possibility for solving the problem of energy transport is the transport of chemically reactive mixtures of substances in a closed cycle. In this case, the energy is transported in the form of latent chemical energy, e.g. as reaction enthalpy of the chemical reaction of the reactive mixture of substances. Approaches to this possibility of energy transfer had been developed a few years ago in the Nuclear Research Center of Jülich, and this possibility is now being taken up again /1/.

The chemically reactive mixture of substances generally presents the mixture of the reacting agents of a chemical reaction. It is characterized by the following facts:

1) The process of the chemical reaction is reversible and its course under specific conditions will be in "forward" direction and, under different conditions, in "backward" direction,
2) in the course of the chemical reaction, heat energy will be taken up or given off, dependent on the direction of the process, and,
3) the process of the chemical reaction is discontinued under certain conditions, for instance in the state of transport.

A chemical reaction is reversible if the products of the "backward" reaction are the reactants of the "forward" reaction. This characteristic of the reactive system means that the energy taken up in the course of the forward reaction will be given off again completely during the process of the backward reaction. The agents of the reactive mixture are neither consumed or generated during this process, but they are being conducted in a "closed cycle".

The feature of reversibility of the chemical reaction will at the same time be a requirement to be fulfilled by the reactive mixture to a maximum possible extent. The production of non-reversible reacting partners requires their extraction and the creation of substitutes.

The direction of the chemical reaction is a function of the state of reaction of the reactive mixture and of the position of chemical equilibrium. The chemical equilibrium of a specific reactive mixture of agents is a function of the temperature, pressure and composition of that mixture. With a view to its applicability, specific requirements have to be met with respect to the position of the chemical equilibrium, for instance with regard to the temperature of the energy conversions, and, consequently, with respect to the nature of the chemically reactive mixture of substances.

In the case of an isobaric process flow, the heat transformation in connection with a chemical reaction is defined by the reaction enthalpy. Dependent on the direction of the reversible chemical reaction flow, the isobaric process involves the uptake or emission of thermal energy in the order of the reaction enthalpy. The reaction enthalpy of a chemical reaction is the product of the reaction enthalpy per formula conversion and the formula conversion or the degree of the formula conversion. For reasons of economy, the energy density shall be as high as possible, that is to say both the reaction enthalpy per formula conversion and the formula conversion of the chemical reaction should be as high as possible. In general, the reaction enthalpy is merely a function of the mixture of substances, but not a function of temperature, pressure or composition. However, the conversion product, which can be obtained, is a function of the position of the chemical equilibrium, i.e. a function of the adjusted conditions of temperature, pressure and composition.

The transport of the reacting agents of the reactive mixture from the energy generator to the energy consumer and from the energy consumer back to the energy generator is carried out at ambient temperature for technical and economical reasons. This means that at least one of the two transport directions the mixture of substances (unless it is separated) will be existing in the state of "stable" non-equilibrium and will be transported in this form. This state is characterized by the fact that although there is a chemical non-equilibrium, the latter will be stable, without any chemical reaction taking place.

If the reacting agents of the chemically reactive mixture are primarily existing in a gaseous state, this mixture is defined for example as latent heat gas.

THE TRANSPORT SYSTEM "SYNTHESIS GAS/METHANE"

Among the great variety of possible chemically reactive systems of agents, the system "synthesis gas/methane" is distinguished by the fact that the individual steps of its implementation involve a well-known and multiply applied technology. This is of advantage with a view to the development and rapid application of such a system of energy transfer. For this reason and for a more detailed elucidation of energy transport in a closed cycle, this system is being investigated in the following description.

Build-Up of the System

1. The latent heat gas "synthesis gas/methane" is a mixture consisting of methane gas CH_4 and water vapour H_2O, on the one hand, and hydrogen gas H_2 and carbon monoxide gas CO, on the other hand. Moreover, due to a side reaction, there is a small portion of carbon dioxide gas CO_2. The adjustment of the chemical equilibrium between these reacting agents can be described by the following two chemical reactions:

1) $CH_4 + H_2O_g \rightleftarrows 3\,H_2 + CO;$ $H_1 = +\ 50$ kcal/mol

2) $CO + H_2O_g \rightleftarrows H_2 + CO_2$

It is noted from the above terms that both chemical reactions are reversible. In the first reaction, methane and water vapour are reacting to hydrogen and carbon monoxide. This reaction is endothermic, i.e. when flowing as forward reaction (→), thermal energy is taken up and, when flowing as backward reaction (←) thermal energy is given off.

It should be taken into consideration that the reacting agent of water may exit in the gaseous (g) and in the liquid (liq) state of aggregation. If referred to the liquid state of aggregation of the water: H_2O_{liq}, the reaction enthalpy of the first reaction will be: $\Delta H_1 = +60$ kcal/mole.

A small portion of the carbon monoxide formed in the first reaction will be reacting in the second dioxide. If referred to gaseous H_2O, this reaction will be: $\Delta H_2 = -10$ kcal/mole (exothermic).

The first reaction will be the principal reaction, i.e. at more than 90 % referred to the conversion rate of water vapour. This means that the second reaction is a side reaction. The flow of the second reaction involves firstly that the reaction heat per mol CH_4 is lightly lower than the reaction enthalpy H_1, and that in accordance with the proportionate conversion rates of the first and of the second reaction, and, secondly, that carbon dioxide CO_2 is existing in a low concentration in the latent heat gas. Because of the insignificant influence and for simplification, the following comments will not particularly refer in each case to the second reaction.

The energy supply system "Nuclear Energy Over Long Distances" is schematically illustrated in Fig. 1. The energy transport is carried out with the latent heat gas "synthesis gas/methane". The energy flow is as follows: the nuclear energy as primary energy is converted in the high-temperature reactor to thermal energy. This thermal energy is transferred with the reactor coolant to helium to the "chemical reactor for the endothermic chemical reaction", defined in an abbreviated manner as "EVA". In this reactor, the thermal energy of the reactor coolant of helium is converted by chemical reactions into the latent chemical energy of the latent heat gas. The backward reaction of the latent gas takes place in the "chemical reactor for the exothermic reaction", which is defined with the abbreviated term "ADAM". Here the latent chemical energy is converted by chemical reactions to thermal energy and used for the generation of hot water or water vapour. The energy transport between the chemical reactor "EVA" and the chemical reactor "ADAM" is carried out by the transport of the latent heat gas.

The abbreviations EVA and ADAM are operation terms for the chemical reactors of the transport system. The term EVA is formed by the abbreviation EVA of the Einzel-Spaltrohr-Versuchsanlage (test unit with single steam reformer tube), by which the reaction $CH_4 + H_2O = 3 H_2 + CO$, being known as steam reforming, has been demonstrated for about two years in the KFA Jülich on a large technical scale and with helium heating. The operation term ADAM was chosen as an analogous supplement to the operation term EVA.

The transport system "synthesis gas/methane" involves the following operation flows: methane from the feedback of the pipe system is conducted, together with water vapour, into the catalyst bed of the EVA reactor, thus forming the forward reaction. The products of the forward reaction primarily consist of hydrogen and carbon monoxide. The mixture of these gases is

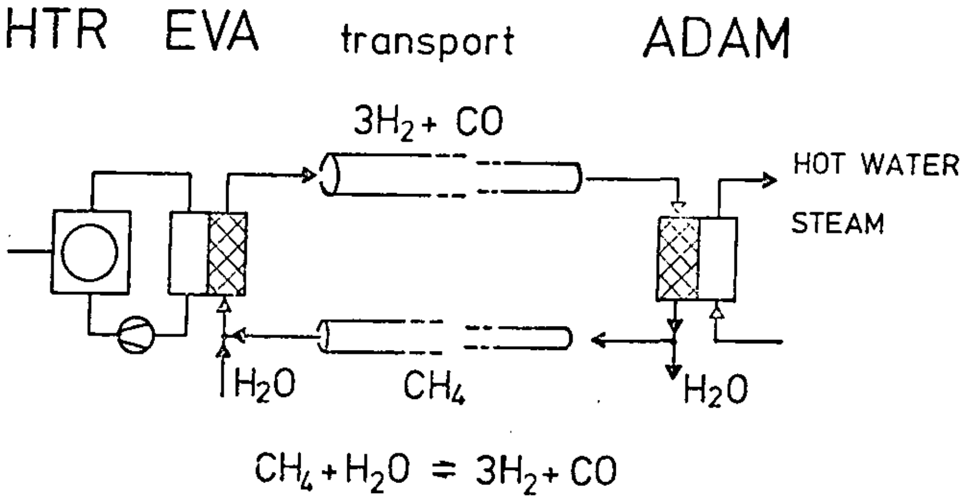

FIG. 1: Nuclear energy transport over long distances, EVA/ADAM system

cooled down to ambient temperature and, thus, passes at increased pressure into the feed conduit of the pipe system. The forward reaction is endothermic and the necessary heating of the catalyst bed of the EVA reactor is ensured by the reactor coolant of helium. The major part of the cooling down heat of the product gas is meaningfully used in the process cycle or elsewhere, while a minor part will be given off as waste heat to the environment.

From the feeding line of the pipe system the mixture of hydrogen and carbon monoxide will be passing into the catalyst bed of the ADAM reactor, where it reacts under formation of methane and water vapour. This backward reaction is exothermic and, consequently, has to be cooled. This cooling is carried out by means of water, i.e. by the production of hot water or water vapour. The products of the backward reaction in the ADAM reactor, u.e. methane and water vapour, are separated from each other by a cooling process, and methane will be passing into the feedback of the pipe system. By means of the feedback of the pipe system, methane is transported back to the EVA-reactor. The separated water is eliminated from the transport system of the gaseous reacting agents. It may be given off to the environment or utilized for industrial purposes or even be recycled.

The EVA Reaction

2. The composition of the equilibrium as a function of the reaction temperature and the conversion of the forward reaction proceeding in the EVA reactor are illustrated in Fig. 2. In the chemical equilibrium and at low

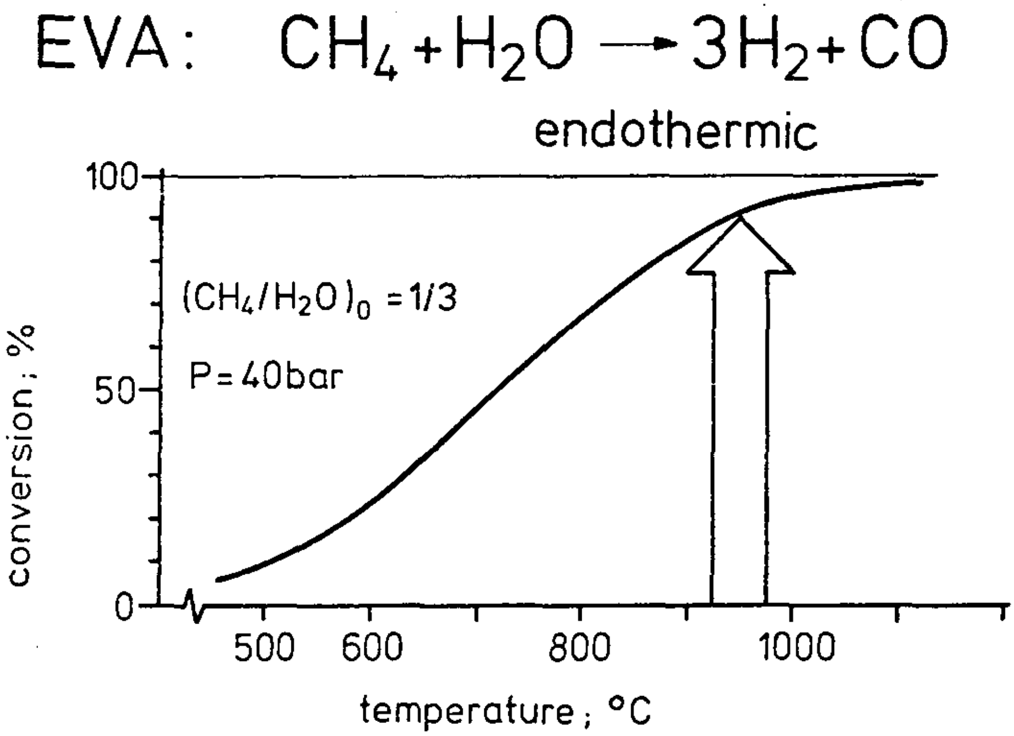

FIG. 2: The composition of the equilibrium versus temperature and the conversion of the forward reaction proceeding in the EVA reactor

temperature, it is shown that the reactants of methane and water vapour are prevailing, whereas at high temperature the products of hydrogen and carbon monoxide are preponderant. Consequently, the conversion rate of the forward reaction will become higher with increasing reaction temperature and, thus, with increasing temperature of the heat supply.

To obtain a maximum conversion rate, the heat supply is carried out at and up to a maximum temperature. For instance, the conversion of the forward reaction at the maximum temperature of the heat supply of say 950 °C according to Fig. 2 and according to the specified conditions regarding pressure and initial composition will thus amount to a maximum of about 90 %.

It is shown by the temperature characteristic of the equilibrium curve in Fig. 2 that the heat supply is not necessarily carried out at a constant temperature, but that a temperature range between e.g. 550 and 950 °C is possible. This means that the chemical reaction in the EVA reactor is excellently adapted to the heat availability of the high-temperature reactor. The composition of the equilibrium of the forward reaction is not only dependent on temperature but also on both the pressure and the initial composition. It may be observed from the stoichiometric coefficients of the forward reaction that a high conversion rate can be reached with a pressure as low as possible and with an abundant availability of water vapour. Fig. 2 represents the temperature curve of the equilibrium composition for the overall pressure of 40 bars and the initial mole ratio of 3 between water vapour and methane. These values are reasonable compromises in technical respect, for the overall pressure in the EVA reactor should be of the order of about 40 bars with regard to the pressure of the reactor coolant of helium and the initial mole ratio should not be much higher than 3 with a view to the mass balance of the EVA reactor. Moreover, an increased availability rate of water vapour in the EVA reactor is required with a view to avoiding any carbon deposition.

Even at increased temperature, the forward reaction will not proceed as a homogeneous gas reaction, but it is necessary to use a catalyst.

The ADAM Reaction

3. The composition of equilibrium as a function of the reaction temperature and the conversion rate of the backward reaction proceeding in the ADAM reactor are illustrated by Fig. 3. In the same manner as in connection with the forward reaction, the chemical equilibrium primarily involves methane and water vapour at low temperature and primarily hydrogen and carbon monoxide at high temperature. However, contrary to the forward reaction, hydrogen and carbon monoxide are the reactants and methane and water vapour the products of the backward reaction. This means that the gas mixture of water vapour and carbon monoxide, which is cooled down to ambient temperature for the transport in the feed line of the pipe system, in this state will exist in the chemical non-equilibrium. But this non-equilibrium is stable, i.e. there will not be any chemical reaction during transport. These facts are commercially known from the application of the town gas essentially consisting of hydrogen and carbon monoxide.

It is therefore necessary to use a catalyst in order to overcome the stable

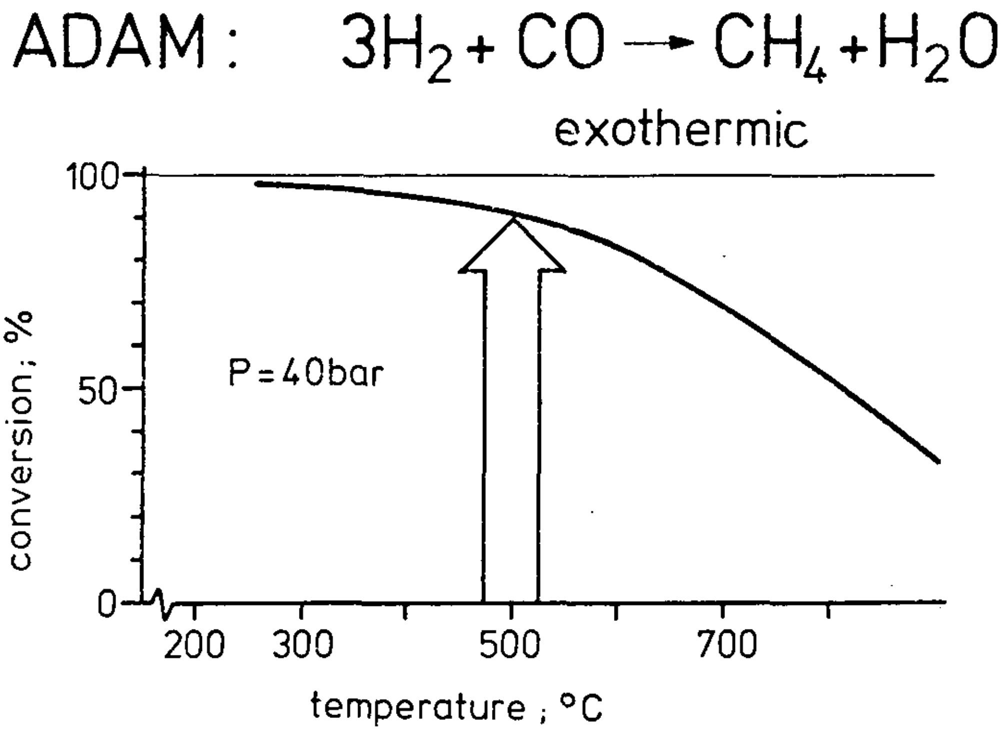

FIG. 3: The composition of the equilibrium versus temperature and the conversion rate of the backward reaction proceeding in the ADAM reactor

non-equilibrium, i.e. to generate a reaction velocity for the backward reaction in the ADAM reactor.

In the stationary condition of the transport system the conversion rate in the ADAM reactor is just as high as that in the EVA reactor in order that the mass balance will be satisfied. This is to say that the maximum value of the temperature at the outlet of the ADAM reactor, in accordance with Fig. 3, for instance amounts to about 500 °C. It can be observed from the temperature curve of the equilibrium composition of the latent heat gas, in accordance with Fig. 3, that by the counterflow method it is also possible to produce heat of a higher temperature, e.g. of 800 °C and more. The application of an increased overall pressure in the ADAM reactor will promote the conversion rate, which can be utilized for an additional increase of temperature of the generated heat. However, it should be noted that the temperature level of the generated heat is not only a function of the equilibrium, but also one of the permissible working temperature of the catalyst.

IMPLEMENTATION OF "NUCLEAR DISTRICT ENERGY" TRANSPORTED OVER LONG DISTANCES

A substantial advantage of the EVA/ADAM transport system for the development and implementation of nuclear energy supply over long distances in comparison with any other practicable systems is presented by the fact that all partial steps for the performance of this procedure are well-known and multiply used technological practices.

The forward reaction in the EVA reactor is known as steam reforming. This process is commercially used for the production of hydrogen out of methane or other hydrocarbons. Several years ago, KFA Jülich had installed the test unit EVA with single steam reformer tubes, in which the nuclear heating of the steam reforming process is simulated with electrically heated helium. This test unit is particularly intended to demonstrate the input of nuclear heat in a chemical process.

The backward reaction in the ADAM reactor is known as methane synthesis or as methanization. This process has been multiply applied for the methanization of the carbon monoxide portion in town gas and is at present being provided in the United States particularly for the generation of high-But-gases. The feed line of the pipe system is comparable to a town gas conduit and the return pipe corresponds to a natural gas conduit.

Thus, the meaningful coordination of largely known technological methods of the recent gas technology proves to give rise to the novel system of energy supply in a closed cycle.

PROBLEMS OF ECONOMY

By means of a study /2/ the commercial efficiency of the energy supply system "Nuclear Energy Supply over Long Distances" has been compared with competitive methods. These methods involve the energy distribution by aid of hot water and the production of hot water by aid of fossil primary carriers especially with fuel oil.

True, the results of the study give proof of the fact that the transport of energy by means of latent heat gas is more expensive than that of natural gas, but that it is far more economical than the transport of energy by aid of hot water or than the transport of electricity.

Altogether it can be proved that the transport distances between the HTR energy generator and the energy consumers of say more than 50 kilometers the "Nuclear Energy Supply over Long Distances" is the most economical energy supply system and, particularly, if in addition to the production of hot water for domestic heating and industrial purposes electricity is being generated as well (known as Wärme-Kraft-Kopplung).

The energy supply system "Nuclear District Energy over Long Distances", consisting of the high-temperature reactor, the EVA/ADAM transport system with the latent heat gas synthesis gas/methane, at short date offers the possibility of utilizing nuclear energy with a view to a sufficient, economical, safe and ecologically beneficial supply of the energy market with thermal energy in the form of hot water and water vapour and with electricity.

REFERENCES:

/1/ SCHULTEN, R.; KUGELER, K.; BARNERT, H.: Nuclear Energy Transport over Long Distances - Recommendations for the Supply of the Heat and Electricity Market with Energy by an Interconnection System. KFA-Paper, January 1974.

/2/ BOHN, Th.; DIETRICH, G.; KUGELER, K.; KUGELER, M; NIESSEN, H.F.; SCHLENKER, H.V.: Nuclear District Heat and Nuclear Energy Supply over Long Distances. JÜL-1077, June 1974.

ACKNOWLEDGEMENT

The authors wish to point out that the system descirbed in this paper is based on the following inventions:

1. Deutsche Offenlegungsschrift 1.601.001: "Verfahren zum Speichern von Wärmeenergie oder von durch radioaktive Strahlung oder Neutroneneinwirkung erzeugter Energie", Anmeldetag: 17.2.1967, Offenlegungstag: 13.5.71, Anmelder: Kernforschungsanlage Jülich GmbH, Erfinder: H.W. Nürnberg, G. Wolff.

2. United States Patent 3,558,047: "Energy Conversion Method", H.W. Nürnberg, G. Wolff.

3. Deutsche Patentschrift 1.298.233: "Verfahren für den Transport von Wärmeenergie", Anmelder: Rheinische Braunkohlenwerke AG, Köln, Erfinder: F. Hilberath, H. Teggers.

The system has been described in:

1. Jahresbericht 1967 der Kernforschungsanlage Jülich, Seite 175: H.W. Nürnberg, G. Wolff: "Nukleare Prozeßwärme"

2. Jahresbericht 1973 der Kernforschungsanlage Jülich, Seite 21: H. Barnert: "Nukleare Fernenergie"

C 2

"COLD" STORAGE/TRANSPORT OF THERMAL ENERGY UP TO 260 °C

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Abstract

The substances containing hydrogen-bond seem to be preferred for the "cold storage" and "cold transport" of thermal energy in the range of up to 260 °C. The criteria for selecting these substances are discussed. For the sake of illustration, the following systems are discussed in more details:

(a) storage of thermal energy of ~260 °C for power peaking with the help of latent heat of eutectic of sodium hydroxide,
(b) ammonia-water system for space heating cold storage and transport,
(c) ammonia-molten salt (e.g. aluminium trichloride-sodium chloride eutectic) as a system for power peaking storage and/or cold transport of heat for industrial users of steam (~260 °C, 60 bar) and/or district heating by means of railway transport.

1. NEED FOR STORAGE OF THERMAL ENERGY

The storage of the energy is a trivial problem in case when:

(a) the carrier of primary energy is a chemical agent (e.g. coal, oil, gas) and is relatively cheap,
(b) the converting machine, which converts the chemical energy into the useful form of energy, e.g. heat (furnace), electrical energy (steam generator, turbine, electrogenerator) are simple and/or cheap.

The period of these carriers of energy is going to be finished. The primary energy in the future has the following properties:

(a) cannot be stored, e.g. solar energy,
(b) the converting machine is very expensive, e.g. nuclear steam generator (fission power reactor).

In this situation the storage of secondary energy begins to play a more important role. The problem of storage of different forms of secondary energy has been discussed in the literature:

- electrical energy in form of batteries, supraconducting circuits,
- mechanical energy in form of flying wheels, compressed air, liquid air, hydro-pumping stations,
- chemical energy in form of reacting agents,
- heat energy in form of steam / hot water containers, melted salts, hot water pools.

The aim of this paper is to discuss the storage of heat energy in form of weak chemical energy especially in connection with the most abundant energy source in form of light water reactors (LWR) power stations which produce the energy in form of steam with a temperature of ~280 °C and a pressure of ~70 bar.

For the sake of illustration, see the energy spectrum in Switzerland in the next future (Fig. 1).

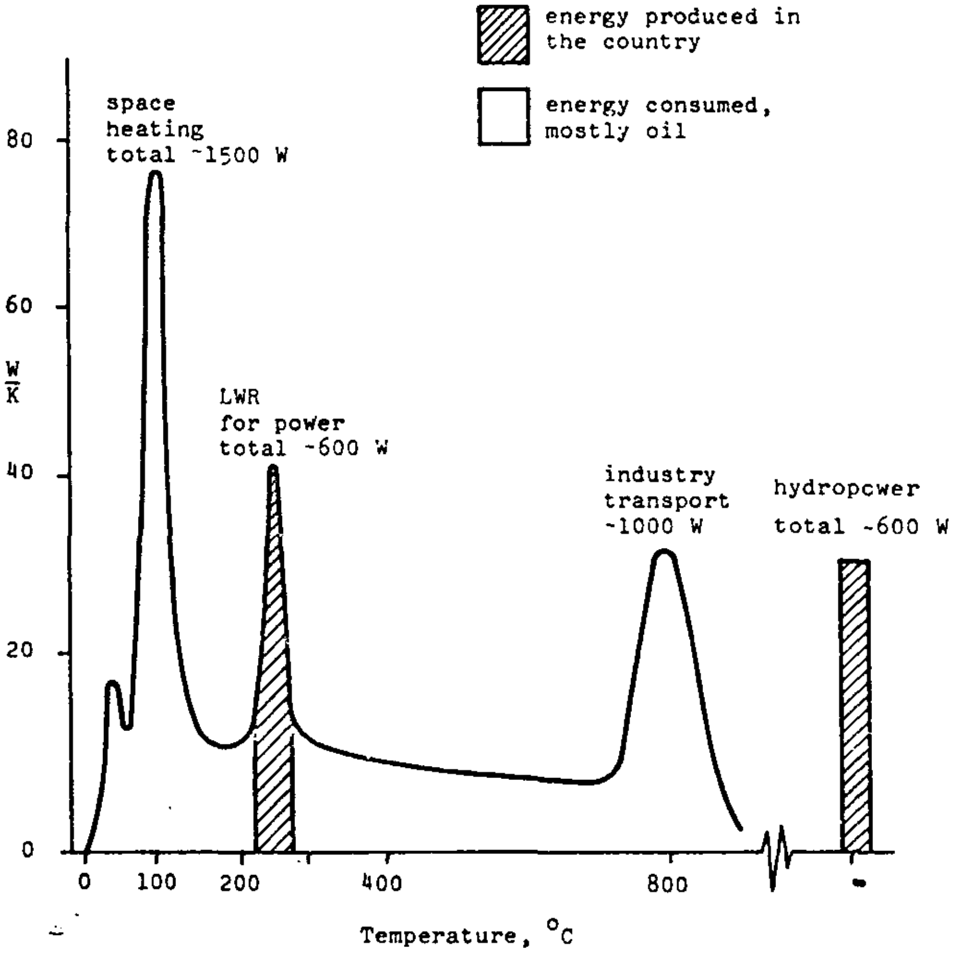


FIG. 1: "Spectrum" of produced and used energy in Switzerland in the future. Minimal case: 4 kW/capita

2. STORAGE OF THE THERMAL ENERGY

The possibility for storage of the thermal energy is given by the following mechanisms:

$$\Delta H_{tot} = \Delta H^{sol} + \Delta H^{melt} + \Delta H^{liq} + \Delta H^{boil} + \Delta H^{chem}$$

ΔH = change of enthalpy (kJ/kg)
sol = solid state
melt = melting
liq = liquid state
boil = boiling
vap = vapour state
sen = sensible heat
lat = latent heat

$$\Delta H^{sol} = \int_{T_1}^{T_{melt}} C_p^{sol} \cdot dT; \quad H^{liq} = \int_{T_{melt}}^{T_{max}} C_p^{liq} \cdot dT$$

T_1 = lower temperature

C_p = specific heat capacity (kJ/kg·K)

$\Delta H^{melt} = T^{melt} (S^{liq} - S^{sol}); \Delta H^{boil} = T^{boil} (S^{vap} - S^{liq})$

S = entropy (kJ/kg·K)

$\Delta H^{chem} = \Delta G + T\Delta S$

ΔG = free enthalpy of chemical reaction

Of course, in a real device only some of these partial enthalpies can play the decisive role. In this paper, the problem of the use of the enthalpy of selected chemical reactions is discussed. The following arbitrarily chosen parameters limited strongly the class of possible chemical agents for the storage of thermal energy:

(a) the temperature region is limited by ~270 °C that is the steam conditions produced by light water reactors.
(b) the sink of the heat is given by the environment that is in some cases up to -10 °C, but also by the temperature of the heat waste from thermal power stations that is ~35 °C.
(c) the system should work in a closed material cycle, that is without material wastes and material pollutions, with only one material input for the inventory.
(d) the carriers of energy react in full reversible manner and the kinetic of reaction is fast enough. For the sake of simplicity the chemical reaction is given by

$$A + B \longrightarrow C + \Delta H^{chem}$$

$$C + \Delta H^{chem} \longrightarrow A + B$$

where A, B and C are the chemical agents.

(e) for simple technological reasons the pressure should be lower than ~20 bar (~2 MPa).

(f) also the following selfevident parameters are included:
- low price of chemical agent (per mole)
- good knowledge of thermodynamical data
- good corrosive behaviour
- low impact of the environment.

The use of chemical agent forheat storage is a special case in the spectrum of all possible systems (Table I, Table II).

For the chemical agents as carriers of heat energy can be used some of the chemical bond types: ionic, covalent, hydrogen-bond and wanderwaals (Fig. 2).

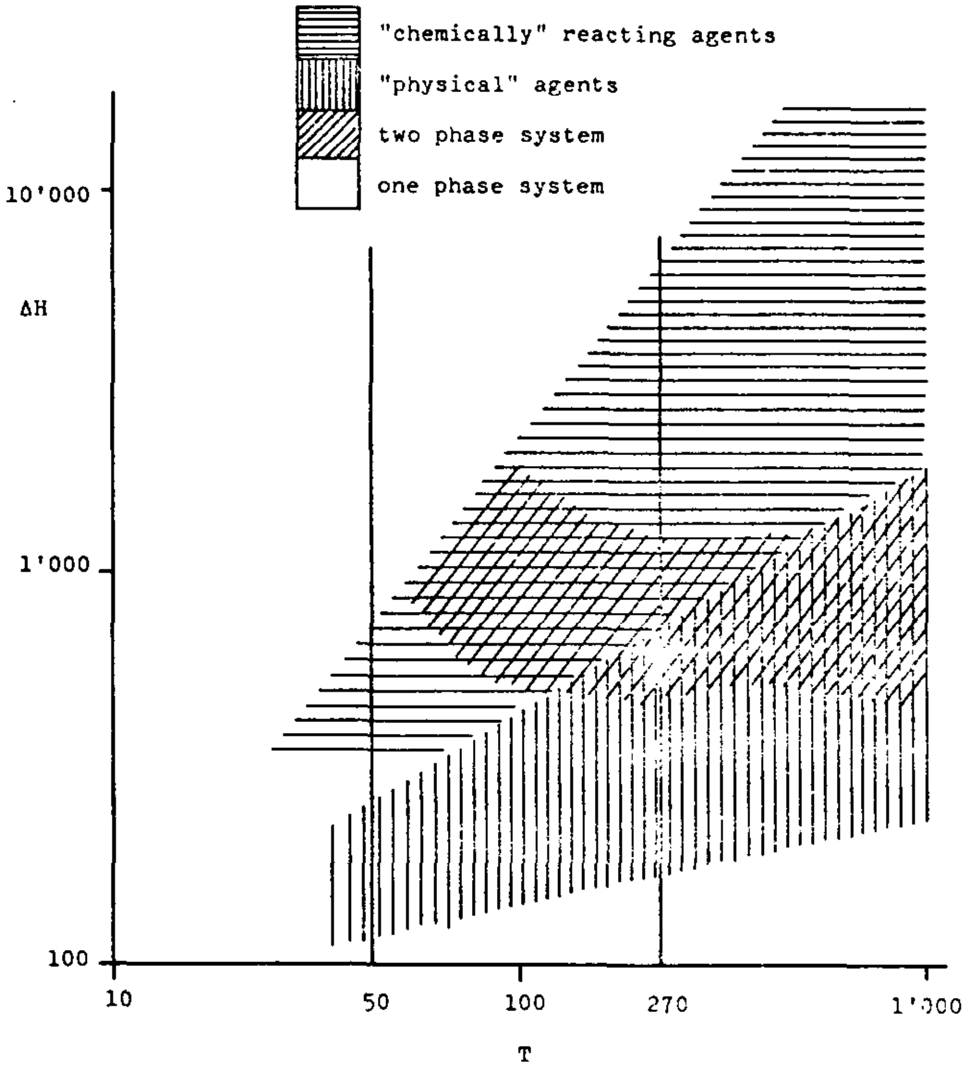


FIG. 2: "Chemical" and "physical" agents
ΔH; Enthalpy (kJ/kg)
T; Temperature (^{o}C)

		Number of chemical individuums	
		one	two or more
Number of phases	one	sensible heat $\Delta H = C_p \cdot \Delta T$ *	$\Delta H^{chem} = \Delta G + T\Delta S$ controlled by additional phase in form of catalysator **
	two or three	latent heat $\Delta H^{melt} = T^{melt}(S^{liq} - S^{sol})$ $\Delta H^{boil} = T^{boil}(S^{vap} - S^{liq})$ *	$\Delta H^{chem} = \Delta G + T\Delta S$ two individiums simple for separation: e.g. one: volatile; second: non volatile **

Table I: Classification of the carriers of the heat storage system (see also Fig. 1)
* "physical" carriers
** "chemical" carriers

		Number of chemical individuums	
		one	two or more
Number of phases	one	water Schöll 8)	Reacting gases Schulten 10)
	two or three	melted fluorides Schröder 9)	volatile and non-volatile agents Alefeld 1) Taube 14 - 20)

Table II: Some examples of the carriers of the heat storage systems

3. STORAGE OF THERMAL ENERGY WITH HYDROGEN-BOND CONTAINING AGENTS

Because of the limitation from the side of the light-water reactors, which produce steam with temperature ~ 270 oC, the validity of the hydrogen-bond containing agents is self-evident (Fig. 3).

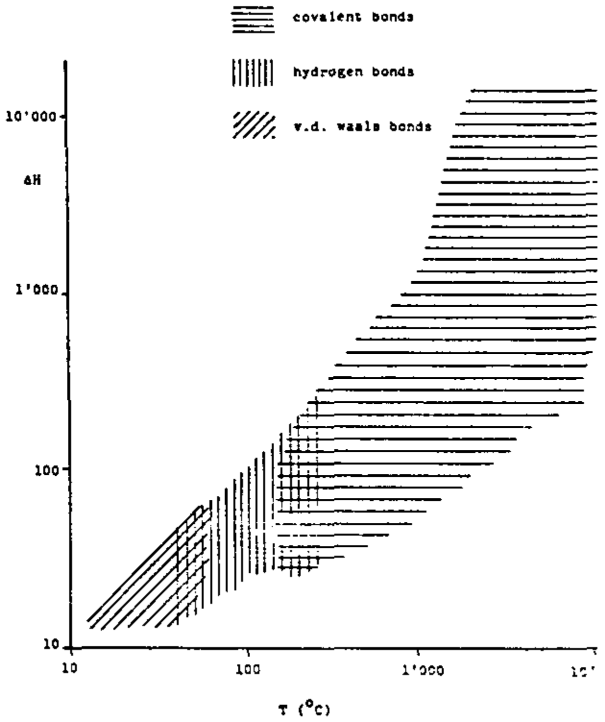


FIG. 3: Types of chemical bonds

But only a limited class of chemical individuums include the hydrogen-bond contrarily to the ionic and/or covalent bond which are the universal chemical bond types.

The following chemical individuums include the hydrogen-bond:

(a) Molecule must include hydrogen atom.
(b) This hydrogen atom must be directly bonded with one of the electronegative elements which have a small atomic radius. These are: fluorine, oxygen, nitrogen, and partially chlorine, sulfur (Fig. 4).

Because of selfevident technological reasons, the following conditions must also be fulfilled:

(a) The molecule must have a small mass.
(b) Stability in a given range of temperature.
(c) Other properties mentioned in 2a) - 2f).

The selected molecules are given in Table III. Because of the above all given criteria the choice falls on the ammonia. But, of course, this choice is partially arbitrary and can be thought only as an illustration for the discussed problem.

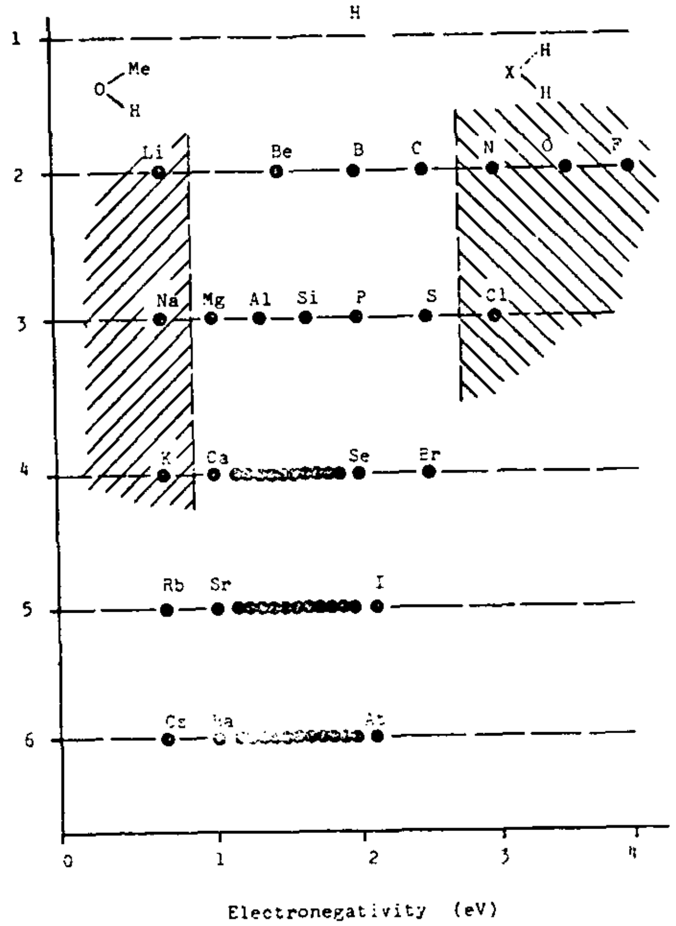


FIG. 4: Electronegativity of elements and hydrogen bond

Atomic number		4	5	6	7
		C	N	O	F
Hydride and mass		CH_4, 18	NH_3, 17	OH_2, 18	FH, -20
		methane	ammonia	water	hydrogen fluorine
Number of possible H-bonds		0	2	4	2
Temp. °C	melting	-182.5	- 77.7	0.0	-83
	boiling 1 bar	-164.0	- 33.3	100.0	-19.5
Critical parameter	Temp. °C	- 82.3	132.0	374.2	188
	Pressure bar	46.6	113.0	218.3	66.2
Heat of vaporization (kJ/kg)		-500	-1370	-2250	-370

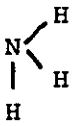
Table III: Properties of some selected hydrides of light electronegative elements (candidates for volatile hydrogen-bond carriers)

Atomic	Z	3	11	19
number	element	Li	Na	K
Hydroxide	formule	LiOH	NaOH	KOH
	name	lithium hydroxide	sodium hydroxide	potassium hydroxide
Temperature °C	melting	450	319.1	360
	boiling	924	1390	1320
Heat of melting (kJ/kg)		431	159	148
Phase transition (kJ/kg)		-	159 at T=292.8 α/β	-

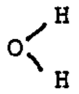
Table IV: Properties of some selected hydroxide of alkaline metals (candidates for non-volatile hydrogen-bond carriers)

The hydrides of electronegative, small radius elements are not the only class of hydrogen-bond containing individuums. The other class are the hydroxide of alkaline metals which can be shortly described per analogiam as follows:

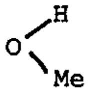
ammonia



water



hydroxide of alkaline metal, Me



The Table IV gives the most probable candidates.

It must be stressed that in the here discussed case the heat energy storage system includes two chemical individuums (see Table I and II). If the one of them is the volatile hydrogen-bond containing agent (see Table III), another non-volatile agent must be used. For several reaons (see Alefeld, 1975), the system with ionic salt seems to be very attractive.

Some, more or less arbitrarily chosen candidates are given in Table V. Because in this paper the impact of the kinetics of the chemical reaction has been postulated as one of the crucial limitation, the use of molten salt carriers seems to give the desired solution, therefore, in Fig. 5 are given the melting points of the selected salts, from which the special situation of the aluminium trichloride is simple to see. Therefore, for further consideration, the system with aluminium trichloride has been selected. Unfortunately, there is no data about the ternary system: NH_3 - $AlCl_3$ - NaCl.

		Fluorides			Chlorides		
		alkali metals	alkaline earth metals	metals of III group	alkali metals	alkaline earth metals	metals III group
Row in	1.	LiF			LiCl		
periodical	2.	NaF	MgF_2	AlF_3	NaCl	$MgCl_2$	$AlCl_3$
table	3.	KF	CaF_2		KCl	$CaCl_2$	
Melting	1.	845			610		
point	2.	995	1263	1272	808	714	192
°C	3.	856	1418		772	782	

Table V: Properties of some selected ionic salts (Candidates for non-volatile carriers for the volatile hydrogen-bond containing agents)

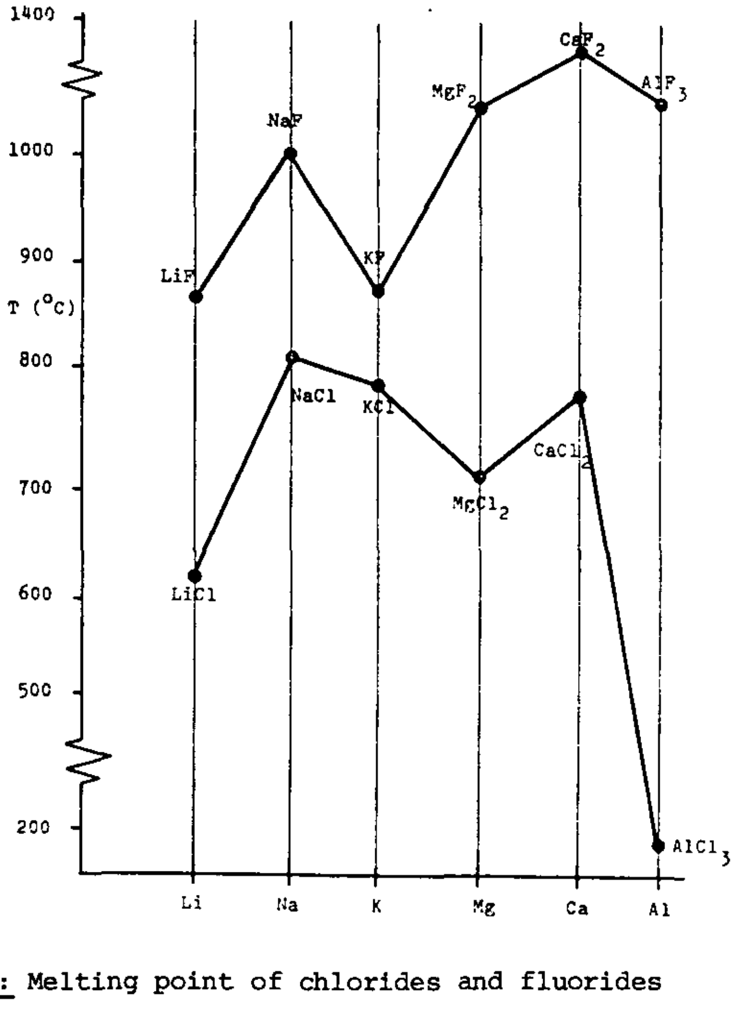


FIG. 5: Melting point of chlorides and fluorides

4. HEAT STORAGE WITH CHEMICAL AGENTS ALLOWS THE "COLD" STORAGE

Here is discussed the heat storage with the use of a couple of chemical agents.

A - volatile hydrogen-bond containing agent
B - non-volatile (less volatile) agent
C - product of the reaction $A + B \longrightarrow C$

The following scenario describes the principal scheme of "cold" storage (Fig. 6).

(1) The heat from the heat source (producer) with temperature T_{max} (e.g. steam from LWR: $T_{max} \cong 270\ ^{o}C$ or from back-pressure turbine $T_{max} \cong 120\ ^{o}C$) is used for heating the substance C, the product of the reactions between A and B, from the temperature T' (environment temperature) to the temperature T" ($T'' \leq T_{max}$) and the separation process could be realized

$$C \xrightarrow[+\ \Delta H]{\text{separation at } T''} A + B$$

(2) The volatile agent A can be separated from the non-volatile (or less volatile) agent B.

(3) Both agents: A and B have been cold from T" to T', the heat of this cooling stage and condensation of the A can be used for external users or for internal use (recuperation).

(4) Both agents: A and B, now in separated and in cold state are stored or/and transported in the "cold" state that is in the environment temperature. Remark: agent A is in liquid state under pressure (probably with pressure ~ 20 bar)!

(5) Both agents: A and B are contacted. Before this reaction the volatile agent A must be vaporized. The boiling enthalpy must be taken from the "environment" (e.g. riverwater with $T > 5\ ^{o}C$, waste heat from thermal power station, $T > 35\ ^{o}C$, other heat waste).

(6) The reaction of $A_{gas} + B_{sol(liq)} \longrightarrow C_{liq} + \Delta H_{chem}$ results in emission of reaction enthalpy ΔH_{chem} which is used for heating the product C. The "warm" product C gives the heat to the secondary heat carrier, e.g. hot water for space heating. The temperature of this reaction

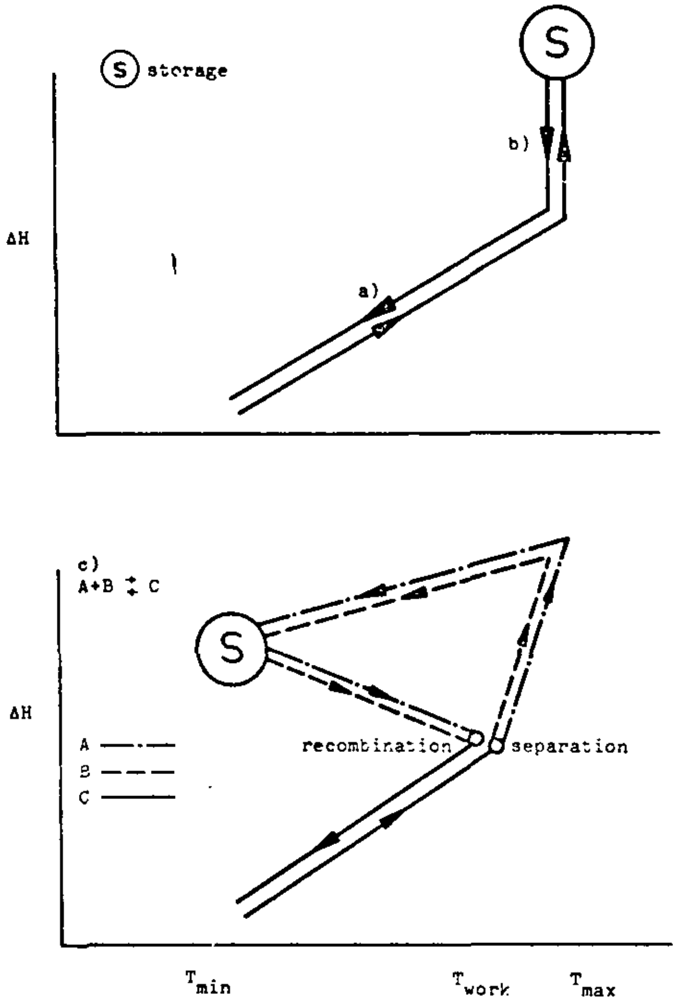
$$T' < T''' \leq T''$$

(7) The liquid product C at temperature $\sim T'$ is stored and/or transported from the heat consumer to the heat producer. The process can be closed; see point (1).

Fig. 7 shows the thermal history of the different agents used for heat storage.

(a) "physical" agent with sensible heat only
(b) "physical" agent with latent heat
(c) "chemical" agent able for "cold" storage

FIG. 6: Scheme of heat storage



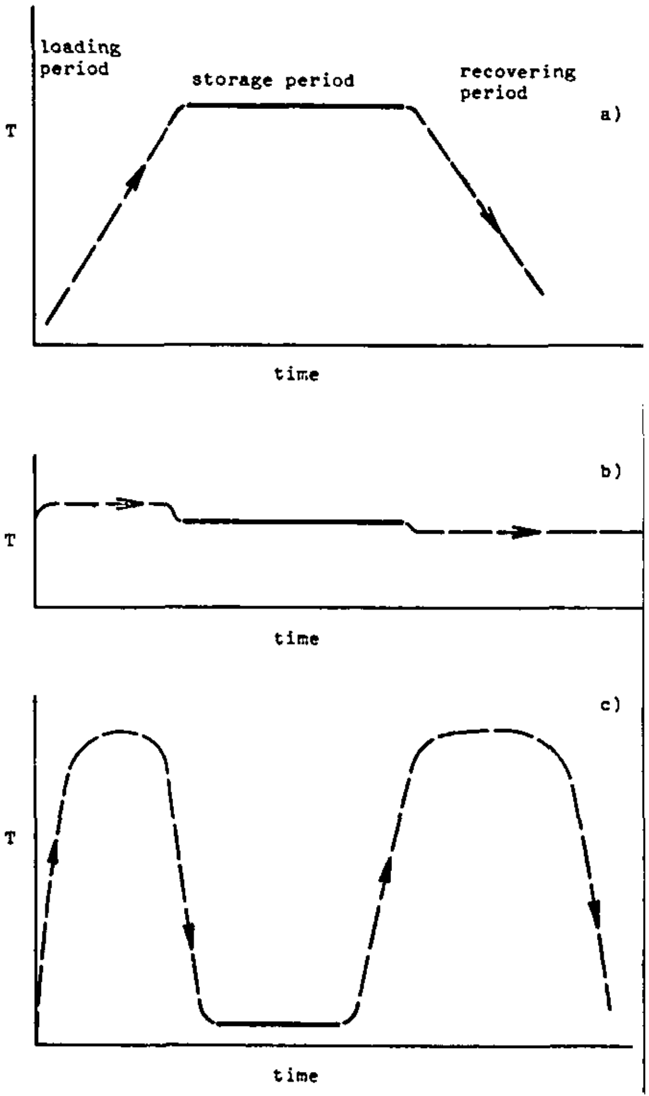


FIG. 7: Temperature of the medium

This unique property of the chemical carriers as heat storage agent make the following operations possible:

(a) shifting in the time, that is the storage in cold state,
(b) shifting in the space, that is the transport in cold state,
(c) shifting in the entropy, that is use the environment and/or waste heat for heat pumping.

5. STORAGE OF THE THERMAL ENERGY FOR POWER PRODUCTION WITH THE HELP OF LATENT HEAT CARRIER

Here is given the simple example of the heat storage by means of a hydrogen-bond containing a non-volatile, low melting agent: sodium hydroxide.

The following peculiarities of this agent are here of importance:

- The relative low melting point of ~319 °C, which can be decreased to the desired temperature of ~ 260 to 270 °C by using an appropriate eutectic mixture. The temperature of ~ 270 °C is given by the steam conditions from LWR.

- The relative high melting enthalpy of ~ 160 kJ/kg and the in the neighbourhood existing phase transmission of alpha/beta solid phases with ~292 °C for pure NaOH and probably very near to the postulated eutectic point of ~ 260 to 270 °C. The enthalpy of phase transmission is also equal 160 kJ/kg. Here has been taken into account the sum of both enthalpies: melting and alpha/beta phase transmission; that is ~320 kJ/kg. The probable decrease of the enthalpy by enthalpy of solution for the eutectic have been postulated as practically negligible /17/.

A simplified calculation has been made for a nuclear power plant, with a total power of 1 GW(el) with LWR. Postulated storage power capacity of ~0.6 GW(th) over a period of 10 hrs that is a total capacity of 6 GWhr(th). This heat can be recovered for production of ~ 1.65 GWhr(el) as 0.3 GW(el) during 5.5 hrs. The system works in the following manner /7/:

(1) At night, when the needed power level decreases to 0.8 GW(el) the rest of steam, from the nuclear steam generating system, at ~280 oC is used for heating in a heat-exchanger (Fig. 8 a). The steam condenses in the tubes and is pumped back to the system. On the shell side of this heat exchanger, flows in opposite direction a suspension of a certain portion of solid eutectic, suspended in the melted eutectic of NaOH. The temperature of the inlet suspension equals 260 °C in the heat exchanger outlet the eutectic comes competely liquid, at approximately the same temperature. The enthalpy of steam/water condensation has been made for the solid/liquid melting of the salt.

(2) The liquid eutectic is then stored in an insulated tank (T = 260 °C) (Fig. 8 b).

(3) During the day peak time the liquid eutectic from the tank flows again on the shell side of the heat-exchanger. On the tube side flows hot

water from the nuclear steam system and evaporates into the steam. In order to obtain a superheated steam the conditions have been selected as: 240 °C, 10 bar. This steam flows to the steam turbine.

(4) This system has some critical points. During the restitution of the stored heat the liquid eutectic flows through the heat-exchanger and partially cristalizes. The obtained cristals can result in the incrustations on the surface on the tubes in the heat exchanger, which reduces strongly the heat transfer, and in the end can block the channels.

(5) Possible solution of this difficulty can be the one of the following:

- control the crystallization rate by means of adding some surface active agents.
- clad the tubes with hydrophilic materials, e.g. teflon.

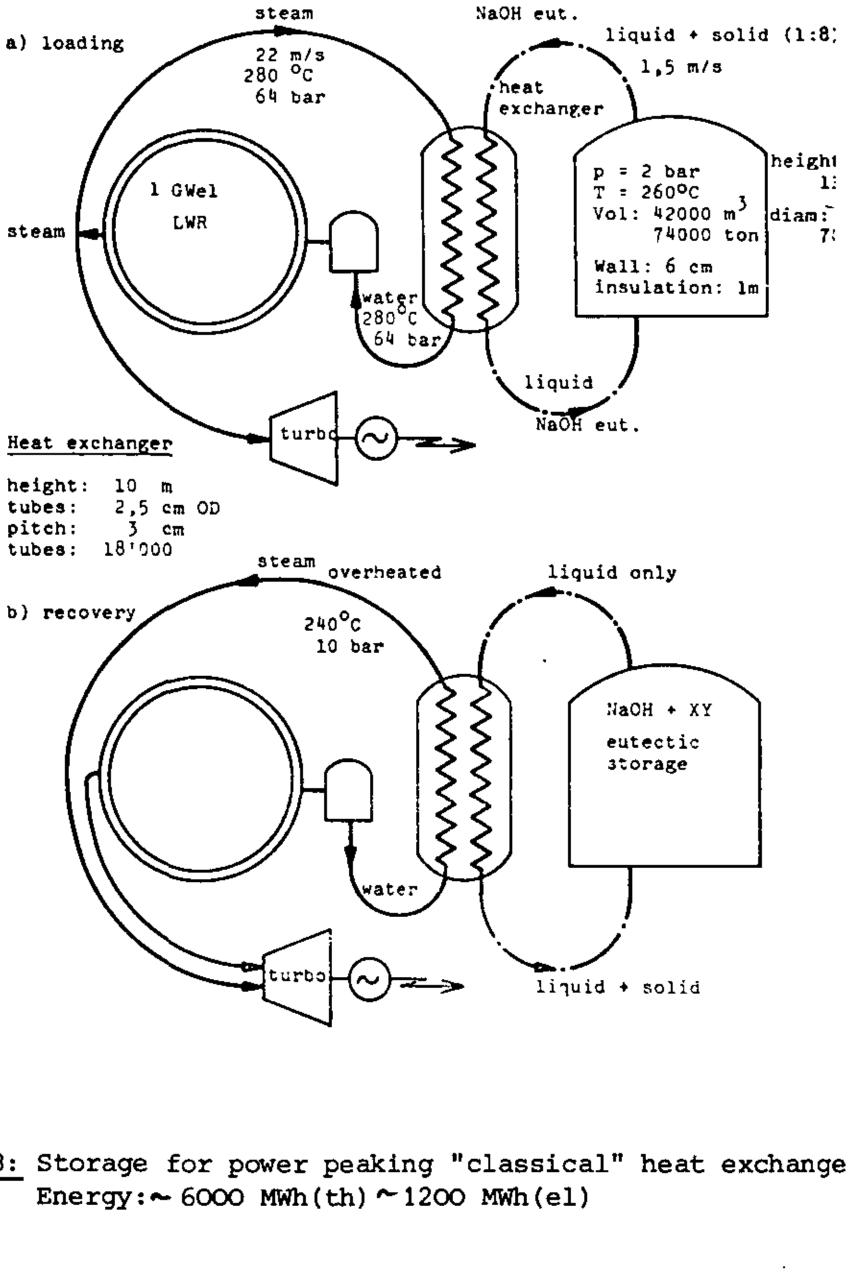


FIG. 8: Storage for power peaking "classical" heat exchanger
Energy: ~ 6000 MWh(th) ~ 1200 MWh(el)

Because of these difficulties another slightly modified system has been proposed /18, 19/ (see Fig. 9). The heat-exchanger between liquid eutectic and water/steam has been eliminated and an intermediate heat circuit has been added. The heat form and the liquid eutectic is transported to a vapour/liquid chemically inert agent e.g. octaine C_8H_{18}. Fig. 9 gives some estimated data for this system. It is quite evident that this system presents in turn some other critical points:

- the chemical stability of the volatile inert agent, octane with molten sodium hydroxide,
- separation of both agent in a liquid state (Fig. 9 b).

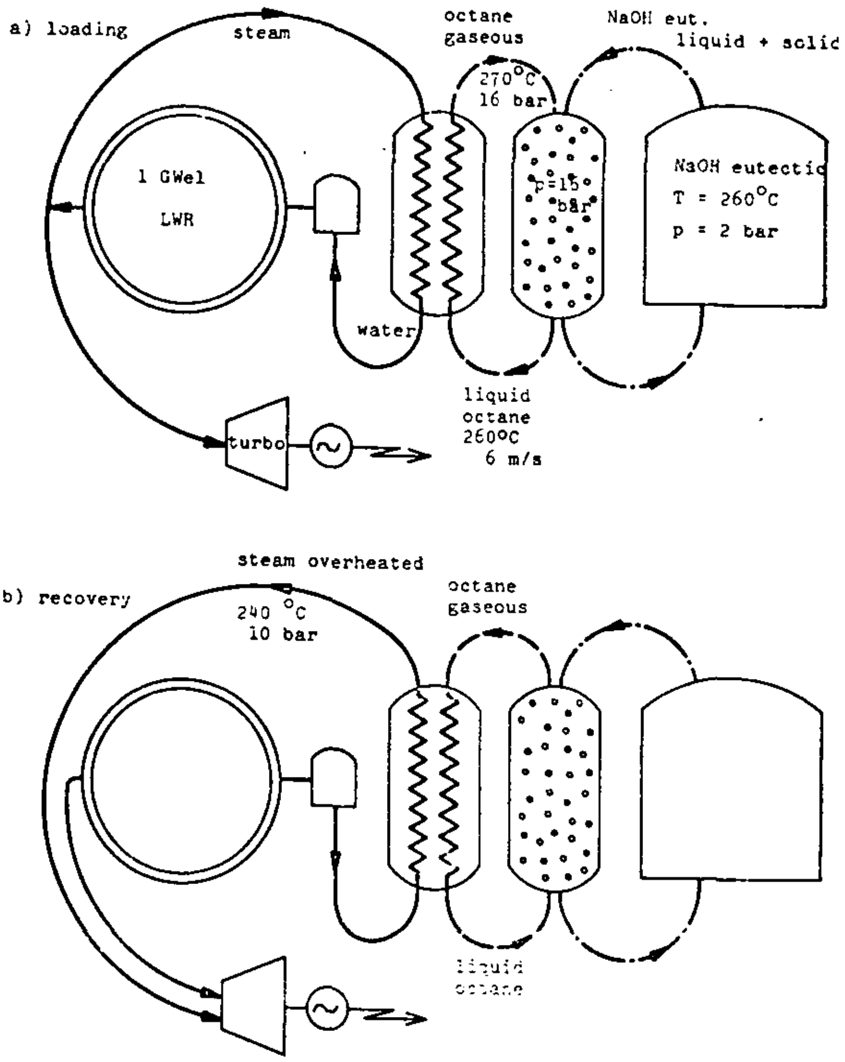


FIG. 9: Storage for power peaking with direct gas/liquid heat exchange (see Fig. 8)

Here must be stressed that in recent papers a case analogue to our proposal has been made by F.P. SUNDY (private information, see /12/). The heat from a high temperature gas cooled reactor of 2.4 GW(th) is partially stored in a "heat bank" with a molten salt mixture, for peaking power of 0.6 GW(th) at 680 °C. The heat from this molten salt is removed by liquid drops of lead (T_{inlet} = 370 °C, T_{outlet} = 670 °C) and used for steam generation at 530 °C. The use of molten lead drops is explained by the author: "to circumvent the reduced heat transfer coefficient encountered in a dense layer of solid salt buildup around heat exchanger tubes in the usual configuration".

It is worthwhile to remember that the use of liquid lead for heat removal from molten salt has been proposed long time ago by an English team for fast molten salt reactors /11/ and by a German team for thermal molten salt reactor /3/. The use of boiling salt ($AlCl_3$) and boiling mercury (Hg_{met}) for heat removal from molten salt fast reactor has also been proposed /13/.

6. AMMONIA-WATER SYSTEM FOR COMPLEX SPACE HEATING, COOLING AND COLD TRANSPORTATION

Here is discussed a system of the volatile hydrogen-bond containing agent: ammonia and non-volatile: water /5,6,14,16/. In the year 1919, L. PFEIFFER has claimed that the ammonia water system can be useful as agent for space heat transport (Patent Nr. 351009). The temperature range of this system is from -10 °C up to +120 °C. The system works in the following manner (Fig. 10):

(1) Loading period: the steam from back-pressure turbine from LWR, with ~90 to 130 °C is used for the separation of an aqueous solution of ammonia (distillation) under pressure of ~6 to 10 bar; the products being: gaseous ammonia and liquid depleted aqueous solution (water with some amounts of NH_3).

(2) The products are cooled and stored by ambient temperature (ammonia in liquid state ~ 10 bar). The separated components can also be transported in "cold" state to the user.

(3) Restitution period: the liquid ammonia is evaporated (the heat source river water, heat waste or partially from the refrigerators) and then reacts with cold water. The process of the reaction of gaseous ammonia with water is egzoenergetic ($\Delta H \cong 1200$ kJ per kg NH at ~ T = 100 °C). The temperature of the water-ammonia solution increases up to 80 to 100 °C according to the parameters used for separation and for ammonia evaporation. The heat is removed and given to the local space heating system. The cold aqueous ammonia solution is stored and transported back to the heat producer (see point 1).

Because the ammonia is in a high concentration rather hazardous, also a modified system has been proposed /15/ in which the:

- volatile hydrogen-bond containing agent is H_2O,
- non-volatile agent is NaOH.

This system can be used only in the temperature range 40 °C $<$ T $<$ 120 °C.

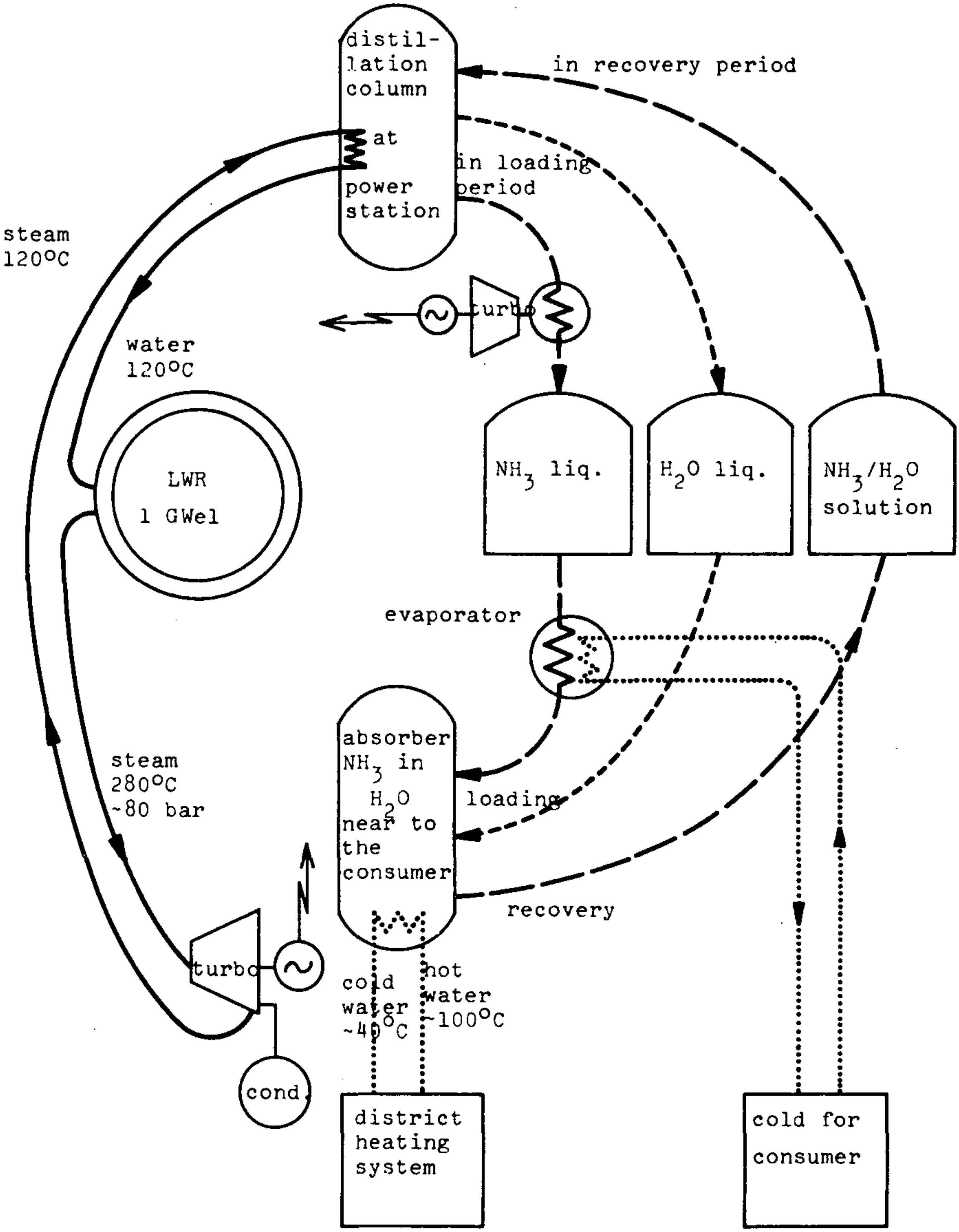


FIG. 10: Ammonia-water system for district heating local cooling and cold storage

7. HEAT STORAGE BY AMMONIA-MOLTEN SALT SYSTEM

7.1 Storage for power peaking and industrial steam users

The storage of heat energy for peaking power by means of ammonia-solid salt system has been described by /1/. The data obtained are very encouraging (Table VI). No thermodynamical data has been shown.

The analogue system for power peaking and industrial remote use of steam ~10 bar has been calculated /2/ and shown in Fig. 11. The system is rather complicated because of the effort of using a heat pump for restitution of heat waste during the night for the power peaking production in day-time.

7.2 Transport of space heating agents by railway

The specific enthalpy pro mass unit for ammonia-molten salt system in ~ 100 °C is high enough for thinking of a remote transport to a small user by railway, in the case, when the cost of the infrastructure of district heating cannot be paid by the too small and too remote users.

In this case, but also in the case of the industrial users of 10 bar-steam (7.1), the use of molten salt instead of solid salt seems to be of importance.

As has been shown in Fig. 5 one of the lowest melting points shows the aluminium trichloride, $AlCl_3$. The same salt in a mixture with sodium chloride gives a low melting eutectic with $T^{melt} = 105\ ^{\circ}C$ (Fig. 12).

The aluminium trichloride reacts rather rigorousily with ammonia (Fig. 13). As a best candidate for our purposes has been arbitrarily selected

$$5\ AlCl_3 \cdot NaCl \cdot 5 \cdot X \cdot NH_3$$

where X is the ratio $NH_3/AlCl_3$ (Fig. 13) and equals 3 to 6.

Once more must be stressed that all these data are given for sake of illustration, no thermodynamical data and phase diagram have been found in the literature.

The pressure of such a system is not known, but the limits can be seen from Fig. 14.

The heat energy can be transported by railway as has been estimated /20/ (Table VII, Fig. 15).

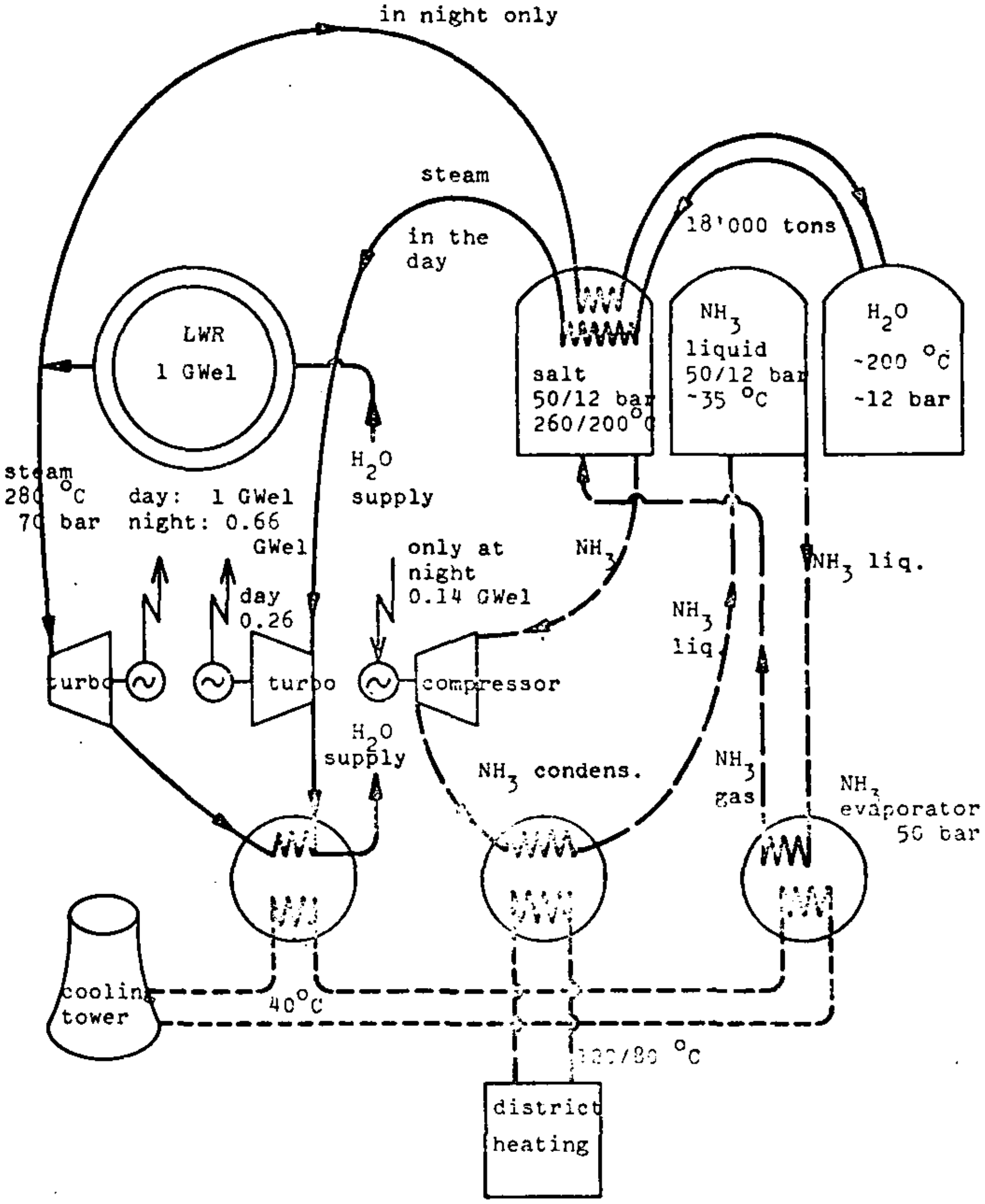


FIG. 11: System salt/ammonia for

a) district heating
b) power peaking

		Working agent			
		H_2(gas)	CO_2	H_2O	NH_3/salt
Heat storage 10 GWhr(th)	Capital 10^6 DM	99	84	181	54
	unit cost DM/KWh(th)	10.9	92	18.1	5.9
Power: 1 GW(th)	relative %	185	156	307	100
Peaking power station 2,5 GWh(el)	capital 10^6 DM	150	135	232	105
	unit cost DM/KWh(el)	66	59	93	45
Power 0,3 GW(el)	relative %	143	128	202	100

<u>Table VI:</u> Heat storage by means of ammonia-solid salt system according to ALEFELD /1/

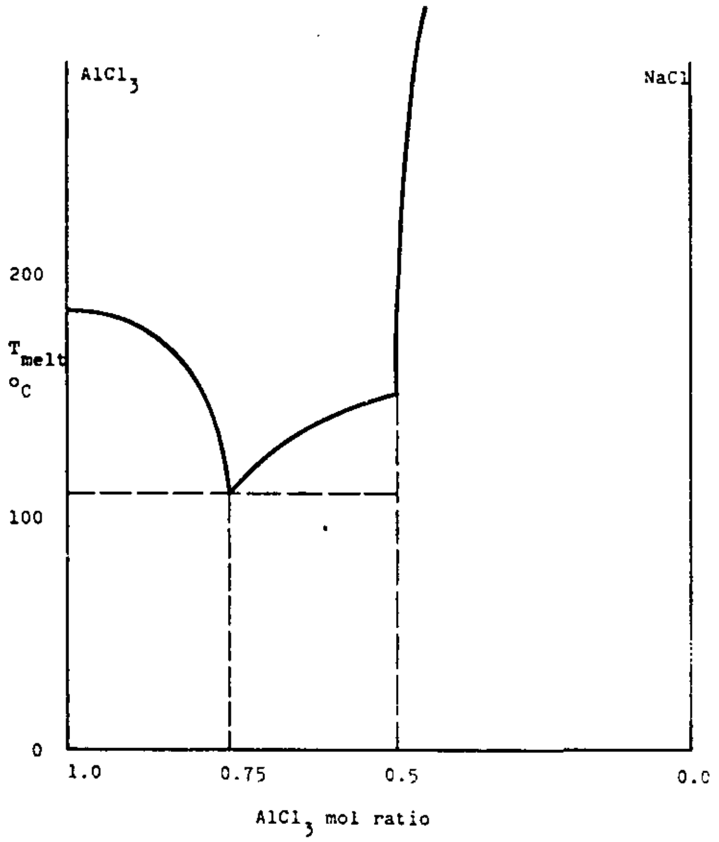


FIG. 12: Aluminium trichloride-sodium chloride

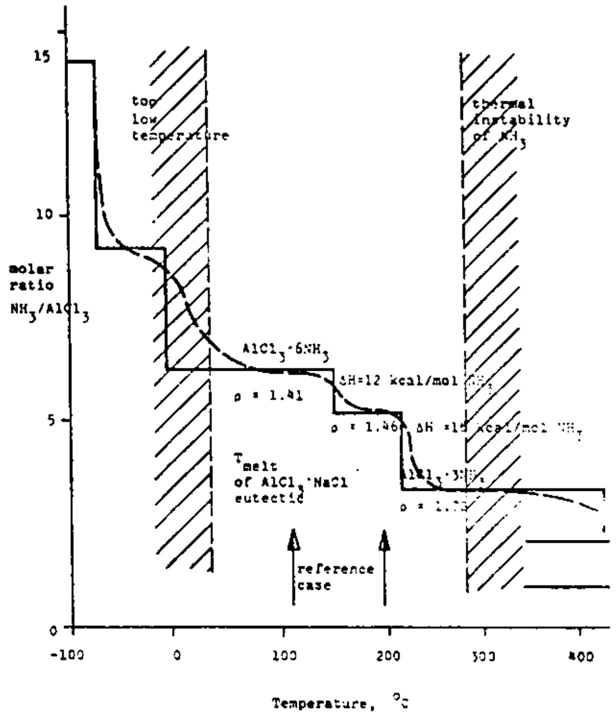


FIG. 13:

Aluminium trichloride - ammonia very roughly

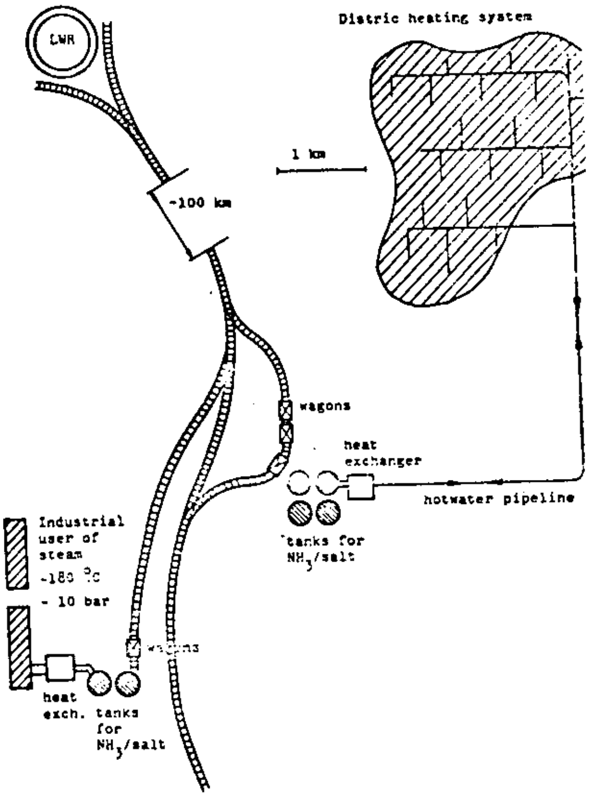


FIG. 14:

Partial pressure of NH_3 over salt-ammonia

	Agent			
	H_2O		NH_3	Oil
	without pressure	pressure ~10 bar	molten salt	
Pressure	<1	~10	~10	<1
Storage at temperature °C	<100	<180	environment	environment
"Working" temperature °C	<95 up to 50	<175 up to 50	<150 up to	very high
Heat capacity kJ/kg	190	520	1500* 800**	20'000***
Way of use	recycling	recycling	recycling	one way
Transport possibilities	insulated tubes	insulated pressure tubes	railway tanks	cars

* in solid $CaCl_2$, according to (4)

** in molten $xAlCl_3 \cdot yNaCl \cdot zNH_3$

*** including 50% efficiency of spaceheating furnace

Table VII: Possible carriers for space heating

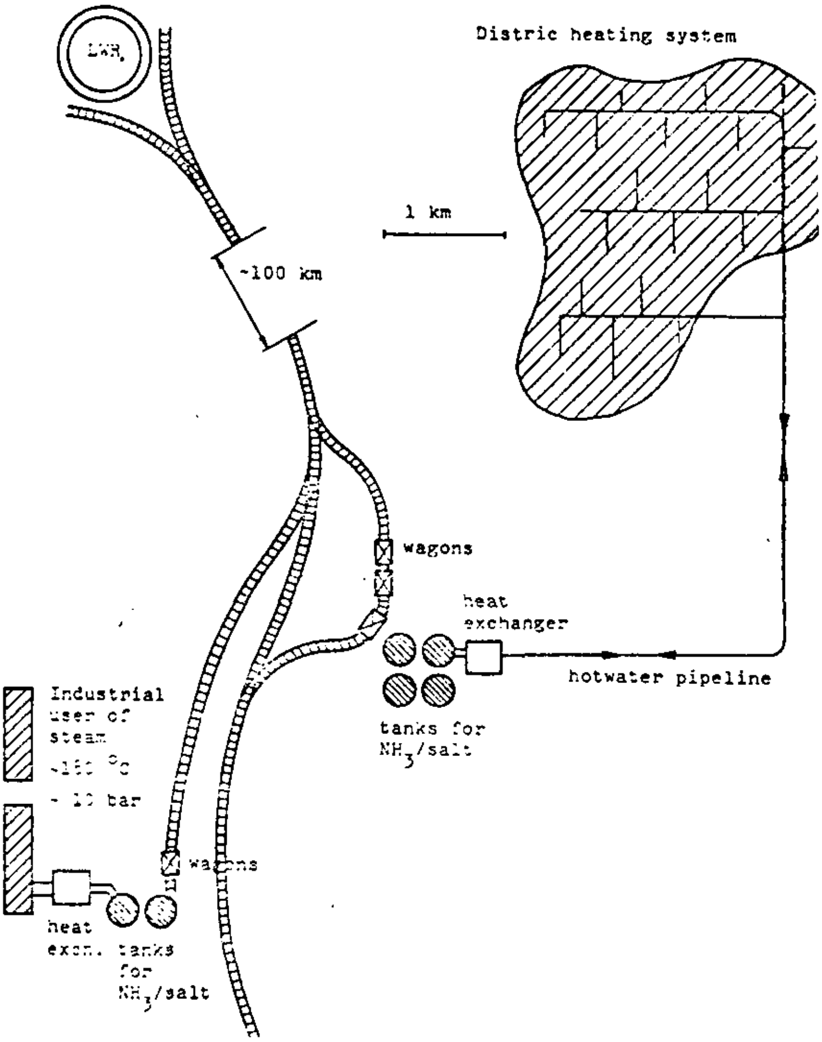


FIG. 15: Railway transport

CONCLUSION

The proposed system for "cold" storage, transport and also for absorption heat pump enlarged the choice of the possible carriers for heat storage in the region up to 270 °C.

The ammonia-water, ammonia-molten salt system seems to be from the point of view of inherent thermodynamical properties rather encouraging.

The technical feasibility seems to be doubtless but detailed studies are necessary.

The economical break-even depends on the evolution of the price of the oil products and of the need for independence.

Remark: In the time for preparation of this paper for printing a further excellent paper of G. ALEFELD has been published /21/. I feel that this paper is rather complementing to than overlapping the discussed problems.

ACKNOWLEDGEMENT

This paper results from many discussion with the following persons:
Dr. Hänny (Sulzer, Winterthur), Prof. G. Sarlos (EIR-Würenlingen), and of course of the co-authors of the EIR-papers: J.C. Mayor, W. Peier, S. Pinto.

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C 3

HYDROGEN PRODUCTION USING NUCLEAR ENERGY PERSPECTIVES AND APPLICATIONS

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- PRESENT DEMAND AND POSSIBILITIES OF SUBSTITUTION
- METHODS OF HYDROGEN PRODUCTION USING NUCLEAR HEAT
- EFFICIENCIES AND ECONOMIC ASPECTS
- ENVIRONMENT ASPECTS
- TIMESCALE OF DEVELOPMENT
- INTERNATIONAL COOPERATIONS AND PROJECTS

HYDROGEN BY END PRODUCT, EEC

END PRODUCT	%
NITROGENOUS FERTILISERS	55
REFINERY USES	23
PLASTICS	8
TEXTILE	4
MISCELLANEOUS	10
ALL USES	100

SOURCE: CONSULT–EUR

HYDROGEN CONSUMPTION BY COUNTRY IN THE EEC 1973

		PROPORTION OF HYDROGEN CONSUMED IN PRIMARY USES %				
COUNTRY	TOTAL HYDROGEN CONSUMPTION '000 TONNES	AMMONIA %	METHANOL %	OTHER CHEMICAL %	MISCELLANEOUS %	REFINERY %
UNITED KINGDOM	540	48	13	8	2	29
W. GERMANY	860	50	17	13	2	18
FRANCE	660 600	62	5	6	2	25
NETHERLANDS	600	73	3	5	2	17
BELGIUM & LUX.	180	66	1	9	2	22
ITALY	535	56	7	3	2	32
DENMARK	15	23	–	–	2	75
IRELAND	12	58	–	–	2	40
TOTAL EEC	3,402	59	9	7	2	23

SOURCE : CONSULT–EUR

RAW MATERIALS FOR HYDROGEN PRODUCTION IN EUROPE

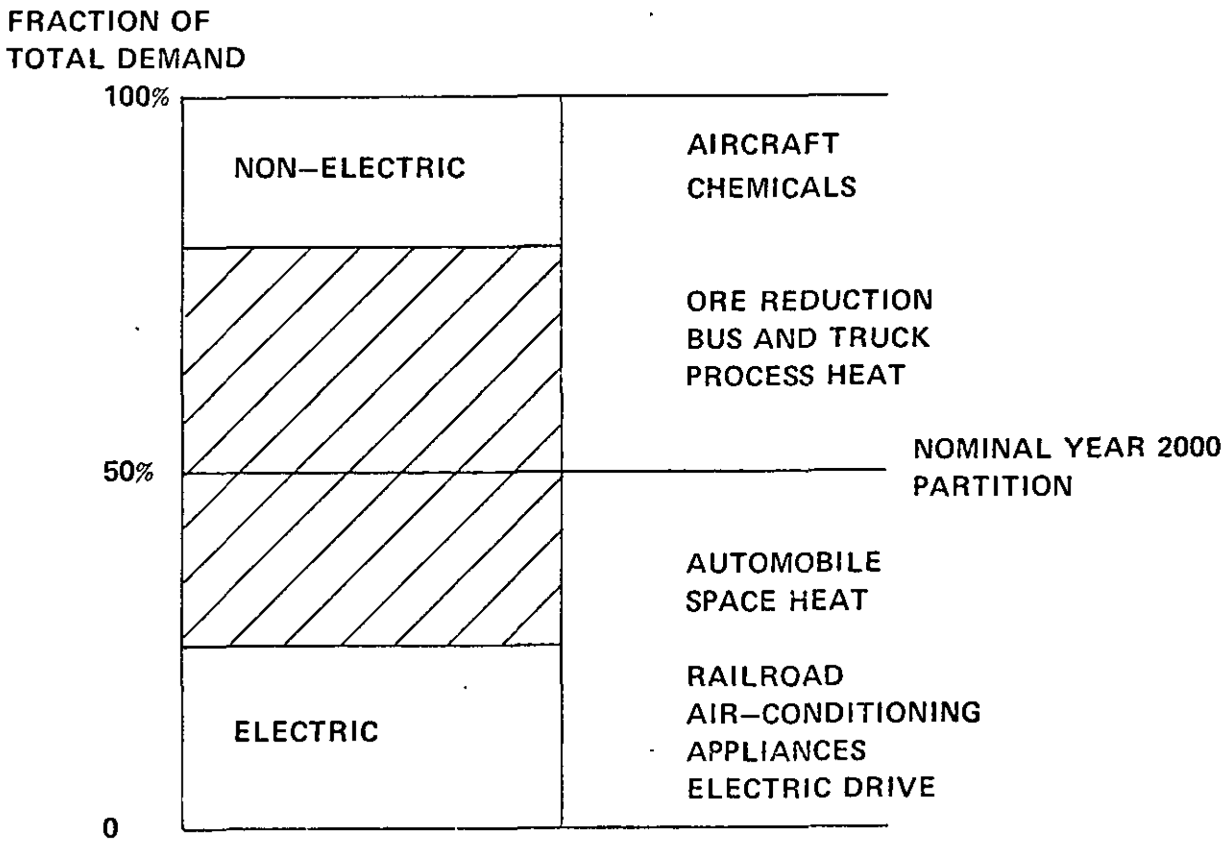
FEEDSTOCK	OVERALL %	AMMONIA SYNTHESIS %
NATURAL GAS	60	71
NAPHTA	26	26
HEAVY FUEL OIL	5	
COKE/COAL	9	3
ELECTROLYTIC	negl.	–
TOTAL	100	100

SOURCE : CONSULT–EUR,ECN

TABLE 2 : FORECAST OF EEC HYDROGEN REQUIREMENTS TO 2000 by primary use - 1000 Tons

	1980		2000	
PRIMARY USE	MIN	MAX	MIN	MAX
AMMONIA	2000	2745	2850	4335
METHANOL	370	450	610	1190
OTHER CHEMICAL & MISCELLANEOUS	230	320	315	840
OIL REFINING	610	610	500	3310
TOTAL	3210	4125	4275	9675

PORTION OF ENERGY SYSTEM BETWEEN ELECTRIC AND NON–ELECTRIC ENERGY FORMS



SOURCE : K.C. HOFFMAN, B.N.L.

POTENTIAL AREAS FOR HYDROGEN USE

TIME		
	MIXTURE WITH NATURAL GAS COAL GASIFICATION – SNG POWER STATIONS : PEAK–SHAVING IRON AND STEEL INDUSTRIAL HEAT	MEDIUM TERM
	AIRCRAFT PROPULSION GROUND TRANSPORTATION SECONDARY FUEL (RESIDENTIAL AND COMMERCIAL) FOOD–PROTEINS	LONG TERM

POTENTIAL MARKET FOR HYDROGEN

- CONSIDERING H_2 CAN SUBSTITUTE 50% OF NATURAL GAS USES,
  HAVING NATURAL GAS AS 20% OF PRIMARY ENERGY DEMAND,
  REDUCING BY A FACTOR 1/2

  POTENTIAL MARKET FOR H_2 IN EEC COULD BE 5% OF PRIMARY ENERGY

- EEC CONSUMPTION YEAR 2000 :

HYPOTHESIS	3,000 Mio tec	3.10^9 tec $2.1.10^{16}$ Kcal/year 2800 GW(t)
5% IS ABOUT	140 GW(t) 50 GW(e)	

USA FORECASTS : YEAR 2000

- D. GREGORY (ATOMIC INDUSTRIAL FORUM
  STATUS REPORT ENERGY RESOURCES AND TECHNOLOGY)

  DEFICIT 50% NATURAL GAS = 33.10^{15} BTU/YEAR

  $\eta = 0.55$

  NEED OF 60.10^{15} BTU/YEAR
  2000 GW(t)
  700 GW(e)

- K. HOFFMAN (BROOKHAVEN NAT. LAB.)

  H_2 DEMAND 8.10^{15} BTU/YEAR
  270 GW(t)
  95 GW(e)

- J. KELLEY (J.P.L. – NASA)

  REFERENCE PROJECTIONS : $5.48.10^{15}$ BTU/YEAR

  EXPANDED PROJECTION : $22.3.10^{15}$ BTU/YEAR
  180 – 750 GW(t)
  60 – 260 GW(e)

METHODS OF HYDROGEN PRODUCTION USING NUCLEAR HEAT

HTGR :

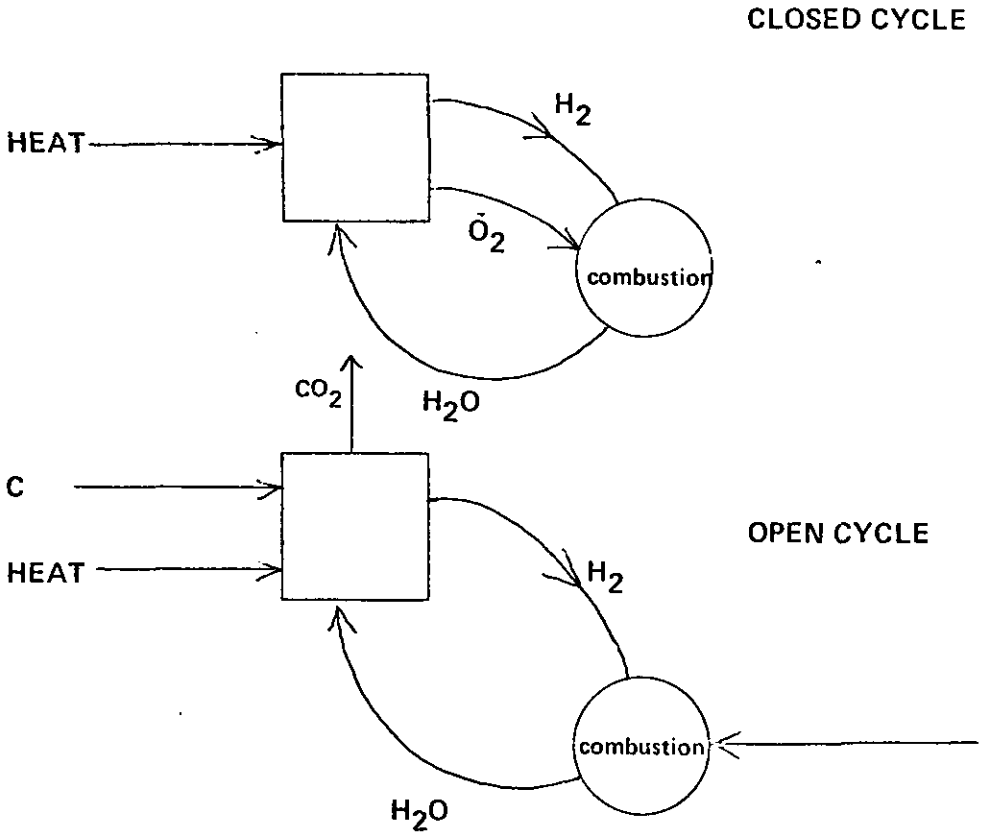
T = 950 – 1000°C IN PRIMARY HELIUM

- OPEN CYCLES

  $C + 2H_2O = CO_2 + 2H_2$

- CLOSED CYCLES

  $H_2O = H_2 + {}^1/_2\, O_2$



CLOSED CYCLES FOR DECOMPOSITION OF WATER

- ELECTROLYSIS OF WATER
- THERMOCHEMICAL PROCESSES

WATER ELECTROLYSIS

	PRESENT	TARGET
AQUEOUS SOLUTION		
TEMPERATURE °C	60 – 80	120 – 150
PRESSURE atm.	1	20 – 30
ENERGY KWh/Nm^3	4.5 – 5	4 – 4.2
CELL VOLTAGE V	1.9 – 2.2	1.5 – 1.6
EFFICIENCY %	65 – 80	90 – 95
CAPITAL INVESTMENT COST 75 $/KW INPUT	250 – 300	150 – 200

THERMOCHEMICAL PROCESSES

- PROCEDURES FOR EVALUATION OF INDUSTRIAL PROCESSES
- CRITERIA FOR SELECTION
- EXAMPLES :

ALL CHEMICAL PROCESS

$SO_2 + I_2 + 2H_2O = 2HI + H_2SO_4$

$2HI = H_2 + I_2$

$H_2SO_4 = SO_2 + 1/2\,O_2 + H_2O$

HYBRID PROCESS

$SO_2 + 2H_2O = H_2SO_4 + H_2$

$H_2SO_4 = SO_2 + 1/2\,O_2 + H_2O$

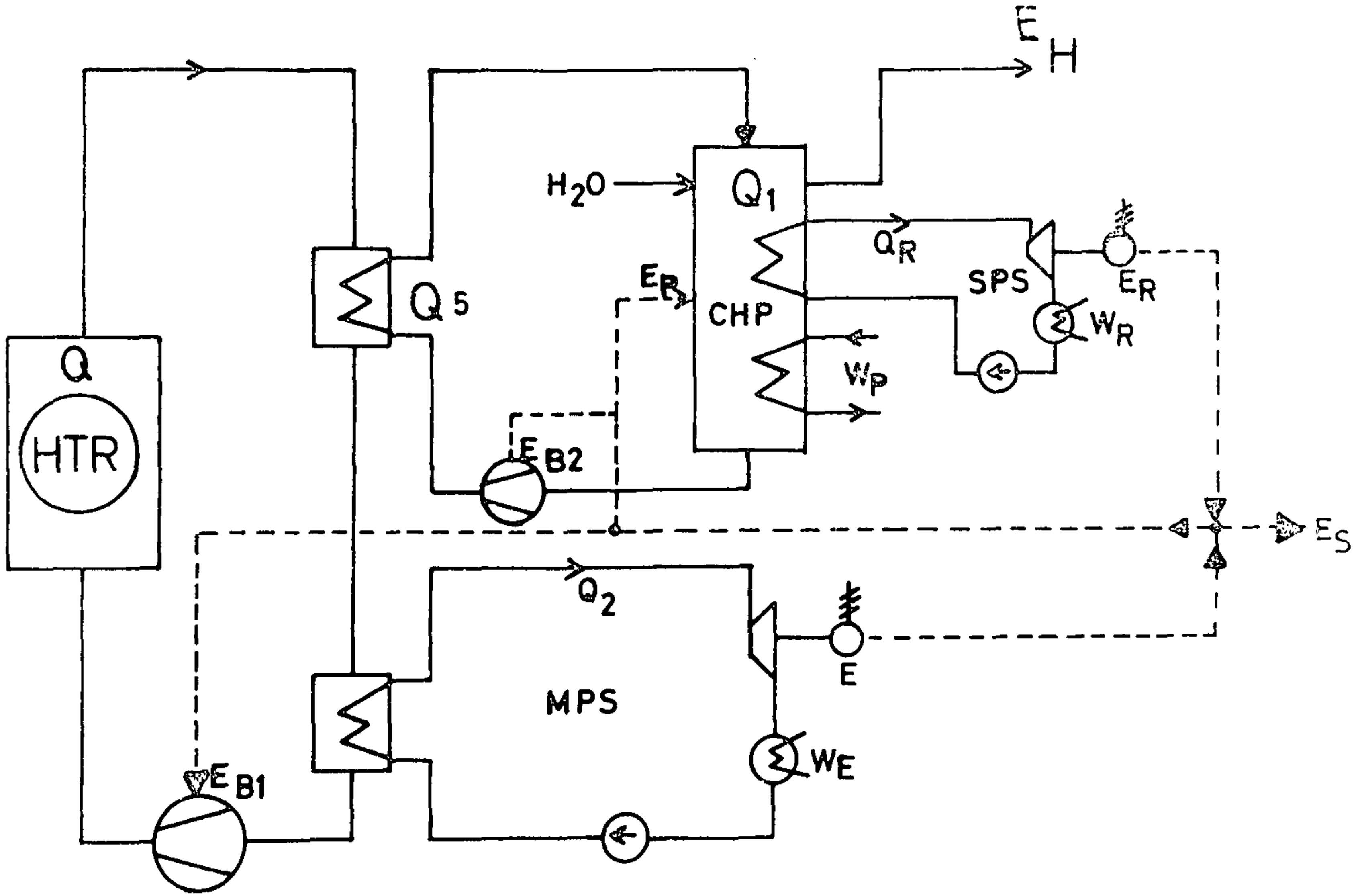
PROBLEM AREAS FOR THE DEVELOPMENT OF THERMOCHEMICAL PROCESSES

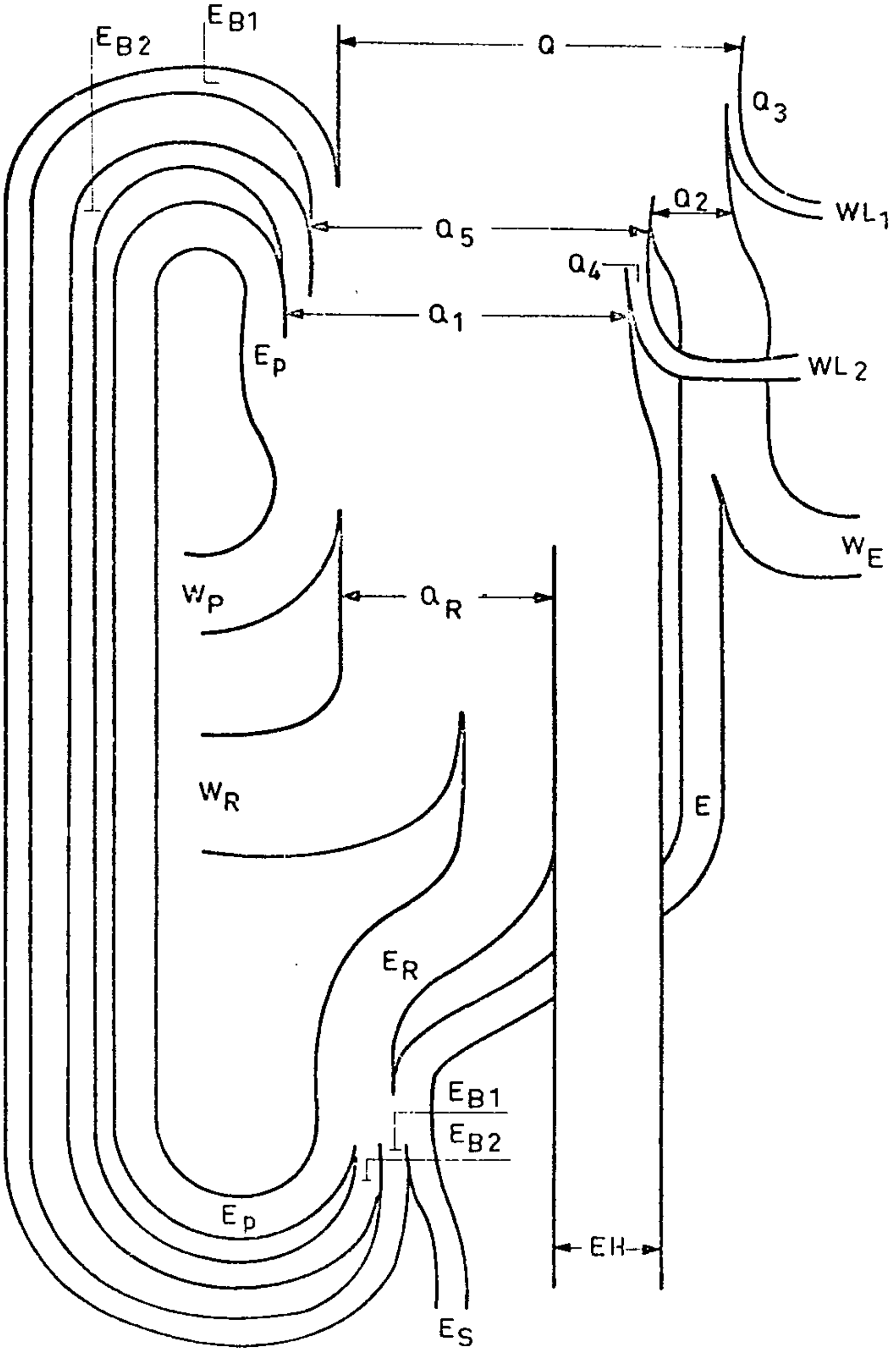
- CHEMICAL ENGINEERING FOR LARGE PLANTS
- HEAT EXCHANGE HIGH–TEMPERATURE TECHNOLOGY
- MATERIAL COMPATIBILITY
- SEPARATION AND TRANSPORT TECHNOLOGY
- INVESTMENT COST

EFFICIENCIES AND ECONOMIC ASPECTS

DEFINITIONS

PROCESS EFFICIENCY	$\eta_P = \frac{E_H}{Q}$
	$\eta_P = \frac{E_H}{Q_1 + \frac{E_R}{\eta_E}}$
HYDROGEN FACTOR	$F_H = \frac{Q - E_S/\xi}{Q}$


E_H
H_2O
Q_1
Q_R
SPS
E_R
W_R
E_B
CHP
W_P
Q_5
Q
HTR
E_{B2}
E_S
Q_2
MPS
E
W_E
E_{B1}



Energy Flow Sheet

INVESTMENT COST FOR CHEMICAL PLANTS

COST ESTIMATION TECHNIQUES

APPROXIMATE FORMULAS :

- **FUNCTIONAL UNITS METHOD**

$$C = K \cdot N \cdot 10^{F_M + F_P + F_T} \cdot (P \cdot R^{0,33})^{0,66}$$

- **STALLWORTHY METHOD**

$$C = K \cdot \sum_{1}^{S} (N \cdot F_M \cdot F_P \cdot F_T \cdot R \cdot V)/A$$

THERMOCHEMICAL PLANT – MARK 16

PRODUCTION	: 100,000 Nm^3H_2/hr
PROCESS EFFICIENCY	: 0.50
MAX. TEMPERATURE	: 800°C
INVESTMENT COST	: 120 M\$ (1975) 1200 \$/1Nm^3H_2/hr^{-1}

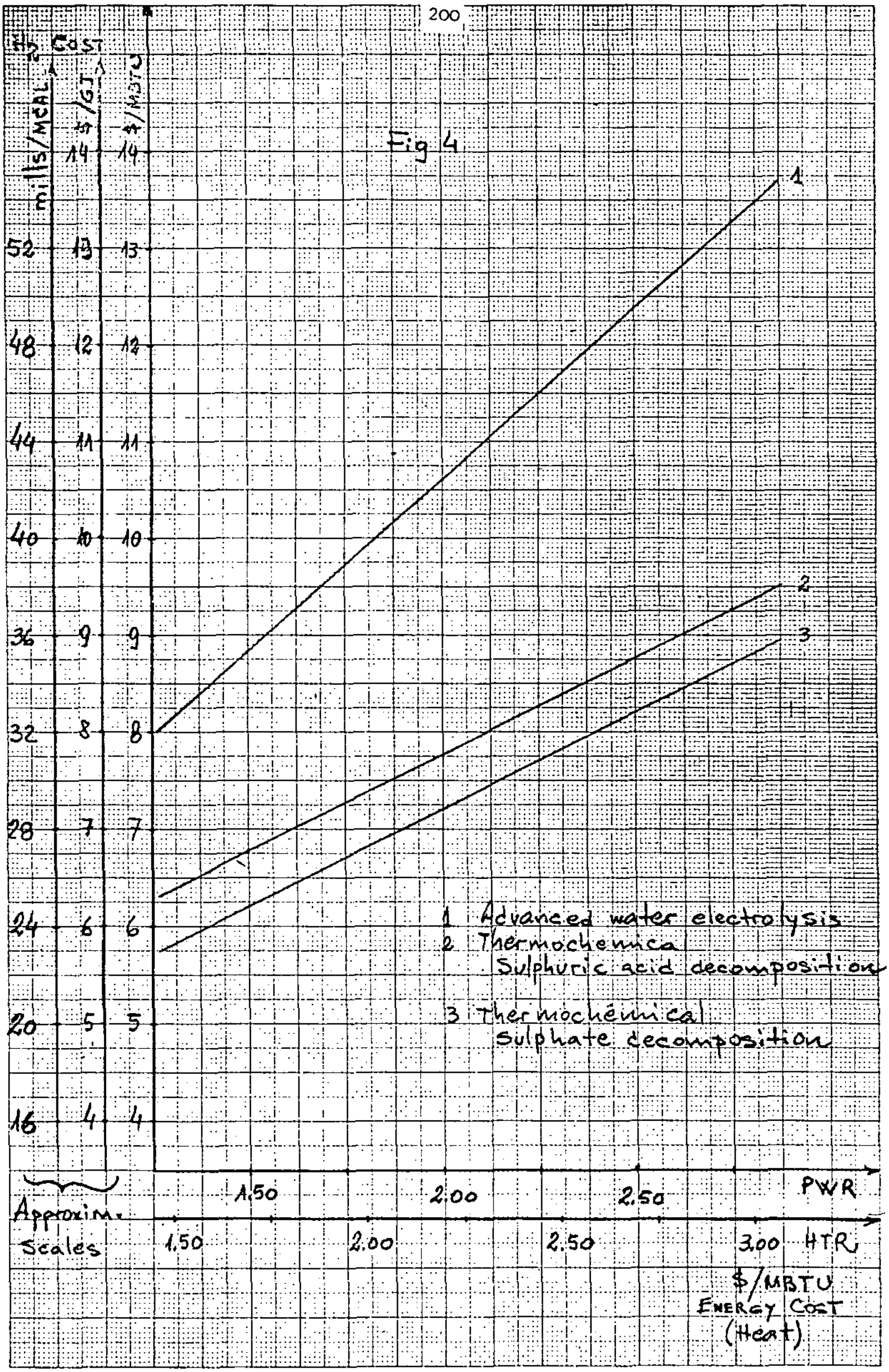


Fig 4

FABRICATION SUISSE

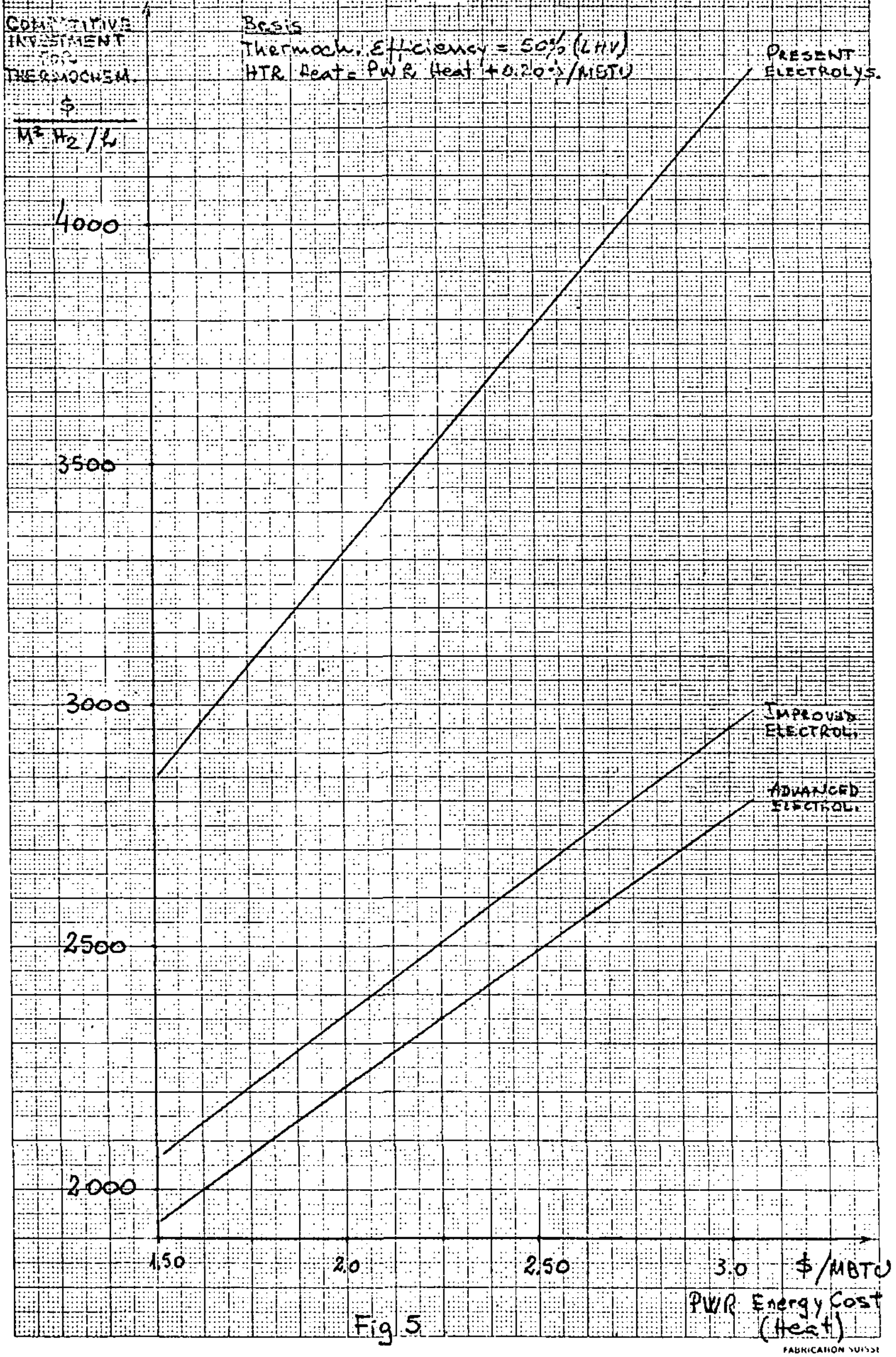

COMPETITIVE INVESTMENT FOR THERMOCHEM.
$ / M³ H₂ / h
Basis
Thermoch. Efficiency = 50% (LHV)
HTR Heat = PWR Heat + 0.20 $/MBTU
PRESENT ELECTROLYS.
IMPROVED ELECTROL.
ADVANCED ELECTROL.
4000
3500
3000
2500
2000
1.50
2.0
2.50
3.0
$/MBTU
PWR Energy Cost (Heat)
FABRICATION SUISSE

Fig 5

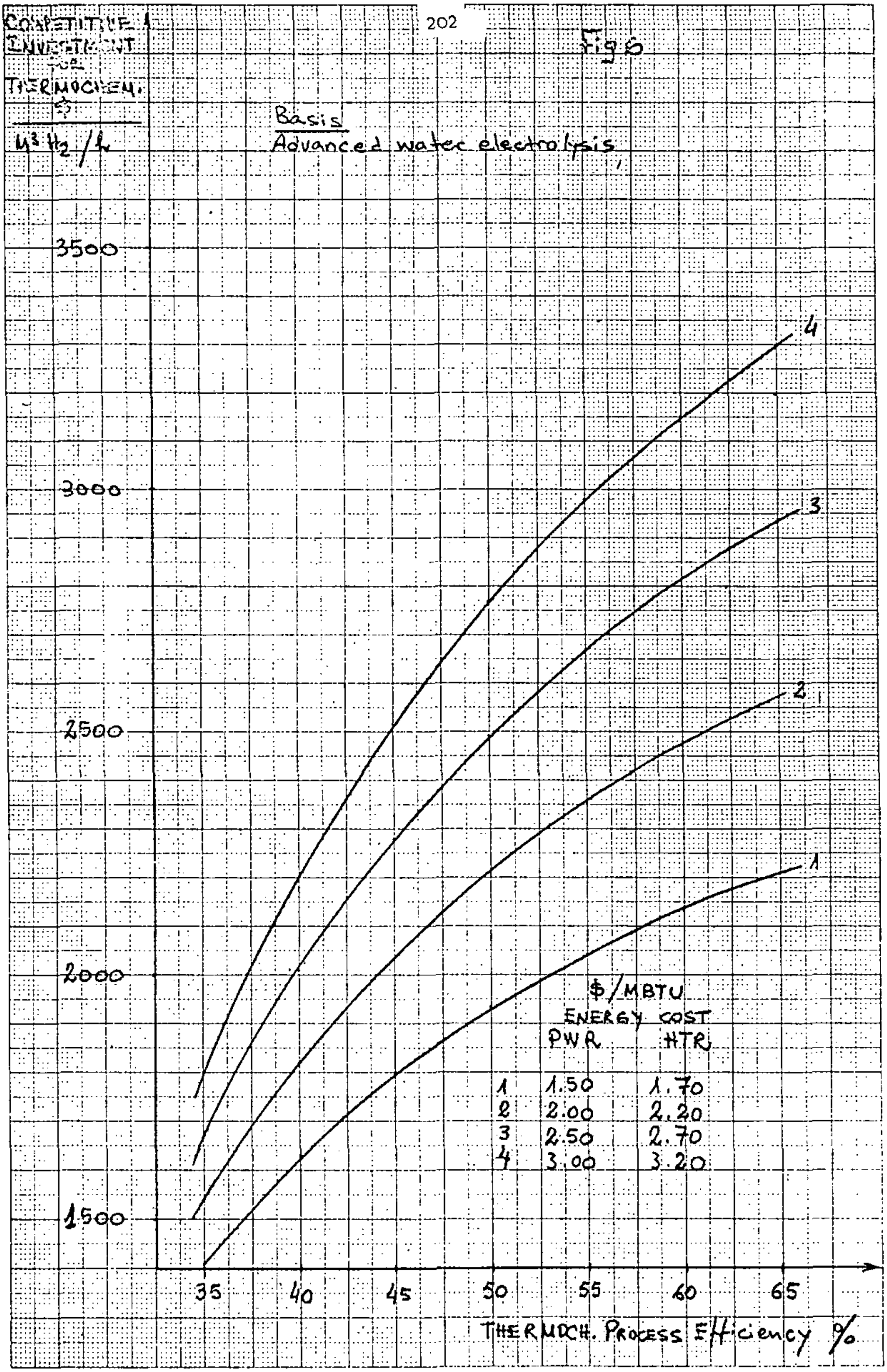


Fig 6

COMPETITIVE
INVESTMENT
FOR
THERMOCHEM.
$
M³ H2 / h
Basis
Advanced water electrolysis
3500
3000
2500
2000
1500
35
40
45
50
55
60
65
THERMOCH. PROCESS Efficiency %
4
3
2
1
$/MBTU
ENERGY COST
PWR HTR
1 1.50 1.70
2 2.00 2.20
3 2.50 2.70
4 3.00 3.20

ENVIRONMENT ASPECTS

STORAGE : ECONOMIC AND EASY IN LARGE UNDERGROUND CAVITIES

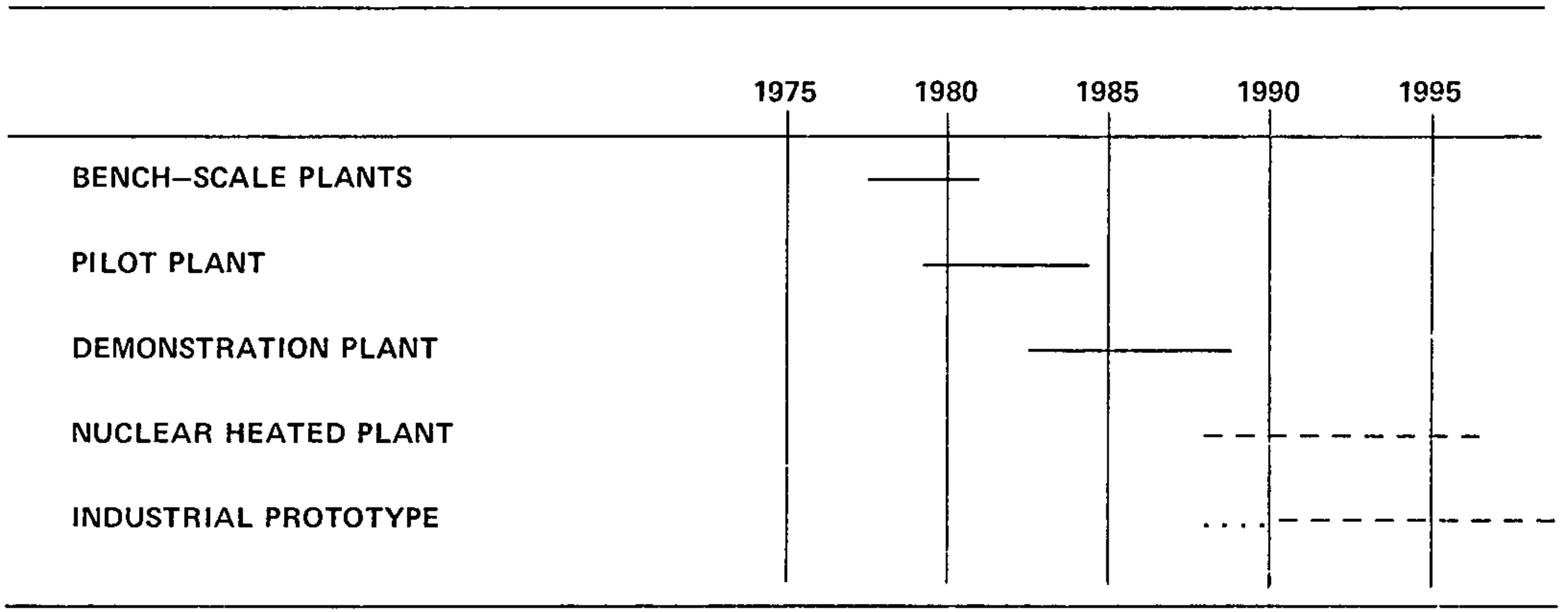
TRANSMISSION : EXISTING TECHNOLOGY
ECONOMIC : 1.5 – 2 TIMES COST FOR NATURAL GAS

CONSEQUENCE : IT IS POSSIBLE TO HAVE LONG DISTANCES BETWEEN PRODUCTION PLANTS AND USERS.
HYDROGEN PRODUCTION PLANTS CAN HAVE VERY LARGE SIZE, OPERATE AT CONSTANT LEVEL, BE SITUATED INDEPENDENTLY FROM UTILIZATION PLANTS.

ECOLOGICAL ASPECTS

- USE : CLEAN COMBUSTION
  NO EFFECTS ON ENVIRONMENT
- PRODUCTION : NO POLLUANT EMISSIONS
  POSSIBILITY OF CHOICE OF SITES FOR MINIMIZING EFFECTS OF THERMAL POLLUTION

THERMOCHEMICAL PRODUCTION OF HYDROGEN FROM WATER



TIMESCALE OF DEVELOPMENT

PROJECTED HYDROGEN PRODUCTION TECHNOLOGY SEQUENCE

PROCESS	CONTRIBUTION IN 1980–90	CONTRIBUTION IN 1990–2000	CONTRIBUTION IN later
• STEAM REFORMING OF METHANE/NAPHTA	LARGE	LARGE	SMALL
• PARTIAL OXIDATION OF HEAVY OILS	LARGE	LARGE	SMALL
• COAL GASIFICATION	SMALL	LARGE	LARGE
• ELECTROLYSIS OF WATER	NEGLIGIBLE	SMALL	LARGE
• THERMOCHEMICAL DECOMPOSITION OF WATER	NONE	NEGLIGIBLE	LARGE

INTERNATIONAL COOPERATIONS AND PROJECTS ON HYDROGEN PRODUCTION FROM WATER

1. AGREEMENT FOR COLLABORATION BETWEEN

KFA – JUELICH (FRG)
RWTH – AACHEN (FRG)
J.R.C. – ISPRA (EEC)
C.E.A. – SACLAY (FRANCE)

2. PROGRAM OF ENERGY R AND D OF EEC

- INDIRECT ACTION :
  RESEARCH CONTRACTS FOR HYDROGEN :
  A. THERMOCHEMICAL PROCESSES
  B. ELECTROLYSIS EMPROVEMENTS
  C. HYDROGEN USES

  TOTAL BUDGET : 13.24 Mu.a. IN FOUR YEARS (1976 – 1979)

- DIRECT ACTION :
  PROGRAM OF J.R.C. – ISPRA
  THERMOCHEMICAL PROCESSES : BUDGET 1976 ~ 2 Mu.a.

3. INTERNATIONAL ENERGY AGENCY (IEA)

COOPERATIVE PROGRAM ON HYDROGEN FROM WATER

PROPOSALS FOR JOINT PROJECTS ON

- CONCEPTUAL DESIGN OF THERMOCHEMICAL PLANTS
- STUDY OF COUPLING HIGH TEMPERATURE REACTOR AND THERMOCHEMICAL PLANT
- ELECTROLYSIS

C 4

THE HIGH TEMPERATURE REACTOR HTR AS THE NUCLEAR HEAT SOURCE FOR THE PRODUCTION OF NUCLEAR HYDROGEN

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Abstract

The motivations for research and development work in the field of "the production of hydrogen from water, using heat from the high temperature reactor HTR" are given. The concept of the nuclear hydrogen economy is explained. Thermodynamical calculations and preliminary optimizations with respect to the maximum process temperature of a thermochemical cycle are summarized with the result that the production of HTR heat with maximum gas outlet temperature of 1000 °C to 1100 °C is feasible with the today existing HTR technology. The nuclear reactors AVR, THTR 300, PR 500 and PR 3000 are briefly described.

1. MOTIVATION AND CONCEPT FOR THE NUCLEAR HYDROGEN ECONOMY

The motivation for the new energy supply system: "Nuclear energy as the primary energy source and hydrogen as the energy carrier, produced from water via a closed-cycle thermochemical process, using heat from the high temperature reactor HTR" is as follows:

- Replacement of primary energy sources with declining reserves, especially oil and natural gas by nuclear energy, especially uranium and thorium.
- Reduction of the degree of dependence upon import of energy.
- Application of nuclear energy alongside the production of electricity, on the non-electrical market for energy.
- Supply of energy to the consumer in a form which is orientated at a pattern of applications in the different sectors of the energy market.
- Complementing of oil and natural gas as a source for hydrogen as a chemical raw material in the chemical industry.

Energy consumption forecasts for the European Community /1/, see Table I, and for the Federal Republic of Germany /2/, predict that natural gas will have a relatively large increase in use and demand in the next 10 years. From this prediction and the fact that the reserves of natural gas are relatively quickly declining it can be concluded that there will be in future a strong demand for substitute gaseous energy carriers. Such an energy carrier will be hydrogen produced from nuclear energy by "Nuclear Water Splitting".

The concept of the "nuclear hydrogen economy" /3/ is as follows: A future "Nuclear Hydrogen Plant, NHP" will consist of the high temperature reactor HTR and of the thermochemical plant TCP /4/. The nuclear hydrogen plant NHP produces hydrogen which is used as an energy carrier by a broad variety of consumers, Fig. 1.

PRIMARY ENERGY DEMAND, EUROPEAN COMMUNITY

	1973		1985 new forecast		1985 old forecast	
Oil	617	61	655	41	1160	64
Coal	227	23	250	16	175	10
Natural Gas	117	12	375	24	265	15
Others	30	3	35	2	40	2
Nuclear Energy	14	1	260	17	160	9
	1005	100	1575	100	1800	100

in 10^6 tons of oil equivalent/yr (and %)

Table I: Demand of Primary Energy in the European Community in 1973 and in 1985. For 1985 two forecasts are given, the old from 1972 and the new from 1974 /1/. Source: Comm. of EC Kom(74)550 endg Brussels, May 29, 74

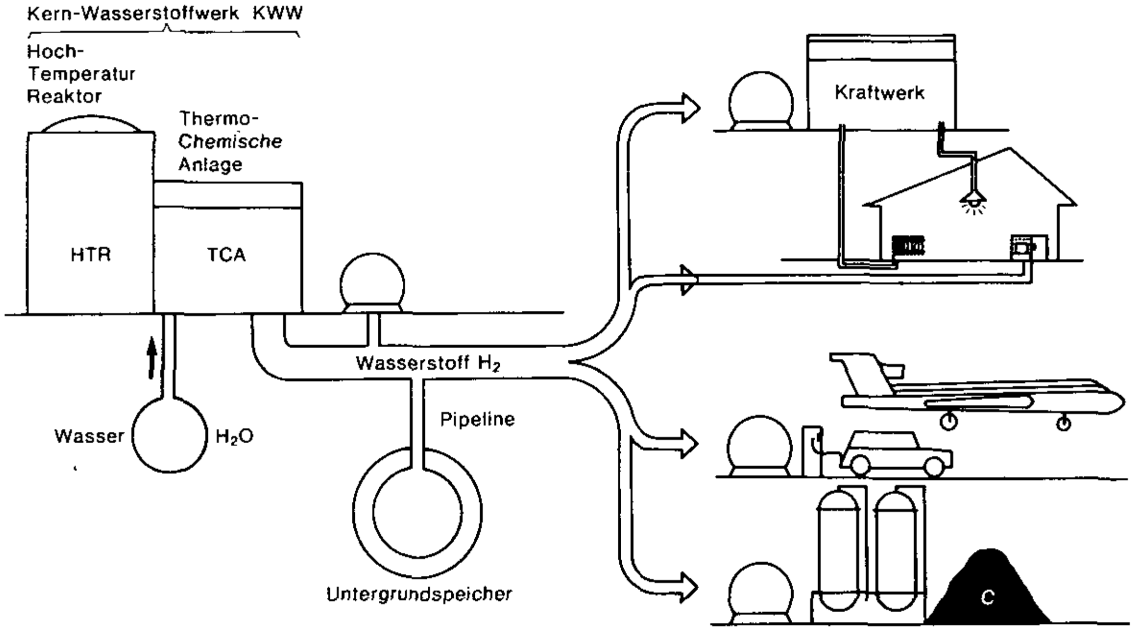

FIG. 1: Schematic drawing, Nuclear Hydrogen Economy

The principle of a nuclear hydrogen plant NHP is explained in Fig. 2: A high temperature reactor, e.g. a pebble bed HTR, produces heat at e.g. 1000 oC, which is consumed by an endothermic chemical reaction in a chemical reactor. The thermochemical cycle is closed by other chemical reactors. The products of the thermochemical plant TCP are hydrogen and oxygen.

2. HIGH TEMPERATURE HEAT FOR THE THERMOCHEMICAL CYCLE

Nuclear energy from High Temperature Reactors HTR is offered as the sensible heat of the reactor coolant helium. In almost all process heat applications of the HTR this heat is used to furnish the heat requirements of chemical reactions.

The actual temperature of the heat at the interface of the HTR and the thermochemical plant TCP is - of course - the result of a compromise between thermodynamical aspects and materials technology. The optimum conditions would be those realizing minimum cost for the product hydrogen.

From thermodynamical evaluations /5/ on heat and temperature requirements and efficiencies of thermochemical cycles it is - in general - concluded that the temperature of the HTR heat should be as high as possible. The reasons for this conclusion are:

(1) higher efficiency, due to the Carnot factor,
(2) higher conversion of the heat consuming chemical reaction,
(3) lower losses due to non-equilibrium of chemical reactions, and
(4) necessity of heat transfer temperature differences for the intermediate heat exchanger IHX and the process heat exchanger PHX.

From knowledge about materials and considerations on existing and proposed HTR heat consuming apparates /6, 7/, Table II, it is realized that the applicable temperature of HTR heat is limited due to the following reasons:

(1) stress, corrosion and diffusion conditions in the heat transfer walls of the intermediate heat exchanger IHX and a process heat exchanger PHX,
(2) load and temperature conditions of the helium ducting, and
(3) insulation and cooling difficulties.

Considering the thermodynamic aspects and the material limits it is today expected that the optimum value of the mean gas outlet temperature of the HTR is relatively high, e.g. in the range of 800 oC to 1100 °C. In the lower half of this temperature range heat of offered from today existing HTRs. Temperatures in the upper half of feasible with the HTR technology.

The nuclear fuel in the core of an HTR, especially of a Pebble-bed HTR with OTTO (Once Through Then Out) fueling scheme has generally the potential to produce heat at temperatures higher than the before mentioned temperature range.

The development work of HTRs for steam production by helium-heated steam generators has reached the stage of completion. The next step in the development is the process of "nuclear methane reforming" /8/.

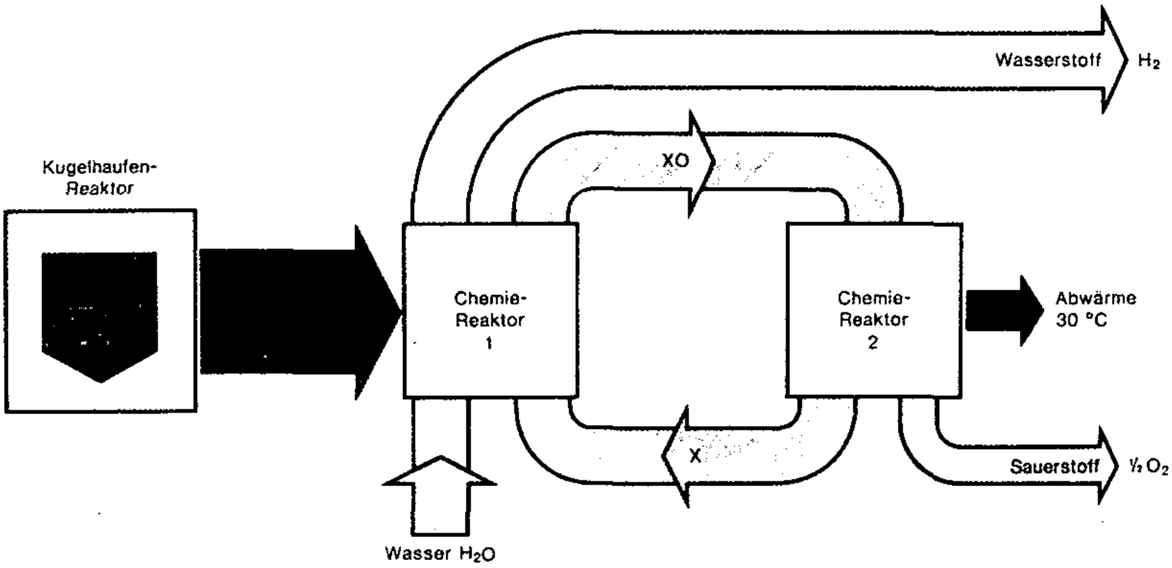

FIG. 2: Principal Flow Diagram of a Thermochemical Process Plant, consuming heat from an HTR with pebble-bed core.

	P MW_t	P' MW_t/m^3	A' m^2/m^3	m/P kg/kW_t
1 Steam Generator	120	3.2	30	0.6
2 Recuperator	275	1.2	80	1
3 Compact HX	550	3.0	1600	0.4
4 Intermed. HX	150	3.0	100	0.9
5 Methane Ref.	300	0.8	16	1.8
6 Exp. CH_4 Ref.	exp.	5	140	0.4
7 Gas Generator	50 t/h	0.2	13	4-8

Table II: Typical Data for HTR-heat Consuming Apparates: size of units, power density, specific area of heat transfer walls, specific mass of heat transfer walls.

Research and development work in the field of the interface between the high temperature reactor HTR and a thermochemical plant TCP is necessary in the following areas:

(1) interface specifications,
(2) size of the process plants and the HTR,
(3) optimum value of the temperature of the HTR heat,
(4) availability of the HTR,
(5) intermediate loop,
(6) materials,
(7) conceptual designs for chemical reactors,
(8) safety, and so on.

3. STATUS OF THE ART OF HTR TECHNOLOGY

HTRs in operation and under construction are now (March 1976) the following: DRAGON, United Kingdom, 20 MW(t), in operation from 1966 to 1976; AVR, Germany, 45 MW(t), in operation since 1967; Peach Bottom 1, USA, 115 MW(t), in operation from 1967 to 1975; THTR 300, Germany, 750 MW(t), in construction since 1971; Fort St. Vrain, USA, 842 MW(t), in the procedure of going into operation.

The German type of HTR is described with the following examples:

AVR, Fig. 3

Since December 17, 1967, the Experimental Nuclear Power Station AVR (Arbeitsgemeinschaft Versuchsreaktor) in Jülich is in operation. It is a high temperature gas cooled (helium) reactor with a pebble-bed core (85,000 pebbles) with a power of 15 MWe and an average gas outlet temperature of 950 °C. Until now the 7 years of operation of the AVR showed very good results. On October 29, 1973, the 500 millionth kWh was produced. On February 27, 1974, the mean outlet temperature was increased from 850 to 950 °C /9/. For the rise of the temperature an increase in the reactivity of 0.5 Nile, equivalent 500 fuel pebbles, was necessary. The calculated maximum fuel temperature is lower than 1200 °C, the local maximum value of the gas outlet temperature is 1040 °C.

Fig. 3 gives the cross section of the nuclear part of the AVR power plant.

THTR 300, Fig. 4

The THTR nuclear power plant at Uentrop (Schmehausen) is under construction since June 1971. The reactor of this nuclear power plant is the "Thorium High Temperature Reactor" THTR. It is a reactor with a pebble bed core (675,000 pebbles), the power is 300 MWe, and the average gas outlet temperature is 750 °C. The plan for the construction foresees that the plant should go in operation in the end of 1978. The THTR will be the first "commercial" HTR in Germany.

Fig. 4 presents a cross section of the reactor showing the primary circuit and the pre-stressed concrete vessel of the THTR power plant.

PR 500, Fig. 5

In cooperation between STEAG, Essen, and KFA there has been made in 1971, 1972 a study for an industrial process heat plant with the high temperature reactor PR 500 with pebble-bed core and OTTO fueling scheme for the production of process steam /10/. In the OTTO fueling scheme the pebbles move only once through the core (once through then out). By this fueling scheme the mean outlet gas temperature of a pebble bed HTR can be made higher for a specified fuel center temperature. Compared with the AVR and THTR fueling concept and with other HTR concepts the OTTO mean gas temperature is 100 to 200 °C higher.

Fig. 5 shows a vertical and a horizontal cross section of the nuclear part of the PR 500 plant. The design for this reactor foresees an underground siting.

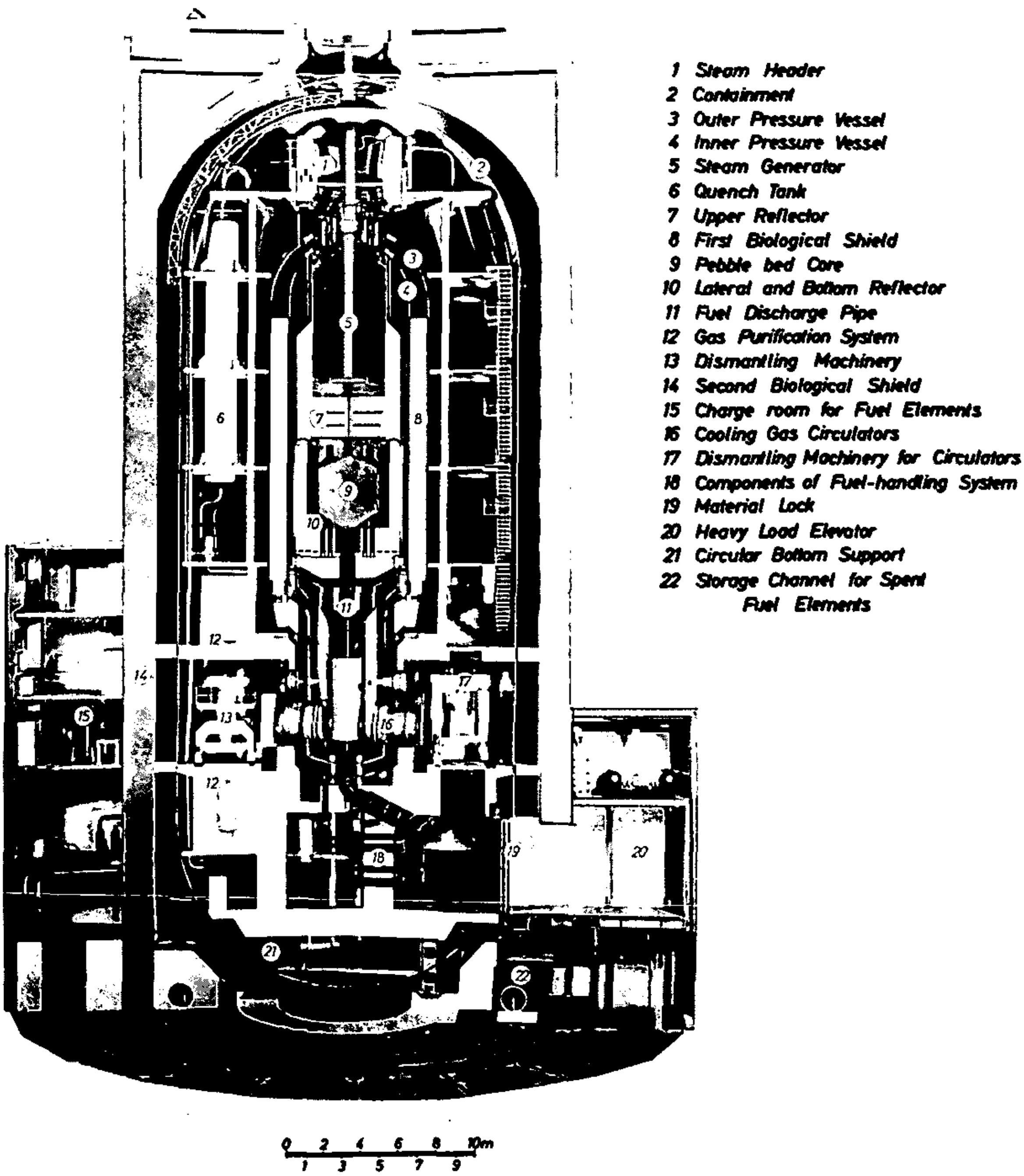

Fig. 3: Model of the Nuclear Part of the AVR power plant in Jülich. This reactor has a pebble bed core and a mean outlet temperature of 950°C /9/. It is in operation since December 1967.

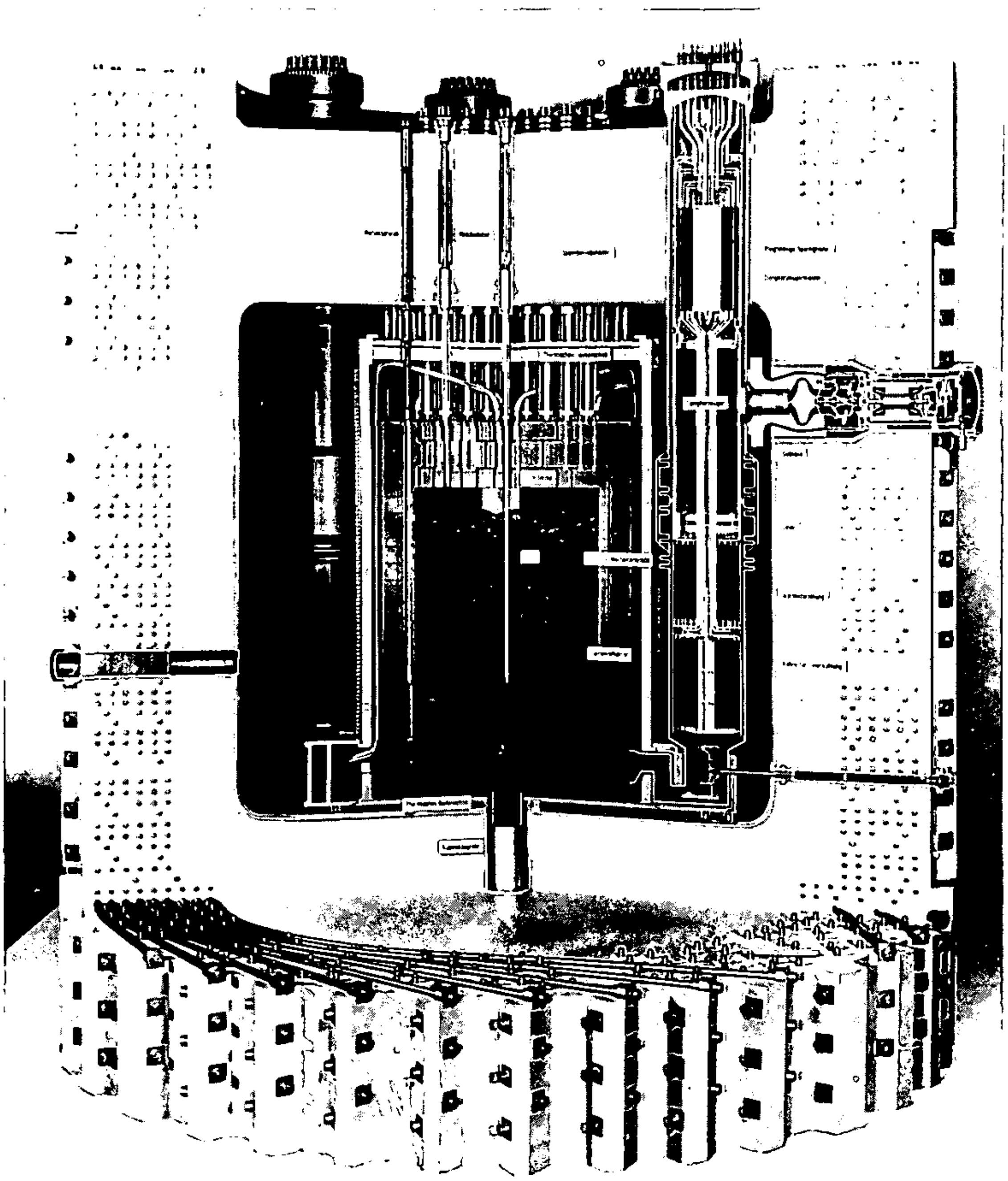

Fig. 4: Model of the Reactor (primary circuit and pre-stressed concrete vessel) of the THTR power plant at Uentrop (Schmehausen). The pebble bed core of this reactors produces a thermal power of 750 MW, equivalent to 300 MWe. The power plant is under construction since Summer 1971.

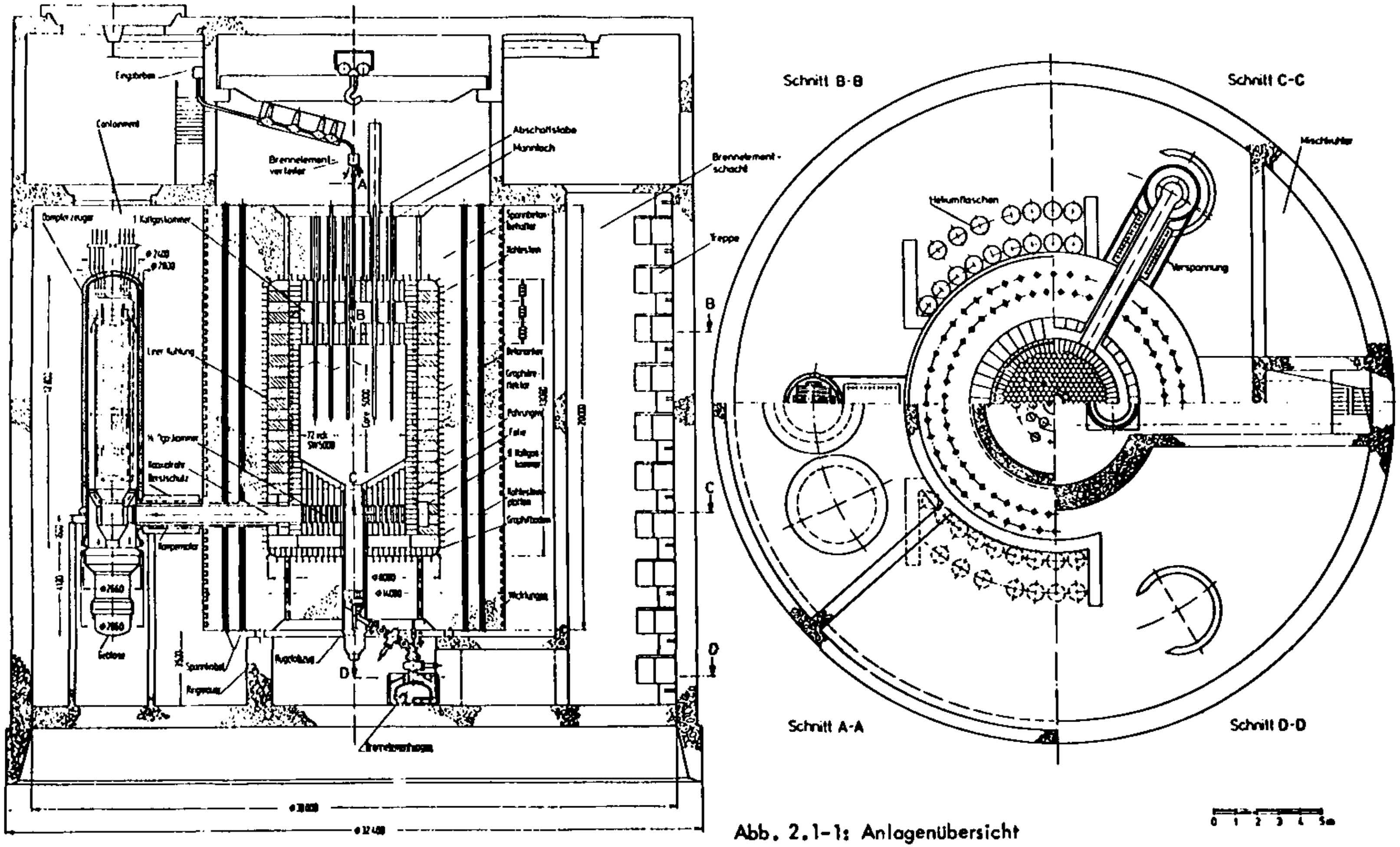

Abb. 2.1-1: Anlagenübersicht

Fig. 5: Conceptual Design of the Nuclear Part of the PR 500-plant: 500 MWt, pebble bed core, OTTO-fueling scheme, non-integrated design, underground siting, production of process steam, /10/.

PR 3000, Fig. 6

Up to now design work has been done for a large process heat reactor for a "Nuclear Methane Reforming Plant" with a power of 3000 MWt and an average gas outlet temperature of 965 °C /11/. Typical for this design is the non-integrated arrangement of the primary circuit: the heat consuming apparatus are located outside of the pre-stressed concrete vessel.

Fig. 6 shows a vertical cross section of the nuclear part of the PR 3000 reactor.

This kind of a nuclear reactor: an HTR with a Pebble Bed Core and OTTO fueling scheme may be used also in a nuclear hydrogen plant.

Intermediate heat exchanger IHX, process heat exchanger PHX

Within the German project "Prototype Nuclear Process Heat, PNP" research and development work for the design and construction of an intermediate heat exchanger IHX and a process heat exchanger PHX for helium heated methane reforming is under way. In an evaluation on process heat applications of HTRs funded by the US ERDA /12/, screening of materials and design work for IHX and PHX has been done.

For the application of HTR heat for thermochemical cycles the following heat consuming chemical reactions are considered to be of importance: the decomposition of sulfuric acid and sulfur trioxyd, the Deacon reverse reaction, the decomposition of hydriodic acid, etc.

4. COST OF THE PRODUCTION OF HYDROGEN

The advance of hydrogen as a secondary energy carrier has been described many times. The technological goal of research and development in the field of nuclear water splitting is a production process which is economically competitive. A summary of results of evaluation on cost figures for the production of hydrogen for several processes is given in /3/.

In the recently published study of the use of heat from high temperature nuclear sources the hydrogen production processes /13/, there has also been made an evaluation on the cost for thermochemical hydrogen production, using the "Sulfuric Acid-Hybrid-Process". The results are: USA conditions: July 1974 $; utility ownership, annual charge rate 15 %, no escalation; plant capacity factor 80 %; plant is not the first of a kind; no credit for oxygen:

(1) thermochemical hydrogen cost 4.2 to 4.8 $/GJ ($H_2$, HHV), equivalent to 5.4 to 6.0 ¢/h$\cdot$m^3 (H_2).
(2) hydrogen from water electrolysis is more expensive, and
(3) hydrogen from the Koppers-Totzek-process and from the Bi-Gas-process is more expensive if the price of the coal exceeds 1.3 $/GJ.

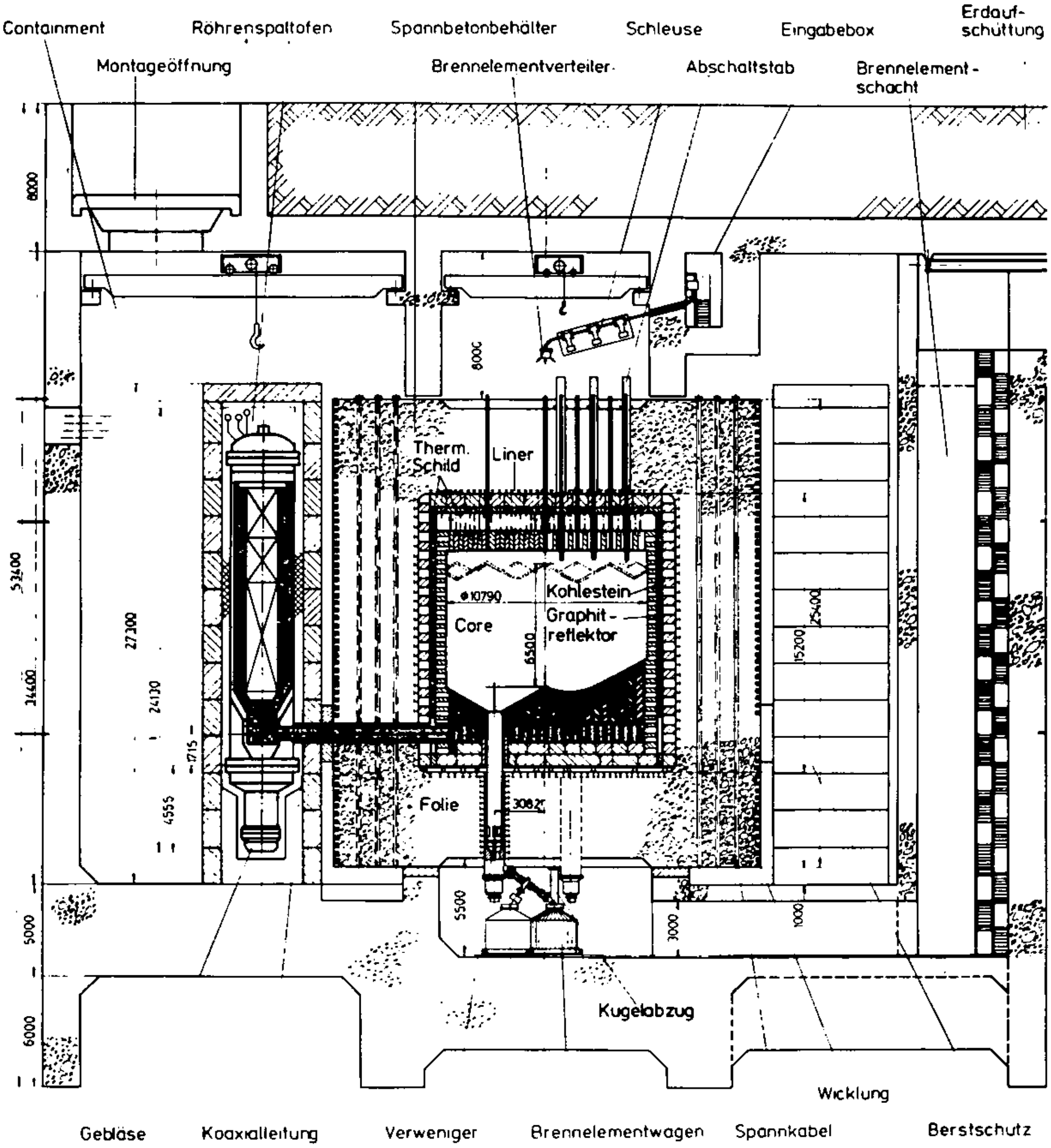

Fig. 6: Conceptual Design of the Nuclear Part of the PR 3000-plant: 3000 MWt, pebble bed core, OTTO-fueling scheme, non-integrated design, underground siting, process of methane reforming, /11/.

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HYDROGEN ECONOMY IN THE BELGIAN CONTEXT

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BELGIUM

1. Introduction

For some time the scientific and technical communities have been attracted by the prospect that hydrogen might become the energy carrier of the future. The motives in favour of this new secondary energy source are multiple, e.g. the unlimited potential of the oceans as hydrogen sources, the ease with which H_2 may be transported over long distances, the wide applicability of this fuel in stationary and mobile applications.

It has to be kept in mind that the production of hydrogen from water is a process which relies on the use of a primary energy source which can be fossil, nuclear, or solar.

The production of hydrogen from natural gas and hydrocarbons by shift conversion is at present the only available technology but the vanishing natural gas and oil reserves call for a new approach which has to be developed within the next 30 years.

It was recently disclosed by oil companies that the total world reserves in liquid and gaseous fossil fuels are sufficient to supply the market in the next 30 years. A delay of 50 years was predicted when present reserves of oil shale are extracted but this cannot be done at the present price levels.

New solutions will have to be found particularly in Western Europe which depends for about 60 % on oil imports. The energy needs of the EEC countries are satisfied by four main primary sources: oil, coal, natural gas, nuclear energy and hydraulic energy. The mean figures of energy coverage are given in Table I.

This situation has not been altered fundamentally in the recent years except a slight decrease in oil consumption balanced by an increase in coal, natural gas and nuclear energy.

It is remarkable that the mean figures of the EEC practically coincide with the Belgian situation, which reflects the fact that our country is a representative sample of the European reality.

Country	Oil	Solid fuels	Natural gas	Other
France	70.2	16.9	8.1	4.8
Federal Republic of Germany	51.2	37	10.2	1.6
Italy	79.3	5.7	11.2	3.8
United Kingdom	47.7	37.6	11.5	3.2
Belgium	61.8	22.8	15.2	0.2
Netherlands	56.9	3.5	39.2	0.4
Denmark	88.8	11.2	-	0
E E C	60.5	24.1	12.7	2.7

TABLE I: Percentage coverage of primary energy in the EEC countries in 1973

2. Role of Hydrogen in the Storage of Electricity

There is a tendency in the Belgian economic evolution to increase the share of electricity and to make an increased use of natural gas and nuclear energy to produce this electricity. Table II shows the evolution of the installed electrical capacity and the contribution of each type of fuel.

As long as the electric power plants are fed with fossil fuels, it is feasible to adapt the production to the instantaneous needs. As soon as 60 % of the electric production stems from nuclear origin small excesses of electric production can occur daily, weekly or even yearly. The situation as expected around 1985 is shown on Fig. 1.

Up to now the most flexible solution is the installation of artificial hydrostatic basins which are filled during night time and release their power during the day with a 70 % efficiency.

The investment costs being relatively high and the potential applications limited to hilly countries, this system could be substituted by an integrated water electrolysis-fuel cell unit; we will call it an electrochemical plant. If advanced electrolysis is supposed to be operable at close to 90 % of the theoretical efficiency and optimized fuel cells at 70 %, an over-all yield of about 63 % can be obtained.

The flexibility of this system can still be improved by coupling it to an underground hydrogen storage as shown on Fig. 2.

However, very recently attention was drawn on the fact that H_2 after underground storage might be polluted with H_2S and particulate matter which might interfere with fuel cell operation.

Taking into account the evolution of the nuclear electricity in Belgium it may be expected that from 1985 a centrally located electrolyzer with connect-

	BASE LOAD UNITS			PEAK SHAVING UNITS		
	Thermal	Nuclear	Total	Pump	Gas-turbines	Total
1970	6 050	145	6 195	-	140	6 335
1975	7 940	1 366	9 306	396	400	10 102
1980	9 140	2 266	11 406	917	530	12 102
1985	10 029	6 766 9 500	16 795 19 529	917	1 280	18 992 21 726
1990	10 000	10 000- 12 000	20.000- 22 000	917	1 280	22 000- 24 000

TABLE II: Installed electrical capacity in Belgium expressed in MWe (neglecting hydraulic power)

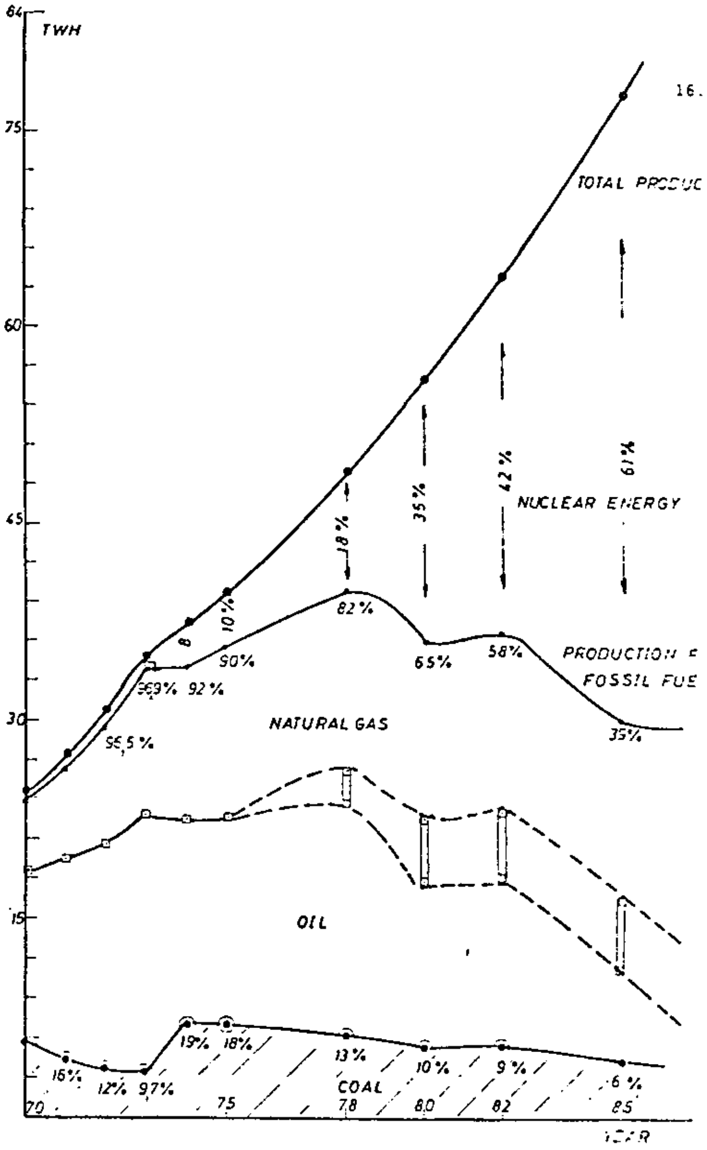

FIG. 1: Evolution of Electricity Production in Belgium

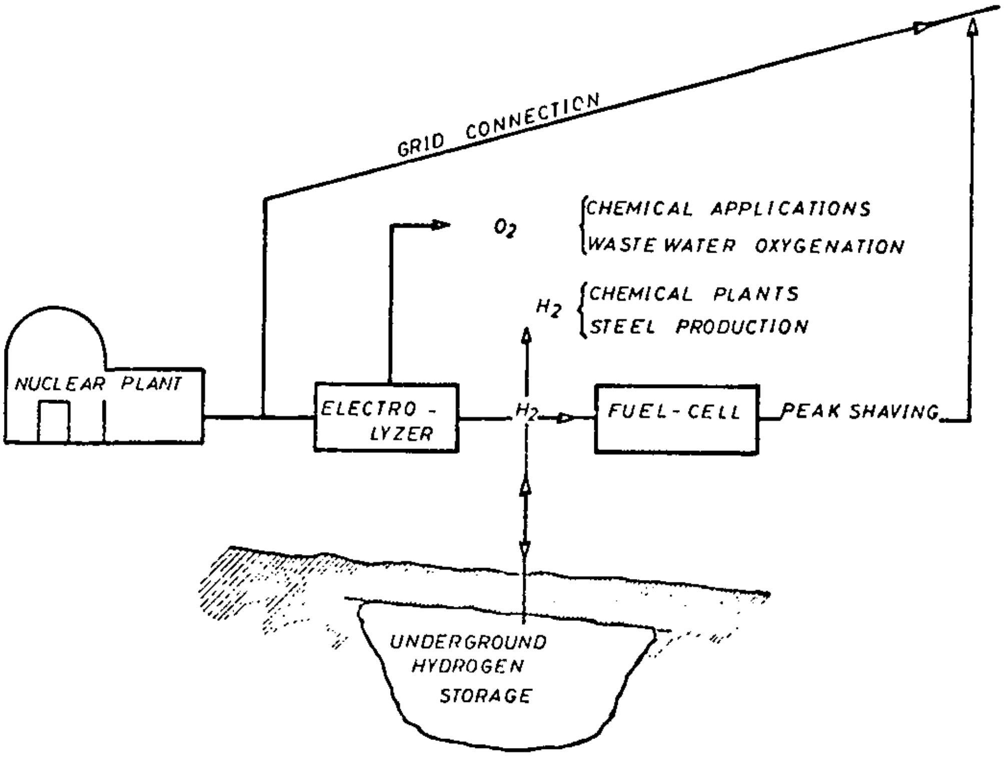

FIGURE 2: Schematic View of an Integrated Electricity-Electrochemical Complex

ions to chemical and petrochemical plants could be technically justified, a production of about 10^9 NM^3 H_2 per year could be expected from such a unit. In a later stage an integrated electrical-electrochemical plant can be envisaged for peak shaving.

3. Substitution of Natural Gas by Hydrogen

Apart from the rather limited role hydrogen could play in electricity storage and conversion, a wider field of application is to be found in the gradual substitution of natural gas by hydrogen.

At present the natural gas contribution to the national energy economy amounts to 15 % and its share is expected to grow if sufficiently cheap imports of north African natural gas can be assured by long term contracts.

In order to decrease our energy dependence from politically unstable or non western countries a gradual substitution of natural gas by hydrogen is a valuable target.

The yearly Belgian consumption of natural gas amounted in 1974 to 11.5 10^9 Nm^3 which is equivalent to 38 10^9 Nm^3 H_2. If we assume that in a first period substitution by hydrogen may be tolerated up to 30 v/o, a market of 3.5 10^9 Nm^3

H_2 is readily available.

Advanced electrolysis can produce H_2 at a power consumption of 3.5 to 4 kWh/Nm^3 H_2 which results in a need for 12.25 to 14 10^9 kWh or an installed capacity of hydrogen producing dedicated nuclear plants of 1750 MWe.

In a more distant future when a H_2 distributing network will have been installed (working under 60 to 100 bars) it is conceivable to substitute all the natural gas used in small industrial and domestic application. A total market of (38 x 0.25 = 9.5 10^9 Nm^3 H_2 will be open for industrial production which necessitates an additional nuclear electrical capacity of about 5000 MWe dedicated to hydrogen production.

The economical competitivity of H_2 versus natural gas only depends on the price of this fossil fuel. In 1974 natural gas was delivered at 1.75 BF/Nm^3 (0.12 DM/Nm^3) for industrial purposes and 4.8 BF/Nm^3 (0.32 DM/Nm^3) for domestic applications.

The 1976 price of Dutch natural gas at the border amounts to 1.8 BF/Nm^3 which corresponds already to the sell price of 1974. From 1973 to 1976 the price of natural gas tripled (0.52 BF/Nm^3 to 1.8 BF/Nm^3) which is an indication that in this vital sector of our economy the word "economic competitivity" may change from one year to another.

By taking the present price level, electricity needed for producing hydrogen should be made available at 0.45 to 0.5 BF/kWh (0.03 DM to 0.033 DM/kWh). Nuclear electricity is presently produced at this cost level which shows that the electrolytically produced hydrogen is very near to economic competitivity with European natural gas and still in a better position with regard to foreign natural gas. However, the major conclusion of this section is that hydrogen has a great future on the condition that it can be produced at economically competitive prices with fossil fuel sources.

4. Hydrogen as Chemical Reagent

In the chemical industry the NH_3 synthesis is the largest user of hydrogen followed by the non-ferro metal and food industry. In Belgium about 50 % of the total hydrogen production is consumed for NH_3 fabrication and this corresponds to 1 M ton/year or 2 10^9 Nm^3 H_2 per year. The other 50 % are used by diverse chemical industries and bring the total production level at 4 10^9 Nm^3/year. If hydrogen production should be based on dedicated nuclear plants a 2000 MWe reactor would be sufficient to cover the immediate needs. The same economic considerations as those given above for natural gas substitution are applicable to H_2 production for chemical purposes except that the added value of the produced chemicals sometimes allow an easier absorption of the basic energy cost.

5. Long Range Views

In a long range view it must be reckoned with that all gaseous and liquid fossil will have to be replaced by hydrogen. In this perspective massive application of nuclear, solar and fusion energy will be required to fulfill the need of our energy hunger. In such futuristic self supporting energy economy, our country would need the production of 100 10^9 Nm^3/year. Off-shore energy islands are probably the only solution to this problem as the sea plays at the same time the role of resource reservoir and cooling medium.

6. Hydrogen Production Methods

The major R & D tasks which have to be performed are related to the production of hydrogen from water without consumption of fossil fuels. Steam reforming and coal gasification are not discussed in this paper. Two ways are envisaged, one being the straightforward electrolysis of water, the other more distant approach is the thermochemical water splitting.

Water electrolysis

This technique is considered as a commercial one which can be put into operation by the industry at any time. Such opinion which is widespread among well informed circles does not entirely correspond to the reality if electrolysis is seen as a necessary intermediate step between electricity and a tertiary energy vector. Present day electrolysis must be improved in order to lower the energy consumption and to increase the current density. Table III shows a very good review of the present achievements /2/ in industrial and experimental advanced electrolysis.

Main efforts have to be directed towards the improvement of the catalytic activity of the electrodes, to the lowering of the overvoltage of the anode to the reduction of ohmic losses in the cell and to the chemical and physical stability of the electrodes as a function of time, temperature and corresponding pressure.

A research programme directed towards the development of electrolysis cells with the following characteristics has been undertaken at the Belgian Nuclear Research Centre (S.C.K./C.E.N.) Mol.

-	Current density	1 to 1.5 A/cm^2
-	Operating voltage	1.45 to 1.6 V
-	Operating temperature	150 °C
-	Operating pressure	max. 20 bars
-	Life time	40 000 h

The membrane electrolysis and the solid polymer concepts are considered as the most attractive and viable routes to achieve these aims.

Thermochemical water splitting

The thermochemical hydrogen production received considerable attention during the last 5 years. Many proposals for closed cycles have been made and most of the once extensively studied ventures have now been abandoned. The thermochemical cycles have one principle advantage compared to electrolysis which is the theoretical possibility to transform heat directly into hydrogen without making the electrical "detour". While the most efficient electrical plants have an efficiency of 40 %, a high temperature nuclear reactor delivering a fluid at 700 °C could reach a theoretical Carnot efficiency of 58 %. This is a major incentive to continue the search for practicable thermochemical cycles.

Company/location	Cell name	Cell design						Experience		
		Type	Current density (A/ft^2)	Operating voltage (V/cell)	Module size (lb H_2/day)	Pressure (psig)	Number of plants	Largest size plant (lb H_2/day)	Earliest plant (year)	Best known plant (year)
A. Norsk Hydro Notodden, Norway	Hydro-Pechkranz	Filter press	140	1.778	1880	1	3	284,000	1927	Rjakon, Norway, 1965
B. Lurgi Frankfurt, Germany	Zdansky-Lonza	Filter press	200	1.832	4200	440	32	22,000	1955[a]	Cuzco, Peru, 1958
C. DeNora Italy	DeNora	Filter press	280	2.00[b]	4100	1	2	110,600	1958	Nangal, India, 1958
D. Pintsch-Bamag Germany	Bamag	Filter press	230	1.788	2600	13.5	200	Unknown	1935	Unknown
E. Electrolyser Corp. Canada	Stuart	Tank	200	2.04	40	0.03	1000	1,130	1930	Teledyne Wah Chang, Alabama, USA, 1971
F. Cominco Canada	Trail	Tank	80	2.142	38	0.1	1	77,000	1939	Trail, Canada, 1939
G. Teledyne Isotopes USA	EGGS	Filter press	400	2.1	65	70	2	50	1968	Teledyne Isotopes, USA, 1972
H. Demag Elektrometallurgic GMBH Duisburg, Germany	Demag	Filter press	92–280	1.75–1.95	900	1	57	177,000	1945	Aswan Dam, Egypt, 1960
I. Electric Heating Equipment Co. USA	Kent	Tank	115	2.2	28	0.1	100	1,610	1920	Hobart, Tasmania, 1949
		Cells being developed								
J. Teledyne Isotopes USA		Filter press	400	1.65	13	2000		Designed for military aircraft application		
K. Teledyne Isotopes		Filter press	250	1.64	94	3000		Designed for nuclear submarine application		
L. General Electric		Solid Ceramic electrolyte	3260	1.2-1.8		1		2000°F, not now under development		
		Solid Polymer electrolyte	1000	1.65		1 to 3000		Designed for Space and Submarine, being developed for Commercial use		
M. Westinghouse		Solid electrolyte	900	0.5[c]		1		Used for CO_2 electrolysis in spacecraft atmosphere control system		

[a] First Zdansky-Lonza plant.

[b] DeNora has indicated an ability to achieve 1.61 V on new cells.

[c] Assumes a fuel depolarized mode of operation (i.e., coal). Does not expect cell to be used as water electrolyzer.

TABLE III: Summary of Electrolytic Hydrogen Plant Equipment

Recently some problems have darkened the HTR outlook which is fundamentally necessary for thermochemical hydrogen production. As long as uncertainty about the future development of the HTR reactors subsist work on thermochemical hydrogen production lacks a frame on which it should be featured.

If we assume that technical and financial solutions will be found for the industrial development of the HTR reactor family, R & D work on thermochemical water splitting should be focused on the following subjects:

- Development of cycles with a process efficiency of at least 50 %;
- Search for new cycles involving only or mainly liquids and gases;
- Development of high temperature heat exchangers standing corrosive environments.

As none of the above goals have been achieved, be it even partly, we expect that thermochemical hydrogen production has a long way to go before it will be competitive with electrolysis.

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HYDROGEN PRODUCTION BY WATER-SPLITTING USING HEAT SUPPLIED BY A HIGH-TEMPERATURE REACTOR

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Abstract

Some aspects of the use of heat of nuclear origin for the production of hydrogen by water-splitting are considered. General notions pertaining to the yield of chemical cycles are discussed and the heat balance corresponding to two specific processes is evaluated. The possibilities of high temperature reactors, with respect to the coolant temperature levels, are examined from the standpoint of core design and technology of some components. Furthermore, subject to a judicious selection of their characteristics, these reactors can lead to excellent use of nuclear fuel. The coupling of the nuclear reactor with the chemical plant by means of a secondary helium circuit gives rise to the design of an intermediate heat exchanger, which is an important component of the overall installation.

Resumé

Quelques aspects de l'utilisation de chaleur d'origine nucléaire pour la production d'hydrogène par décomposition de l'eau sont envisagés. Les notions générales relatives au rendement des cycles chimiques sont rappelées et le bilan thermique correspondant à deux procédés particuliers est évalué. Les possibilités des réacteurs à haute température, en ce qui concerne les niveaux de température de fluide caloporteur, sont examinées du point de vue de la conception du coeur et de la technologie de certains composants. D'ailleurs ces réacteurs peuvent, par un choix judicieux de leurs caractéristiques, conduire à une très bonne utilisation du combustible nucléaire. Le couplage du réacteur nucléaire avec l'usine chimique à l'aide d'un circuit secondaire d'hélium conduit à étudier un échangeur intermédiaire qui est un élément important de l'ensemble de l'installation.

1 INTRODUCTION

Hydrogen, considered as an energy carrier, possesses characteristics comparable to those of natural gas: economical, trouble-free transportation, flexibility of use. It is distinguished from electricity by its storage possibilities, which represent a decisive advantage for certain uses and for the use of power plants during slack hours. It is a non-pollutant fuel. The introduction of hydrogen into the energy market may be gradual, and at the outset may exploit existing installations for transport, storage, distribution and use of natural gas, which can henceforth accomodate, without transformation, 10 to 15 % of hydrogen /1, 2/.

The use of hydrogen as a second energy carrier jointly with electricity offers considerable advantages for future energy distribution systems. It implies the development of economic processes for producing this gas by the dissociation of water through nuclear energy. The only proven process immediately available to split water is electrolysis in its traditional form, which can be coupled with an electricity-producing reactor.

In order to avoid the intermediate conversion of heat into electricity, FUNK /3/ followed by several authors /4,5,6/ suggested the implementation of chemical cycles designed for the thermolysis of water at temperatures accessible with high temperature reactors. These processes are at the stage of laboratory research and energy balance assessment on the basis of thermochemical data. Much work remains to be done to determine their competitivity.

The outlook for their growth, as compared with electrolysis, depends in particular on the efficiencies of use of primary energy which can be achieved, and the possibilities of coupling with a heat-producing nuclear reactor. In order to clarify this potential, this article deals with the following aspects: chemical cycles and thermal efficiency, nuclear fuel cycle economy, high temperature heat-producing reactors, and adaptations necessary for coupling with the thermochemical process.

2 CHEMICAL CYCLES

2.1 General Obervations Concerning Yields

We know that a sequence of chemical reactions, equivalent in overall terms to the decomposition of water, necessarily includes one or more endothermic steps and one or more exothermic steps. In order to maintain the endothermic chemical reactions at high temperature, heat needs to be added, and the exothermic reactions of the sequence liberate heat to a cold source. In order to complete a cycle in the thermodynamic sense, in other words, to return to the initial state, it is necessary to add to the sequence the reaction $H_2 + 1/2\ O_2 \longrightarrow H_2O$. This reaction may be effected reversibly in a fuel cell which supplies usable energy. This implies a cycle similar to that of a thermal power plant producing power from heat and featuring a theoretical yield which can be computed from the second principle /7,8/.

Cyclic thermochemical processes for water splitting which convert the heat into chemical energy held by the hydrogen, are fully comparable from the thermodynamic standpoint to electrolysis combined with an electricity-producing plant. The maximum "theoretical" yields are the same. The comparison must hence deal with the practical yields resulting from optimization, with due consideration of the additional investments required to reduce the irreversibilities /9, 10/.

For chemical cycles, an evaluation of the irreversibilities of thermal origin was carried out by means of a theoretical and general approach involving statistical values defining the energy content of intermediate compounds exploited /10/. For average values, it appears that the thermal yields of chemical processes are comparable to the net electrical outputs of electric power plants emplying the same nuclear reactors. The need to also consider the chemical irreversibilities (as compared with the irreversibilities of the electrolysis cell) leads to the consideration that the two systems, thermochemical and electrochemical, are closely comparable.

The properties of the reactions and compounds involved in chemical cycles can nevertheless have a substantial effect on losses due to irreversibilities in heat transfer, and each cycle must be subjected to a specific assessment of the energy balance, and must account for coupling with a specific heat-generating reactor and of the possibilities of internal heat recovery.

The results of estimates made for two thermochemical cycles are given in articles 2.2 and 2.3.

2.2 Iodine-Arsenic Cycle

This process, which includes four reactions, is based on the decomposition of water under the combined action of an oxidizing agent, iodine, and a reducing agent, arsenous oxide:

(1) $As_2O_3 + 2\ I_2 + 5\ H_2O \longrightarrow 2\ H_3AsO_4 + 4\ HI$

Reaction (1) is well known in an aqueous medium; however, in order to facilitate the separation of reaction products, it is better to work in a solvent, such as ethyl ether, in which the arsenic and hydriodic acids are slightly soluble. The arsenic acid precipitate is separated from the solution and then decomposed at 300 oC under the action of heat according to the following reaction:

(2) $2\ H_2AsO_{4_s} \longrightarrow As_2O_{5_s} + 3\ H_2O$

The solid arsenic pentoxide decomposes at 650 ^oC as follows:

(3) $As_2O_{5_s} \longrightarrow As_2O_{3_g} + O_2$

The arsenous oxide obtained in the gaseous state is separated from the oxygen and recycled to react with the water. Part of the arsenous oxide is obtained in the state of the gaseous dimer As_4O_6. Finally, the hydriodic acid is decomposed by heat in accordance with the following reaction:

(4) $4\ HI_g \longrightarrow 2\ H_2 + 2\ I_2$

The cycle reaction temperatures and the variations in enthalpy H and free enthalpy G (Gibbs function) are indicated in Table I. The reaction temperatures correspond to the possibilities of high temperature reactors due to be achieved in the relatively near future, as indicated in Chapter 3.

According to the thermodynamic data, the reactions of the sequence appear feasible. It should be stressed, however, from the kinetics standpoint, that the validity of the reactions still requires confirmation. In particular, an experimental study is necessary to determine whether reaction (1) can be realized at a sufficient rate in a suitable solvent.

As an example, we examined the coupling of the arsenic-iodine cycle with a nuclear reactor equipped with a secondary circuit in which the helium coolant is heated from 450 to 850 °C. The minimum temperature difference to ensure heat transfer is set at 50 °C. The enthalpy variations corresponding to the conversions occuring in the cycle were calculated: reactions, temperature rises and drops of reagents and products, as well as any phase changes. The enthalpy balance was prepared, accounting for the heat given up by the helium and received by the different steps of this chemical cycle, and for the heat recovered and exploited inside the chemical plant.

reaction number	temperature θ °C	$\Delta H\ \theta$ kcal	$\Delta G\ \theta$ kcal	observations
1	40	+ 4	*	suitable solvent, e.g. ether or carbon disulfide
2	300	+ 50.8	negative	atmospheric pressure
3	650	+ 78.4	- 1.8	
4	630	+ 24**	+ 3.1 x 2	40 atm pressure

* value unknown in ethyl ether, equal to -3 in water.

** the value of +24 was selected to calculate the enthalpy balance, but several authors give lower values.

The sign + indicates that the energy is supplied to the chemical system.
The sign - indicates that the energy is given up by the chemical system.

TABLE I: Characteristics of arsenic-iodine cycle reactions

Part of the sensible heat given up by the helium is not employed in the chemical process. This heat can be converted into electricity in an electric power plant connected to the installation. The overall efficiency of the process can be defined by the ration R:

$$\frac{\text{power produced in the form of hydrogen and electricity}}{\text{thermal power produced by the helium}}$$

By defining the energy contained in the hydrogen by the lower caloric value (57.9 kcal/mole) and assuming an efficiency of 33 % for the heat-electricity conversion, the efficiency R approaches 57 %.

In actual fact, this value cannot be achieved in practice, because the calculation fails to account for the chemical irreversibilities and energies required for the separation and flow of the products. However, it is interesting to note that, taking account of thermal irreversibilities, it is possible to find high efficiency chemical cycles, even for moderate maximum temperatures.

Various chemical cycles present the drawback of using toxic elements such as mercury, arsenic and other heavy metals, and corrosive compounds such as halogenated acids. In attempting to overcome this obstacle, we examined, from the thermodynamic standpoint, reaction sequences involving oxides of carbon and metallic oxides and carbonates. One cycle involving this family of compounds is the carbon-manganese cycle described in paragraph 2.3.

2.3 Carbon-Manganese Cycle

This cycle involves three reactions:

(1) $CO + H_2O \longrightarrow CO_2 + H_2$

(2) $3\ CO_2 + Mn_3O_{4s} \longrightarrow 3\ MnCO_{3s} + 1/2\ O_2$

(3) $3\ MnCO_{3s} \longrightarrow Mn_3O_{4s} + 2\ CO_2 + CO$

The feasible operating conditions are indicated in Table II, with the corresponding values of variations in enthalpy ΔH and free enthalpy ΔG.

The ΔG values which are negative and approach zero confirm the validity of the cycle from the thermodynamic standpoint. Reaction (1) is already implemented in industry. The kinetics of reactions (2) and (3) must be specified. The key reaction is the oxygen liberation reaction.

reaction number	temperature θ °C	pressure atm	ΔH kcal	ΔG kcal
1	500	40	- 9.8	- 3.4
2	60	100	- 27.2	- 0.16
3	600	9.7	94.9	- 8.5

TABLE II: Operating conditions for carbon-manganese cycle reactions

A first estimate of efficiency, made with the same assumptions and approximations as for the As-I cycle, gave the value of 38 %. A more accurate estimate, taking account of the energies required for separations and recyclings of the gases, was made on a detailed basis, with special attention paid to energy recovery. The value calculated in this case was 35 %.

2.4 Discussion

The example of the arsenic-iodine cycle confirms that efficiency is not directly dependent on maximum temperature; it shows that, at least in relation to thermodynamic estimates, a promising efficiency level can be obtained for a maximum coolant temperature in the neighbourhood of 850 °C, which is an accessible level. However, some of the intermediate compounds are toxic or corrosive. The carbon-manganese cycle does not feature this disadvantage, but the gas separations are liable to lead to prohibitive energy consumption. By organizing the heat recovery in a suitable manner, it is still possible to reach a satisfactory yield. This result does not appear to have been achieved at the cost of an inconsiderable increase in the ratio of total power exchanged in the chemical process to the power produced in the form of hydrogen, this ratio being equal to 5. These initial indications are encouraging for further work in the area of chemical processes.

Adequate information is not available to select a chemical process on which efforts should be concentrated. Hence it is advisable to continue general investigations of cycles on the basis of existing thermochemical data. The main criteria for an initial selection are affinity for chemical reactions, the approximate heat balance, and the temperature level which depends on the nuclear reactor and which is discussed in Chapter 3.

For selected chemical cycles, two activities may be undertaken simultaneously:

- Experimental verification that the reaction rates involved are sufficient for industrial application, and that any disadvantages caused by spurious reactions are not insurmountable,

- Preparation of estimates covering the overall process in order to determine the various energy losses and efficiency, and to assess the possibilities of application from the materials compatibility technology and chemical engineering standpoints.

3 USE OF HIGH TEMPERATURE REACTORS (HTR)

3.1 Reasons for Choosing HTRs

How can thermochemical processes use heat of nuclear origin?

The temperature level required eliminates light water reactors and fast neutron reactors currently on the boards. However, the latter, subject to core modifications, can give sodium temperatures of 700 °C, an ultimate possibility.

In this case, the coupling with a thermochemical process is not inconceivable, to the extent that one of the rare cycle featuring a high temperature of 650 °C is shown to be viable with a good yield.

However, the most attractive possibilities are those of high temperature nuclear systems involving either helium or molten salts. Molten salt reactors are in the stage of preliminary studies and basic experiments: no power prototype has yet been planned. On the other hand, helium reactors are close to an industrialization phase, and a 330 MWe demonstration plant (Fort Saint Vrain, United States) is in the process of startup. Electricity-producing helium reactors today supply primary calories at the core exit at 750 °C. Plans for helium turbines call for core design involving a temperature of 815 °C at least. Currently developed technology is expected to reach 850 °C, and the next step should lead to a level exceeding 900 °C.

In the current context, helium reactors consequently constitute the most promising means for hydrogen production by means of nuclear energy, and in practice they are the only ones to have been subjected to adaptation studies for this purpose. The following pages summarize their possibilities and provide observations on certain specific aspects of their coupling to a thermochemical unit of the type considered.

3.2 Fuel Cycle Economy

The massive production of hydrogen from nuclear energy poses the problem of long-term consumption of natural uranium. Whereas for the production of electricity the long-term solution presumes recourse to breeder reactors which lead to a considerable decrease in natural uranium consumption, the production of hydrogen appears to be feasible by HTRs alone, which are not breeders.

This problem can be remedied by improving the conversion factor.

Table III summarizes consumption figures of natural uranium over a 40 year period for different HTR core design intended to increase the conversion factor by the use of semi-annual refueling, an increase in the thorium load, and a decrease in power density, a factor which will also enhance the achievement of high temperatures. Assuming a hydrogen production yield of 50 %, the consumption of natural uranium would be 5 T/Gth; for the production of hydrogen by electrolysis using a PWR reactor, assuming an electrolysis yield of 80 %, this figure would be about 40 T/Gth. In the case of HTRs, it is necessary to add 0.4 T thorium/Gth, which can be reused after about ten years of storage.

In the longer term, resorting to a hybrid system employing a breeder reactor with a thorium blanket producing uranium 233 for use in the HTR, can be considered. A 1000 MWe breeder reactor with a conversion factor of 1.45 can supply three 3000 MWt HTRs with a conversion factor of 0.85 /12/. Hydrogen production would be effected from the thorium only, and consumption, assuming recycling of all products, would be on the order of 0.1 T/Gth.

Reactor type	uranium requirement for 40 years tons of U_3O_8/MWe	conversion factor
PWR: HTR type GA	6.8	0.61
. HTR type GA 8.4 MW/m^3 C/Th = 230	3.7	0.66
. same with semiannual refueling	3.2	0.71
. same C/Th = 180	2.7	0.76
. same P = 4 MW/m^3	1.5	0.88

TABLE III: Natural uranium consumption for different types of high temperature reactor

3.3 Core Design

In current electricity-producing HTRs of the General Atomic type, the mean helium outlet temperature is 750 °C, for a mean fuel temperature of 890 °C and a maximum temperature of 1400 °C. Several parameters may be adapted to obtain a higher helium temperature, while maintaining the current fuel technology.

The first parameter involves the reactor inlet temperature. The choice of this temperature is fairly wide if, as will be seen later, one uses an intermediate helium circuit between the reactor and the chemical plant. Fig. 1 illustrates the variations in outlet temperature as a function of power density for different inlet temperatures, for a maximum fuel temperature of 1400 °C. It can be seen that a gain of 100 °C is achieved in the outlet temperature for an increase of 200 °C in the inlet temperature.

A second parameter concerns power density. Several factors argue in favour of reducing the power density of 8 MW/m^3 of current electricity-producing reactors to 4 to 5 MW/m^3. As shown in the article 3.2, this would immediately lead to high conversion factors and hence low raw material consumption. As shown in Fig. 1, the helium exit temperature can be increased by about 50 °C when going from 8 to 4 MW/m^3. The pressure drop is also considerably decreased.

The third parameter concerns power flattening within a blowing region, which can be improved by a better layout of control rods and by decreasing the age factor, which can be achieved by using high thorium loads, which also have the advantage of increasing the conversion factor. Fig. 2 shows the variation in outlet temperature as a function of power density for two flattening values 1.25 and 1.65, and indicate the degree to which this parameter is sensitive.

In conclusion, current fuel technology makes it possible to reach helium outlet temperatures of about 1000 °C, provided one selects a low power density of 4 to 5 MW/m^3, a helium inlet temperature of about 500 °C, and good power flattening within a blowing region.

3.4 The Need for an Intermediate Helium Circuit

It is obviously tempting to couple the chemical plant directly with a nuclear reactor without using an intermediate circuit, which implies a significant price increase, a process temperature loss of about 50 °C, and an increase in power consumption required by supplementrary blowing.

The use of an intermediate circuit is mainly associated with the problem of hydrogen contamination in normal and accidental operation. At the outset it is important to define the permissible contamination, knowing that the hydrogen may be consumed in domestic applications, and thus distributed throughout the country, or in a very concentrated manner in chemical plants, thermal power plants etc. In view of this fact, it appears reasonable to presume that the activity picked up by the hydrogen will be limited to the permissible value in radioactive wastes of a nuclear power station of the current generation. As an example, this leads to limiting the activity of iodine 131 to a value of $6 \cdot 10^{-12}$ Ci/m^3 of hydrogen; this value is far lower than the maximum allowable concentration for the public, which is $3 \cdot 10^{-10}$ Ci/m^3.

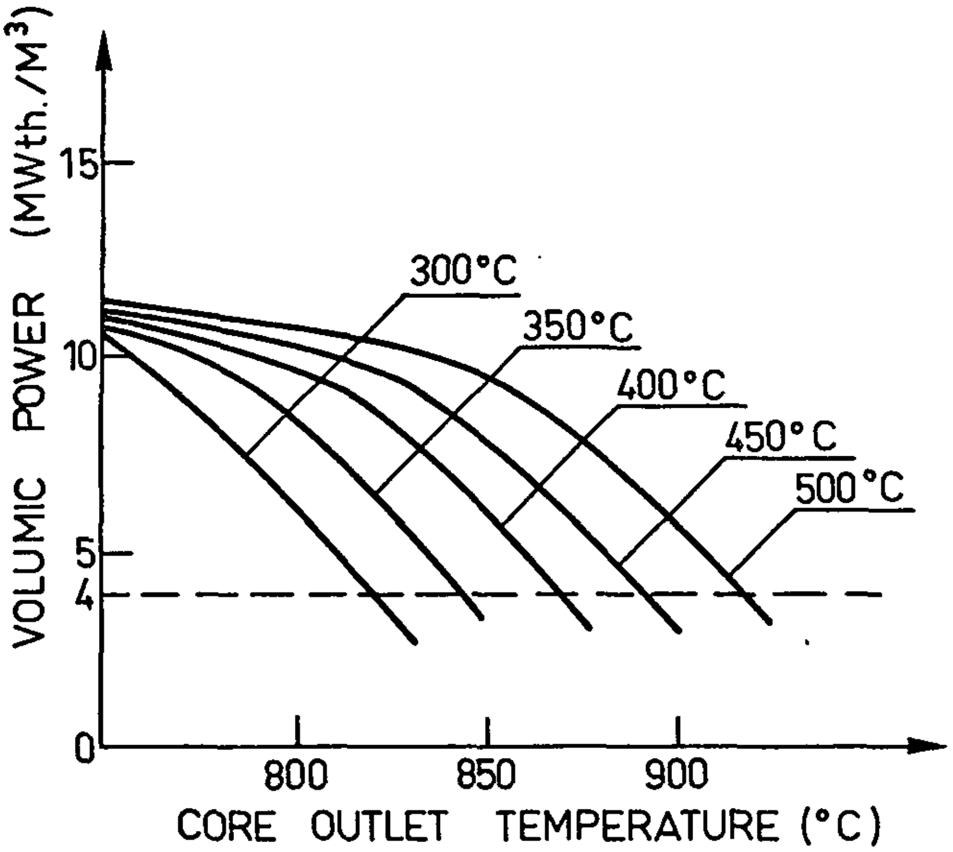

FIG. 1: Influence of the helium inlet temperature on the outlet temperature

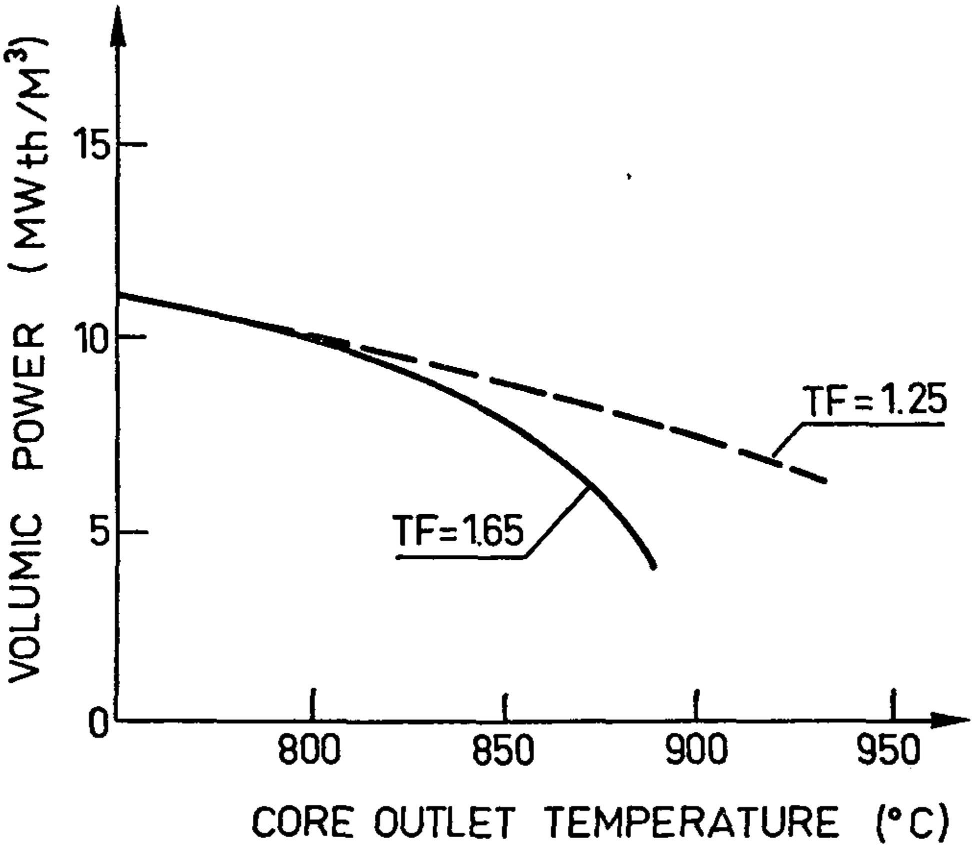

FIG. 2: Influence of the tilt factor (T.F.) on the outlet temperature

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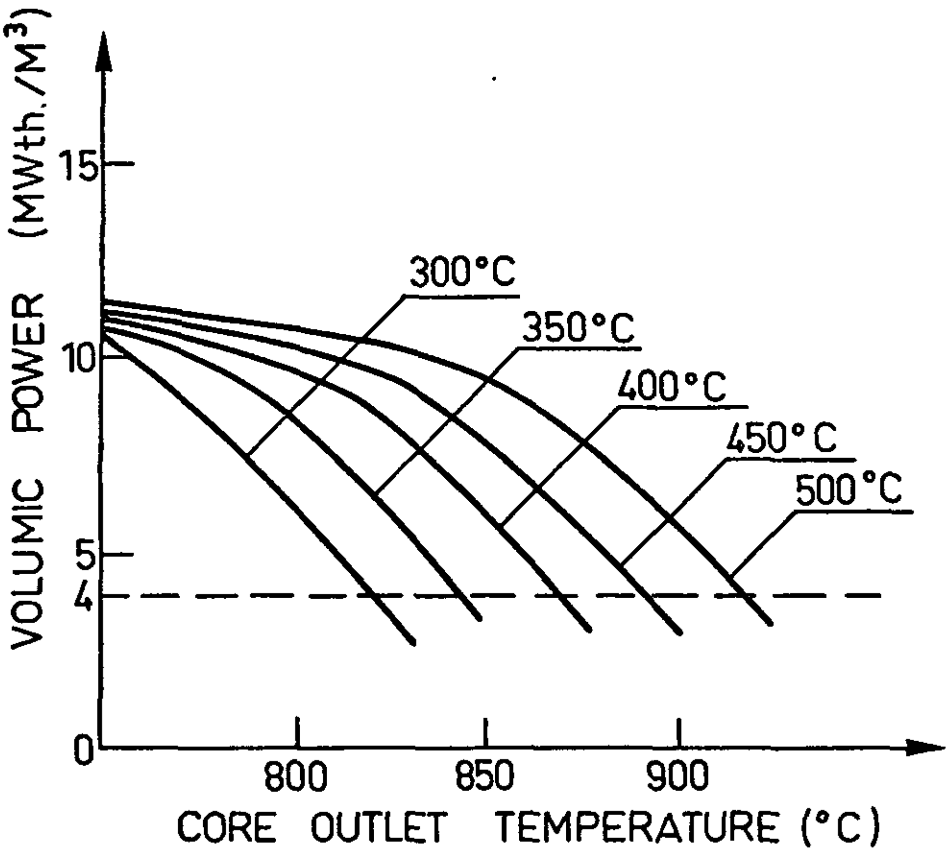

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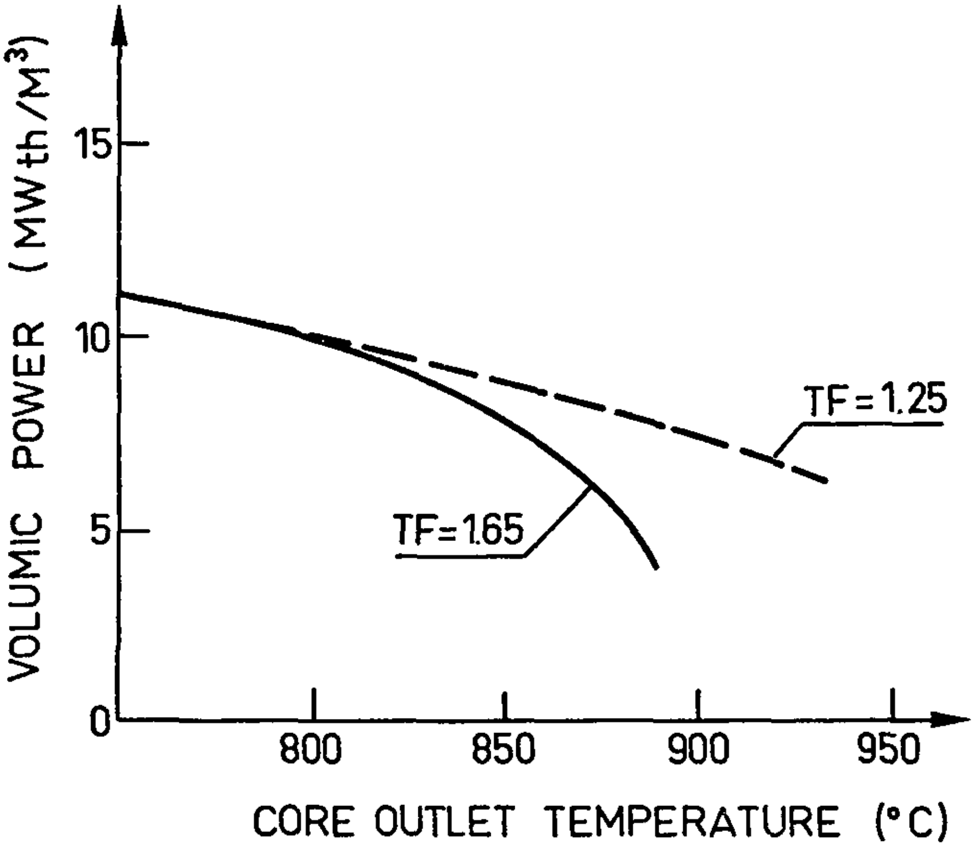

FIG. 2: Influence of the tilt factor (T.F.) on the outlet temperature

The adoption of these severe standards appears necessary to ultimately persuade the public to consume nuclear hydrogen and to guarantee that this type of hydrogen production effectively fails to involve any danger.

The problems of hydrogen contamination by fission products also depend on the types of reagent employed in the chemical cycles. If gas phase reagents are employed at a pressure greater than the reactor helium pressure, it is perhaps unnecessary to use an intermediate circuit, provided that the chemical circuit is isolated by means of quick-closing gastight valves, a matter which raises certain technological problems.

Unfortunately, in most chemical cycles considered for hydrogen production, many reagents are solid, practically eliminating the possibility of gastight isolation of the circuit, and the pressures of gas phase reagents are often lower than the reactor pressure, leading to leaks of fission products from the primary reactor circuit to the chemical plant. A study made with these hypotheses /13/ shows that radioactive wastes in normal and accidental operation are significantly higher than the standards previously established in case of direct coupling of the reactor with the chemical plant. The main problems were caused by iodine-131 in normal operation, with wastes twenty times higher, and strontium-90 in case of heat exchanger fracture, leading to wastes fifty times higher. A valid question is that of the design of the *intermediate circuit intended to play the role of a supplementary barrier* to fission products.

The first criterion is concerned with the leakage of fission products in normal operation. It has been shown /13/ that the ratio permissible between the activity of the secondary circuit and that of the primary circuit is 0.42 for tritium, 0.01 for cesium-137, and 0.002 for strontium-90. This indicates that the use of carbon bearing materials which arenot gastight, but have high retention power for metallic fission products, can be considered, provided that one employs a secondary circuit helium pressure slightly greater than the primary circuit pressure. The gastight level required depends on the flow rate in the purification circuit for primary helium which is reinjected into the secondary circuit.

The second criterion involves the behaviour of the exchanger in case of secondary circuit fracture. In effect, the secondary circuit plays the role of a barrier against fission products, and the fracture of this barrier must not lead to fracture of the He-He heat exchanger. If this occurs, it will be necessary to isolate the secondary circuit by gastight valves at high temperature but operating in helium.

4 SOME CONSTRUCTIONAL ASPECTS OF COMPONENTS OF AN HTR WITH SECONDARY HELIUM CIRCUIT

Proceeding from the above, we may mention three components which drew our particular attention in our deliberations concerning heat-producing HTRs coupled with industrial units. These components are the following:

- intermediate heat exchangers,
- primary circuit gas circulators,
- auxiliary cooling loops.

4.1 Intermediate Heat Exchangers

The previous chapter demonstrated the virtual necessity of satisfactory separation between the primary circuit fluid liable to convey fission products and the secondary circuit fluid which flows through the chemical plant. The system must therefore include a group of intermediate heat exchangers ensuring both this separation between the fluids and also heat transfer.

It has often been stated that metallic heat exchangers are feasible up to a temperature level lying between 800 and 900 °C. We are in a position to provide indications concerning particularly metallic intermediate heat exchangers, thanks to a study made by the company CCM-Sulzer (Paris) for the CEA and Technicatome. The value of this feasibility study lies in its industrial character and in its technical data.

The operating conditions of the unit investigated are the following:

	primary helium	secondary helium
- high temperature	800 °C	750 °C
- low temperature	374 °C	239 °C
- mean pressure	40 bars	45 bars
- total helium flow rate	472 kg/s	393 kg/s
- power exchanged	1043 MW	
- number of units	4	
- required service life	100,000 hours	

The heat exchanger is shown in Fig. 3. It is subdivided into a large number of modules so as to avoid thick, large dimension tubesheets. The cold manifolds connecting the upper part of each module to the "cold" penetration are distributed at the periphery, and provide support for the tube bundle; the hot helium flows upwards from the bottom outside the tubes, while the cold helium flows from top to bottom inside the tubes.

The material employed is Incoloy-800, for which the required servide life leads to allowable stresses of 1.4hbar in the hottest, most highly stressed zones. Other materials are suitable for higher operating temperatures. Behaviour in case of depressurization was examined.

The overall unit is integrated in a prestressed concrete pressure vessel, laid out in a 4 m diameter cavity. The bundle heat exchange length is 7.5 m. It should be stressed that a heat exchanger of this type is laid out in the cavity in the same manner as a steam generator; hence the same architectural principles are employed in this area.

4.2 Motor-Driven Gas Circulators

The primary circulators are responsible for creating primary helium flow through the core and the intermediate heat exchangers. As mentioned above, the company CCM-Sulzer (Paris) carried out a feasibility study of these machines.

For the system in question, motor-driven gas circulators, namely, circulators driven by an electrical motor, were naturally adopted.

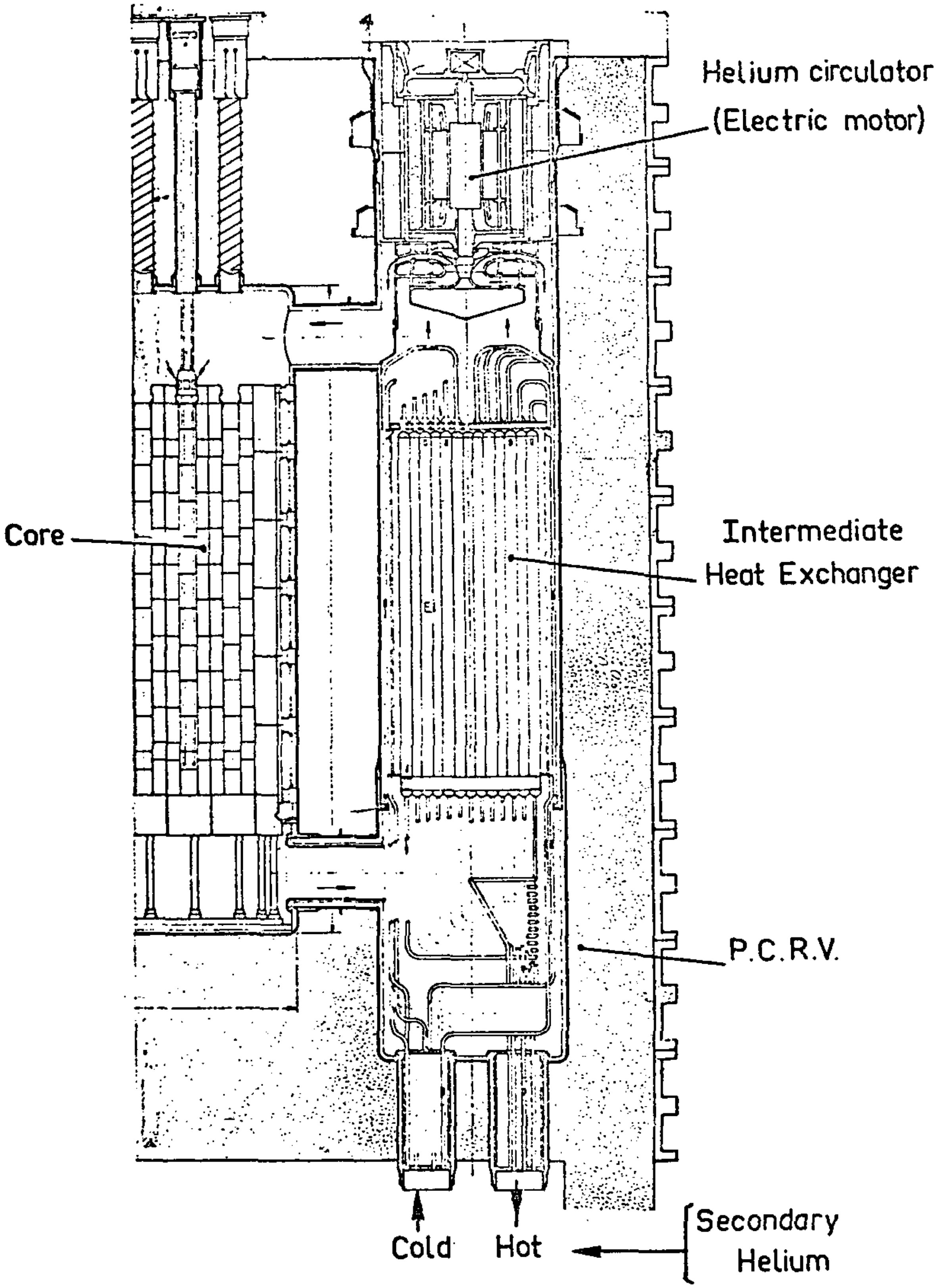

FIG. 3: Intermediate heat exchanger and helium circulator in a PCRV cavity (CCM-SULZER, Paris, study)

The main characteristics of the machines are the following:

- suction temperature	380 °C
- helium flow rate	122 kg/s
- discharge pressure	40 bars
- overpressure	0.90 bar
- speed of rotation	3000 r.p.m.
- power consumption	4.6 MWe
- impeller diameter	1.33 m

With an "open" centrifugal impeller of a suitable material, it is possible to ensure helium flow at temperatures exceeding 400 °C.

This machine is also shown in Fig. 3. Similarly to the circulators of steam cycle high temperature reactors, it is placed above the intermediate heat exchanger, on the main plug blocking the cavity. Similar to the intermediate heat exchanger (article 4.1), a traditional type of assembly is shown here. Rotation is provided by a suitable combination of axial gas bearings and an upper oil type thrust bearing separated from sensitive areas and readily accessible. The speed of rotation is adjustable, thanks to variable frequency power supply.

In conclusion, the feasibility of the primary circulators for heat-producing applications is confirmed.

4.3 Auxiliary Cooling Systems

Owing to the increased outlet temperature in reactors intended for high level heat production or hydrogen production, it is probably advisable to define a satisfactory auxiliary cooling system, as current systems are likely to prove inadequate for the new conditions.

A study has just been completed in this area and Fig. 4 provides an initial illustration.

A system of this type must perform the following functions:

- emergency cooling,
- shutdown cooling,
- diminution of substantial temperature variations in internal structures (main circuit configuration comprising gas-gas heat exchangers and not steam generators containing significant quantities of water),
- cooling of some structures thanks to the presence of a permanent cold gas source,
- trapping of some fission products in the coldest zones.

It is distinguished by continuous operation and by auxiliary energy production, as a rule in the form of steam employed directly for heat requirements or for supplementary electricity production. The steam generators concerned operate at moderate temperatures and pressures, downstream from a heat exchanger-recuperator.

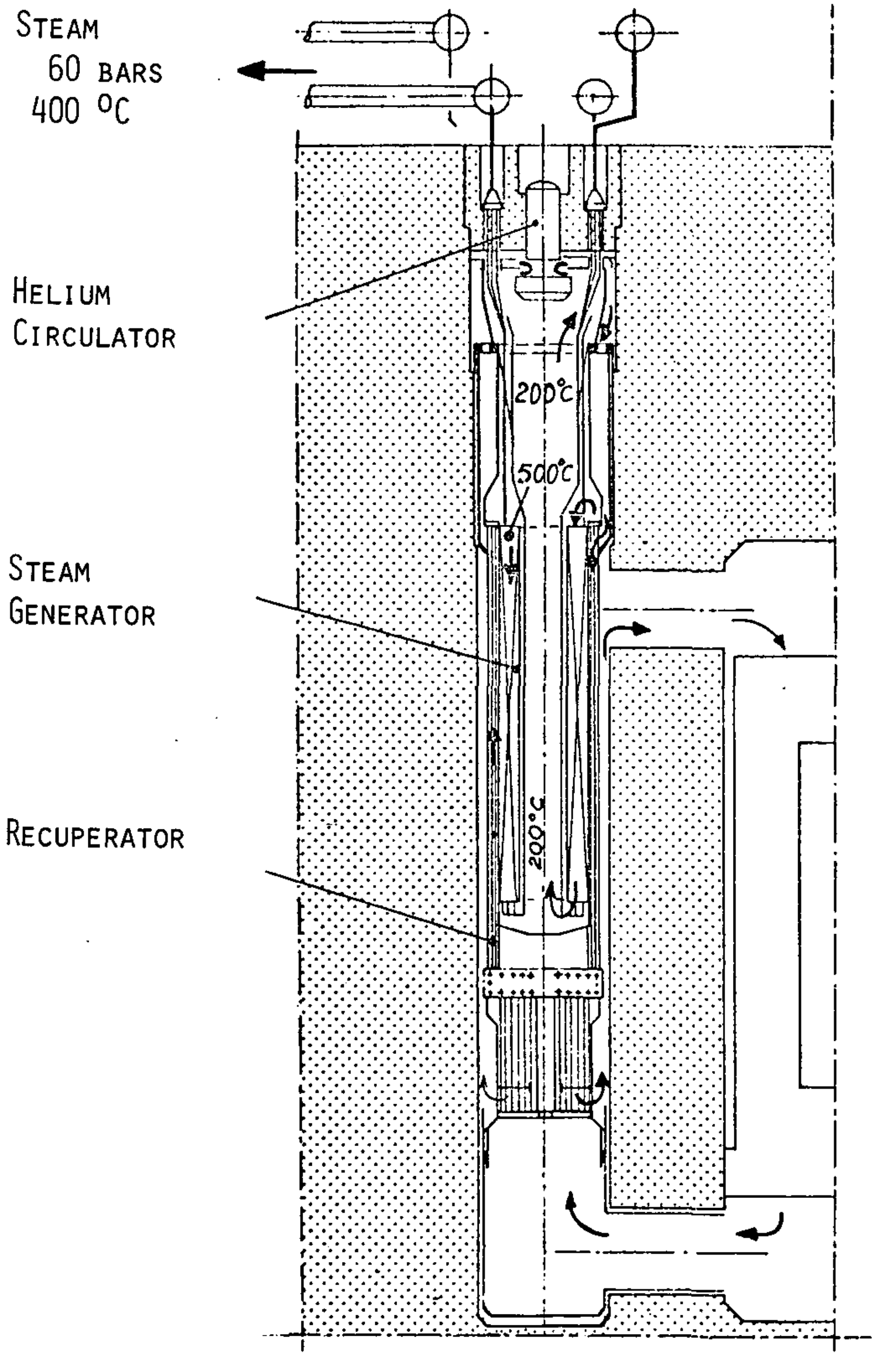

FIG. 4: Auxiliary Cooling Loop with Recuperator and Steam Generator for H.T.G.R.

5 CONCLUSIONS

The new specifications associated with coupling helium reactors to chemical hydrogen production plants are essentially concerned with heat transfer from the nuclear core to the chemical reactors. The fuel developed for electricity production, most of the internal structures, the pressure vessel, circulators and blowers can be maintained approximately in their current configuration. The research effort should be directed into two areas of equal importance:

(1) The chemical cycle:
  - kinetics of chemical reactions,
  - energy and material balances,
  - chemical engineering (design and technology of reactors and separators),
  - choice of materials.

(2) Heat transfer:
  - intermediate heat exchanger,
  - hot piping and associated valves,
  - thermal insulation,
  - migration and trapping of fission products,
  - material problems,
  - operation and safety (emergency cooling).

Only by moving simultaneously towards both these objectives can the best solution be found for thermochemical hydrogen production. At the present time, it is too early to select a chemical cycle for subsequent industrial development. Investigations undertaken concerning the intermediate heat exchangers and the secondary circuits make it possible to orient investigations relating to chemical processes, by setting a maximum secondary helium temperature of about 850 °C in an initial stage, and 950 °C in the longer term. The question as to whether the thermochemistry-HTR complex will be competitive vis-à-vis electrolysis cannot be answered conclusively today. Too many unknowns prevail on the subject of practical cycle yields and concerning the investment in the chemical plant and the intermediate circuit. Current estimates show that the complex offers the advantage of high uranium use efficiency, encouraging further investigations. If, following an initial research phase, a decision is taken to develop the process, it would be necessary to create relatively high financial commitment and set up a relatively long period for work, both comparable to those which distinguished the development of a given type of nuclear reactor. It is desirable that the exchanges and, in certain cases, collaboration, which have been evidenced between countries interested in resorting to the hydrogen carrier and nuclear energy, should continue actively.

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THERMOCHEMICAL PROCESSES FOR WATER DECOMPOSITION

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The activity on thermochemical water splitting started at the Ispra Establis ment of the Joint Research Centre few years ago when it was recognised that another energy carrier, beside electricity, was necessary in order to allow nuclear energy to take over, in the medium or long term, the role of primar energy source now played by oil and natural gas.

The development of HTRs with the increasing outlet temperature of the heliu coolant was the motivation for starting research on thermochemical water splitting processes, that are able to use in an efficient way the high grad heat, and potentially better than other energy conversion systems.

After the first cycle studied at that time (1969) a certain effort has been spent on iron-chlorine cycles, whose appealing features are the low cost of the constituents and the fact that the products involved are already familiar to the chemical industry, and on sulphur compounds cycles.

Quite recently we were convinced that the iron-chlorine cycles very unlikel can produce hydrogen at a competitive price, essentially for the presence o the very inefficient step of the iron trichloride thermal decomposition.

Our activity is now concentrated on sulphuric acid cycles, even if a little effort is still devoted to the search of other possible alternatives.

The cycles based on the decomposition of sulphuric acid are particularly at tive because in this step a major portion of the energy necessary for the w ter decomposition can be fed into the chemical system. We are studying thre different alternatives for closing the cycle containing the sulphuric acid decomposition: these alternatives are the cycles Mark 11, Mark 13, and Mark

The reactions of <u>Mark 11</u> are the following:

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

$$SO_2 + 2\ H_2O \longrightarrow H_2SO_4 + H_2$$ electrolytic reactio

This cycle is often referred to also as the Westinghouse cycle.

<u>Mark 13:</u> $H_2SO_4 \longrightarrow H_2O + SO_2 + 1/2\ O_2$

$$SO_2 + 2\ H_2O + Br_2 \longrightarrow H_2SO_4 + 2\ HBr$$

$$2\ HBr \longrightarrow Br_2 + H_2$$ electrolytic reactio

<u>Mark 16:</u> $H_2SO_4 \longrightarrow H_2O + SO_2 + 1/2\ O_2$

$SO_2 + 2\ H_2O + I_2 \longrightarrow H_2SO_4 + 2\ HI$ in liquid SO_2

$2\ HI \longrightarrow I_2 + H_2$

We got already a good amount of results on the thermal decomposition of the sulphuric acid. The decomposition of gaseous SO_3 diluted with an equimolar amount of inert gas is achieved almost to the equilibrium composition at 810 °C (about 76 %) with a volume of catalyst about half of what is needed for the synthesis of an equivalent amount of sulphuric acid.

The electrolytic decomposition of aqueous concentrated solutions of hydrobromic acid, the key reaction of Mark 13, is the object of an intensive study for finding suitable electrodes. Apart from noble metals, graphite electrodes seem to show acceptable voltage-current density relationship. As the reaction between sulphur dioxide and bromine is relatively easy, a direct comparison between Mark 13 and Mark 11 cycles can be made on the basis of the performances and the costs of the electrolytic cells.

The key problem of Mark 16 cycle is the separation of sulphuric from the hydroiodic acid and the formation of enough concentrated acids. These two goals are achieved by using liquid SO_2 as solvent in which HI is soluble, but H_2SO_4 is insoluble, and with addition of suitable products capable of complexing the HI in the SO_2 phase.

Another part of our activity is related to the behaviour of construction materials in the chemical environment foreseen in these cycles. Screening tests are made in order to know the importance of material problems and the class of materials that can be used. We have results of corrosion tests up to some thousands hours. This enables us to have to data for a rough estimate of the plant cost.

Engineering studies are also made on relatively simple flow-sheets, in order to evaluate the mass and thermal balance. With a suitable computer code it is possible to optimize the internal heat recovery and, taking into account also the work of compression of gases, to obtain a figure of the thermal efficiency. The various input data can be dealt with as parameters, in order to make sensitivity analysis; by this way we can identify the key points of every system and obtain useful indication for the orientation of the experimental work.

From the thermal efficiency, the primary heat cost and the estimated plant cost it is also possible to estimate the cost of the product hydrogen.

CONFERENCE SUMMARY

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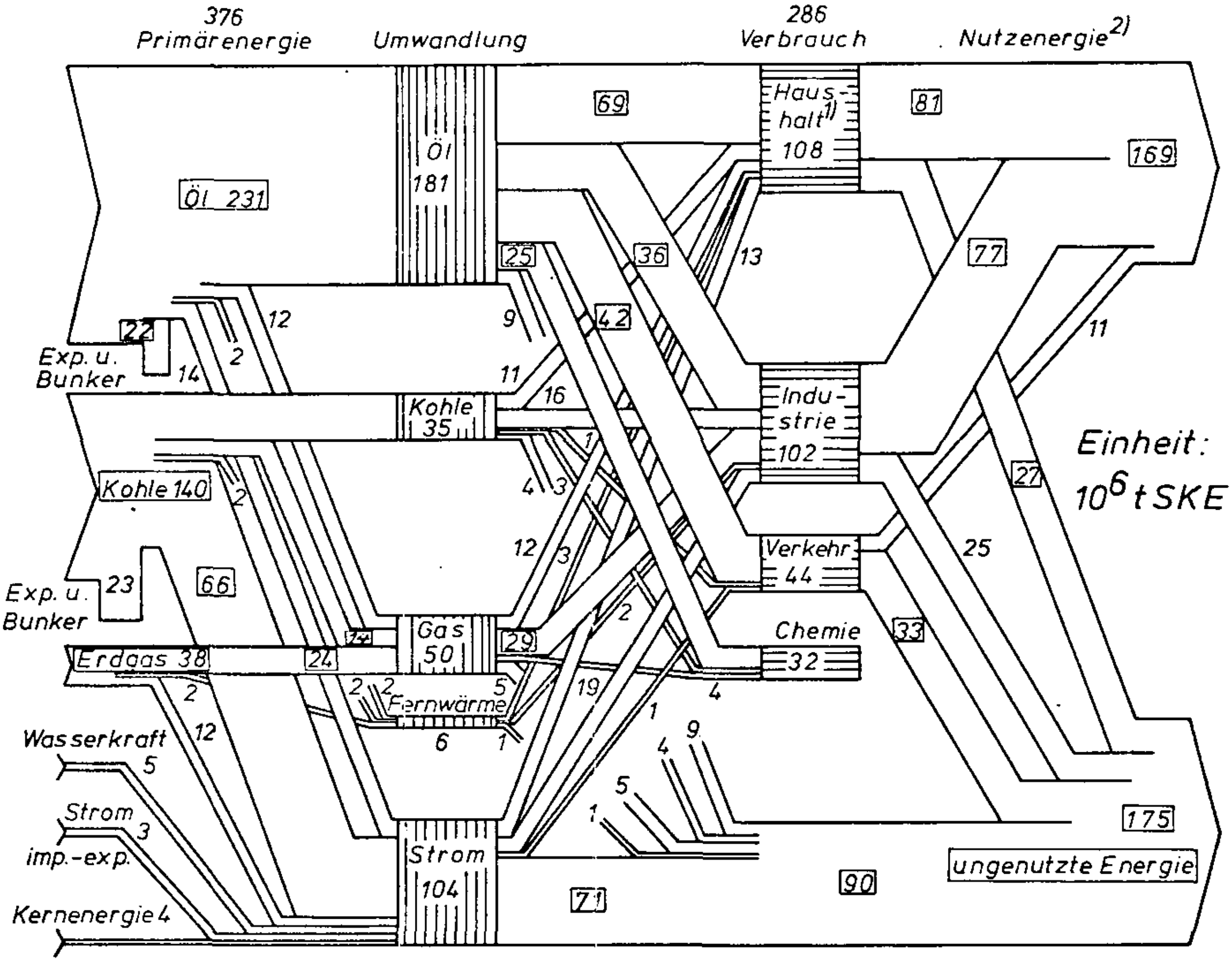
I have the honour and the burden to summarize this conference on Nuclear Energy Applications other than Electricity Production. I will not repeat what had been said by the excellent speakers during this conference. It might be of more interest to point out some problems which are common to all the promising concepts and ideas which had been mentioned.

Most of you are familiar with the scheme (see figure 1) showing for the year 1972 the energy balance of the Federal Republic of Germany. The energy situation in the European countries may differ in details but the basic problems are more or less the same. In the left the diagram shows the amount of different primary energy sources which are used. In the middle the energy conversion is listed and the right gives the consumption of energy.

One can read from this graph that only 11 % of the energy is used in form of electricity. The rest is the principal potential for the nuclear energy applications other than electricity production which is the topic of our conference. In the future the use of electricity will increase but the increase will be limited for a number of different reasons. One of the reasons for the limitation might be the distribution. A short time ago in Southern Germany we had a very serious black-out. The most important reason for this black-out which had been mentioned was that the construction of a large transmission line was delayed due to interveners. This means that we are not very far from the possible limits of extension of air transmission net work. If one would assume for the end of the century the use for electricity to a high percentage like 40 % and takes into account a very moderated increase in the total energy consumption only, the capacity of the net work would have to be increased by a factor of 5 or more. I doubt if this will be possible.

From the energy graph we can read quite clearly the very high dependence on oil which is common for all European countries.Talking about non-electric application of nuclear energy means talking about reduction of dependence in oil. None of the difficult applications which have been discussed during this conference will be able to reduce the dependence on oil sufficiently alone. The question is not which is the best application, the problem is how to bring as many as possible of the promising ideas we discussed as soon as possible to reality.



1) Haushalte und Kleinverbraucher 2) Nutzenergie = Energie, die dem Endverbraucher zur Nutzung zugeführt wird

Energy balance 1973 of the Federal Republic of Germany

We have seen that the principal overall potential of the applications of nuclear energy is very, very large. But probably none of these applications will be able to pay alone for the very high costs of development, introduction into the market and the bluid-up of the necessary infrastructure. Mr. Barnes has pointed out this very clearly and I believe that is true for all applications. For this reason we have a very strong interdependence of all different applications and we have to include in these contexts also the electricity production. All applications are using the nuclear reactor development, experience and economical background of the electric power stations and all expenditures which have been made already or will be made in the future of the electrical application.

Looking on the list of applications we have discussed during this conference:

steam for industrial application,

coal gasification,

steel production, metallurgy,

use of waste heat (district heating),

desalination,

transport of chemical bound energy,

hydrogen production.

We can divide for example in applications which need the high temperature reactor and applications which could use any reactor type.

high temperature reactor:	any reactor type:
coal gasification,	steam production,
steel production,	waste heat,
transport of chemical bound energy,	desalination
hydrogen production	

Or we can look for the interdependence due to the same infrastructure.

pipe-line system:	hot water and steam distribution:
coal gasification,	steam for industry,
steel production,	waste heat,
transport of chemical bound energy,	transport of chemical bound energy,
hydrogen production	hydrogen production

The consequence of this is: The development and optimalization for one application can not be made independently from the others. I would like to give some examples for this.

The installation of a district heating system infrastructure should be flexible with respect to the feed possibilities. It should be possible to feed such a system either with waste heat from power stations or with only heat producing power stations or with the system of chemical bound energy transport. Having this in mind it leads to boundary conditions as well for the infrastructure system itself as for the different applications.

For the HTR it is important to realize that for the development and introduction into the market both electricity production and process heat application have to help each other. The consequence is that the concepts for the plants should be as similar as possible for both applications to make use as far as possible of the expenditures for development and market introduction from both sides.

The gas composition for iron reduction can be varied in certain limits. The dependence during the development and introduction phase from other related applications leads to additional boundary conditions for the development of the reducing process vice versa.

During this conference we have seen that the potential of non-electric applications of nuclear energy is in principle very large. We have also heard that in many cases the future cost and price estimates are rather promising in some cases even for today. But we have to be aware that for any application which will contribute to a real percentage to the energy market in any case there is a need of a large infrastrucutre. To build up such infrastructures is a long term problem. Mr. Margen has mentioned some of the aspects which has to be taken into account. Political, sociological and legal questions will play an important role. Decisions have to be made very early. We have to face the problem to convince the people to make the necessary decisions early enough and in the right direction.